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Technology Administration

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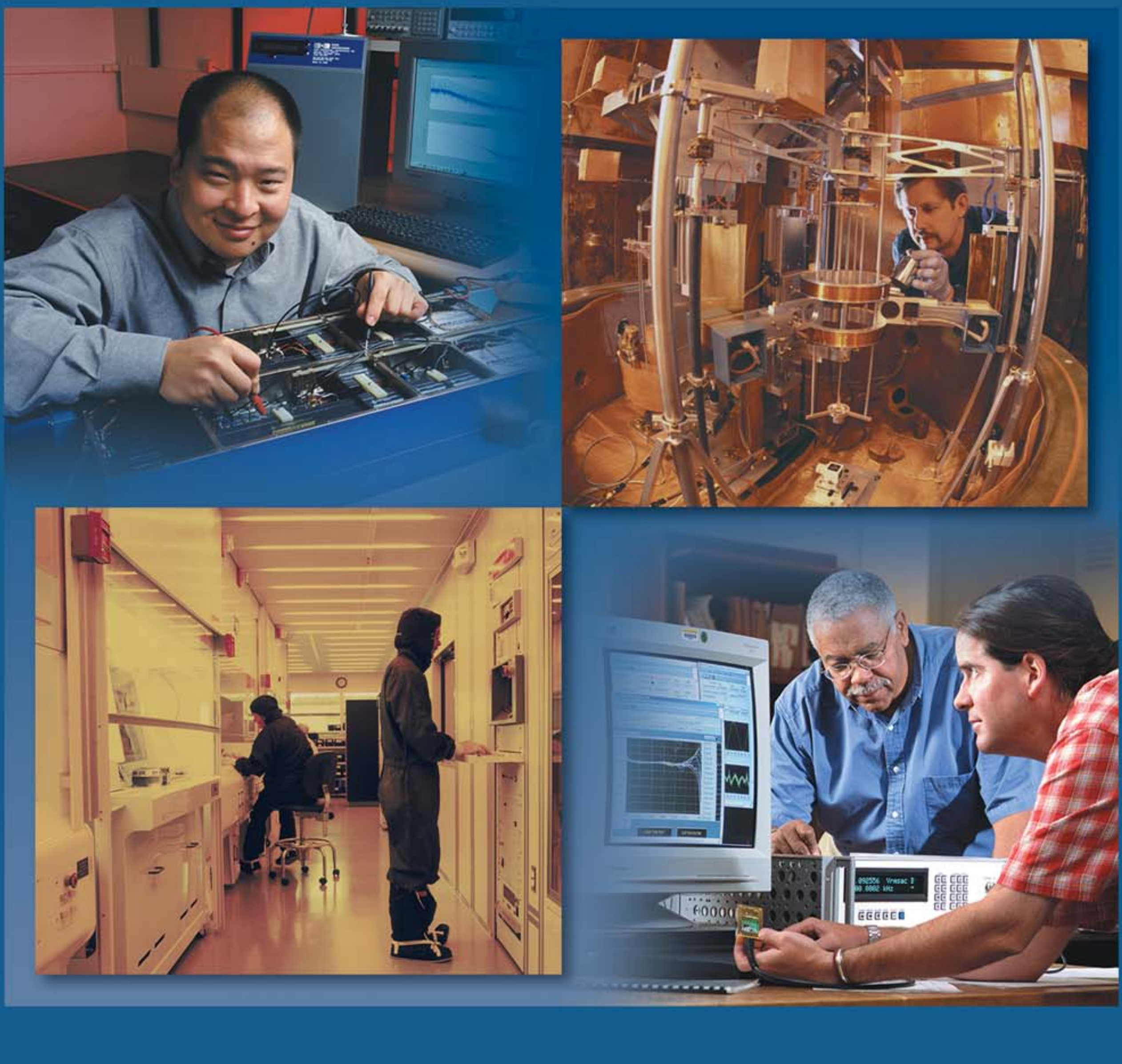
January 2005

Electronics and Electrical Engineering Laboratory

Quantum Electrical Metrology Division

Programs, Activities, and Accomplishments



THE ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

One of NIST's seven Measurement and Standards Laboratories, EEEL conducts research, provides measurement services, and helps set standards in support of: the fundamental electronic technologies of semiconductors, magnetics, and superconductors; information and communications technologies, such as fiber optics, photonics, microwaves, electronic displays, and electronics manufacturing supply chain collaboration; forensics and security measurement instrumentation; fundamental and practical physical standards and measurement services for electrical quantities; maintaining the quality and integrity of electrical power systems; and the development of nanoscale and microelectromechanical devices. EEEL provides support to law enforcement, corrections, and criminal justice agencies, including homeland security.

EEEL consists of four programmatic divisions and two matrix-managed offices:

Semiconductor Electronics Division

Optoelectronics Division

Quantum Electrical Metrology Division

Electromagnetics Division

Office of Microelectronics Programs

Office of Law Enforcement Standards

This document describes the technical programs of the Quantum Electrical Metrology Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS 8100, Gaithersburg, MD 20899-8100, Telephone: (301) 975-2220, On the Web: www.eeel.nist.gov

On the cover (clockwise from upper left): Sae Woo Nam tests electronics for Johnson noise thermometry; Richard Steiner works on the watt balance; Robert Palm (left) and Bryan Waltrip (right) examine test data; and staff fabricating nano- and micro-electronic devices in the Boulder fabrication facility.

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U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Hratch G. Semerjian, Acting Director

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Welcome

The Quantum Electrical Metrology Division was created in November, 2003, with the merger of the Electricity Division in Gaithersburg, Maryland, and the Electromagnetic Technology Division in Boulder, Colorado. The Electricity Division brings a proud 100-year history of precise electrical measurements. The Electromagnetic Technology Division brings a younger 35-year history of creating world-leading quantum-based standards and measurements. The new division was formed to emphasize interdependence of the Electricity Division's use of the Electromagnetic Technology Division's quantum standards. The combined division unites fundamental electrical metrology and leading-edge quantum-based metrology research to create a dynamic organization poised to lead quantum metrology into the future.

This document is organized into two main sections, Quantum Standards, and Quantum Measurements. Within those sections each Division project is described without reference to its geographical location. Appendix C describes the organizational location of all the projects we present. In addition Appendix D is a Division staff list for readers wishing to phone or e-mail us more about a topic.

By creating this new merged division, it is our intention to serve our customers better than ever. We appreciate your interest and welcome your comments. We also invite you to visit our web page at http://www.eeel.nist.gov/817/.

James K. Olthoff

Quantum Standards

At the National Institute of Standards and Technology our ultimate objective is to create what we call intrinsic standards. As part of the Electronics and Electrical Engineering Laboratory the Quantum Electrical Metrology Division concentrates primarily on intrinsic electrical standards. Such standards can be widely used by any careful operators to give results that are ultimately as accurate as those produced within NIST by our expert metrologists.

An intrinsic standard that is based on quantum effects is particularly attractive. Such effects offer tiny rulers permitting counting the number of quanta that make up a quantity to be measured. The quantum effects we use are the counting rate of flow of superconducting flux quanta or the much larger resistance quanta in the quantum Hall effect. We are also developing techniques for counting individual electrons. All of these effects occur at very low temperatures close to absolute zero.

Other organizations at NIST use atomic transitions to measure time and frequency of the wavelength of light from a certain laser to measure length.

Quantum Standards

Quantity	Quantum	Magnitude
Voltage	Magnetic flux quantum	$h/2e$
Current	Single electron	e
Resistance	Resistance quantum	e^2/h
Time and frequency	Atomic transition of a Cs atom	9.192631770 GHz
Length	Wavelength of a HeNe laser	632.99139822 nm

Fundamental Constants

Constant	Symbol	Magnitude
Planck constant	h	$6.626\ 0693 \times 10^{-34}$ J s
Elementary charge	e	$1.602\ 176\ 53 \times 10^{-19}$ C
Boltzmann constant	k_B	$1.380\ 6505 \times 10^{-23}$ J k^{-1}

The Quantum Electrical Metrology Division uses intrinsic standards that occur in condensed matter systems. Two of these, superconductivity and the quantum Hall effect, are macroscopic quantum systems. They are particularly convenient because in some cases it is not necessary to have particularly small structures to isolate the quantum. Both have been developed to make definitive measurements of voltage and resistance.

At present the Division is pursuing two standards that are not for electrical standards but that depend on our experience with electrical measurements. The first is a potential new standard of mass based on the equivalence of gravitational forces and electrical forces. If fully successful, this work may lead to an “electronic kilogram” in which the unit of mass is based on electrical quantities. In the second the temperature-dependent electrical noise of a resistance is compared with the quantum-based ac voltage standard to measure temperature. If this work is fully successful it might lead to a definition of temperature in terms of electrical quantities — an “electronic kelvin.”

In this section we discuss our progress with quantum standards and our uses of them. These standards are for voltage, both constant and time-varying, current and capacitance, resistance, capacitance, and inductance.

Quantum Voltage Metrology

The voltage pulse developed by each junction depends on fundamental physical constants and never needs to be calibrated.

Goals

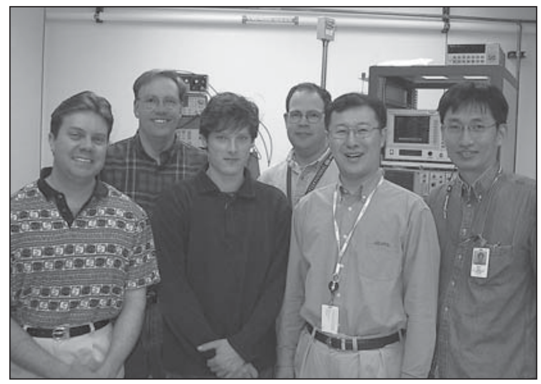
Meet the nation's voltage metrology needs. By developing state-of-the-art precision dc and ac voltage standard systems and by providing high-performance voltage measurements founded on quantum-based superconducting circuit and system technology, internationally consistent, accurate, and reproducible voltage measurements are readily and continuously available for U.S. industrial, governmental, and scientific applications.

Customer Needs

The demands of modern technology for accurate voltage calibrations have exceeded the capability of classical artifact standards. To meet current needs, an international agreement signed in 1990 redefined the practical volt in terms of the voltage generated by a superconductive integrated circuit developed at NIST and the Physikalisch-Technische Bundesanstalt in Germany. This circuit contains thousands of superconducting Josephson junctions, all connected in a series array and biased at a microwave frequency. The voltage developed by each junction depends only on the frequency and a fundamental physical constant; thus, the circuit never needs to be calibrated. This allows any standards or commercial laboratory to generate highly accurate voltages without the need to calibrate an artifact standard. This advance has improved the uniformity of voltage measurements around the world by about a hundredfold. These systems are rapidly becoming essential for meeting legal and accreditation requirements in commercial, governmental, and military activities.

The U.S. electronics instrumentation industry maintains its world-leading position through the development and deployment of accurate, flexible, and easy-to-use instruments. This increasingly sophisticated instrumentation places mounting demands for higher accuracy voltage metrology both in calibration and testing laboratories and on production lines and factory floors. We meet this need by providing some customers who need immediate realization of the highest possible in-house accuracy with their own quantum voltage standard systems, and other customers with a calibration service for their Zener voltage references. We provide the foundation for voltage metrology that enables the U.S. electronics instrumentation industry to compete successfully in the global market.

Through this strong voltage metrology foundation, we also support scientific research in high accuracy voltage measurements. We support the standards community by developing voltage standard systems with new capabilities, including lower cost, increased functionality, and ease of use. Other customers are the superconductive electronics community and the U.S. military, which we support through development of novel superconductive circuits and high-performance systems, and by providing technical expertise.



Charlie Burroughs, Sam Benz, Nicolas Hadacek, Paul Dresselhaus, Yonuk Chong, and Hirotake Yamamori in the quantum-voltage development laboratory.

Technical Strategy

Over the past 20 years, we have developed superconductive Josephson junction array technology for quantum voltage standard systems. Groundbreaking work at NIST led to commercialization of the first practical dc Josephson voltage standard system. Recent improvements in system design and operation have led to a portable Josephson voltage standard system that is compact, low cost, and transportable for calibration of Zener reference standards. The technology for this conventional Josephson voltage standard system has been completely transferred to the private sector, where systems are produced and supported by a number of small companies.

In order to provide world-class voltage measurement services at NIST, we provide precision voltage calibrations of all instruments, including chemical and electronic reference standards. We continually achieve the lowest possible uncertainty by performing regular checks for subtle systematic errors and by maintaining long-term observations of well-characterized check standards. We also periodically verify our consistency with the international com-

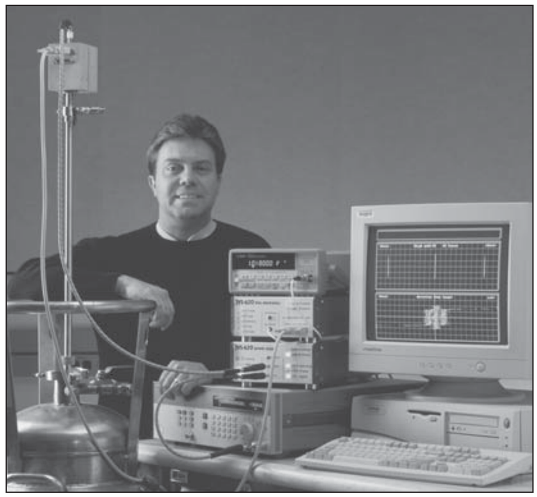
June Sims and Yi-hua Tang in the NIST voltage metrology laboratory.

munity through international comparisons. Finally, we continually investigate the physical and statistical limitations of metrology equipment and protocols both presently in use and those under development.

In recent years, an increasing number of quantum voltage standards have been deployed both around the world and throughout the U.S. It has proven very difficult to verify the performance of these quantum standards because the accuracy of the interlaboratory measurements is limited by the performance of the Zener voltage references used as transfer standards. In order to verify these standards, a traveling compact Josephson voltage standard (JVS) has been developed specifically to compare Josephson systems in geographically separated locations. This traveling Josephson system should reduce the uncertainty of Josephson voltage comparisons by an order of magnitude compared to that using the Zener references.

A few years ago, we developed a novel superconductor-normal metal-superconductor (SNS) junction technology that adds the features of stability and programmability to the accuracy of conventional Josephson voltage standards. Using this technology we implemented a 1 V programmable Josephson voltage standard (PJVS) system that has been in use for the past three years in the primary voltage calibration laboratory. The PJVS has been implemented in the voltage calibration service to replace the banks of electrochemical cell banks, the physical artifact standards that have been in daily use for many years. PJVS systems have also been delivered to, and installed in, a number of metrology experiments — namely the watt-balance experiments at NIST and Switzerland's Federal Office of Metrology (OFMET) and the metrology triangle experiment at France's Central Laboratory for Electrical Industry (LCIE), where these systems have reduced the uncertainty of the experimental measurements.

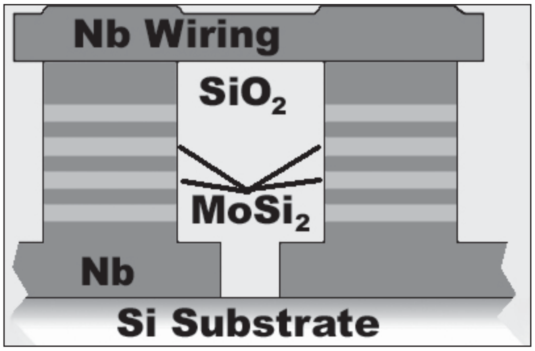
With the implementation of the compact Josephson voltage standard and programmable voltage standard, we will be able to serve our customers' needs for dc voltage metrology with reliability, efficiency, and accuracy, and to meet the most demanding requirements for voltage measurements in scientific research and development.



Charlie Burroughs with the 1 V programmable voltage standard system showing (left to right) the low thermal probe, the microwave and high-speed bias electronics, and the computer control.

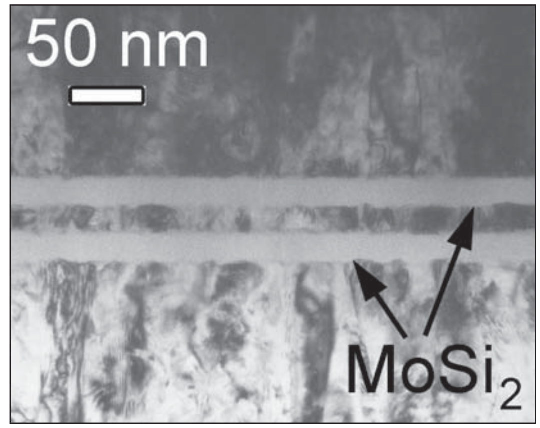
A quantum-based ac voltage source provides an entirely new instrument and methodology for ac voltage metrology.

One of our primary goals is to develop the world's first quantum-mechanically accurate ac voltage standard source. This system is essentially a digital-to-analog converter capable of synthesizing arbitrary waveforms and, like the previously described dc-only systems, exploiting the perfectly quantized pulses of Josephson junctions. The concept for this new device was co-invented by NIST and Northrop-Grumman researchers in 1996. Present ac voltage calibrations are done using ac-dc thermal voltage converters. A quantum-based ac voltage source would provide an entirely new instrument and methodology for ac voltage metrology. Its use as a stable generator of accurate arbitrary waveforms would also be useful for calibration of other scientific instruments such as ac voltmeters, spectrum analyzers, amplifiers, and filters. A low-voltage version of this system is also being developed as a pseudo-noise voltage reference to calibrate the measurement electronics of a novel Johnson noise thermometry system (see the JNT Project chapter). The major challenge for the general-purpose ac system is to achieve practical output voltages of at least one-quarter volt. Over the past few years we have made impressive progress toward this goal by developing high-density junction arrays and by improving the broadband microwave Josephson circuits.



Schematic diagram depicting a four-junction stacked series array with molybdenum-disilicide normal metal barriers, superconducting niobium electrodes, and silicon dioxide insulating dielectric.

In order to increase the junction density and thereby the output voltage of an array, we invented a nanoscale junction fabrication technology in which the spacing between junctions is reduced from 7 µm to less than 100 nm. We have spent the last few years exploring various fabrication methods and determined that vertically stacking the junctions on top of each other was the best method. To date, we have demonstrated uniform arrays of junctions with as many as 10 junctions stacked on top of each other. The stacked-junction technology has matured to level that we can make useful programmable voltage standard circuits with over 100000 junctions on a single chip as well as ac voltage standard circuits with 200 mV peak output voltage. More improvements are expected and such stacked-junction arrays will become the basis for our next-generation dc and ac Josephson voltage standard systems.



Transmission electron microscope (TEM) image of a two-junction stack with molybdenum-disilicide barriers and niobium outer and middle electrodes. The image shows that the $MoSi_2$ deposits uniformly on the niobium, even when the niobium is as thin as 20 nm. (Image by John Bonevich-MSEL, NIST)

Accomplishments

■ In early 2004, the NIST voltage metrology laboratory moved into the new Advanced Metrology Laboratory (AML) to take advantage of its superior control of environmental parameters such as temperature and humidity. This significantly challenging move was accomplished with no disruption in the measurement services, and required establishment of an interim measurement facility in the AML and validation that its performance was equivalent to that of the existing measurement laboratory. All Josephson voltage standard systems have been validated via comparisons directly or indirectly with other Josephson voltage standards. The regular calibration systems have been reconstructed and their performances have also been verified. These measurement systems are now ready to provide calibrations.

■ In collaboration with Tom Witt of the BIPM, NIST undertook a study of correlation in high-precision electrical measurements. Through the application of advanced statistical analyses to the detailed noise measurements on many voltage references and the associated measurement instrumentation, we have developed more efficient protocols for high-precision measurements of laboratory standards. We have studied the voltage noise of electronic voltage standards based on Zener diode references (Zeners). Ten volt Zener outputs were compared to NIST Josephson standards using a digital voltmeter (DVM) to record voltage differences. These kinds of international analyses are an important contribution to worldwide agreement on the use of standards.

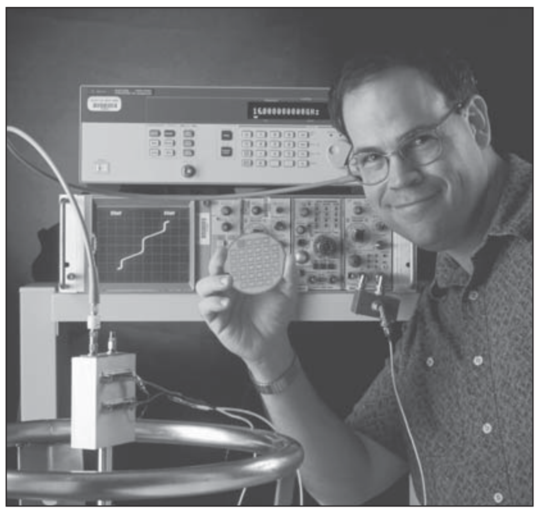
The NIST 10 V and 1 V Josephson voltage standard systems relocated in the new Advanced Measurement Laboratory.

■ In collaboration with Michael Lombardi and David Howe of the Time and Frequency Division in Boulder, we studied the frequency uncertainty and its consequence to voltage measurement in a Josephson voltage standard. The 10 MHz time base from various commonly used frequency standards for the JVS was analyzed using Allan variance to determine the contribution to the uncertainty budget for voltage measurement. The results provide realistic estimations for uncertainty contributions of time base and frequency measurements in Josephson voltage standards and frequency reference selection guidelines for Josephson voltage standards.

Voltage measurement in the electronic-mass or watt-balance experiment is essential to achieve the expected uncertainty for monitoring the mass of the international prototype of the kilogram. A PJVS has been used in the electronic mass experiment. In order to evaluate the performance of the PJVS, we have performed two array-to-array direct comparisons — one between the Watt PJVS and the NIST compact JVS and another between the Watt and Volt Lab PJVS systems. Both comparison results were consistent with an uncertainty of 1–3 parts in 10^9 at 1.018 V.

We have increased by tenfold the junction density of Josephson arrays. This was achieved by vertically stacking 10 superconducting Josephson junctions on top of each other at a spacing of 45 nm. We developed a process for stacking and patterning these novel arrays that are made when multiple molybdenum disilicide normal metal layers are alternately sandwiched between niobium superconducting layers. The biggest challenge was to vertically etch the stacked thin films so that the junctions in the stacks have the same area and achieve the same electrical characteristics. This was achieved and demonstrated by measuring the electrical characteristics of 1000 stacks arrays with and without a 9 GHz microwave bias. The 10000 series-connected junctions had uniformity sufficient to produce constant voltage steps over a frequency range from 8 GHz to 10 GHz. The voltage steps were flat; that is, they produced a precision constant voltage, based on the Josephson effect, over a large current range of 1 mA. This large operating range indicates impressive uniformity for these nano-stacked arrays and significant progress toward our goal of using nanotechnology to increase the performance of ac and dc voltage standard systems. Higher junction density is required to increase the output voltage as well as the operating bandwidth of the superconducting circuits whose quantum mechanical properties enable precise synthesis of arbitrary waveforms.

Nanotechnology is critical for the development of future voltage standard systems.

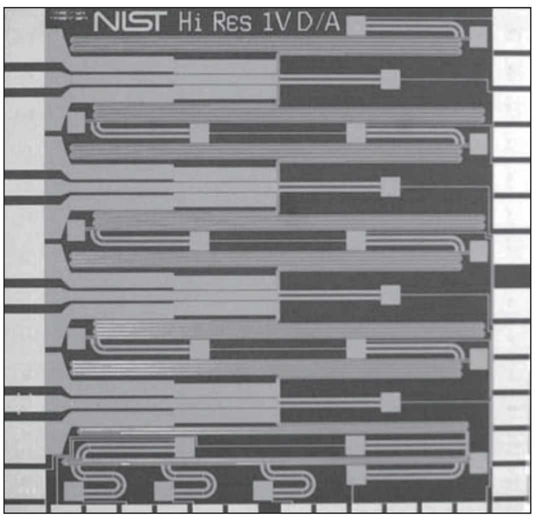


Paul Dresselhaus holds a silicon wafer containing superconducting integrated circuits and shows the current-voltage characteristics of a Josephson junction array.

■ Using nano-stacked Josephson junction arrays, we more than doubled the precision stable output voltage for programmable voltage standard circuits. In order to increase the performance of Josephson voltage standards, the project has been developing fabrication techniques to vertically stack superconducting Josephson junctions on top of each other with a junction spacing of only 45 nm. The stacks are made by alternately sputtering multiple normal-metal layers of molybdenum disilicide between superconducting niobium layers. The stacks are then interconnected in series with superconducting wiring in order to create a long series-connected array of junctions for the maximum output

The concept of an arbitrary voltage waveform generator with quantum-mechanical accuracy has enabled the possibility of making an electronically based thermometer.

voltage. For the past few years, the record output voltage for programmable Josephson voltage standards has been limited to about 1 V. These new fabrication techniques have allowed us to double and triple the number of junctions in the circuit, which, combined with a small increase in the drive frequency from 16 GHz to 19 GHz, has allowed us to reach 2.5 V maximum output voltage. The circuit can produce precision output voltage over a current range of 1 mA and over a frequency range from 14 to 19 GHz. The operating current and frequency ranges are also large compared to previous programmable circuits and indicate good uniformity for the 67410 total junctions. This is the first successful application of stacked Josephson junctions, and the results suggest that further output voltage improvements may result from taller stacks and larger arrays.



A 1 cm × 1 cm superconducting integrated circuit with 67,406 double-stacked SNS Josephson junctions for the 2.6 V high-resolution PJVS operating at 18.5 GHz.

■ This year we have developed and combined three new technologies to create an improved, more robustly packaged programmable voltage standard with higher performance. First, we built a new circuit that produces 50-times higher voltage resolution. We also developed a flexible, microwave-compatible cryopackage that improves electrical contact reliability. By combining these two breakthroughs with previously demonstrated stacked-junction fabrication technology, we have assembled a robust, cryopackaged programmable voltage standard that produces a record 2.6 V output with 77 μV resolution using the same electronics. The new standard will replace an older programmable circuit in the voltage calibration lab that was capable of 1 V output and 4 mV resolution. The novel superconducting integrated circuit of this new system uses a ternary-logic design to achieve the increased voltage resolution. As compared to previous double-stacked circuits and the older non-stacked programmable circuit, the double-stacked junction uniformity was improved, effectively increasing the operating margins two fold to 2 mA for full chip operation. The new cryopackage uses a "flip-chip on flex" technology that we hope will improve the service life and reliability of our Josephson systems, because directly soldered connections to the chip replace less reliable press contacts. This technique eliminates the most common failure mode for our Josephson chips, namely degradation and variation of the contact resistances of the chip pads over time owing to mechanical wear. Additionally, the materials used in the flex technology increase the operating bandwidth of the package from 18 GHz to 30 GHz. The system also utilizes an improved four-way microwave power divider for improved operating margins. The system is currently being implemented in the voltage calibration service.

PLAN

- Increase performance of ac JVS system to higher voltage and higher frequency
- Demonstrate and deliver triple-stacked PJVS circuits
- Explore applications of stacked-junction SQUIDs for improved multiplex readouts in the detector project
- Establish the viability of using the 2.6 V high resolution programmable JVS for regular calibrations
- Upgrade and improve the measurement control systems (hardware and software) used for calibrations
- Perform a series of comparisons using NIST compact Josephson voltage standard with other national metrology institutes or with high-level industrial metrology laboratories
- Upgrade the hardware and software of Josephson voltage standard and voltage calibration system in the AML to improve the quality and efficiency of voltage dissemination
- Achieve continuous improvement of programmable array design and fabrication for applications in volt maintenance, electronic mass, and metrology triangle

Collaborations

■ AIST, 10 K cryocooled 10 V programmable voltage standards

■ Korea Research Institute of Standards and Science (KRISS), applications of high-resolution programmable voltage standards

■ Swiss Federal Office of Metrology (OFMET) PJVS system for watt-balance experiment

- BIPM, correlation in electrical measurements
- NCSLI, implementation of NIST compact JVS for ILC to improve uncertainty
- Fluke, improvement of humidity characteristics for solid-state voltage standard
- NIST Division 847 (Time and Frequency Division), Michael Lombardi and David Howe, frequency uncertainty measurement for JVS application

Recent Publications

S. P. Benz and C. A. Hamilton, "Application of the Josephson effect to voltage metrology," invited paper, Proc., IEEE 92, (10), (October 2004).

M. Ishizaki, H. Yamamori, A. Shoji, P. D. Dresselhaus, and S. P. Benz, "A programmable Josephson voltage standard chip using arrays of NbN/TiN/NbN/TiN/NbN double-junction stacks operated at 10 K," Digest, 2004 Conference on Precision Electromagnetic Measurements, 27 June–2 July 2004, London, England, pp. 8-9 (June 2004).

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T. J. Witt and Y. Tang, "Investigations of noise in measurements of electronic voltage standards," Digest, Conference on Precision Electromagnetic Measurements, 28 June - 2 July, 2004, London, England, pp. 172-173 (June 2004).

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M. Ishizaki, H. Yamamori, A. Shoji, S. P. Benz, and P. D. Dresselhaus, "Critical current control and microwave-induced characteristics of $(NbN/TiN_x)_n/NbN$ stacked junction arrays," IEEE Transactions on Applied Superconductivity, 13, (2), pp. 1093-1095 (June 2003).

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AC-DC Difference Standards and Measurement Techniques

Technical Contact:
Thomas E. Lipe

Staff Years (2004):
2 professionals
1 technician (75 %)

"[The AC-DC staff] ... was extremely helpful in assisting us with the calibration of test equipment ... [they] helped us ensure that our procedures are correct. Thank you very much for your help."

Michelle Stadel
Beale AFB

Goals

Provide U.S. industry with the link between the dc and corresponding ac electrical standards, by maintaining and improving the U.S. national standards for ac-dc difference that are used to provide calibrations and measurement services for thermal converters and shunts.

Customer Needs

Increasingly accurate, easier-to-use instruments and devices for precision ac voltage and current measurements are being developed by U.S. electronic instrumentation and test equipment manufacturers for use in a wide variety of industrial and scientific applications throughout the world. These instruments are beginning to press the best available uncertainties, especially for calibration of ac current and for ac voltages below 100 mV. The need continues for better calibration tools with which to verify accuracy claims, achieve consistency, and to help avoid international trade barriers based on technical difficulties. Examples of specific customer requirements are cited below.

- The U.S. Army primary standards laboratory uses the same primary standards for ac current metrology as NIST. New standards are required to replace these aging devices.

- The U.S. Air Force primary standards laboratory calibrates 100 A current amplifiers for their secondary laboratories. Although these amplifiers are specified to 100 kHz at 100 A, NIST presently supports only 100 A measurements to 10 kHz. The Air Force requires an expansion of the frequency range for high-current calibrations. The Air Force also requires improved devices for measuring ac voltages from 100 mV to 2 V with smaller uncertainties than those of existing devices.

- Several NIST customers who support the electric power industry require lower uncertainties at power frequencies at 120 V and 240 V than NIST routinely provides. Since the AC-DC Difference project supports power and energy calibrations at NIST, this demand for lower uncertainties increases the demand for more precise calibrations, particularly for ac current measurements.

- Instrument manufacturers have developed new methods for calibrating thermal transfer standards at voltages less than 100 mV. The new methods will likely result in uncertainties close to what NIST gives for routine calibrations, and is likely to require reductions in the achieved uncertainty of NIST calibrations.

Research and development are required to maintain and to expand NIST calibration and special test services for thermal converters and shunts, especially for calibrating high-current shunts and high-voltage converters.

Technical Strategy

The NIST primary standards presently in use for ac currents above 500 mA are traditional, handmade thermal converters consisting of a thermocouple attached to a heater. While these devices still provide world-class performance, they are old, prone to age-related failures, and commercially unavailable. In order to maintain a world-class calibration service for ac-dc difference, NIST has an urgent requirement for the replacement of these devices with more modern, accurate and reliable standards. NIST and other laboratories have shown that devices made using new thin-film technology are viable replacements for the older standards.

The NIST parameter space for ac-dc voltage transfer difference ranges from 2 mV to 1000 V at frequencies from 10 Hz to 1 MHz. Maintaining world-class standards for each point in this large parameter space is time-consuming, and simplifying the maintenance of this parameters space is becoming critical. In addition, higher-voltage thermal converters are characterized using a range-to-range buildup process. Errors associated with input level coefficients must be accounted for in the buildup by including an uncertainty for the level coefficients, and hence increasing the overall uncertainties. Experiments have shown that a calibration system based on an inductive divider has the potential to address both of these requirements.

To address the requirement for maintaining the NIST calibration service for ac currents above 500 mA, a collaborative of personnel in the NIST AC-DC Difference project, the National Metrology Institute of Argentina (INTI), the Quantum Devices Group fabrication facility at NIST Boulder, and Sandia National Laboratories is designing and fabricating new thermal converters based on thin-film fabrication technology. Prototypes of these devices indicate that, in addition to being more efficient and economical to produce than traditional wire thermal converters, these devices have significantly improved performance with respect to the earlier designs. These thin-film thermal converters will replace the legacy standards for ac metrology at NIST, as well as provide required replacements for aging standards at the Army laboratory. To achieve current measurements up to 10 A, a multiconverter module is being fabricated.

In order to support required high-voltage calibrations, particularly at power frequencies and at 1000 V, NIST has designed and tested a comparator system based on an binary inductive voltage divider (BIVD) to perform 2:1 scaling of thermal converters. This design is an improvement on an earlier design which itself was comparable in accuracy to the traditional bootstrapping process. In the future, systems with other scaling ratios will be developed. These systems will largely replace the bootstrapping process, greatly simplifying the parameters space and leading to improvements in accuracy.

To address the Air Force requirements for an expansion of the frequency range for 100 A current shunts, NIST is continuing to assess the stability of the 100 A shunts composing the working standards for high current. An additional set of high-current shunts was recently acquired to aid in the scaling process from 10 A to 100 A, and a set of two-stage current transformers is being used to check the frequency flatness of the shunts.

To address the Air Force requirements for more accurate thermal converter standards in the 100 mV to 2 V range, thin-film thermal voltage converters have been fabricated and are being packaged and tested for delivery to Department of Defense primary laboratories. These devices have been shown to have extremely small ac-dc differences from 10 Hz to 100 kHz, and the ac-dc differences are essentially independent of input level from 150 mV to 2 V. Similar devices will soon be the NIST working and reference standard converters.

To maintain compliance with NIST calibration service requirements, the uncertainties for thermal current converters are being reevaluated. Significant reductions (as much as a factor of 5) in these uncertainties are expected.

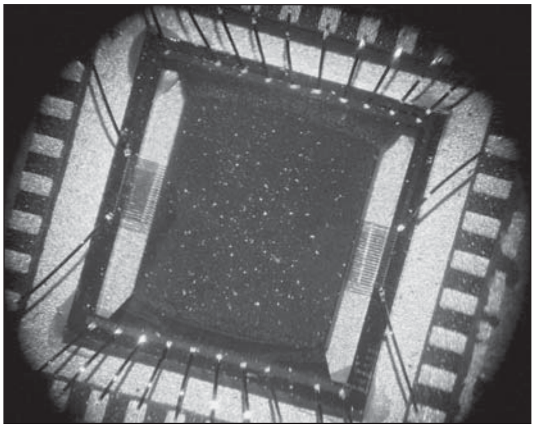
To address the uncertainty requirements for low-voltage calibrations, the AC-DC Difference project is characterizing thermal transfer standards for use at voltages down to 2 mV. In conjunction with existing low-voltage MJTCs, the AC-DC Difference project will have the capability to calibrate thermal converters from 2 mV to 1000 V. Having the calibrations performed in one laboratory, instead of being split between two projects (the present situation) will not only lead to reduced uncertainties for the calibrations, but will also reduce the turnaround time for calibrations.

PLAN

- Fabricate new thin film thermal converters and test these devices
- Complete multiconverter modules for current measurements up to 10 A; implement thin-film converters as NIST standards for routine measurements
- Test improved comparator system at 1000 V up to 100 kHz
- Make IVDs with different ratios and integrate them with the comparator system
- Offer measurement services at higher frequencies for currents above 30 A
- Deliver two characterized thin-film thermal converters to each of the DoD primary laboratories. Begin using similar devices as working standards in the AC-DC Difference laboratory at NIST
- Publish the revised uncertainty analysis for ac current shunts

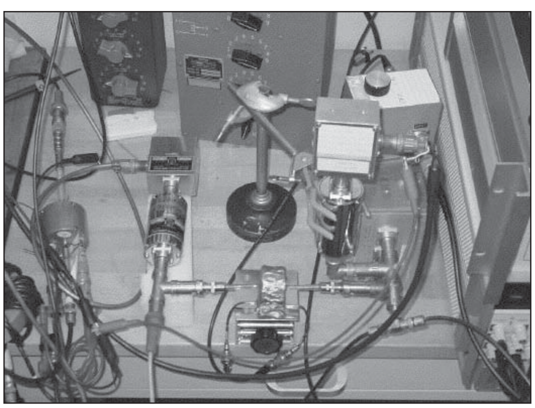
ACCOMPLISHMENTS

■ A prototype 1 A thermal current converter, designed by the NIST/INTI/Sandia collaboration and fabricated at Sandia, was shown to have ac-dc differences of less than 5 μA/A over the frequency range from 10 Hz to 100 kHz. This performance indicates that the design of the MJTC and the use of a copper-gold alloy for the heater reduces errors due to thermal tracking of the ac waveform by the heater at low frequencies, reactance effects at high frequencies, and thermoelectric effects at audio frequencies. In comparison, the NIST reference 1 A standard has an ac-dc difference of about +50 μA/A at 10 Hz and about –50 μA/A at 100 kHz. The new 1 A MJTC is almost certainly the best 1 A thermal converter ever made.



Photograph of a NIST/Sandia 1 A thermal current converter chip, showing the copper-gold heater, thermocouple banks suspended across the silicon nitride membrane, and wire bonds to chip carrier.

■ The IVD-based high-voltage comparator system was tested and found to agree well with the traditional bootstrapping process. The tests involved a binary divider, and the system was used to test a 100 V thermal converter against a 50 V thermal converter with both converters operating at their rated input voltage. This arrangement removes level-dependent errors in the high-voltage converter that limit the accuracy of the traditional scaling technique. Measurement of a specially constructed thermal converter with large frequency-dependent errors showed that the new BIVD systems agrees with predicted values to within a few parts per million, well within the measurement uncertainty.



Photograph of the BIVD-based high-voltage comparator system. The BIVD is in the large metal box on the right, the detector winding is at the center of the photograph, and the injector is at the left. The thermal converters under test are the square boxes connected to the cylindrical enclosures.

■ The ac-dc project participated in three international intercomparisons during the year. Results from these international comparisons will become available in 2005.

– CCEM-K11 (ac-dc difference at 10 mV and 100 mV)

– CCEM-K12 (ac-dc difference at 10 mA and 5 A). NIST helped establish the reference value

– A SIM intercomparison encompassing CCEM-K6a (ac-dc difference at the lowest uncertainty), CCEM-K9 (ac-dc difference at high voltage), and CCEM-K11

■ Several calibration documentation efforts were completed. They included:

– Assessment of the AC-DC Difference project relevant to ISO Guide 17025. The project passed the assessment and is now declared in conformity with Guide 17025.

– Publication of the technical manual for the present ac-dc difference calibration software. The manual also includes a guide to setting up the systems for calibrations.

– Publication of the revised uncertainties for thermal voltage converter calibrations. The reassessment resulted in an overall reduction of the uncertainties, in some cases by a factor of 4.

Collaborations

■ Hector Laiz (National Institute for Industrial Technology (INTI), Argentina), Kent Irwin, James Beall (NIST Division 817-B), Thomas Wunsch, Sara Sokolowski (Sandia National Laboratories), to design and fabricate thin-film MJTCs.

■ Mamdouh Halawa (National Institute of Standards (NIS), Egypt), to improve the NIS ac-dc calibration capabilities, funded by the Joint U.S.–Egypt Science and Technology Board.

■ Michael Surdu (Science and Technology Center (STCU), Ukraine), to improve ac voltage and impedance metrology, particularly in Ukraine.

■ Joseph Kinard was invited to perform a technical peer review at a major national metrology institute, the Australian National Measurement Laboratory (NML). NML has elected to obtain international, technical peer review and periodic reassessment as part of its quality system and for the registration of its calibration services with the Australian National Association of Testing Authorities.

The topics covered in the assessment included ac-dc transfer, instrument calibration, ac quantities such as power, energy, and magnetism.

Calibrations

During this year, the AC-DC Difference project completed 16 calibrations that included nearly 1000 points with revenues of about $128K.

Selected Publications

J. R. Kinard, T. E. Lipe, and S. Avramov-Zamurovic, "Determination of frequency coefficients for thermal voltage converters and digital voltmeters by comparison to inductive voltage dividers," Digest, Conference on Precision Electromagnetic Measurements 2004, London, England, 26-30 June 2004, pp. 463-464.

H. Laiz, T. F. Wunsch, J. R. Kinard, and T. E. Lipe, "1 A and 120 mA thin-film multijunction thermal converters," Digest, Conference on Precision Electromagnetic Measurements 2004, London, England, 26-30 June 2004, pp. 457-458.

J. R. Kinard, T. E. Lipe, and S. Avramov-Zamurovic, "Determination of frequency coefficients for thermal voltage converters and digital voltmeters by comparison to inductive voltage dividers," Proc., NCSLI Workshop and Symposium, Salt Lake City, UT, 12-16 July 2004.

H. Laiz, T. F. Wunsch, J. R. Kinard, and T. E. Lipe, "1 A and 120 mA thin-film multijunction thermal converters," Proc., NCSLI Workshop and Symposium, Salt Lake City, UT, 12-16 July 2004.

T. E. Lipe, J. R. Kinard, and C. D. Reintsema, "AC-DC Difference at cryogenic temperatures," Proc., NCSLI Workshop and Symposium, Tampa, FL, 17-21 August 2003.

T. E. Lipe, C. D. Reintsema, and J. R. Kinard, "An improved sensor for the NIST cryogenic thermal transfer standard," Digest, Conference on Precision Electromagnetic Measurements 2004, Ottawa, Ontario, Canada, 16-21 June 2002, pp. 108-109.

J. R. Kinard, T. E. Lipe and T. F. Wunsch, "Improved high-current thin-film multijunction thermal converters," Digest, Conference on Precision Electromagnetic Measurements 2004, Ottawa, Ontario, Canada, 16-21 June 2002, pp. 364-365.

J. R, Kinard, T. E. Lipe, T. F. Wunsch, and R. P. Manginell, "Design and fabrication of multijunction thermal converters at NIST and Sandia National Laboratories," Proc., Sensors for Industry Conference 2002, Houston, TX, 19-21 November 2002.

T. E. Lipe, J. R. Kinard, T. F. Wunsch, and R. P. Manginell, "Design and fabrication of multijunction thermal converters at NIST and Sandia National Laboratories," Proc., Nano- and Micro-systems Technology and Metrology Conference 2002, Huntsville, AL, 4-5 December 2002.

Single Electronics for Standards and Metrology

Technical Contacts:
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Mark Keller
Neil Zimmerman

Staff-Years (FY 2004):
3 NIST staff
2 post-docs
1 guest scientist

Imagine what you could do if you could build circuits that precisely manipulate and detect individual electrons.

Goals

Develop novel integrated circuits for standards and metrology based on the unique properties of electronic devices that can manipulate and detect individual electrons.

Customer Needs

This project addresses three different needs: a fundamental representation of capacitance, a fundamental representation of electrical current, and general applications of single-electron tunneling (SET) devices, with a particular emphasis on future integrated nanoelectronics.

For the first need, NIST is working on the development of intrinsic standards based on fundamental physical principles, such as the volt, based on the Josephson effect, and the ohm, based on the quantum Hall effect. The present representation of the SI farad is through silica-based artifact capacitors. Although these capacitors are of high quality, they are susceptible to drift in time and may depend on other parameters such as temperature, pressure, and frequency. The metrology community, including both the national standards laboratories and domestic secondary calibration laboratories, needs a capacitance representation that is based on fundamental physical principles rather than on properties of individual physical artifacts.

For the second need, at present, there is no fundamental representation of current; the representation of current is via the representations of voltage and resistance. Though these representations are based on fundamental physical principles and are of high quality, the representation of current is dependent upon them. An independent representation of current could provide significant additional confidence in the coherency of the representations of the SI electrical units through closure of the "metrology triangle" V = I R with all measurements based on fundamental constants.

For the third need, various classes of future nanoelectronics beyond CMOS are projected to work with one or a few electrons. These include molecular electronics, semiconductor-based integrated circuits using single-electron memory or logic, and quantum computing (QC). For example, in QC, we are using our expertise to elucidate properties of transfer of superconducting "Cooper pairs," which are the basic mechanism for one realization of QC circuits. As another example, one endemic problem in single-electron logic is the "charge offset" phenomenon, which makes it difficult or impossible to integrate multiple SET-based devices together; again, we are using our expertise to attack this problem. In all three cases, our project has the capability to offer early guidance to these burgeoning fields, and to assist companies in pursuing productive areas and rejecting problematic ones; because these fields are not yet mature, as our relatively small efforts progress, they can yield large payoffs for the customers.

Technical Strategy

Our basic strategy for this project is to develop important applications in our areas of world-leading expertise. These areas, which are all intimately related to the single-electron tunneling transistor and other SET devices, include:

- Advanced fabrication of nanoscale metal devices (features as small as 20 nm) using our clean room facility in Boulder, CO.
- Cryogenic measurement equipment, including custom filtering, and low-noise electronics.
- Fundamentals of SET physics in metal-based devices.
- Fundamentals of SET physics in Si-based devices.

Capacitance Standard

At present, the most mature application of SET devices within the project is using SET devices to develop an electron-counting capacitance standard (ECCS). By depositing a counted number, N, of electrons (of order 10^8) onto the plate of a capacitor (of value approximately 1 pF) and measuring the resulting voltage (approximately 1 V), one can calibrate the capacitance, C, through the definition of capacitance, C = Q/V, with the charge determined by the number of electrons, Q = N e.

A prototype of the ECCS has been demonstrated with repeatability on the order of 1 part in 10^7. At this point, the major tasks remaining are to continuing to improve accuracy and to develop a robust system for possible widespread use.

Current Standard

Using the expertise described earlier, we are pursuing three tracks towards a current standard based on counted electrons:

■ Superconducting Single Cooper Pair Tunneling (SCPT) devices combine the physics of single-electron devices and Josephson junctions. Our first application of this new technology will be to develop a SCPT charge pump. Because superconducting tunneling is a coherent process, in principle the SCPT pump should be able to operate at significantly higher frequencies, allowing larger currents to be produced with metrological accuracy. To build the SCPT pump will require significant advances in the fundamental understanding of how these devices work. This work will also have direct impact on worldwide progress towards using these devices for quantum computing.

■ Si-based SET pumps, turnstiles, and CCDs offer significant promising avenues as well. First of all, because the typical device capacitance is smaller by at least a factor of 10 than the non superconducting pump, they offer the concomitant increase in speed and thus current value. Also, because they lack the charge offset problem, we can parallelize a large number of pumps to increase the current.

■ Passive counting using the rf-SET: Using rf techniques, we can perform electrometry up to 100 MHz. This will allow us to attempt to monitor the charge passing through a single junction at an unprecedented combination of speed and precision. This technique offers the possibility of multiplexing a number of these charge sources to build a larger current source (100 pA to 1 nA).

One of the primary motivations for developing larger currents is our work to close the metrology triangle. This experiment can not be performed with the currents presently available from single-electron pumps.

Ultra-Sensitive Charge Electrometry for Molecular Electronics/Biological Applications

SET devices also can be used as tools to measure the performance of other devices that operate with individual electrons.

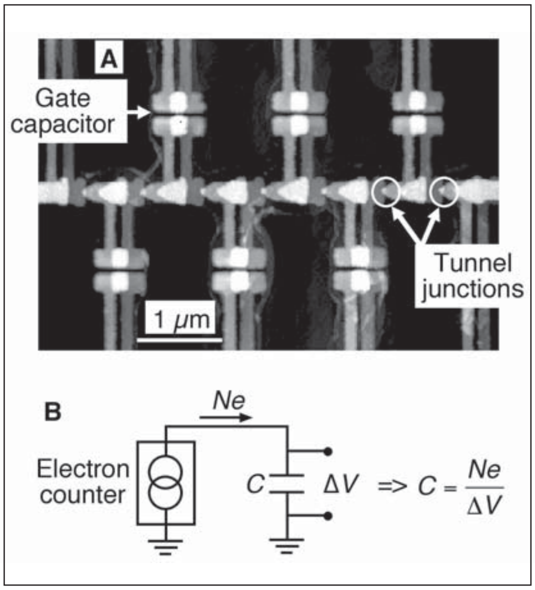
We are pursuing the study of electrostatic charge reconfiguration of self-assembled monolayers (SAM) by fabricating and assembling a "nano-gap" capacitor. This device, made using Si micromachining, allows us to make a capacitor with a gap of only 50 nm, but an area of (80 mm)^2; the area is large enough to give us a measurable signal, while the gap is small enough to measure charge motion over 1 nm or less.

PLAN

- Perform detailed performance verification of the SET-based capacitance standard, and perform detailed uncertainty analysis of the integrated system
- Determine the value of the ECCS relative to the calculable capacitor, and thus close the charge-on-a-capacitor method of the metrology triangle within 0.1 ppm
- Quantify and evaluate the differences in charge offset between metal-based and Si-based SET devices; suggest ways of improving the performance of the metal-based ones
- Produce a prototype device with parallel SET electron pumps
- Verify Cooper-pair pump operation; this involves studies of individual elements, including eliminating quasiparticle poisoning, verifying the suppression of the Josephson coupling energy in a high impedance environment
- Produce prototype passive counting device with 10 MHz bandwidth. Determine practical limits of passive counting bandwidth and suggest strategies for multiplexing for larger currents
- Pursue individual elements, including larger-current SET-based current source, resistor, null detector, and control/monitoring electronics
- Close metrology triangle to within 0.02 ppm via the current-through-a-resistor method
- Develop a robust repeatable nano-gap capacitor.
- Verify or refute the belief in the molecular electronics field that nonlinearities in the transport are due to motion of charge within the molecules

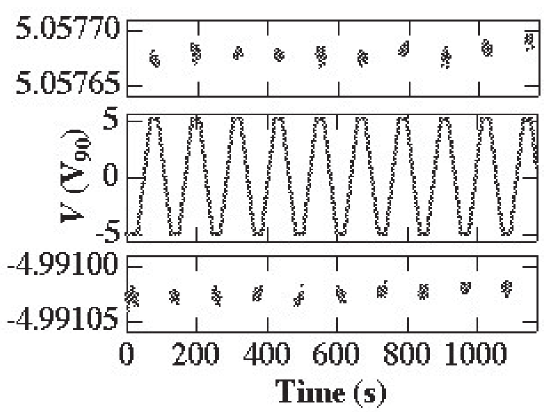
Accomplishments

■ *Electron Counting Capacitance Standard Demonstrated* — At present, the most advanced application for SET devices within the project is a new capacitance standard based on the fundamental definition of capacitance. The past few years have brought to fruition the results of a decade of research aimed at creating this standard. A prototype of an Electron Counting Capacitance Standard (ECCS) has now been demonstrated. The components of the standard are an electron counter, a capacitor, and an electrometer to monitor the process, as illustrated in the figure below. The electron counter, shown in the Atomic Force Microscope image below, is based on seven nanometer-scale tunnel junctions in series. It can "pump" electrons onto the capacitor with an error rate of less than one electron in 10^8. The electron pumping is monitored with an SET-based electrometer fabricated on the same chip as the pump, with a charge sensitivity better than 10^{-2} electrons. The capacitor operates at cryogenic temperatures and uses vacuum as the dielectric, resulting in a frequency-independent measure of capacitance.



Atomic force microscope image of an electron counter, the heart of a new capacitance standard based on counting electrons. The standard, shown in the schematic, consists of the electron counter, a capacitor, and a single-electron electrometer to monitor the process (not shown). The electron counter, based on seven nanometer-scale tunnel junctions in series, can "pump" electrons onto the capacitor with an error rate of less than 1 electron in 10^8.

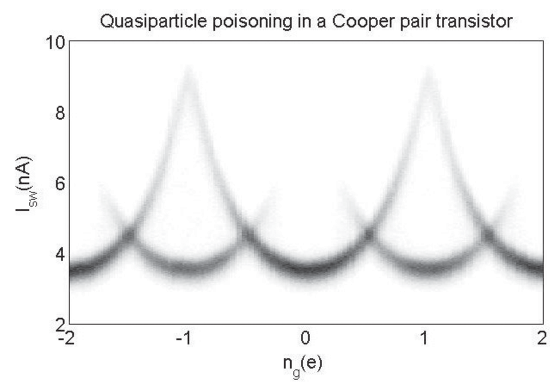
To operate the ECCS, approximately 100 million electrons are placed, singly, on the capacitor. The voltage across the capacitor is then measured, resulting in a calibration of the cryogenic capacitor. This capacitance can then be transferred to room temperature by use of a standard ac bridge measurement technique. The figure below shows the result of pumping electrons on and off the capacitor, with a 20 s pause when fully charged to measure the voltage. The result is a value of capacitance with a repeatability of one part in 10^7.



Demonstration of pumping electrons onto and off a prototype capacitance standard.

■ *Quasiparticle Poisoning in Cooper Pair Transistors Elucidated* — In collaboration with Professor Michel Devoret (Yale), we have performed a number of experiments that verified a model for erratic quasiparticle tunneling in superconducting Cooper pair transistors (these are the superconducting versions of the SET). This phenomenon, quasiparticle "poisoning," will limit the operation of the superconducting Cooper pair pump as well as charge-based qubits. Our work showed that the gap energies in the leads versus the island played a significant role in determining these poisoning rates.

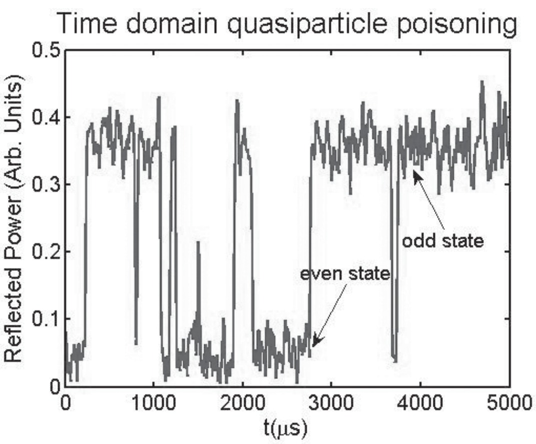
In addition, we have confirmed a "remote poisoning" phenomena, whereby a voltage-biased junction device can cause poisoning in other devices on the same chip, even if it is electrically isolated. This has important implications for the electrometry that we will use in the Cooper pair pump, as well as in charge-based qubits.



Switching current histograms (z-axis) versus gate polarization charge on a superconducting Cooper pair transistor. The double peaks for fixed gate polarization indicate that quasiparticles are poisoning the transistor island.

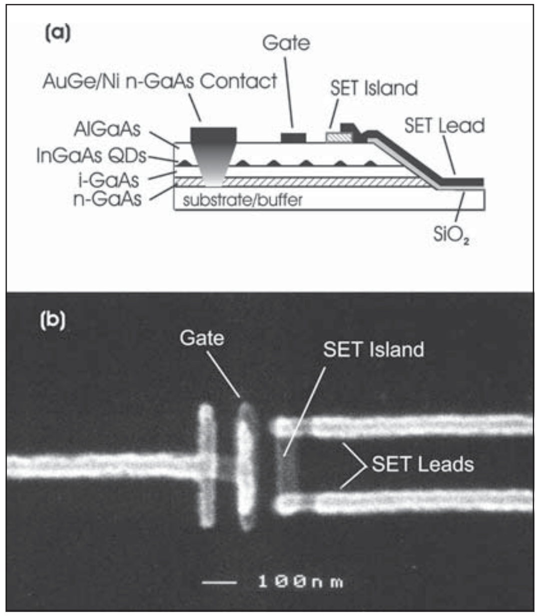
■ *rf-SET demonstrated* — In collaboration with Konrad Lehnert at JILA, we have assembled and demonstrated operation of a rf-SET at NIST, a version of an SET electrometer read out by microwave reflectometry. This approach greatly increases the bandwidth of the electrometer (to 3 MHz in our present setup) and improves the charge resolution (to 50 me/Hz$^{1/2}$). This is the basic technology we will use to perform the passive electron counting experiments. Future work will focus on expanding the bandwidth and narrowing the charge resolution to perform better than the quantum limit.

■ *Real-Time Observation of Quasiparticle Poisoning Using a Novel rf Measurement Mode* — Conventional operation of the rf-set involves biasing the device on the quasiparticle branch of the current-voltage characteristic. This quasiparticle current creates quasiparticles in remote devices (which may be charge qubits or Cooper pair pumps), which may prevent successful operation. Recently, we have successfully demonstrated that it is possible to measure the Josephson inductance of a Cooper pair transistor while it is biased on the supercurrent branch. Using the same techniques as in the rf-SET, we have measured the quasiparticle poisoning in a single Cooper pair transistor in the time domain. Since this technique operates on the supercurrent branch, we expect minimal generation of quasiparticles.



Using techniques similar to the rf-SET measurement, we have measured the modulation of the Josephson inductance of a Cooper pair transistor while it is biased on the supercurrent branch. In this example, when a quasiparticle enters the transistor island, the Josephson inductance shifts, changing the reflected power. In this plot, when a quasiparticle has entered the island (the "odd state"), the reflected power increases. With this technique we can observe these quasiparticle tunneling events in the time domain as a telegraph signal.

■ *SET Electronics Developed to Probe GaAs Quantum Dots for Single Photon Source* — The past two years have produced significant progress towards the development of a single-photon turnstile, a device designed to generate single photons on demand using semiconductor quantum dots (QD) and single-electron principles. A key step towards this goal is to measure the tunneling of single electrons onto individual quantum dots. We have succeeded in making these measurements by integrating an SET electrometer over a low density field of GaAs quantum dots (grown by Rich Mirin of the Optoelectronics Division). A schematic cross-section of the device is shown below, along with a scanning electron micrograph of the SET electrometer. Such nanoscale device integration is difficult and required extensive process development. Using these devices, we have clearly identified the addition of single electrons onto single quantum dots located below the SET. We have counted up to 3 electrons added to a single dot, and have measured the energy spectrum associated with adding electrons on this dot.



(a) Schematic cross-section of our SET electrometer integrated on a GaAs chip containing self-assembled quantum dots. (b) SEM micrograph of an SET electrometer. We have identified single-electron tunneling events into individual quantum dots located beneath the electrometer.

■ *Si-based Pumps Turnstiles, CCDs Demonstrated* — Our work in collaboration with a group in NTT, Japan, has made a great deal of progress in investigating Si-based devices that can control the motion of single electrons. In the past two years, we have demonstrated such control in three different types of devices: pumps, turnstiles, and CCDs. The most promising device for the future is the CCD, both because we have recently demonstrated in subsequent work that such devices can be made with improved reliability and homogeneity, and because we demonstrated that this device has the potential to run at higher speed. In one of our publications we showed that the CCD can pump single electrons at rates as fast as 100 MHz, corresponding to 15 pA; this is an improvement by about a factor of 5 over previous results in metal-based pumps. However, we have to note that we were not able to measure error rate in detail in the CCDs; this work is now in progress.

We also recently have finished our first theoretical analysis of error mechanisms and error rates in Si-based turnstiles and CCDs. From a fundamental point of view, the most interesting result was the elucidation of a new mechanism, the "dynamical error." This error can result from the inability of the quantum dot to form the Coulomb blockade quickly enough; research into this mechanism should advance fundamental understanding of Coulomb blockade. By considering in addition thermal, frequency, and heating errors, we predicted that with devices accessible at present we should be able to achieve error rates of 0.01 ppm at frequencies up to 200 MHz. Of course, we need to perform the experimental work to verify or refute these predictions.

More recently, we have done a detailed study of the SET transistor behavior of several different devices made using the CCD architecture. In addition to an interesting array of fundamental properties, we found that in three different devices the parameters (specifically, a variety of cross capacitances) vary by no more than 15 % between the devices. In previous fabrications using the pattern-dependent oxidation process, the homogeneity was no better than 50 %, and sometimes much worse. This substantial improvement in homogeneity makes it much more likely that we should be able to integrate devices for general applications, and specifically to parallelize a number of CCDs to get a higher value of current.

Collaborations

- NIST/JILA, passive electron counting for current standard
- NIST Semiconductor Electronics Division, Si-based SET devices
- NIST Optoelectronics Division, single-photon competence project
- Nippon Telegraph and Telephone, Si-based SET devices
- University of Colorado Departments of Physics and Chemistry, detection of molecular rotors

Selected Publications

M. W. Keller, A. L. Eichenberger, J. M. Martinis, and N. M. Zimmerman, "A capacitance standard based on counting electrons," Science 285, pp. 1706 (1999).

M. W. Keller, "Standards of current and capacitance based on single-electron tunneling devices," in *Recent Advances in Metrology and Fundamental Constants*, FERMI School CXLVI, Varenna, Italy, ed. T.J. Quinn, S. Leschiutta, and P. Tavella, Amsterdam: IOS Press, pp. 291-316, (2001).

Y. Ono, N. M. Zimmerman, K. Yamazaki and Y. Takahashi, "Turnstile operation using a silicon dual-gate single-electron transistor," Jpn. J. Appl. Phys 42, pp. L1109 - 11 (2003).

X. Jehl, M. W. Keller, R. L. Kautz, J. Aumentado, and J. M. Martinis, "Counting errors in a voltage-biased electron pump," Phys. Rev. B 67, 165331-1 - 165331-9.

N. M. Zimmerman, M. A. El Sabbagh, and Y. Wang, "Larger value and SI measurement of the improved cryogenic capacitor for the electron-counting capacitance standard," IEEE Trans. Instrumentation and Measurement 52, pp. 608-11 (2003).

A. Fujiwara, N. M. Zimmerman, Y. Ono, and Y. Takahashi, "Current quantization due to single-electron transfer in Si-wire charge-coupled devices," Appl. Phys. Lett. 84, pp. 1323 (2004).

N. M. Zimmerman, E. Hourdakis, Y. Ono, A. Fujiwara, and Y. Takahashi, "Error mechanisms and rates in tunable-barrier single-electron turnstiles and CCD's," accepted for publication in J. Appl. Phys. (2004).

K. D. Osborn, M. W. Keller, and R. P. Mirin, "Single-electron transistor spectroscopy of InGaAs self-assembled quantum dots," Physica E 21, pp. 501-505 (2004).

J. Aumentado, M. W. Keller, J. M. Martinis, and M. H. Devoret, "Nonequilibrium quasiparticles and 2e periodicity in single-Cooper-pair transistors," Phys. Rev. Lett. 92, pp. 066802 (2004).

Metrology of the Ohm

Goals

Maintain the U.S. legal ohm and provide for the dissemination of an internationally consistent, accurate, reproducible, scalable, and traceable resistance standard that is readily and continuously available for the U.S. scientific and industrial base.

Physicist Rand Elmquist fills a cryogenic chamber with liquid helium in preparation for measuring the international standard for electrical resistance — the quantum Hall effect.

Customer Needs

The U.S. electronics instrumentation industry, along with military and aerospace industries, maintains a position of world leadership through the development and deployment of increasingly sophisticated multi-function, high-precision, and low-maintenance instruments. U.S. laboratories and manufacturers use NIST resistance standards calibrations for cutting-edge measurements such as gene-mapping and protein synthesis, which require extremely stable temperature control. To meet the present challenging needs and in anticipation of the increasingly strict demands of advanced scientific processes, this project develops instruments and standards that enable the dissemination of a reliable unit of resistance. Many electrical measurements (*e.g.*, at very high or low current levels) are converted to resistance measurements. Resistance standards are used to support a wide variety of measurements of impedance, temperature, strain, and power over a wide range of frequency and at very high levels of accuracy. Through this very broad customer base, the activities of this project enable U.S. industry to demonstrate and verify in a cost-effective way the accuracy of electrical measurements and the performance of high-precision instrumentation in a competitive world environment.

Technical Strategy

Maintenance of the U.S. legal ohm with the quantum Hall resistance (QHR) requires research and the pursuit of scientific breakthroughs in quantum metrology to maintain an accurate local representation of the unit, and close collaboration with other National Metrology Institutes (NMIs), including participation in international metrology comparisons to ensure international consistency of electrical measurements.

Following the CCEM-K2 Key Comparison guided by NIST, there has been a marked improvement in the quality of standards and measurements on high resistance. The world's first Cryogenic Current Comparator (CCC) for direct scaling from the QHR up to 1 MΩ was developed at NIST in 2002. This measurement technique now has been extended to values of resistance 100 times higher, and a prototype has been used to characterize room-temperature standards and cryogenic resistance samples at 100 MΩ. While working to perfect high-ratio CCC scaling, we are pursuing the development of high-valued thin-film resistance standards for the quantum metrology triangle (QMT).

The challenge of the QMT experiment is to test the fundamental concepts underlying the Josephson voltage standard, the QHR standard, and current standards based on single-electron tunneling (SET) technologies. This experiment requires an extremely quiet high-ratio CCC, combined with SET current sources orders of magnitude larger than are presently available. Ultimately these could be used to build a source producing useful levels of quantum current. Our work on scaling to high resistances, however, represents an initial practical step toward resistance measurements using quantum current sources built up from an SET pump.

CCC systems have replaced room-temperature current comparators in many NMIs because they allow much lower uncertainty in resistance scaling. Commercialization of CCC systems has ceased for the time being because a few such systems failed to operate successfully over the long term at NMIs.

Technical Contact:
Randolph E. Elmquist

Staff-Years:
3.0 Professionals
1.0 Technician

NIST is a world leader in designing and using CCCs, and has contracted to build a turnkey CCC system for Sandia National Laboratory (SNL). This system will duplicate a CCC used regularly at NIST for scaling and maintenance of standards between 1 W and 10 kW.

Completion of the new Advanced Metrology Laboratory (AML) has allowed the NIST resistance metrology project to operate in a superior environment with improved control of parameters such as temperature and humidity. In addition to the substantial improvement in typical laboratory conditions, this move represented a significant accomplishment, since it was completed with no disruption in the measurement services. Our most heavily used calibration systems for high-quality 1 W and 10 kW resistance standards were duplicated in the AML to facilitate the move of these calibration services. One duplicate system will now be used to study the new generation of 1 W standards built using improved resistance alloys. Improved 100 kW and 1 MW services are already in place using the updated and modified 10 kW system, allowing better measurements on newer air-type standards.

PLAN

- Construct improved low-noise CCC device and new cryogenic resistors for comparing the QHR to 100 MW
- Deliver and install a CCC system at SNL to allow decade-value scaling
- Establish a program to precisely characterize Thomas-type and newer types of 1 W resistance standards to better predict behavior under transport

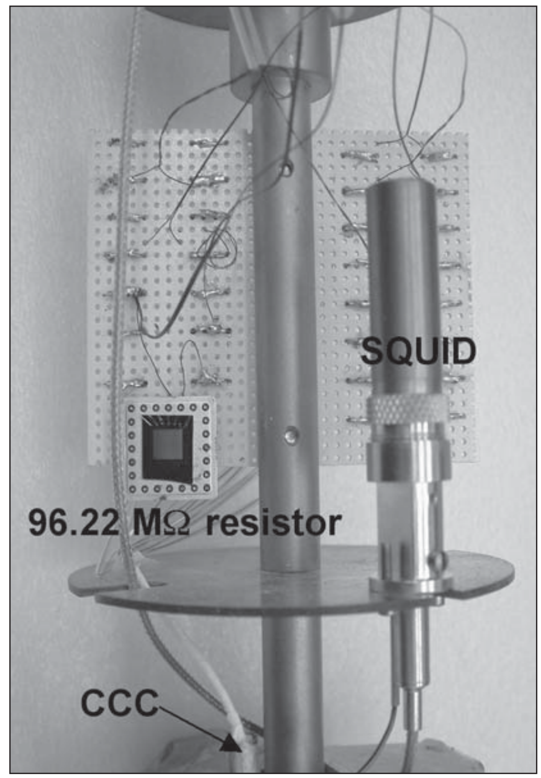
ACCOMPLISHMENTS

■ We developed high-resistance CCC measurements using a cryogenic resistor, and ways of using that type of CCC for a QMT experiment relating the Josephson effect (Josephson constant K_J) to the quantum Hall effect (von Klitzing constant R_K) and the precise control of SET pump electrical charge (e). Based on Ohm's law, this would relate the ratio of the Josephson microwave frequency f_{JVS} and the SET pump cycle frequency f_{SET} to the dimensionless product,

$$e R_K K_J = \frac{a f_{JVS}}{f_{SET}} = 2 ,$$

where a represents a ratio of experimental integers, including the Josephson step number n, Hall plateau quantum number i, and number of electrons per pump cycle. From the 1998 CODATA-recommended values of fundamental constants, this dimensionless combination of fundamental constants is known to a combined relative uncertainty of $u_r = 7.8 \times 10^{-8}$.

High-resistance standards and thin-film samples have been studied using CCCs and the NIST Active-Arm Bridge (AAB). These methods complement one another, with the CCC giving fast-response data and the AAB providing automated, long-duration data at higher voltages. Tests show great variation in absorption due to dielectric materials used to seal some high-resistance standards. The NIST thin-film cryogenic samples with resistance 100 MW are nearly free of dielectric absorption.



Cryogenic current comparator for measurement of ~100 MW resistance samples directly against the quantum Hall resistance.

■ NIST has developed high-resistance standards and Hamon-type scaling networks for calibrations up to 100 TW. The development of a number of high-resistance standards was partially funded by contracts with DoD and DOE calibration laboratories. Improved standards and automated measurement techniques at these levels allowed measurement uncertainties to be lowered by 80 % to 95 % in 2004.

Other lower-value resistor and shunt calibration uncertainties also were reduced concurrent with the distribution of Technical Note 1458, *NIST Measurement Services for DC Standard Resistor*, and the move to the AML, in March 2004.

Calibrations

Over 330 calibrations were performed with approximately $360,000 income received (October 1, 2003 to September 30, 2004).

Collaborations

- Four sets of sealed resistance standards with values 1 GW, 10 GW, 100 GW, and 1 TW were delivered to the DoD's Army and Air Force primary standards laboratories.

- A contract to build, test, and install a 100-to-1 ratio CCC for DOE's Sandia Primary Standards laboratory was finalized in June 2004.

Selected Publications

R. E. Elmquist, E. Hourdakis, D. G. Jarrett, and N. M. Zimmerman, "Direct resistance comparisons from the QHR to 100 Megohm using a cryogenic current comparator," to be published in IEEE Trans. Instrum. Meas. Special Issue on Selected Papers, Conference on Precision Electromagnetic Measurements 2004.

D. G. Jarrett, R. E. Elmquist, "Settling times of high-value standard resistors," to be published in IEEE Trans. Instrum. Meas. Special Issue on Selected Papers, Conference on Precision Electromagnetic Measurements 2004.

R. E. Elmquist, D. G. Jarrett, G. R. Jones, Jr., M. E. Kraft, S. H. Shields, and R. F. Dziuba, "NIST measurement service for dc standard resistors," Natl. Inst. Stand. Technol. Tech. Note 1458, (December 2003).

D. G. Jarrett and R. F. Dziuba, "CCEM-K2 key comparison of 10 MΩ and 1 GΩ resistance standards," IEEE Trans. Instrum. Meas. 52, (2), pp. 474-477 (April 2003).

R. E. Elmquist, N. M. Zimmerman, and W. H. Huber, "Using a high-value resistor in triangle comparisons of electrical standards," IEEE Trans. Instrum. Meas. 52, (2), pp. 590-593 (April 2003).

N. F. Zhang, N. Sedransk, and D. G. Jarrett, "Statistical Uncertainty Analysis of CCEM-K2 Comparison of Resistance Standards," IEEE Trans. Instrum. Meas. 52, (2), pp. 491-494 (April 2003).

R. F. Dziuba and D. G. Jarrett, "CCEM-K2 key comparison of resistance standards at 10 MΩ and 1 GΩ," Appendix B of Mutual Recognition Arrangement Bureau International des Poids et Mesures (BIPM) Report, also in Appendix B of the Bureau International des Poids et Mesures (BIPM) Key Comparison and Calibration Database http://www.bipm.org/pdf/final_reports/EM/K2/CCEMK2.pdf (also link from Metrologia, 39, Tech. Suppl., 01001 (2002).

D. G. Jarrett, "Analysis of a dual-balance high-resistance bridge at 10 TΩ," IEEE Trans. Instrum. Meas. Special Issue on Selected Papers, Conference on Precision Electromagnetic Measurements 2000, 50, (2), pp. 249-254 (April 2001).

R. E. Elmquist, A.-M. Jeffery, and D. G. Jarrett, "Characterization of four-terminal-pair resistance standards: A comparison of measurements and theory," IEEE Trans. Instrum. Meas. Special Issue on Selected Papers Conference on Precision Electromagnetic Measurements 2000, 50, (2), pp. 267-271 (April 2001).

R. E. Elmquist, M. E. Cage, Y.-H. Tang, A.-M. Jeffery, J. R. Kinard, Jr., R. F. Dziuba, N. M. Oldham, and E. R. Williams, "The ampere and electrical standards," J. Res. Natl. Inst. Stand. Technol., 106, pp. 65-103 (January/February 2001).

Farad and Impedance Metrology

Technical Contacts:
Yicheng Wang

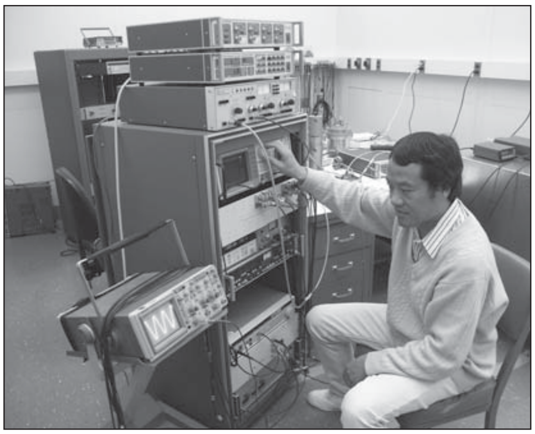
Staff-Years:
4.5 Professionals
2.0 Technicians
0.8 Contractor

"...the research you are doing related to the frequency response of the fused-silica standards, some of which you shared with us, has also raised eyebrows and left positive impacts both here and with others I just met at the NCSLI..."

Steve Kaplan,
Vice President,
Andeen-Hagerling, Inc.

Goals

Maintain the farad and tie the U.S. legal farad to the international system of units, support and improve NIST's impedance measurement services, and ensure the critically needed access of the U.S. industrial base to internationally consistent, reliable, reproducible, and traceable electrical measurements.



Yicheng Wang sets up an automated system for determining the frequency dependence of fused-silica capacitors.

Customer Needs

This project ties the U.S. legal system of electrical units to the International System of Units (SI) through the realization of the SI unit of capacitance. This work also forms the foundation of NIST's measurement services for electrical impedance, ensuring the sound metrological basis for all impedance measurements, both nationally and internationally, and ensuring that the claims of measurement accuracy by U.S. industries are recognized and accepted worldwide. The need continues for better representation of capacitance and also for better test and calibration tools at NIST with which to verify objectively claims of improved performance specifications, to achieve consistency, and to help avoid technical trade barriers.

Technical Strategy

The primary facility for connecting the U.S. legal system of electrical units to the international system of units is the NIST calculable capacitor, with which the measurement of capacitance is effectively achieved through a measurement of length. Both the calculable capacitor and the chain of high-precision measurements that transfers the SI unit to the calibration laboratories must be maintained, improved, and compared with other national metrology laboratories to ensure measurement consistency on an international level.

AC measurements linking the calculable capacitor to the set of standards comprised by the National Farad Bank have been performed only at 1592 Hz and 1000 Hz. However, customer standards are often calibrated at other frequencies; as a result, the uncertainty provided for customer calibrations was significantly increased to account for differences in the capacitance unit due to frequency dependence. In order to better support customers' needs in the broader frequency range from 50 Hz to 20000 Hz, the frequency dependence and dissipation factor of the Farad Bank need to be determined.

Many national laboratories are developing the capability to do ac quantum Hall resistance (QHR) measurements as a means to obtain a capacitance unit because of the difficulty in establishing a calculable capacitor measurement system. The remaining technical challenge for using ac QHR as a quantum representation of impedance is to characterize the linear frequency dependence of a QHR device. With the availability at NIST of the calculable capacitor, NIST is ideally situated to perform measurements to link the capacitance as determined with the ac QHR to NIST's present unit of capacitance.

Development of wideband impedance measurement services requires reference standards that can be characterized over the impedance and frequency ranges of interest. NIST has developed a system to characterize commercial four-terminal-pair (4TP) capacitance standards from 1 pF to 1 nF over the frequency range from 1 kHz to 10 MHz. This system is being used to offer special tests for 4TP capacitors as well as provide reference standards for general impedance measurements using a commercial LCR meter. A bootstrapping technique using the LCR meter and an inductive voltage divider (IVD) can be used to extend the characterization from the 1 nF standard to higher-valued capacitance standards up to 10 μF. A major source of error associated with the bootstrapping technique is due to the in-phase and quadrature errors of the IVD. The newly developed straddling bridge will allow for the accurate self-calibration of single-decade, two-stage reference IVDs over the frequency range of 20 Hz to 100 kHz.

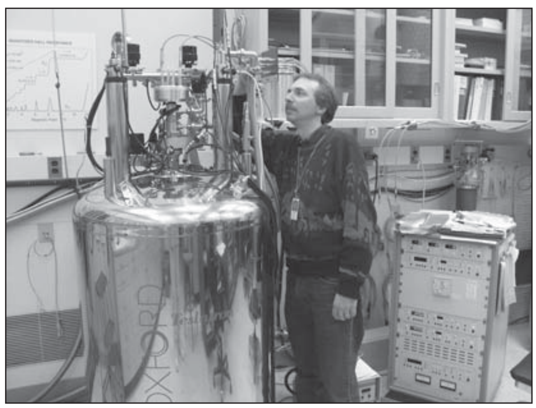
PLAN

- Establish references for determining the dissipation factor of the National Farad Bank from 50 Hz to 20 kHz
- Develop special tests for determining the dissipation factor of fused-silica capacitance standards from 50 Hz to 20 kHz
- Determine and analyze the linear frequency dependence of a QHR relative to a calculable resistor
- Develop a multi-frequency quad bridge to compare the frequency dependence of a calculable resistor with that of a well-characterized capacitance standard
- Perform SI measurements of the ac QHR via the calculable capacitor
- Analyze and document a recently developed system to characterize four-terminal-pair capacitance standards of values from 1 pF to 100 mF for use as primary reference standards for measuring general impedances (inductors, capacitors, and resistors) at frequencies from 20 Hz to 100 kHz
- Complete construction of a Capacitance Scaling Bridge for high-accuracy capacitance measurements from 50 Hz to 20 kHz

ACCOMPLISHMENTS

■ *Developed special tests for the frequency dependence of capacitance standards over the entire audio frequency range based on recent advances in capacitance measurement capabilities, driven by several requests from Sandia, other national laboratories, and from industry.* The value of a typical standard capacitor may vary slightly with frequency due to the effects of electrode surface films, an imperfect medium between the electrodes, and non-ideal connecting leads. Using a combination of a 1 pF "cross capacitor" having a negligible frequency dependence due to surface films, and a 10 pF nitrogen dielectric capacitor with a very small residual inductance as references, we have measured the frequency dependence of 10 pF and 100 pF reference fused-silica capacitors from 50 Hz to 20 kHz. Once these standards were characterized, we were then able to measure the frequency dependence of two reference capacitors provided by Sandia National Laboratories' Primary Standards Lab. The capacitance uncertainties for Sandia's standards at frequencies of 100 Hz and 400 Hz are smaller by a factor of 5 than those previously assigned. This improvement allows the Primary Standards Lab to reduce the uncertainties reported on calibrations they provide to their internal Sandia customers and to other DOE laboratories.

■ *Developed and characterized a programmable capacitance standard to provide accurately known values of capacitance over 6 orders of magnitude below 100 pF with a resolution of 0.1 fF.* The potential applications of a well-characterized programmable capacitance standard are numerous. The current work on a capacitance standard based on single electron tunneling (SET) involves an "odd value" cryogenic capacitor. The programmable capacitor will provide a crucial link to compare an SET-based capacitance standard with the SI farad represented by the Farad Bank. This comparison is not only important to confirm the accuracy of the new standard but also necessary for closing the metrology triangle via the SET-based capacitance standard. Another example that requires precise measurement of an "odd value" capacitor is a new pressure standard based on measurements of the dielectric constant of helium. The NIST Chemical Science and Technology Laboratory has proposed to use cross capacitors for accurate measurements of the dielectric constant; however, it is difficult to construct a cross capacitor with a precise value. A programmable reference capacitor can also be used to test the linearity of commercial precision capacitance bridges.



Scott Shields assists with the installation of the ac QHR measurement system.

■ *Performed and analyzed first NIST ac QHR measurements*. We have demonstrated that all dc QHR guideline properties and all dc and ac QHR values can be measured without changing sample probe lead connections at the QHR device and that ac QHR values converge to the dc value. We have also demonstrated that quadratic frequency dependence of an ac QHR device can be analytically modeled and corrected within a few parts in 10^9. The remaining challenge for using ac QHR as a quantum representation of impedance is to characterize and minimize the linear frequency dependence.

■ *Fully tested a straddling bridge*. The bridge has been used to self-calibrate two IVD — a low-frequency (20 Hz to 20 kHz), single-decade IVD and a high-frequency (1 kHz to 1 MHz) IVD. Test results indicate that the low-frequency IVD exhibits in-phase and quadrature errors of less than ±5 parts in 10^8 of full-scale ratio at 1 kHz, increasing to ±1 part in 10^6 at 20 kHz. In addition, a method to compensate for the internal admittance loading errors of the low-frequency IVD was verified by calibrating the IVD with the straddling bridge both with and without compensating networks installed. The measurements indicate that the compensation scheme reduces the IVD's in-phase and quadrature errors by more than an order of magnitude at 20 kHz.

■ *Designed and implemented a system to characterize four-terminal-pair capacitance standards of values from 1 pF to 100 mF for use as primary reference standards for measuring general impedances (inductors, capacitors, and resistors) at frequencies from 20 Hz to 100 kHz*. New commercial capacitance bridges and LCR meters are becoming more and more accurate. To satisfy the need for this demanding calibration service by U.S. industry, we have to modernize the NIST calibration facilities. The new calibration system has been designed with particular emphasis on automation. An uncertainty analysis is underway.

■ *Completed the key international comparison for inductive voltage dividers (CCEM-K9)*. The existing NIST IVD calibration system was used with the new straddling bridge to determine the in-phase and quadrature errors of the precision IVD used for a CCEM sponsored international comparison. Results indicate that agreement between the two systems is better than 3 parts in 10^8 for in-phase error components, and better than 5 parts in 10^8 for quadrature error components. The results of the worldwide comparison will be available in 2005.

■ *Acted as pilot laboratory for SIM capacitance key comparison SIM-EM.K4 and supplemental comparisons SIM-EM.S4 and SIM-EM.S3, completed protocol documentation and first round of measurements*. The CCEM K4 key comparison for capacitance standards was completed in 2000 with NIST serving as the pilot laboratory. As the only country with a working calculable capacitor in the Americas, NIST has the obligation to provide the link between SIM and CCEM for capacitance measurements. In partial fulfillment of this obligation, NIST is serving as the pilot lab for an international comparison of capacitance measurements between many of the National Metrology Labs in North, Central, and South America.

■ *Completed moving the Farad Bank, the quad bridge bank, the capacitance calibration lab, and ac QHR lab into the new Advanced Measurement Laboratory (AML) without causing major disruption of impedance dissemination*. We have checked the Farad Bank against the calculable capacitor after the move. Initial results indicate that the Bank value changed by less than 2 parts in 10^8. We will to continue monitoring the Farad Bank for six more months before moving the calculable capacitor to its new environmentally controlled room in the AML.

Calibrations

■ 206 tests were performed on 123 artifacts for 85 customers for impedance standards and inductive voltage dividers, providing income to the division of approximately $209,763 (October 1, 2003 to September 30, 2004).

Collaborations

■ Yicheng Wang collaborated with the Physical and Chemical Properties Division in a competence project to develop an atomic standard of pressure based on capacitance metrology.

Selected Publications

Y. Wang and L. Lee, "A digitally programmable capacitance standard," Rev. Sci. Instrum. 75, pp. 1158 (2004).

Y. Wang and S. Shields, "Improved capacitance measurements with respect to a 1 pF cross capacitor from 200 Hz to 2000 Hz," Digest, Conference on Precision Electromagnetic Measurements, (London, England, 27 June – 2 July, 2004), pp. 489-490.

J.W. Schmidt, M.R. Moldover, and Y. Wang, "Measured permittivity ratio of Argon/Helium using cross capacitors," Digest of Conference on Precision Electromagnetic Measurements (Conference on Precision Electromagnetic Measurements 2004), (London, England, 27 June – 2 July, 2004), p. 491.

S. Avramov-Zamurovic, B. Waltrip, K. Stricklett, and A. Koffman, "A balancing algorithm for systems with correlated injections," Proc., of the IEEE Instrumentation and Measurement Technology Conference (IMTC/2004), 18–20 May, 2004, Como, Italy.

Y. Wang, "Frequency dependence of capacitance standards," Rev. Sci. Instrum. 74, pp. 4212 (2003).

N. M. Zimmerman, M. El-Sabbagh, and Y. Wang, "Improved Cryogenic Capacitor for the ECCS: Larger Value (10 pF) and SI measurement by tuning the calculable capacitor," IEEE Trans. Instrum. Meas. 52, pp. 608 (2003).

A.-M. Jeffrey and A. D. Koffman, "Improved 1 kHz capacitance calibration uncertainty," IEEE Transactions on Instrumentation and Measurement, 52, (4), pp. 1284-1288 (August 2003).

THE ELECTRONIC KILOGRAM

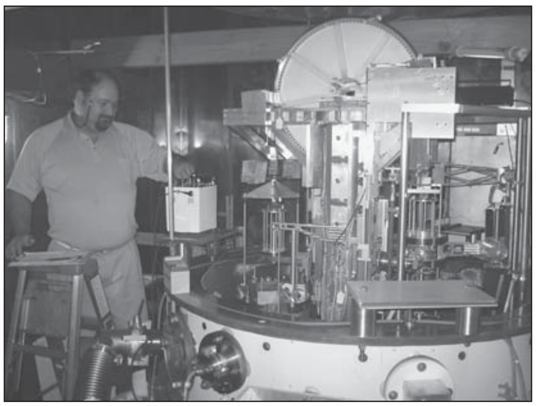
Technical Contact:
Richard L. Steiner

Staff-Years:
3.0 Professionals
1 Guest Researcher
0.25 Student

GOALS

Realize the electrical unit of voltage and provide an alternative definition of the unit of mass that is based on measured quantities determined by fundamental physical constants of nature.

Realize the unit of Force in the International System of Units (SI) through the electrical units at the nanonewton level; provide calibrated force artifacts for research groups and industry; and establish intrinsic force standards of nature at the nanonewton level traceable to the SI.



Daniel Winester, Geodesist NOAA - NOS - National Geodetic Survey, performing a gravity transfer to the level of the reference mass, in the small cage hanging on the left side of the watt balance wheel.

CUSTOMER NEEDS

The kilogram is the only remaining base unit in the SI whose definition is based on a physical artifact rather than on fundamental properties of nature. Environmental contamination or material loss from surface cleaning, or other unknown mechanisms, are causing the mass of the kilogram to vary by about 3 parts in 10^8 per century relative to sister prototypes. This observed drift highlights a significant shortcoming of the SI system. The measured values of many physical constants are based on mass, and these constants are regularly used in quantum-based measurement systems, such as the Josephson effect, which are becoming more significant to the growth of international technology and trade accreditation. Thus, with a time-drifting mass standard, adjustments to the value of physical constants must be made periodically to maintain the consistency of the SI system. Moreover, each future change will adversely affect a continuously growing technology base that relies increasingly on electronic testing, quality control, and environmental monitoring. The adoption of the electronic kilogram as the mass standard will improve the consistency of the SI and will also provide better determinations of many fundamental physical constants, such as the charge and mass of the electron, that serve the general scientific and technological communities.

Commercial and custom mechanical test instruments, including instrumented indentation machines and atomic force microscopes, have been developed with force detection capabilities extending to the nanonewton regime. Correspondingly, a desire for accurate and traceable force measurement is emerging within the International Organization for Standardization (ISO) task groups and American Society for Testing and Materials (ASTM) committees. However no methods for establishing force measurement traceability at levels below 10^{-5} N are currently available. It is within this context that the Microforce Realization and Measurement project has developed facilities and instruments capable of providing a viable primary force standard below 10^{-5} N; the ultimate goal is to realize force in this range at a relative uncertainty of as little as 10 pN/μN.

TECHNICAL STRATEGY

The equivalence of electrical and mechanical power provides a convenient route to the measurement of mass in terms of other quantum-mechanically defined measurement units. The apparatus at the Electronic Kilogram facility is a force balance connected to an induction coil in a large magnetic field. Configured as either an electric generator or motor, both kinds of power are measured in a way that is unaffected by the dissipative forces of friction and electromagnetic heating. The experimental observables are time, length, voltage, and resistance, measured with respect to fundamental and invariant quantum phenomena, respectively: atomic clocks, lasers, the Josephson effect, and the quantum Hall effect.

The entire experiment is a complex mesh of mechanical and electronic components controlled by computer. The systems are not only for watt data acquisition but also include reference standards, servo control, and environmental monitoring. All systems need to perform accurately and consistently 24 hours a day. Some peripheral systems include a programmable Josephson array voltage standard, a gravimeter, an ac resistance temperature bridge, a temperature controller for the building, and a current controller for the magnetic field solenoid. Even though the apparatus has been rebuilt and improved since 1998, a number of additional improvements are recognized as necessary for better instrument performance, easier operational use, and preventative maintenance. This is expected to compose much of the work in 2005.

Using a carefully designed Electrostatic Force Balance (EFB), measurements of length, capacitance, and voltage provide a viable primary small force standard consistent with the SI. The NIST EFB has been used to measure the force sensitivity of transfer artifacts such as piezoresistive microcantilevers and load cells. These transfer standards will be used to compare the EFB and the primary standards from the emerging small force programs at the NPL and PTB. Ultimately the EFB and transfer artifacts will be used to investigate and provide SI traceability to intrinsic standards such as capillary forces, atomic bond ruptures, and molecular structure reordering.

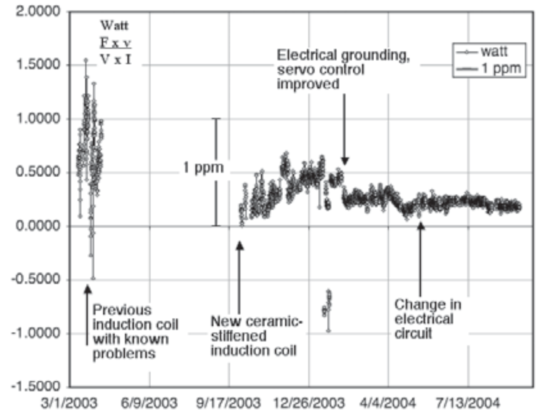
PLAN

- Publish a value for the Planck constant at about 0.1 ppm uncertainty or better to compare a NIST 2004 value with the international Avogadro and other Watt groups' values, including NIST 1998
- Upgrade electronics for regular monitoring of the kilogram at an uncertainty level of 0.01 ppm
- Complete a thorough phase II intercomparison transfer of small force standards between NIST, NPL, and PTB

ACCOMPLISHMENTS

■ *Electronic Kilogram* — For the electronic-kilogram before fiscal year 2004, the relative standard deviation of the acquired watt data was 0.25 ppm. At this time the third version of the induction coil was finally put into use and noise in the watt data was immediately reduced by a factor of 5. With enhanced resolution, smaller drifts in day-to-day values were more easily identified and more metrological problems solved. In May 2004, an electric circuit reconfiguration reduced a nagging electrical problem, and the long-term (monthly) drift was further reduced. By September 2004, the relative standard deviation of the daily averaged watt values stood at 0.008 ppm.

Also by May 2004, the watt balance had a stable alignment, an improved electrical measurement circuit, and all reference standards maintained at a high level of accuracy; so highly sensitive systematic error checking at the 0.01 ppm level began. Tests included using different reference mass materials, reversing the magnetic field, checking hysteresis in the superconducting solenoid's magnetic field, and seeking correlation between watt variations and environmental parameters. Even the value of gravity at the level of the mass had to be checked, given the changes around the lab from rebuilding the apparatus (see photo on page 23). Systematic corrections have been found, but are less than 0.04 ppm.



The graph shows the level of improvement in the resolution and stability of the watt results. The watt values are the deviation from identity in ppm for force × velocity relative to voltage × current. The actual values do not contain all corrections, including a control uncertainty of up to 0.2 ppm. The NIST 1998 number and the CODATA value is approximately 0.0 ppm.

■ *MicroForce Realization* — The MicroForce Realization Project EFB has achieved agreement between an electrostatic and gravitational force of 10^{-5} N to within a few hundred pico/micro Newtons. The EFB has subsequently been used to measure the force sensitivity of a piezoresistive microcantilever by directly probing the EFB. The calibrated cantilever was used as a secondary force standard to transfer the unit of force to an optical lever-based sensor mounted in an atomic force microscope. This experiment was perhaps the first ever force calibration of an atomic force microscope to preserve an unbroken traceability chain to an appropriate national standard. Recently a calibrated piezoresistive cantilever was shipped to a university researcher to verify a thermal and dimensional calibration technique for AFM cantilevers. The agreement between the three methods was within 10 %. This was the first time an SI traceable small force standard was provided to an independent research effort by a national metrology institute.

Collaborations

R. Steiner, E. Williams, and D. Newell are collaborating via periodic workshops with NPL-UK, METAS-Switzerland, and BNM-LCIE-France as part of the international CCEM group on the watt balance realization of the kilogram.

Edwin Williams and David Newell are collaborating with the Automated Production Technology, Precision Engineering, and Ceramics Divisions at NIST in a competence project for Microforce Realization and Measurement.

Collaboration with Physics Professor Nancy Burnham at Worcester Polytechnic Institute has yielded a comparison of three separate calibration techniques of AFM cantilevers showing agreement to within 10 %.

Collaboration with Peter Cumpson of NPL has yielded an agreement to compare NIST and NPL small force transfer artifacts in November 2004.

Selected Publications

R. L. Steiner, D. B. Newell, E. R. Williams, R. Liu, and P. Gournay, "The NIST project for the electronic realization of the kilogram," IEEE Trans. Instrum. Meas. (Conference on Precision Electromagnetic Measurements 2004), to be published (2005).

R. L. Steiner, E. R. Williams, and D. B. Newell, "Details of the 1998 watt balance experiment determining the Planck constant," NIST J. Res., submitted (2004).

R. L. Steiner, D. B. Newell, E. R. Williams, R. Liu, and P. Gournay, "The NIST electronic realization of the kilogram project," 2004 Conference on Precision Electromagnetic Measurements, June, 2004, London, England, pp. 52-3. (June 2004).

G. A. Matei, E. J. Thoreson, J. R. Pratt D. B. Newell, and N. A. Burnham, "Thermal method of cantilever calibration over a 200 kHz bandwidth," Nanotechnology, submitted September 8, 2004.

J. R. Pratt, D. T. Smith, D. B. Newell, J. A. Kramar, and E. Whitenton, "Progress towards SI traceable force metrology for nanomechanics," J. Mater. Res., 19 (1), pp. 366-379 (2004).

J. R. Pratt, D. B. Newell, J. A. Kramar, and E. Whitenton, "Calibration of piezoresistive cantilever force sensors using the NIST electrostatic force balance," Proceedings of IMECE'03: 2003 ASME International Mechanical Engineering Congress & Exposition, Washington, DC, 16-21 November 2003.

J. R. Pratt, D. T. Smith, J. A. Kramar, and D. B. Newell, "Microforce and Instrumented Indentation Research at the National Institute of Standards and Technology," Proc. 4th Inter, Symposium on MEMs and Nanotechnology, 2003 Society of Experimental and Applied Mechanics Annual Conference, Charlotte, NC, pp. 299-306, 2-4 June 2003.

J. R. Pratt, D. Newell, J. Kramar, J. Mulholland, and E. Whitenton, "Probe-force calibration experiments using the NIST electrostatic force balance," Proc. of the American Society for Precision Engineering 2003 Winter Topical Meeting, University of Florida, pp. 64-69 (2003).

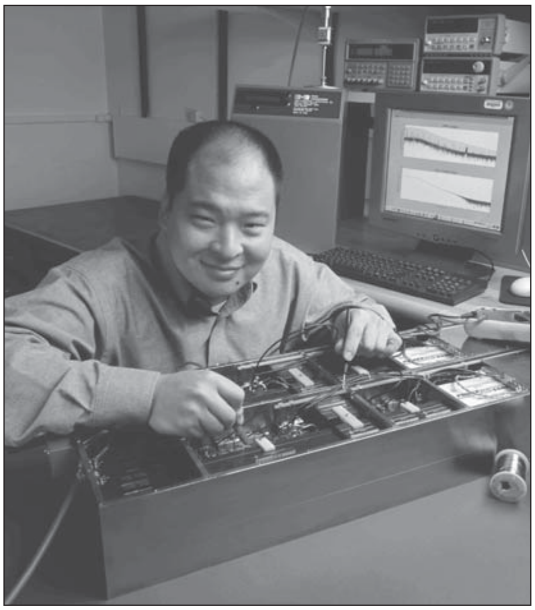
D. B. Newell, J. A. Kramar, J. R. Pratt, D. T. Smith, and E. R. Williams, "The NIST microforce realization and measurement project," IEEE Trans. on Instrum. Meas., Special issue of Conference on Precision Electromagnetic Measurements 2002 52(2), pp. 508-511 (2003).

J. P. Schwarz, R. Liu, D. B. Newell, R. L. Steiner, E. R. Williams, D. Smith, A. Erdemir, and J. Woodford, "Hysteresis and related error mechanisms in the NIST watt balance experiment," J. Res. Natl. Inst. Stand. Technol., 106 (2), pp. 381-389 (2001).

Johnson Noise Thermometry

Goals

Use a quantum-based voltage source to reduce the uncertainty of Johnson noise thermometers, with the ultimate goal of creating an intrinsic quantum-based electronic temperature standard for use by the NIST Chemical Science and Technology Laboratory.



Sae Woo Nam tests the cross-correlation electronics for the Johnson noise thermometry system. A gallium triple-point cell at 302.916 K is behind him.

Customer Needs

Gas-based and fixed-point methods of precision thermometry are either limited to specific fixed temperatures or require considerable effort to reduce uncertainties below parts in 10^5. An electronic quantum-based method would provide another approach as well as advantageous features such as improved linearity of temperature calibrations. It would also provide an improved realization of the Kelvin thermodynamic temperature scale, and a direct link between temperature and electrical standards, possibly providing a route to a redetermination of the Boltzmann constant. More importantly, this quantum-based Johnson noise thermometry (JNT) method is a new paradigm to realize the thermodynamic temperature scale through electrical and quantum-based standards. This JNT approach to create an "electronic Kelvin" is analogous to the watt-balance program to realize an "electronic kilogram."

Our customers and collaborators include the NIST Chemical Science and Technology Laboratory, the temperature calibration laboratories of other national measurement institutes, and industrial applications requiring long-term temperature stability or with temperature sensors in difficult or remote locations.

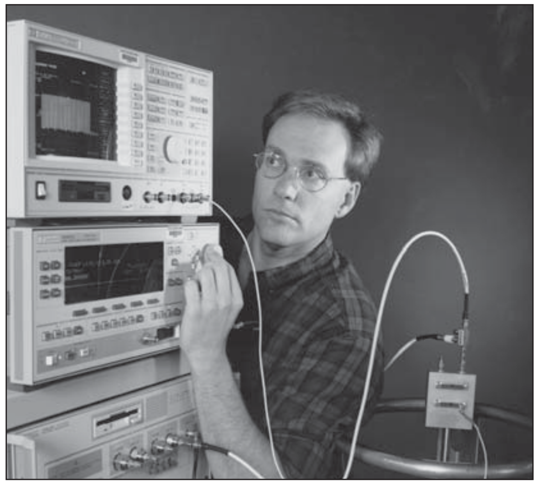
In order to meet these needs and to create a quantum-based electronic temperature standard, we have developed new technology in a number of different areas. We have constructed low-noise cross-correlation electronics, developed a quantum voltage noise source (QVNS) specifically for this application, and performed the first calibrations of the electronics using the QVNS. We have compared the QVNS synthesized pseudo-noise voltage waveforms with the voltage noise of resistors in triple point cells of both gallium and water. We have also devised a novel ratiometric method that uses the QVNS to compare the voltage noise of resistors at different temperatures.

Technical Strategy

The goal of the Johnson noise thermometry program at NIST is to build an electronic temperature standard based on the quantized voltage pulses of superconducting Josephson junctions. In a Johnson noise thermometer (JNT) system, the temperature T is inferred from a measurement of the Johnson noise voltage V_T across a calibrated resistance R. The mean-squared voltage noise is given by the Nyquist formula $\overline{V_T^2} = 4kTR\Delta f$, where Δf is the bandwidth for the measurement and k is Boltzmann's constant. Cross-correlation techniques are typically used to measure these extremely small voltages to remove the error introduced by the noise in amplifiers. In 1999, John Martinis realized that the Josephson arbitrary waveform synthesizer being developed by the Quantum Voltage Project might be able to produce a stable, accurate, pseudo-noise voltage to provide a better means of calibrating the low-noise cross-correlation electronics. A stable, programmable, and intrinsically accurate noise source, such as that provided by the QVNS, would provide the advantages of direct calibration of the cross-correlation electronics, matching of the calibration voltage noise to that of the sense resistor, and matching of the source impedance to both the sense resistance and the output transmission-line impedance. These features reduce the measurement uncertainty, increase the measurement bandwidth, and decrease the measurement time for the entire JNT system.

Using a QVNS, we hope to achieve uncertainties of better than a few parts in 10^5 for temperatures in the range of a several hundred kelvins. At these temperatures the noise signals are small, on the order of 1 nV/Hz$^{1/2}$ for a 100 Ω resistor. However, in order to achieve such small uncertainties for such low-voltage signals, the noise power spectral density must be integrated for a long time and over a wide bandwidth. Thus the QVNS must be stable for long integration times but does not need to generate large voltages. We have devised a special method of biasing the QVNS that meets these requirements and allows it to be much simpler than the Josephson arbitrary waveform synthesizer, where the primary focus has been to obtain the highest voltages.

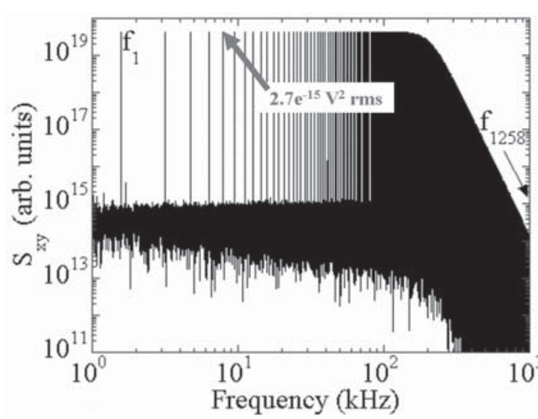
NIST has constructed custom cross-correlation electronics for the JNT program. Two pairs of voltage leads are measured with separate amplifier channels to perform the cross correlation measurement. Each signal is first measured with an ac-coupled differential FET, followed by an anti-alias filter with a cutoff frequency at 2 MHz. The resulting amplified and filtered signals are digitized at 50 MHz by a 14-bit analog-to-digital converter. Field-programmable gate arrays (FPGAs) at the output of the digitizers then digitally filter the signal with a low-pass frequency of 100 kHz. The digitally filtered data are transmitted via a 50 megabit/s optical link into a custom PCI card installed in a computer. Each channel transmits 2.08333 million samples per second, which is the effective sampling frequency of the signal. In the present system, a dual-CPU computer is used to calculate two 2^{21}-point fast Fourier transforms (FFTs) in real-time (less than 1 s). The cross-correlation and auto-correlation power spectra are then calculated, accumulated, and stored for later analysis.



Sam Benz optimizes the operating margins for the Josephson arbitrary-waveform synthesizer.

Accomplishments

- Sae Woo Nam, Wes Tew (NIST Chemical Sciences and Technology Laboratory), and Sam Benz have performed many comparisons between the Johnson noise voltage of a resistor in a gallium cell and the synthesized pseudo-noise waveforms of the quantum voltage noise source. Similar measurements have been done with a water triple-point cell. Measurements were made using the custom built cross-correlation electronics system. The computer-controlled optically interfaced system correctly sampled at the 50 MHz sampling rate and stored and processed the waveforms in real time. This correlation electronics is different from other systems because we digitally process the signal in an



Log-log plot showing the measured spectrum of a QVNS-synthesized pseudo-noise waveform. The spectrum was measured with the JNT cross-correlated electronics and shows the power (V2) spectrum Sxy of the 1258 tones synthesized by the QVNS. Each bin has a width of 1 Hz and is an average of 200 samples. The power spectrum is in arbitrary units based on the digitizer bins.

FPGA before sending it to a computer. This is necessary to reduce the data rate to the computer.

■ Paul Dresselhaus fabricated numerous circuits specifically to improve the performance and optimize the circuits for the JNT program. Benz has tested the circuits with appropriate pseudo-noise waveforms and demonstrated proper cross-correlation using an HP FFT spectrum analyzer. Benz also performed extensive measurements of input-output coupling for the JNT circuits and devised a novel unipolar bias method to decrease the coupling by about 40 dB. These results allowed us to take the next step and measure the arrays at much smaller voltages and higher bandwidth using Nam's cross-correlation electronics.

■ Nam, Benz, and Dresselhaus, in collaboration with Wes Tew of the Chemistry Laboratory, have continued development of the Johnson noise thermometry system. Unwanted distortion was observed when the Josephson signal was measured with the cross-correlation electronics. Nam and Benz were able to significantly reduce this distortion by using inductive chokes on the input of the electronics. The cause of the distortion appears to be mixing in the first FET amplifier stage of 100 MHz to 400 MHz delta-sigma modulator tones synthesized by the Josephson array. With this dramatic improvement, the Josephson synthesized noise waveform and the gallium and water triple point cells were directly compared. We found agreement to 2 parts in 10^3 with a 1s uncertainty of 1×10^{-3} between the voltage noise of a 100 W resistor in a triple-point gallium cell (T_{90} = 302.916) and a pseudo-noise waveform with the same average power that is synthesized by a quantized voltage noise source. We estimate the temperature of the resistor to be 302.5 K ± 0.3K 1σ uncertainty based on the uncertainty from the cross-correlation). With better characterization of our JNT system, we expect to achieve relative accuracies of parts in 10^5 for arbitrary temperatures in the range between 27 K and 1000 K.

■ Tew proposed using a new "ratiometric method" that takes advantage of the linearity of the Josephson waveforms to independently compare different noise powers. The Johnson noise power at a known temperature is first balanced with a synthesized noise power from the QVNS. The process is then repeated by balancing the noise power from the same resistor at an unknown temperature. When the two noise power ratios are combined, a thermodynamic temperature can be derived where the scaling is accomplished by the ratio of the two QVNS spectral densities. Using this method, preliminary results of the ratio between the gallium triple point and the water triple point were used to demonstrate the accuracy of the measurement system with a standard uncertainty of 0.04 %.

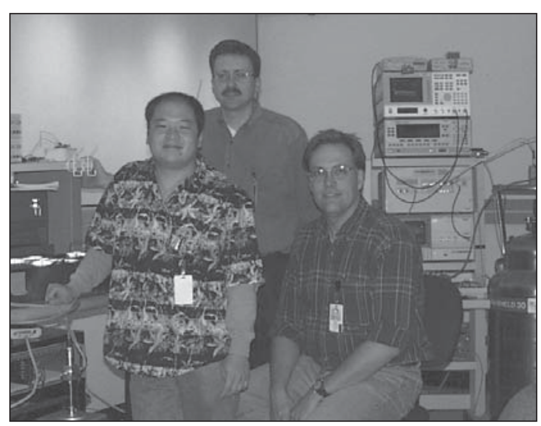
■ This year we have been able to measure the ratio of the gallium and water triple-point temperatures to within an accuracy better than 100 mK/K using the ratiometric method. This was accomplished by making improved Josephson circuits with smaller common mode signals, using flip-chip on flex packaging developed by the Quantum Voltage Project, and improving the output transmission lines and electrical connections in the electronics by eliminating distortion-producing poor contacts. Future efforts will focus on understanding the frequency dependence of the absolute measurements, which probably are due to the frequency response of the transmission line. These errors should be correctable or able to be reduced significantly. In the next year we also plan to perform more absolute and relative mode measurements at higher temperatures (273 K to 1000 K) through comparisons with an ITS-90 calibrated platinum resistance thermometer.

PLAN

Deliver cross-correlation electronics to CSTL temperature calibration laboratory

COLLABORATIONS

We are collaborating with Weston Tew of the Process Measurements Division (836) in the NIST Chemical Science and Technology Laboratory. This JNT development program has been supported by a five-year NIST competence award as well as with additional funds from NIST Divisions 836 and 817.



Sae Woo Nam, Wes Tew, and Sam Benz with the quantized voltage noise source.

Dr. D. Rod White from the Measurement Standards Laboratory in Lower Hutt, New Zealand is also consulting and collaborating with us, because he has many years of expertise in Johnson noise thermometry.

Selected Publications

S. Nam, S. Benz, P. D. Dresselhaus, W. L. Tew, D. R. White, and J. M. Martinis, "Johnson noise thermometry using a quantum voltage noise source for calibration," Digest 2004 Conference on Precision Electromagnetic Measurements, 27 June – 2 July 2004, London, England, pp. 664-665 (2004).

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S. P. Benz, P. D. Dresselhaus, and J. Martinis, "An AC Josephson source for Johnson noise thermometry," IEEE Trans. Instrum. Meas., 52, 2, pp. 545-549 (April 2003).

S. W. Nam, S. P. Benz, J. M. Martinis, P. D. Dresselhaus, W. L. Tew, and D. R. White, "A ratiometric method for Johnson noise thermometry using a quantized voltage noise source," *Temperature: Its Measurement and Control in Science and Industry*, 7, (1), pp. 37-42, Dean C. Ripple Ed., Proc. The Eighth International Temperature Symp., AIP Conf. Proc. 684, New York: Melville (2003).

S. P. Benz, J. M. Martinis, S. W. Nam, W. L. Tew, and D. R. White, "A new approach to Johnson noise thermometry using a Josephson quantized voltage source for calibration," Proc. TEMPMEKO 2001, the 8th Int'l Symp. on Temperature and Thermal Measurements in Industry and Science, B. Fellmuth, J. Seidel, and G. Scholz, Eds., Berlin: VDE Verlag, pp. 37-44 (April 2002).

Quantum Measurements

In earlier parts of this Technical Accomplishments Book for the Quantum Electrical Metrology Division, we discuss *standards* based either directly or indirectly on naturally occurring quanta.

In this section we present *measurements*, but not standards, many of which are achieved using quantum systems. Predominantly the system used is superconductivity, which is a macroscopic quantum system. Superconductors are particularly attractive for electrical metrology because they can carry current with very low loss, and with zero loss if the current is constant.

For measurements for quantum communications we use superconducting microcalorimeters to count single photons, the quanta of light. We use similar devices for X-ray microanalysis of materials and as ultra-sensitive or ultra-accurate detectors of infrared and X-ray radiation. Other superconducting detectors are use for terahertz frequency radiation. Our measurements of high-frequency electrical pulses and electrical power are based on fundamental standards that in turn rely on superconductors.

In a completely different way we are using superconductivity to contribute to a major NIST and international effort to realize the concept of quantum computing. If a quantum computer can be practically realized, it may be capable of vastly more computational power than any other known computing technique. It is of potentially profound national importance. As a result, NIST is investing heavily in this area because it is a very challenging measurement problem. Measurements are NIST's expertise and we are able to make essential contributions to this exciting technology.

Quantum computing is completely different from the computing we know. It relies on the manipulation of the wave functions that are the basis of quantum systems. The measurement of the output from a quantum computer is performed at the very fundamental limit of measurements, based on the Heisenberg uncertainty principle. As a result we are striving to realize measurement of unprecedented delicacy, using approaches that surely will be of use much broader than just quantum computing as we progress through the 21st century.

Quantum Computing Using Integrated Josephson Junction Circuits

Goals

Develop techniques for making highly coherent quantum systems using integrated circuits. This includes developing new high-fidelity measurement techniques for quantum systems. Ultimately, we would like to help make large-scale quantum information processing systems a reality.

Ray Simmonds probes the resistance of Josephson junctions on a new wafer of quantum bits.

Customer Needs

The integrated circuit components of classical computers are rapidly approaching the so-called "quantum limit." Instead of avoiding quantum effects, we have the opportunity to exploit them as a means for more effective computation. A quantum computer has the ability to use the intrinsic properties of quantum systems to naturally perform parallel processing during a calculation. This allows a quantum computer to solve problems considered intractable for classical computers. Three such problems have been of considerable interest: discrete logarithms, factorization, and search algorithms for large databases. The practical significance of building a successful large-scale quantum computer is tremendous:

- It could provide a powerful tool for encryption. A quantum computer is seen as the only instrument that could break the most secure encryption codes in use today. This is an immensely important subject for national security.
- It could be used to solve highly complex (many-body) problems in a reasonable amount of time. This will become increasingly important for the chemical and biological sciences.
- It could provide rapid search engines to help navigate us through the information age.
- It could allow us to simulate large quantum systems efficiently.

In a conventional computer, information is often stored as electrical charge on tiny capacitors. The presence or absence of charge stored on a single capacitor represents a (classical) bit, which can represent two (classical) information states "0" and "1." All logical computations are done using groups and combinations of this binary information. A quantum bit or "qubit" is described in terms of two quantum states denoted by "|0>" and "|1>". Remarkably, a quantum bit can be placed in a state that is a mixture of *both* "|0>" *and* "|1>"! Even more remarkable is the fact that multiple qubits can be placed in a massive mixture of all combinations of their possible states, a phenomenon known as entanglement. Entanglement is the "magic" of quantum mechanics and allows a quantum computer to stir up quantum information in order to produce a meaningful calculation with incredible speed.

Whether or not quantum computing becomes practical, our work will produce new knowledge for the precise measurement of quantum systems. Through our research with quantum-mechanical superconducting circuits, we are learning how to directly control and measure quantum systems in new ways. We have already shown (as described below) the ability to detect previously unknown nanoscale quantum systems that could never be seen before. By gaining the ability to control quantum systems directly, we are exploring untouched regimes of nature and may find ways to direct unforeseen advancements in nanotechnology.

Technical Contact:
Raymond W. Simmonds

Staff-Years (FY 2004):
1 professional
1 technician
2 guest researchers
1 graduate student

The integrated circuit components of classical computers are rapidly approaching the so-called "quantum limit." Instead of avoiding quantum effects, we should exploit them as a means for more effective computation. Ultimately our work will produce new knowledge for the precise measurement of quantum systems.

By gaining the ability to control quantum systems directly, we are exploring untouched regimes of Nature and may find ways to direct unforeseen advancements in nanotechnology.

Through the first ever simultaneous measurement of two superconducting qubits, we have recently witnessed two coupled phase qubits entangle themselves by performing coherent state oscillations. This is a tremendous step forward!

Technical Strategy

The strategy of this effort is to develop a highly coherent set of quantum bits that can be isolated, controlled, coupled and measured. These are the building blocks for quantum computing. Along these lines, we have developed a high-impedance current bias and measurement scheme for controlling a Josephson "phase" qubit, while providing sufficient isolation from the external environment. Josephson junctions are electrical circuit elements that resemble capacitors. They are made from two pieces of metal separated by a thin insulating barrier. When the metal electrodes become superconductors at low temperatures (in this case, the superconducting temperature is about 1 K, while the measurement temperature is below 0.030 K or 30 mK), current can flow through this capacitor due to the quantum-mechanical mixture of the superconducting wavefunctions on either side of the junction. Each wavefunction is described with the help of a quantum-mechanical "phase" whose gradient is related to the zero-resistance flow of superconducting (Cooper) pairs of electrons. The current that flows through the Josephson junction is proportional to the sine of the quantum mechanical phase difference Δ across the junction. A qubit is made by including a Josephson junction in a superconducting loop, as shown in the following figure. Microwave current lines are capacitively coupled to the junction while a dc bias coil is placed some distance from the "qubit loop." For an applied magnetic flux through the loop, the potential energy stored in the Josephson junction as a function of the superconducting phase difference Δ is shown in the following figure. The flux bias is chosen that the qubit states, |0> and |1>, are formed in the left (~cubic) well. One can imagine these states as very rapid phase or current oscillations in this well. The |1> state is measured by an induced tunneling event to states in the (~quadratic) right well. This changes the flux in the qubit loop by roughly a flux quantum, a relatively large flux difference that can easily be detected using a pulsed DC SQUID magnetometer.

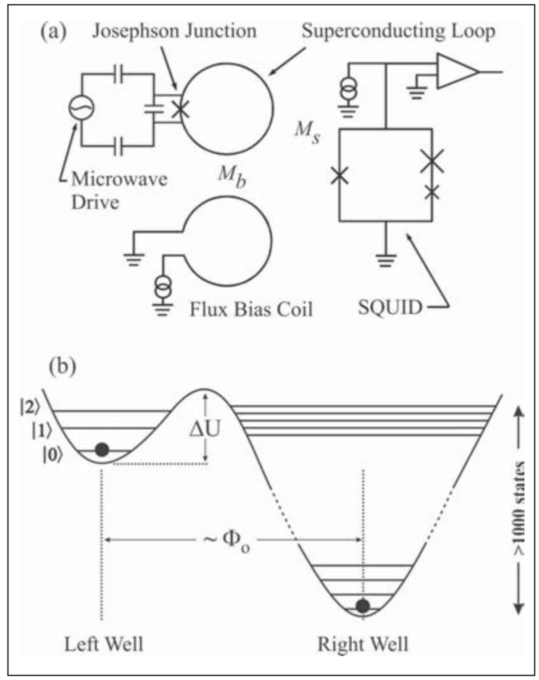
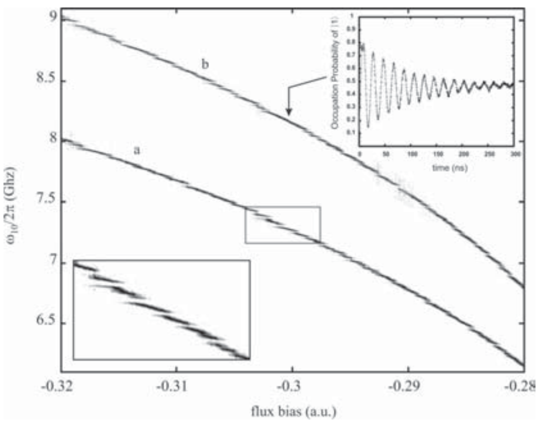


Figure 2. (a) The phase qubit schematic circuit. (b) The potential energy at a particular flux bias applied to the qubit loop.

The qubit transition frequency w_{10}, which is directly related to the energy level separation of the |0> and |1> state, is measured spectroscopically as a function of the applied flux bias to the qubit loop. First we prepare the qubit in the |0> (ground) state. If we apply a microwave drive current at frequency w *and* w = w_{10}, then the qubit will make a transition to the |1> state; otherwise it will remain in the ground state. If we sweep the value of w and measure the occupation probability of state |1>, we can determine the precise value for w_{10} at that particular flux bias. We measure the occupation of the |1> state by using a "fast" qubit state measurement technique. This is done by applying a quick dc flux pulse to the qubit loop so that the potential barrier DU is lowered just enough so that, if occupied, the |1> state has a high probability for tunneling to the right well and will be detected using the SQUID. This procedure is done for many different values of the flux bias in order to determine the energy level separation or transition frequency w_{10} as a function of the qubit loop flux bias. If we know the transition frequency w_{10}, then we are able to fully control the state of the qubit. Varying the flux bias simply allows us to operate the qubit at different frequencies (typically from 7 to 10 GHz).

An example of "qubit spectroscopy" is shown in the following figure. We find the expected decrease in the transition frequency with flux bias as the current through the junction approaches its critical or maximum current. Notice (in the lower inset) that there are "gaps" or "splittings" in the spectra. We have identified these spurious resonators as nanoscopic two-level systems within the junction's insulating barrier. Away from any spurious resonators, we have applied microwaves on resonance (w = w_{10}) to performed coherent state oscillations, known as "Rabi oscillations", between the |0> and |1> state (upper inset). Near spurious resonators, we have found coupled interactions between the qubit and the resonator as described briefly in Accomplishments. Although these resonators are undesirable in an ideal qubit, so far they have been useful for testing coupled interactions and estimating the limits of coherence in solid-state nanosystems. At present we are collaborating with David Pappas in Electromagnetics Division to improve the materials properties of our Josephson junctions to eliminate these defects.



An example of qubit spectroscopy for qubits (a) and (b) showing the transition frequency w_{10} for various flux biases to the qubit loop. Notice the small "splittings" indicative of microscopic quantum systems residing within the tunnel junction coupling to our superconducting quantum bit. Top inset shows Rabi oscillations away from resonators.

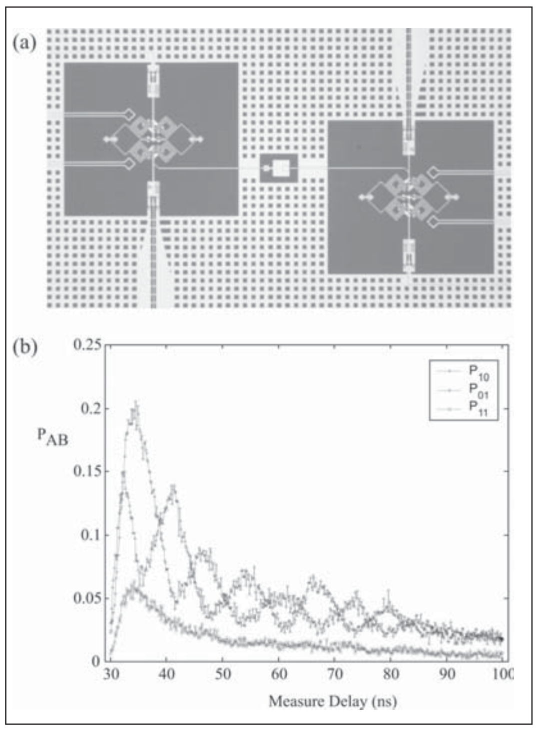
Our long-term strategy is to produce highly coherent single and coupled qubits, and to successfully perform error-tolerant quantum logic operations. With these building blocks we should be able to quickly take advantage of existing integrated circuit technology to make progress towards a full-scale superconducting quantum computer.

PLAN

We will continue to refine qubit designs and materials with the objective of increasing energy relaxation and Rabi decay times; we will also extend out investigations of coupled qubits

Accomplishments

Although this project began only three years ago, we have made significant progress over this short period. The first qubit design used a current-biased Josephson junction made from niobium with an amorphous aluminum-oxide tunnel barrier. It was successful in showing Rabi oscillations by varying the power of the microwave drive. The energy relaxation time was 300 ns, and the Rabi decay time was estimated to be 10 ns. The next qubit design was made from aluminum with an amorphous aluminum-oxide barrier and incorporated copper-gold quasiparticle traps along with a normal metal-insulator-superconductor shunt across the current biased qubit junction. This showed a reduction in excess tunneling events caused by quasiparticle heating. Many of our accomplishments over the past year are included in the list below.



(a) A fabricated coupled qubit circuit.
(b) Simultaneous measurement of two coupled qubits during state oscillations.

■ *Developed a New Flux Biased Josephson Phase Qubit* — We developed a new qubit design that is well isolated from the external environment while still providing an extremely sensitive readout. In addition, this qubit does not generate quasiparticles during measurement. This system has shown Rabi oscillations with up to 75 % visibility with 100 ns decay times. We have also seen energy relaxation times as long as 500 ns.

■ *Discovered Spurious Resonators Within Josephson Tunnel Junctions* — Using our new improved qubit we have developed spectroscopic measurements of the qubit transition frequency over a wide range of possible operating flux biases. In doing so, we discovered nanoscopic spurious resonators within the tunnel junctions of the qubit. Elimination of these resonators in future Josephson junctions could improve the performance of *all* superconducting devices.

■ *Developed a Method for Characterizing Tunnel Junctions and Phase Qubits* — Using a low frequency nonlinear current bias, we have developed an effective way to measure extremely small quasiparticle currents in the current-voltage characteristics of tunnel junctions fabricated using various novel methods. These measurements are then correlated with qubit spectroscopy, Rabi oscillations, and energy relaxation times in order to characterize the performance of these new tunnel junctions and the qubits that incorporate them.

■ *Developed a New, Faster Method to Read Out the Phase Qubit* — We have implemented a new qubit state-measurement technique that is a faster order of magnitude than our former method. Previously, we utilized a microwave pulse tuned to promote transitions between the |1> state and the |3> state, inducing a tunneling event when the |1> state was occupied. In this new method, with a temporal resolution of less than 5 ns, a flux bias pulse is applied to the qubit so that the |1> state, if occupied, is suddenly presented with a very small energy barrier, through which it rapidly tunnels. This new advance has allowed us to monitor rapid qubit state variations, opening the door to tracking strongly coupled interactions between phase qubits and other quantum systems.

■ *Observed Quantum Oscillations Between a Josephson Phase Qubit and a Nanoscopic Resonator* — We have detected coherent quantum oscillations between Josephson phase qubits and two-level resonator within the tunnel barrier of a superconducting phase qubit. These results reveal a new aspect of the quantum behavior of Josephson junctions, and they demonstrate the means to measure two-qubit interactions in the time domain. The junction-resonator interaction also points to a possible mechanism for decoherence and reduced fidelity in superconducting qubits.

■ *Coupled-Qubit Interactions* — Through the first ever simultaneous measurement of two superconducting qubits, we have recently witnessed two coupled phase qubits entangle themselves by performing coherent state oscillations. This is a tremendous step forward! Soon, we hope to have the ability to perform simple logic operations between two qubits, the building blocks for a full scale quantum computer.

Collaborations

■ David Pappas – Electromagnetics Division, NIST, Boulder, Epitaxial Josephson junctions with new materials.

■ John Martinis – University of California, Santa Barbara, Measurement electronics and qubit development.

■ Dale Van Harlingen – University of Illinois, Urbana-Champaign, 1/f noise measurements of Josephson junctions.

Selected Publications

K. B. Cooper, M. Steffen, R. McDermott, R. W. Simmonds, S. Oh, D. A. Hite, D. P. Pappas, and J. M. Martinis, "Observation of quantum oscillations between a Josephson phase qubit and a microscopic resonator using fast readout," cond-mat/0405710 accepted by Phys. Rev. Lett. (2004).

R. W. Simmonds, K. M. Lang, D. A. Hite, D. P. Pappas, J. M. Martinis, "Decoherence in Josephson phase qubits from junction resonators," Phys. Rev. Lett. 93, 077003 (2004).

J. M. Martinis, S. Nam, J. Aumentado, K. M. Lang, C. Urbina, "Decoherence of a superconducting qubit due to bias noise," Phys. Rev. B 67, 094510 (2003).

K. M. Lang, S. Nam, J. Aumentando, C. Urbina, and J. M. Martinis, "Banishing quasiparticles from Josephson-Junction qubits: why and how to do it," IEEE Trans. Appl. Supercond. 13, p. 989. (2003).

J. M. Martinis, S. Nam, J. Aumentado, and C. Urbina, "Rabi oscillations in a large Josephson-junction qubit," Phys. Rev. Lett. 89, 117901 (2002).

Quantum Communications

Technical Contact:
Sae Woo Nam

Goals

Develop and apply single-photon detectors (optical/infrared) for metrology and science.

Customer Needs

New quantum-based communication and measurement systems that use single and correlated photons have been developed; however, the current tools to calibrate the components in these systems are inadequate for the emerging applications. For accurate calibration, a detector capable of determining the number of photons in a single pulse of light is needed. We are developing high-efficiency detector systems with this capability in the three telecommunication windows (850 nm, 1310 nm, and 1550 nm). These new instruments will also aid in the understanding and advancement of new photon sources such as the single-photon turnstile (SPT). They can be used as a spectroscopic diagnostic tool or characterization tool for optical elements, optical materials, and optical systems at ultra-low light levels. A near-term use of the detectors is for initial research in Quantum Key Distribution, a method of communication where security is assured by the laws of quantum mechanics rather than by mathematical complexity.

Technical Strategy

Two distinct strategies are being pursued in this project. The first, which is best suited for counting photons at telecommunication wavelengths or measuring the energy of a single photon, is a refinement of superconducting transition-edge sensor (TES) detector technology that was previously developed by the Quantum Devices Group and researchers at Stanford University. In this device a thin film of tungsten is cooled to its superconducting transition temperature (~100 mK). The tungsten is biased at its transition from the normal to superconducting state such that the input of a small amount of heat from the arrival of a single infrared photon, dramatically changes in the tungsten resistance. The change in resistance is proportional to the heat absorbed.

These TES detectors can be operated in two distinct modes, depending on the photon source properties. For single-wavelength (monochromatic) sources such as lasers and Spontaneous Parametric Down-Conversion (SPDC) crystals (used for quantum information and metrology) the sensor response is directly proportional to absorbed photon number (Photon Number Discrimination mode). For broadband sources (such as white-light or multiple fluorescence emissions) the energy-resolving ability of the TES devices allows photon-counting spectroscopy to be performed across the entire near-infrared/optical band (2 µm to 200 nm). In this mode, the photon number is discarded in favor of determining the energy (*i.e.*, color) of the incoming photons (Spectroscopic mode).

Array of four Transition Edge Sensor (TES) single-photon detectors. The larger squares are 50 µm on a side and the smaller ones are 25 µm. The arrows are for alignment.

Over the past year we have increased the quantum efficiency of the TES detector system from less than 20 % to over 80 %. This was done by incorporating the tungsten film in a carefully designed "optical cavity" that prevents the incident photon from passing through the detector or reflecting off its face and increases the probability that a photon incident on the detector will be absorbed in the tungsten. Additional work is underway to eliminate losses in the fiber optic components that couple photons to the detector, made to increase the system detection efficiency. Our goal is to get as close as possible to 100 % efficiency.

Conventional semiconductor-based single-photon detectors suffer from high rates of "dark counts" (false positives), at the communication wavelengths of 1300 nm and 1550 nm, which severely limit single-photon applications. The TES detectors have no intrinsic dark counts, allowing them to be operated at much lower light levels than any existing metrological instrument. As the efficiency of TES systems has increased this has led to the investigation of previously unknown sources of dark counts in fiber optic systems. One such source at 1,550 nm is now thought to be the black body radiation incident on a fiber at room temperature.

Their unparalleled sensitivity allows these detectors to be a significant tool in the development of quantum-based communication protocols and the evaluation of the security of optical quantum cryptographic systems.

The second technical strategy involves the use of a different type of superconducting detector. These detectors, called Superconducting Single Photon Detectors, or SSPDs, have been previously investigated at the University of Rochester. They incorporate a very narrow (~100 nm) serpentine line of metallic superconductor such as Nb or NbN carrying a bias current very close to its critical current. When a photon strikes the superconductor a small "hot spot" is created locally, reducing the critical current to a value below the bias current. This develops a voltage across the superconductor that can easily be detected. While the detector is not photon-number resolving (one or more photons will create the hot spot), it is extremely fast, producing pulses of order a few tens of picoseconds. Such a device would be potentially very useful in a quantum communication system. At the present time, these devices have very low quantum efficiency (a few percent) and are incapable of long-term unattended stable operation. We are initiating work to address both of these issues.

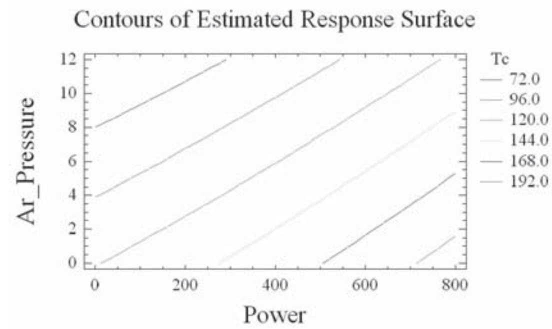
PLAN

We will develop and characterize TES detectors with higher QE and higher speed; these will be evaluated in QKD and fundamental physics experiments

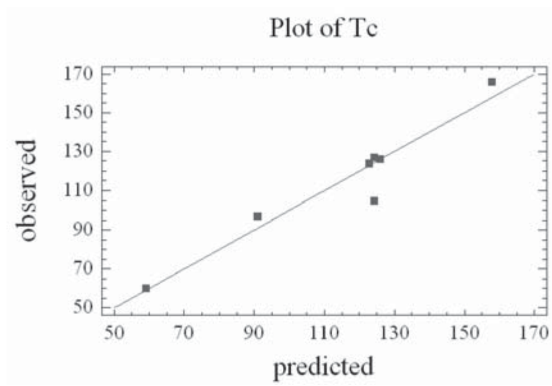
Contingent upon funding we will fabricate and characterize SSPD detectors and integrate these with compact cryocoolers for use in Quantum Communication networks

Accomplishments

■ *Development of a process for reliably fabricating thin film tungsten detectors with a controllable transition temperature* — Previously tungsten films for TES had been successfully made at Stanford, at Munich Technical University, and at NIST, but only with low yield and widely varying properties. During 2004 a development program using statistical process control methodology was completed that enables us to deposit films with high yield and controllable Tc.



Response of Tungsten superconducting transition temperature (Tc, in millikelvins) to Argon pressure and sputtering power. These variables were found to be primary determinants of Tc.



Comparison of Tc predicted from response surface and that observed (Tc in millikelvin).

■ *Increase in speed of TES detectors by 2 to 3x* — Improvements in the etching process used to pattern the TES detectors has resulted in improved edge definition and devices that are 2 to 3 times as fast as earlier-generation sensors.

■ *Increase in TES system quantum efficiency from <20 % to >80 %* — The reliable process for fabricating tungsten films has enabled us to explore a variety of configurations for increasing quantum efficiency. A structure incorporating a metallic mirror and dielectric layer below the tungsten and an anti-reflection layer on top has yielded 93 %+ absorption of 1,550 nm photons in the tungsten and an overall system efficiency over 80 %.

■ *Fabrication of thin, high-Tc NbN films* — The development of SSPDs has been limited by the availability of thin (~4 nm) high Tc (~10 K) films. Previously these films were available from only one institution in Moscow, Russia. In 2004 we succeeded in fabricating a series of films which initial tests indicate have large area Tc, equivalent to those from Moscow.

Collaborations

■ Alan Migdall from NIST's Optical Technology Division (Physics Laboratory) is developing a single-photon source using SPDC, and we will be using our detectors to verify the performance of this type of photon source.

■ With Xiao Tang from the Convergent Information Systems Division (Information Technology Laboratory), Carl Williams from the Atomic Physics Division (Physics Laboratory), and Alan Migdall, we are working on installing one of our detector systems in the quantum communication testbed being developed at NIST Gaithersburg.

■ We collaborate with Prof. Alexander Sergienko, his colleagues, Prof. Melvin Tesch, and Prof. Baha Saleh, and their research group at Boston University. Prof. Sergienko is an expert in the use of SPDCs.

■ We work closely with Prof. Blas Cabrera at Stanford University on the use of tungsten-based TES detectors for astronomy applications. We work closely in developing advanced electronics for the readout and operation of TES detectors.

■ We work closely with Dr. Richard Hughes, Dr. Jane Nordholt, and their colleagues at Los Alamos National Laboratories on the use of TES detectors in QKD links.

■ We work with Prof. Roman Sobolewski, University of Rochester, and Chip Elliot and Henry Yeh of BBN, on the packaging of SSPD for use in QKD links and other quantum information applications.

Selected Publications

S. Nam, A. J. Miller, and D. Rosenberg, "Low-temperature optical photon detectors for quantum information applications," Nuclear Instruments and Methods in Physics Research A 520, pp. 523–526 (2004).

D. Rosenberg, S. W. Nam, A. J. Miller, A. Salminen, E. Grossman, R. E. Schwall, and J.M. Martinis, "Near-unity absorption of near-infrared light in tungsten films," Nuclear Instruments and Methods in Physics Research A 520, pp. 537-540 (2004).

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A. J. Miller, S. W. Nam, J. M. Martinis, and A. V. Sergienko, "Demonstration of a low-noise near-infrared photon counter with multiphoton discrimination," Appl. Phys. Lett., 83 (4): pp. 791-793 (28 July 2003).

S. W. Nam, J. Beyer, G. Hilton, K. Irwin, C. Reintsema, and J. M. Martinis, "Electronics for arrays of transition edge sensors using digital signal processing," IEEE Transactions on Applied Superconductivity 13(2): pp. 618-21, (June 2003).

B. Cabrera, J. M. Martinis, A. J. Miller, S. W. Nam, and R. W. Romani, "TES spectrophotometers for near IR/optical/UV," Proc., 9th Int'l Workshop on Low Temperature Detectors, 22-29 July 2001, Madison, WI, pp. 565-570 (2002).

Quantum Sensors

Technical Contact:
Kent Irwin

Staff-Years (FY 2004):
14

"[T]his type of resolution, very simply, was something that I thought was truly, truly a dramatic advance. And I really would like to encourage the people working on this at NIST and the equipment industry to get this into commercialization as soon as they possibly can."

Mark Melliar-Smith, President and Chief Executive Officer of SEMATECH

Goals

Develop detector systems that will redefine the measurement abilities of currently available technology, often by orders of magnitude, and continue to develop groundbreaking detector systems for both industry and research groups.The Quantum Sensors Project develops sensors based on quantum phenomena for spectroscopy, imaging, and other precision measurements for wavelengths from dc through gamma rays. We integrate these sensors with custom superconducting and room-temperature electronics, cryogenic structures and software to create complete measurement systems. Applications of this measurement capability include materials analysis, astronomy, and homeland defense.

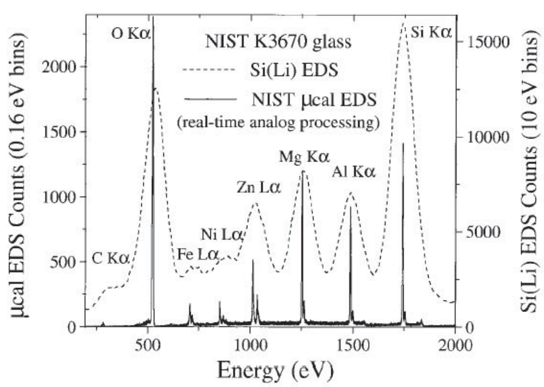
By operating at temperatures below 1 K, a new generation of photon detectors is achieving unparalleled sensitivity. Because they operate at such low temperatures, these detectors are able to measure very small differences in the energy of photons. At these low temperatures, they are able to take advantage of quantum phenomenon, including quantum interference (SQUIDs), quantum phase transitions (superconducting transition-edge sensors), and quantum tunneling (normal-insulator-superconductor tunnel junctions).

The Quantum Sensors Project has been a world leader in developing these new detector systems. We have developed transition edge sensor (TES) bolometers for use in a variety of applications. These devices utilize a strip of superconducting material, biased in its transition from normal to superconducting states, as an extremely sensitive thermometer. This thermometer is attached to an absorber that is isolated from a cold (~100 mK) heat sink by a micromachined structure. The heat deposited by incident photons is then measured to accurately determine their energy.

Applications include ultra-high-resolution X-ray spectroscopy for materials analysis for the semiconductor industry, and the development of large-scale arrays of quantum sensors for high-throughput imaging and spectroscopy of electromagnetic radiation for materials analysis and astronomy.

Customer Needs

Improved X-ray detector technology has been cited by SEMATECH's Analytical Lab Managers Council (ALMC) as one of the most important metrology needs for the semiconductor industry. In the International Technology Roadmap for Semiconductors, improved X-ray detector technology is listed as a key capability that addresses analysis requirements for small particles and defects. The transition-edge sensor (TES) microcalorimeter X-ray detector developed at NIST has been identified as a primary means of realizing these detector advances, which will greatly improve in-line and off-line metrology tools that currently use semiconductor energy-dispersive spectrometers (EDS). At present, these metrology tools fail to provide fast and unambiguous analysis for particles less than approximately 0.1 µm to 0.3 µm in diameter. Improved EDS detectors such as the TES microcalorimeter are necessary to extend the capabilities of existing SEM-based instruments to meet the analytical requirements for future technology generations. With commercialization and continued development, microcalorimeter EDS should be able to meet both the near-term and the longer-term requirements of the semiconductor industry for improved particle analysis.



Comparison of resolutions of NIST microcalorimeter EDS to standard semiconductor EDS.

In addition, the astronomy community has an ever-increasing need for instruments capable of supplying extremely high energy-sensitivity coupled with large-format arrays for imaging and photon collection. TES detector arrays promise to greatly expand the abilities of astronomers to study objects ranging from solar flares to supernova remnants to the formation of galaxies. The Quantum Sensor project has formed collaborations to transfer our TES technology into astronomical instruments with several institutions, including NASA, Stanford University, the Lockheed-Martin Solar Astrophysics Laboratory and the UK Astronomy Technology Center.

Technical Strategy

The ability to detect photons with high-energy resolution and near-unity quantum efficiency promises to dramatically improve the field of X-ray microanalysis. Improved energy-dispersive X-ray spectroscopy will be used to solve a wide range of problems in materials analysis. For instance, in semiconductor manufacturing, improved X-ray materials analysis is needed to identify nanoscale contaminant particles on wafers and to analyze very thin layers of materials and minor constituents.

To make this technology available to the materials analysis community, NIST is working on the commercialization of these inventions. Additionally, NIST's Chemical Science and Technology Laboratory is using a prototype microcalorimeter system constructed by our group to improve its own materials-analysis capability.

The transition-edge-sensor (TES)-based X-ray microcalorimeter developed in our group has been shown to have world-record energy resolution and to have wide application in many areas of X-ray microanalysis. In trying to deliver maximum benefit of this technology to industrial and scientific users of microanalysis, we are concentrating our efforts in three areas; support of existing systems, development of improved and simplified single detector pixels, and development of arrays of detectors as a means of increasing X-ray collection area and count rate.

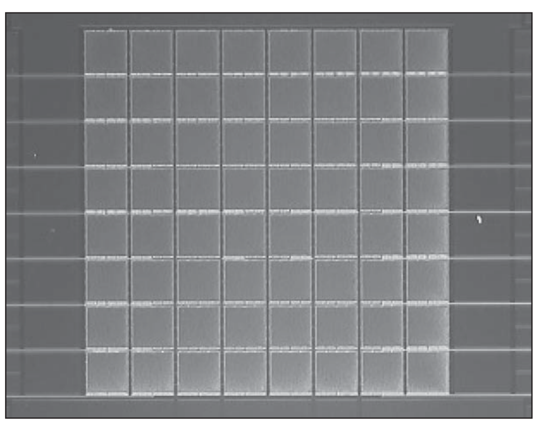
The low operation temperature of TES microcalorimeters (~100 mK), necessitates a fairly complex arrangement of cryogenic and electronic elements in order to construct a complete X-ray spectrometer. In this case, we have developed superconducting electronics to read out the detectors, compact adiabatic demagnetization refrigerators to simplify cooling the detectors to millikelvin operating temperatures, and room-temperature electronics to process the output signals.

An important part of our effort is to provide support to our existing customers, most notably the users of the prototype microcalorimeter system at the Chemical Science and Technology Laboratory in Gaithersburg, Maryland. We continue to provide expertise and training in detector and SQUID (readout electronic) operation and optimization, and operation of millikelvin refrigerators to CSTL, including consultations and site-visits. Additionally we continue to make improvements to the components in the spectrometer system. We will continue to provide information on these improvements to our customers.

While the performance of the detectors we have made is much better than that of existing detectors, improvements in energy resolution (particularly at higher energies) are both theoretically possible and desirable by the user community. Improvements in energy resolution require new understanding of the limitations on performance of present microcalorimeter detectors. We have begun to explore novel detector geometries and materials, including the use of magnetically doped superconductors for the TES material. One key advantage of the magnetically doped TES microcalorimeter is that the fabrication would require approximately half as many steps as the currently-used bilayer TES microcalorimeter. We are exploring this and other means to make TES microcalorimeters cheap and reliable to produce.

For many X-ray microanalysis applications, improvements in count-rate and collection area are far more important than further improvements in energy resolution. This can be achieved by the creation of multipixel arrays of detectors. In addition to the fabrication difficulties in making such arrays, the cold- and room-temperature electronics to read out the arrays must also be created. The work on the readout electronics (SQUID multiplexers, high-density wiring and room-temperature signal processing) is discussed in more detail in the section titled "Superconducting Electronics." We currently are exploring two means of developing arrays of Mo/Cu bilayer TES detectors, bulk micromachining and surface micromachining. These two methods require different modifications of our existing process; thus we are exploring both means of making arrays.

The astronomy community has long been the driving force behind improvements in photon detection systems at all wavelengths. Because of TES detectors' extremely good sensitivity, they are ob-



An 8 × 8 array of TES X-ray detectors fabricated by a surface micromachining technique.

"NIST-Boulder has been a world leader in the development of superconducting detectors, and has produced working systems and components for X-ray microanalysis, X-ray astronomy, and far-infrared astronomy based on this technology…In short, a large fraction of the cutting-edge astronomical research currently being performed by US astronomers is directly supported by the NIST lab's production of these devices… future astrophysics research would suffer greatly in the event that NIST-Boulder's capability is lost."

Catherine Pilachowski, President of the American Astronomical Society vious candidates to solve many problems faced by this community. The same X-ray detectors used in our microanalysis efforts, for example, are well suited to analyzing the X-ray spectra of supernova remnants and solar flares. By redesigning these detectors, they may be used as bolometers to measure far infrared and submillimeter radiation on ground-based telescopes, allowing astronomers to probe the evolution of galaxies and search for planets around other stars.

The Quantum Sensors Project has collaborations with several institutions to deploy our detectors for use in astronomical applications. As these collaborations push the technical abilities of our detectors, they often drive us to create improvements that are then applied to our more commercial applications, such as X-ray microanalysis.

Many of the requirements for X-ray astronomy are identical to those for our X-ray microanalysis project: high energy resolution, large arrays, high counting rates and multiplexed readout. We have two principal collaborators in this area: NASA's Laboratory for High Energy Astrophysics (LHEA) and the Lockheed-Martin Solar Astrophysics Laboratory (LMSAL).

NASA has an ongoing program to study X-ray astrophysics as part of its Structure and Evolution of the Universe theme. Following on its successful Chandra mission, Constellation-X is the next generation of X-ray astronomy telescopes. To accomplish its goals, Constellation-X will need to have an imaging array of X-ray spectrometers to place at the focal plane of an orbiting X-ray telescope.

A similar telescope is planned by LMSAL to study the mechanisms behind solar flares and coronal mass ejections (CMEs). CMEs cause significant financial impact around the world, as they disrupt satellites in Earth orbit and can knock out power grids on the ground. Scientists hope to understand and possibly predict these solar phenomenon by study the spectra of solar flares, and LMSAL is working with the Quantum Sensor project to develop TES detectors for this purpose.

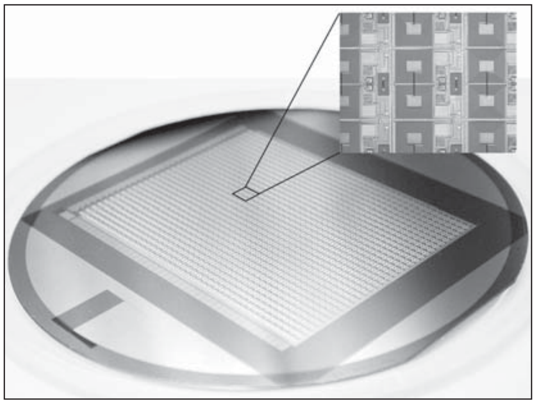
In the infrared regime, our TES bolometers have achieved world-record sensitivity. This impressive result confirms the utility of TES technology for this application as well. For several years, we have been involved in a collaboration with the Laboratory for Astronomy & Solar Physics (LASP) at NASA's Goddard Space Flight Center, to develop far-infrared bolometers. A result of this collaboration was the Fabry-Perot Interferometer Bolometer Research Experiment, (FIBRE), an eight-pixel multiplexed TES bolometer array that was deployed on the Caltech Submillimeter observatory at Mauna Kea, Hawaii.

In addition, the Quantum Sensor project, in collaboration with the United Kingdom's Astronomy Technology Center, is developing both sensors and readout technology for the second Submillimeter Common User Bolometer Array (SCUBA-2). The SCUBA-2 instrument is designed to detect radiation from astronomical sources at wavelengths of 450 and 850 μm and will be installed on the James Clerk Maxwell Telescope (JCMT) in Hawaii. This array will be, by orders of magnitude, the largest bolometer array ever deployed, having 12800 individual pixels. It will allow astronomers to map the sky at speeds over 1000 times faster than previously achieved.

The detector systems discussed above all share a common technical requirement: large arrays of TES detectors. This requirement brings with it the complication of reading out such large arrays. All these arrays must operate at temperatures below 1 K. If each pixel in the array requires a separate readout all the way to the room temperature electronics, then the heat load on the array's refrigeration system will rapidly become unmanageably large. A system to multiplex the readout of these detectors at the cold stage of their refrigerator is thus required to reduce the number of wires from the cold stage to warmer parts of the cryostat.

Fortunately, TES devices have low impedance, which allows them to be read out by superconducting SQUIDs. Because SQUIDS, in their unbiased "off" state, are superconducting, they may be effectively multiplexed without adding the noise of each individual SQUID to the whole.

The Quantum Sensor project has been at the forefront of SQUID multiplexing for several years now. Our first-generation 8-channel SQUID MUX was successfully deployed with the FIBRE far-infrared bolometer array on the CSO telescope on Mauna Kea, Hawaii. We have now built upon that success by developing a second generation, 32-channel SQUID MUX that has better bandwidth and two orders of magnitude lower power dissipation than the first design. The first fabrication run yielded devices that work at the design specifications. These MUX chips should have sufficient performance to multiplex X-ray TES detectors, which are much faster than the infrared bolometers in FIBRE. We are now building full 1280-pixel multiplexed arrays for the SCUBA-2 project.



A 1,280-pixel SQUID array fabricated at NIST for the SCUBA-2 instrument.

NIST has a long tradition of exploiting physical phenomena that occur at ultralow temperatures to produce electronic devices with properties that cannot be achieved by conventional electronics. For instance, NIST has developed Transition-Edge Sensor (TES) X-ray sensors that operate at temperatures near 100 mK and provide improved analytical capabilities to the semiconductor industry. The recent development of two-stage Adiabatic Demagnetization Refrigerators (ADRs) has made these low operating temperatures significantly more accessible. Nonetheless, even a two-stage ADR adds considerable complexity, size, and expense to an analytical station. To overcome this challenge, NIST has recently begun development of a thin-film refrigerator that is capable of cooling sensors from 300 mK to 100 mK.

The refrigerator consists of Normal-Insulator-Superconductor (NIS) tunnel junctions. Current flow through the insulating barrier separating the electrodes preferentially removes the hottest electrons from the normal electrode, thereby producing cooling. When coupled to a helium-3 cryostat, NIS coolers may provide a significantly smaller, cheaper, and less complex means of reaching temperatures near 100 mK.

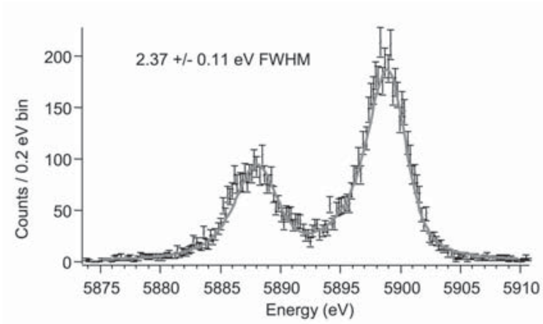
PLAN

- We have provided the Chemical Science and Technology Laboratory (CSTL) of NIST with a complete prototype microcalorimeter system for collaborative use in studying problems of interest to our customers; we will continue to provide support and improvements for this system
- We will develop models of single-pixel microcalorimeter performance to assist in improving detector sensitivity, and will fabricate and test novel detector designs based on these models
- We will fabricate, instrument and test a small array of X-ray microcalorimeter detectors to demonstrate the increase in collection area and count rate achievable through arrays
- We will work with NASA to adapt our existing microanalysis detector arrays to use in the Constellation-X project
- We will work with LMSAL and Stanford to optimize the performance of our TES X-ray detectors for solar observations; we will also consult with LMSAL on developing their cryogenic systems to test these detectors
- We will develop arrays of detectors optimized for imaging infrared bolometry, along with the necessary wiring, SQUID MUX and room temperature DSP electronics to read the array

ACCOMPLISHMENTS

■ We have developed an X-ray detector of extremely high energy resolution and demonstrated a complete X-ray spectroscopy system. This detector and spectrometer have been made possible by broad expertise within the Division in such fields as superconductivity, device fabrication including silicon micromachining, superconducting electronics, cryogenic engineering, and low-noise, room-temperature electronics. Without expertise in all of these areas, the complete systems that have provided the compelling demonstrations for the power of this technology would not have been possible.

■ This system holds the world record for energy resolution for an EDS detector of 2.37 eV at 5900 eV, which is over 30 times better than the best high-resolution semiconductor-based detectors currently available. The figure shows this new world-record energy resolution. We have used the system to identify submicrometer particles of materials such as W on Si substrates, an identification problem that is impossible with standard EDS detectors and of great importance to the semiconductor industry. It has also demonstrated energy shifts in the EDS X-ray spectra of materials such as Al, Fe, and Ti, depending on their chemical bonding state, thus allowing differentiation between a particle of Al and Al_2O_3, for example.



World-record 2.4 eV energy resolution achieved with NIST microcalorimeter at 6 keV.

- We have made significant progress towards fabricating a practical on-chip, solid-state microrefrigerator using Normal metal – Insulator – Superconductor (NIS) tunnel junctions. Presently, cryogenic instruments that operate near 100 mK use complex, expensive adiabatic demagnetization refrigerators and dilution refrigerators. The thin-film microrefrigerators are compact and readily integrated on-chip with devices requiring sub-kelvin cooling such as microcalorimeter X-ray spectrometers for X-ray microanalysis. We have fabricated an NIS refrigerator designed to operate at bath temperatures of 300 mK, which is accessible with relatively simple and inexpensive ^{3}He refrigerators. The normal metal in the junction is an Al thin film doped with ferromagnetic (Mn) impurities in order to suppress superconductivity. These are the largest working NIS refrigerators made to date and the only ones fabricated with photolithographic techniques.

- We have demonstrated the first multiplexed readout of an X-ray microcalorimeter array. This breakthrough establishes a clear path to the instrumentation of kilopixel microcalorimeter arrays, which will have wide-ranging implications for fields as diverse as materials analysis and X-ray astronomy. A challenge in the development of large arrays of X-ray microcalorimeters, which measure the energy, or color, of X-rays with high resolution, is that providing an amplifier channel for each detector in the array requires too many wires to be connected to the cryogenic detectors. Time-division SQUID multiplexing, a scheme in which the signals from many detectors are read out through a single amplifier, is one way to conquer this challenge. In the experiment, we measured the energy resolution of four microcalorimeters, using both conventional and multiplexed readout techniques. The multiplexed detectors (superconducting transition-edge sensors) measured the energy of 5.9 keV X-rays emitted from an 55-Fe source with an average resolution of 6.94 ± 0.05 eV, which represents only a small and well-understood degradation in resolution from the non-multiplexed performance of the detectors. Based on an analysis of their data and of planned upgrades to the multiplexing system, the researchers estimate that they can multiplex 32 detectors with an energy-resolution degradation of only 0.1 eV. This would allow a square, 1024-detector array to be read out with only 32 signal channels.

- We have demonstrated the first microwave SQUID multiplexer. This breakthrough opens a path to reading out very large arrays of SQUIDs for magnetoencephalography and non-destructive evaluation, and CCD-scale arrays of low-temperature detectors. In this circuit, the outputs of many SQUID amplifiers are simultaneously monitored by a single high electron mobility transistor (HEMT) amplifier channel. Each SQUID amplifier is placed in a high-Q resonant circuit with a different resonant frequency, and excited by a comb of microwave signals at each of the resonant frequencies. The amplitude of the reflected microwave signals at each frequency is a function of the input signal at each SQUID. In an initial experiment, we demonstrated the low-noise readout of SQUIDs using this microwave reflectometer approach, and multiplexed two SQUIDs simultaneously near 500 MHz. Future work will focus on operation at 5 GHz and developing technology for much larger SQUID arrays. Because of the large bandwidth available with microwave measurements, it should be possible in the future to read out many thousands of SQUIDs in a single coaxial cable, and to instrument arrays of SQUIDs with thousands or millions of pixels.

- We have developed a surface micromachining method for producing freestanding pixels above the surface of a silicon wafer. This process has been integrated into the X-ray TES fabrication process, and TES devices have been produced and cooled down. The surface micromachining process did not appear to affect the TES process, although further development is needed to produce working detectors.

- We have delivered a full, 1,280-pixel multiplexed submillimeter bolometer array to the SCUBA-2 project. This is the first true submillimeter camera available to the community.

Collaborations

UK Astronomy Technology Center, SCUBA2 camera

University of Edinburgh/Scottish Microelectronics Centre, SCUBA2 camera

Raytheon Vision Systems Inc., SCUBA2 camera

University of Cardiff, SCUBA2 camera

NIST Division 837, X-ray microcalorimeter for microanalysis

Intel, X-ray microanalysis using our microcalorimeter system

Lockheed Martin, X-ray detector development for solar physics

Stanford University, X-ray detector development for solar physics

Jet Propulsion Laboratory, SQUID multiplexer for IR detectors

NASA Goddard Space Flight Center, SQUID multiplexer for IR detectors

NASA Goddard Space Flight Center, X-ray microcalorimeter arrays

NASA Goddard Space Flight Center, Magnetic Microcalorimeters

JILA, Microwave SQUID multiplexer

Star Cryoelectronics, X-ray detector development

Selected Publications

C. D. Reintsema, J. Beyer, S. W. Nam, S. Deiker, G. C. Hilton, K. D. Irwin, J. M. Martinis, J. Ullom, L. R. Vale, M. MacIntosh, and Rev. Sci. Instrum, "A Prototype System for SQUID Multiplexing of Large-Format Transition-Edge Sensor Arrays," 74(10): pp. 4500-4580 (October 2003).

A. M. Clark, A. Williams, S. T. Ruggiero, M. L. ven den Berg, and J. N. Ullom, "Practical electron-tunneling refrigerator," Appl. Phys. Lett. 84 (4): pp. 625-627; 26 (January 2004).

J. N. Ullom, W. B. Doriese, G. C. Hilton, J. A. Beall, S. Deiker, W. D. Duncan, L. Ferreira, K. D. Irwin, C. D. Reintsema, and L. R. Vale, "Characterization and reduction of unexplained noise in superconducting transition-edge sensors," Appl. Phys. Lett. 84(21): pp. 4206-4208 (May 24, 2004).

J. P. Pekola, R. J. Schoelkopf, and J. N. Ullom, "Cryogenics on a Chip," Physics Today 57(5): pp. 41 (May 2004).

S. W. Deiker, W. Doriese, G. C. Hilton, K. D. Irwin, W. H. Rippard, J. N. Ullom, L. R. Vale, S. T. Ruggiero, J. N. Ullom, L. R. Vale, S. T. Ruggiero, A. Williams, and B. A. Young, "Transition edge sensor using dilute AlMn alloys," Appl. Phys. Lett. 85(11): pp. 2137-2139 (2004).

K. D. Irwin and K. W. Lehnert, "Microwave SQUID multiplexer," Appl. Phys. Lett. 85 (11): pp. 2107-2109 (2004).

W. B. Doriese, J. A. Beall, S. Deiker, W. D. Duncan, L. Ferreira, G. C. Hilton, K. D. Irwin, C. D. Reintsema, J. N. Ullom, L. R. Vale, and Y. Xu, "Time-division multiplexing of high-resolution TES X-ray microcalorimeters: Four pixels and beyond," Appl. Phys. Lett., in press.

D. R. Schmidt, A. M. Clark, W. Duncan, K. D. Irwin, N. Miller, J. N. Ullom, and K. W. Lehnert, "Microwave reflectometer readout for large-format superconductor-insulator-normal metal bolometer arrays," Submitted to Applied Physics Letters.

J. Beyer, D. Drung, and K. D. Irwin, "Bias conditions of DC-SQUID for a time-domain SQUID multiplexer," Review of Scientific Instruments, 75, pp. 502 (1994).

Terahertz Technology

Technical Contact:
Erich Grossman

Goals

Develop metrological methods, components, and technology for imaging and spectroscopy from ~100 GHz to several terahertz (THz).

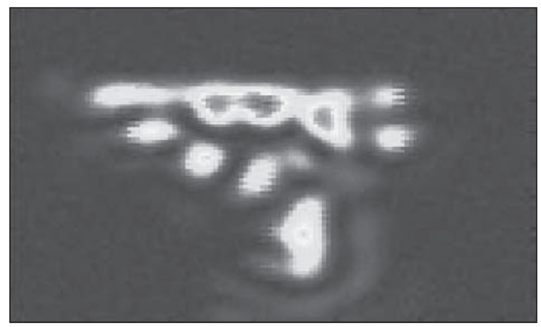
Customer Needs

Imaging in the ~100 GHz to ~2 THz range offers the possibility of detection of concealed weapons and remote detection of contraband (*e.g.*, explosives under clothing) without the use of ionizing radiation. Spectroscopy in this frequency range has additional applications in industrial processing and remote identification of chemicals. We have developed unique capabilities in detectors, optics, and metrology methods. These capabilities are being used to construct improved imaging systems and to provide government agencies with unbiased evaluations of systems and components developed in industry.

Technical Strategy

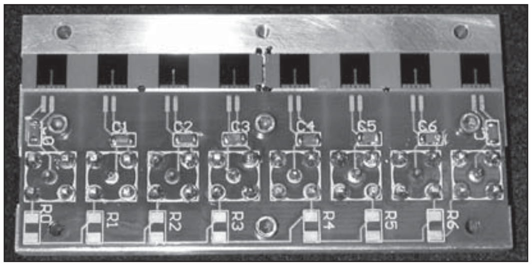
Over the past several years this project has focused on bolometric detectors, initially developed for cryogenic electronic applications, but also useful in the detection or frequency conversion of radiation from millimeter to infrared wavelengths. The work on cryogenic detectors has been extended to antenna-coupled bolometers operating at room temperature. These detectors provide a rugged, low-cost alternative for Homeland Security applications, for example mobile police units or portal scanners in airports. We have systematically investigated the transmission between 100 GHz and 1 THz of materials commonly used in clothing and have established that imaging in this frequency range has the potential for effectively detecting weapons and contraband concealed by clothing. We fabricated a wafer-scale 120-element focal-plane array of antenna-coupled bolometers and demonstrated real-time imaging. We have also investigated the efficiency of various illumination schemes establishing the viability of actively illuminated imagers in portal applications. Collaborative work with NIST's Physics Laboratory, funded by the NIST Advanced Technology Program (ATP), was started in 2001 to demonstrate the usefulness of this technique as an industrial plasma diagnostic and to develop a practical system that can be applied to it. Considerable progress was made on this system; however, the current focus has shifted to applications to homeland security and defense.

Millimeter-wave images of a representative handgun (bottom) compared with optical image (top).

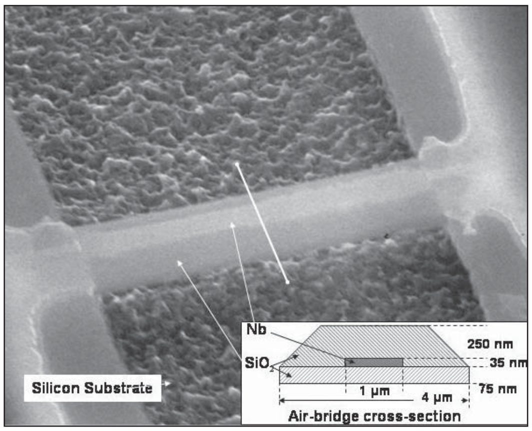


Sub-array of eight airbridge detectors. Sixteen sub-arrays are assembled into a 1.2 m long linear array of 128 detectors.

The program continues to improve antenna-coupled bolometric detectors and has been charged by DARPA to establish facilities and protocols for testing components developed in industry. Currently we are constructing a 40 kilopixel scanning imaging testbed operating at 95 GHz that will be capable of real-time (30 frames/second) imaging of human subjects. This facility will employ a 128-element linear array of room temperature Nb airbridge detectors. These detectors provide an improvement by approximately 5x in signal to noise ratio (S/N) compared to the detectors used in the 120-element focal-plane array, and presently offer the best cost/performance metric in this frequency range.



Sub-array of eight airbridge detectors. Sixteen sub-arrays are assembeld into a 1.2 m long linear array of 128 detectors.



Scanning electron micrograph of SiO_2-encapsulated Nb microbolometer. The figure insert shows a schematic of the cross-section of the bolometer and the encapsulating oxide.

An important aspect of our current program is the evaluation of a variety of terahertz detectors developed in academia and industry. Many of these devices are antenna-coupled, and our prior microantenna array experience indicates that the greatest remaining obstacle to uniform and systematic comparison of microantenna device performance lies in unambiguous measurement of coupling efficiencies. This in turn requires amplitude and phase pattern measurement of the microantennas, which is difficult to do with conventional techniques at high frequency because of errors introduced by moving cables. We are currently building an all quasi-optic test setup for measurement of complex millimeter-wave antenna patterns. This complex pattern data will then be incorporated into a comprehensive analysis of coupling efficiency for each device tested. The complex antenna setup will be scalable to terahertz and IR frequencies because of the quasi-optic nature of the coupling.

High performance room-temperature bolometers provide adequate sensitivity and S/N for actively illuminated imaging, but fundamental noise considerations dictate that cryogenic detectors will be required for real-time passive imaging. The air-bridge detectors are directly applicable to cryogenic operation, and we expect to extend our work on room-temperature niobium airbridges to low-temperature operation.

PLAN

- We will complete assembly and test of the 40 kilopixels scanning imaging testbed and use it to characterize various configurations of source, optics, and detector
- We will complete construction and commissioning of the all quasi-optic test setup for measurement of complex millimeter-wave antenna patterns and commence testing of detectors from collaborators

Accomplishments

■ *Real-Time Imaging with Slot-Ring Antenna-Coupled Uncooled Millimeter-Wave Bolometer Arrays* — Imaging applications in the terahertz spectral range require large numbers of pixels, and an appropriate balance between sensitivity and cost. One approach to achieving all three goals simultaneously is to use lithographic antennas to couple the radiation into micrometer-sized detectors. In this case, the antenna engineering challenge is to develop an array-compatible antenna with the highest possible directivity in a completely planar monolithic structure. This is the motivation behind a new antenna design we have developed, in which slot-ring antennas with finite ground planes are patterned on electrically thin substrates. Because the application is imaging, sensitivity to radiation from only one side of the substrate is desired, so a planar backshort is employed to reflect radiation from the backside of the substrate into the forward direction. With the backshort at the proper position behind the plane of the slot-ring antenna, constructive interference occurs between the directly received radiation and that reflected by the backshort, increasing the directivity. Measured beam patterns are highly circular and exceptionally narrow (22° at –3 dB) from a completely planar antenna. They can be arrayed at a spacing of 1.5 wavelengths with negligible measured effect on performance. A 120-element array for 95 GHz has been fabricated and used to obtain real-time images.

■ *Actively Illuminated Scanned 40k pixel 95 GHz Imaging System* — Fundamental considerations dictate the use of actively illuminated imaging systems for indoor applications, and active illumination favors a scanned architecture. We have completed design and fabrication of all the major components — line source, detector array, lenses and scanner of a real-time whole-body imaging system. System test will commence in late 2004 and continue through 2005.

■ *Characterization of Sb-Heterostructure Quantum Tunneling Diodes as Submillimeter Wave Detectors* — We have measured the diode I(V) and noise of Sb-heterostructure quantum tunneling diodes fabricated from epitaxial layers of InAs and AlGaSb by an industrial collaborator. These devices exhibit exceptionally high nonlinearity in the I(V) characteristic, which produces the rectification without bias. Thus the device does not suffer from the 1/f noise associated with a dc bias. Our measurements indicate that these devices have a sensitivity that challenges that of other existing room-temperature detectors in this frequency range, and that they could be attractive candidates in the millimeter and submillimeter wave region.

Collaborators

We have collaborated with H. P. Moyer, J. N. Schulman of HRL on the evaluation of zero-bias quantum tunneling Sb-heterostructure diodes as terahertz detectors

Selected Publications

A. Luukanen, E. N. Grossman, H. P. Moyer, and J. N. Schulman, "Low-frequency noise properties of quantum tunneling Sb-heterostructure millimeter wave diodes," Submitted to Appl. Phys. Lett. (2004).

A. Luukanen, E. N. Grossman, H. P. Moyer, and J. N. Schulman, "Noise and THz rectification characteristics of zero-bias quantum tunneling Sb-heterostructure diodes," Submitted to Int'l J. High Speed Electronics (2004).

A. J. Miller, A. Luukanen, and E. N. Grossman, "Micromachined antenna-coupled uncooled microbolometers for terahertz imaging arrays," Proc. of SPIE, 5411, pp. 18-24 (2004).

E. N. Grossman, A. Luukanen, and A. J. Miller "Terahertz active direct detection imagers," Proc. of SPIE, 5411, pp. 68-77 (2004).

A. Luukanen, R. H. Hadfield, A. J. Miller, and E. N. Grossman, "A superconducting antenna-coupled microbolometer for THz applications," Proc. of SPIE, 5411, pp. 121-126 (2004).

A. Luukanen, A. J. Miller, and E. N. Grossman, "Active millimeter-wave video rate imaging with staring 120-element microbolometer array," Proc. of SPIE, 5410, pp. 195-201 (2004).

E. N. Grossman, T. E. Harvey, and C. D. Reintsema, "Controlled barrier modification in Nb/NbOx/Ag metal insulator metal tunnel diodes," J. Appl. Phys. 91(12), pp. 10134-10139 (June 15, 2002).

S. Nolen, T. E. Harvey, C. D. Reintsema, and E. N. Grossman "Properties of cavity-backed slot-ring antennas at 95 GHz," Proc. SPIE 4373, pp. 49 (2001).

E. N. Grossman, S. Nolen, N. G. Paulter, and C. D. Reintsema, "Concealed weapons detection system using uncooled, pulsed, imaging arrays of millimeter-wave bolometers," Proc. SPIE, 4373, pp. 7 (2001).

N. G. Paulter, E. N. Grossman, G. N. Stenbakken, B. C. Waltrip, S. Nolen, and C. D. Reintsema, "Design of an active mm-wave concealed object imaging system," Proc. SPIE., 4373, pp. 64 (2001).

Pulse Metrology and Time Domain Measurements

Goals

Improve and expand the range and scope of NIST time-domain waveform measurement services to continue and better support manufacturers and users of high performance samplers and digitizers, as well as of fast pulse and impulse sources, operating at frequencies from dc to 80 GHz.

Robert Palm and Bryan Waltrip evaluate the performance of the NIST-developed Sampling Waveform Analyzer and its associated input probes for accurately measuring pulse waveforms.

Customer Needs

The U.S. electronic instrumentation and test equipment industry maintains its leadership position through the development and distribution of increasingly accurate, high-speed samplers and digitizers, fast electrical pulse/impulse sources, and easier-to-use arbitrary waveform generators. To prove their accuracy in a highly competitive environment, manufacturers and users need objective calibration methods and standards that are traceable to the derived electrical units maintained and disseminated by NIST. There is a need for better means of characterizing the output of impulse, pulse and arbitrary waveform generators; the step response of fast samplers and digitizers; jitter in data transmission signals; delay in transmission lines and other delay devices; and the impulse response/transfer function of passive electrical devices and components. Manufacturers and users of high-performance data converters have developed a performance standard (IEEE Std. 1241) with which to objectively compare digitizing devices, and have expressed the need for calibration support at NIST.

Technical Strategy

Accurate measurements of arbitrary waveform parameters, from basic root-mean-square (rms) values to crest factor, signal-to-noise ratio (SNR), harmonic distortion, etc. have been realized at NIST using a specially designed strobed analog comparator device. Success with the first-generation custom integrated circuit implementation has led to the development of two separate and distinct comparator-based probes for accurate waveform sampling from power-line frequencies to 5 GHz. One of the new probes is fabricated in a fast bipolar silicon process with an f_T of 28 GHz and uses a circuit architecture refined from the previous design. The other probe is built for lower speed operation but with a wider input range, higher input impedance, and much lower noise. These probes were successfully applied to novel metrology applications including calibration of the area function of oscilloscopes and determining the frequency content of multisines for testing devices used in wireless applications. A numerical correction algorithm was also developed for the lower-speed probe to compensate for nonlinear error behavior, resulting in improved harmonic distortion performance and better gain and phase accuracy.

NIST's 65100S (Impulse Spectrum Amplitude) special test service was improved by using swept-frequency calibration methods that not only allowed reduction of the published uncertainties by 5x, but also reduced measurement time and allows increasing the bandwidth of the service without impacting published uncertainties. The 65100S (Network Impulse Response) service now provides not only improved impulse spectrum amplitude measurements for the EMI/EMC community but also a measurement service useful to the ultrawideband (UWB) community by providing measurements of modulation envelope characteristics of the UWB pulse.

The ability to map uncertainties between time-domain waveforms and frequency-domain spectra (real and imaginary components or magnitude and phase spectra) is necessary when providing the impulse response and/or transfer function of an electronic or electrical device. With this recently acquired capability, the 65300S special test service can now provide uncertainties for impulse response and transfer function of coaxial devices. However,

Technical Contact:
Nicholas G. Paulter, Jr.

Staff-Years:
3.0 professionals
1.0 technician
1.75 contractor

Calibration Services (3 %)

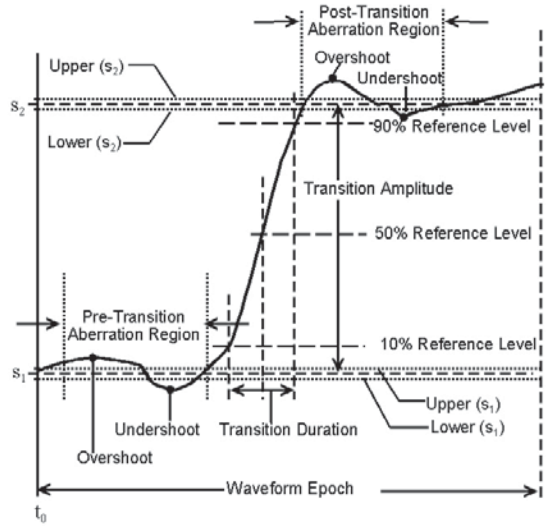
"The new digitizer calibration system developed by NIST's … [Quantum Electrical Metrology] Division enables Sandia to calibrate digitizers using well characterized pulse inputs for the first time. The digitizers support critical pulse voltage and pulse current measurements ... NIST staff developed specific calibration procedures for Sandia digitizers, as well as an uncertainty analysis for the calibration process."

Richard B. Pettit, Manager, Retired Primary Electrical Standards uncertainty bounds on these waveforms and spectra will be more useful to the customer since these define the possibility of observations.

The development of a precision time delay system is almost complete. Using an input strobe, the system provides three electrical output pulses where one of the output pulses can be delayed relative to the others from tens of femtoseconds to one second. The uncertainty in the delay is dependent on the stages used to generate the delay and is on the order of femtoseconds for the fine delay stage (0 s to 600 ps), less than 1 ps for the medium delay stage (0.5 ns to 16 ns), and a 10^{-8} of the delay setting for the long delay stage (12 ns to 1 s). The delay system will expand the measurement range of and reduce the uncertainties in the 65400S (Pulse Time Delay Interval) series tests, reduce the uncertainties in the 65100S series tests, and will be used to develop cycle-to-n^{th}-cycle jitter measurement capability, which is an important performance parameter in digital telecommunications and computing systems.

PLAN

- Update the SP250 65250S (Repetitive Pulse Waveform Measurement) service, including the uncertainty analysis, to reflect the capabilities offered by the new probes
- Complete the formal calibration service documentation of the SP250 65100S special test and complete the writing of the uncertainty computation software
- Complete development of point-by-point uncertainty estimate for acquired waveforms
- Complete the development of the estimation of bounding waveforms and spectra
- Complete the development of the programmable time delay system by replacing poor performing pulse generators and optical splitters and implement this system for jitter measurements
- Apply the delay system to reduce the uncertainties in the 65400S Differential Time Delay Interval special test service
- Implement the delay system for measuring cycle-to-n^{th}-cycle jitter



Some of the pulse waveform parameters defined by international standards and measured by NIST's 65200S calibration service.

Accomplishments

■ The bandwidth of the Fast Repetitive Pulse Transition Parameters Special Test service, SP250 65200S, which is used for measurements of the step response of high-speed (transition duration ≥ 4.5 ps) samplers and output characteristics of high-speed pulse generators was increased to 80 GHz.

■ The precision time delay system was completed but then modified to provide significantly improved laser safety and system portability. Further modifications were and are being implemented to accommodate poor performance of certain key instruments and optical components.

■ The calibration procedure used in the 65100S, Impulse Spectrum Amplitude, measurement service was improved and the uncertainty analysis modified accordingly. These changes resulted in a 5x decrease in published uncertainties and the ability to expand the service to higher frequencies without suffering an increase in published uncertainties, which will allow NIST to support measurement requirements for the ultrawideband (UWB) industry.

■ The U.S. Air Force approached NIST with a chronic performance problem exhibited by their specially designed optical time-domain reflectometer calibration system (which has the acronym, "FOCUS"). The reason for the malfunction of the FOCUS was identified and a solution implemented. Potential improvements to the FOCUS hardware to improve its performance have also been determined.

■ A reference ballistic chronograph was designed, built, and tested. This system is expected to have a reduction by 10 to 100 times in the uncertainty of measurement of bullet speed as compared to conventional ballistic chronographs, thereby permitting NIST's system to serve as a reference measurement system.

Calibrations

18 tests performed on 18 items for 10 companies and government agencies with approximately $35 692 income received. (October 1, 2003 to September 30, 2004).

Collaborations

An on-going intercomparison with the National Physical Laboratory (NPL) was continued regarding high-speed electrical pulse parameters.

Standards Committee Participation

IEEE I&M Society TC-10 - N. Paulter, D. Larson, B. Waltrip, and D. Bergman participate as members of the TC-10 on Waveform Measurement and Analysis and the subcommittees on Waveform Recorder, A/D Converters, and Pulse Techniques.

N. Paulter participates as chair of the IPC High-Frequency/High-Speed Test Methods Subcommittee (D-24), the IPC High-Frequency /High-Speed Controlled Impedance Task Group (D-21c), and the IEEE Subcommittee on Pulse Techniques (SCOPT).

Selected Publications

N. G. Paulter, D. R. Larson, and J. J. Blair, "The IEEE standard on transitions, pulses, and related waveforms, Std-181-2003," IEEE Trans. Instrum. Meas. 53, pp. 1209-1217, (August 2004).

N. G. Paulter and D. R. Larson, "NIST impulse spectrum amplitude measurement service," NCSL Int'l 2004 Workshop and Symposium, Salt Lake City, UT, (11-15 July 2004).

N. G. Paulter and D. R. Larson, "NIST service for measuring the step response of high-speed samplers and the output of high-speed pulse generators," Digest 2004 Conf. on Precision Electromagnetic Measurements Digest, London, England, pp. 640-641, (27 June - 2 July 2004).

D. I. Bergman and B. C. Waltrip, "A low thermal error sampling comparator for accurate settling measurements," IEEE Symp. Circ. Sys., pp. I-521 - I-524, (May 2004).

N. G. Paulter and D. R. Larson, "The effect of tilt on waveform state levels and pulse parameters," IEEE Instrumentation and Measurement Technology Conference, Como, Italy, pp. 1296-1300, (18 - 20 May 2004).

D. R. Larson, N. G. Paulter, and D. I. Bergman, "Pulse parameter dependence on transition position and epoch duration," IEEE Instrumentation and Measurement Technology Conference, Como, Italy, 18 – 20, pp. 1291-1295, (May 2004).

N. G. Paulter, R. H. Palm, A. R. Hefner, and D. W. Berning, "Low-impedance time-domain reflectometry for measuring the impedance characteristics of low-impedance transmission lines," Rev. Sci. Instrum., Vol. 74, pp. 5204-5211, (December 2003).

N. G. Paulter, A. J. A. Smith, D. R. Larson, T. M. Souders, and A. G. Roddie, "NIST-NPL interlaboratory pulse measurement comparison," IEEE Trans. Instrum. Meas., Vol. 52, pp. 1825-1833, (December 2003).

N. G. Paulter and D. R. Larson, "Sources of uncertainty in the nose-to-nose sampler calibration method," IEEE Trans. Instrum. Meas., Vol. 52, pp. 1618-1626, (October 2003).

N. G. Paulter and D. R. Larson, "Measuring the response of high-speed pulse generators and samplers," NCSL Int'l Annual Workshop and Symposium, Tampa Bay, FL, 17 – 21 (August 2003).

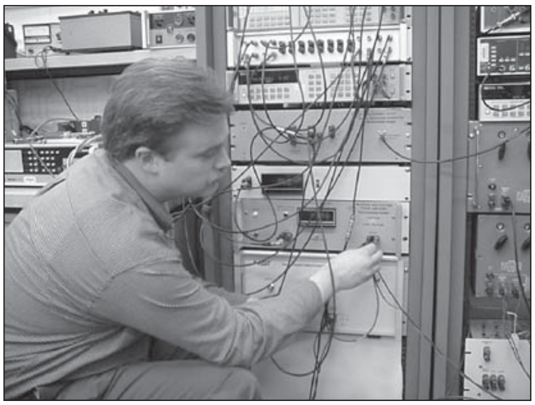
Electric Power Metrology

Technical Contact:
Thomas Nelson

Staff-Years:
2.5 Professionals
0.5 Guest Researcher
1.8 Technicians

Goals

Maintain and disseminate precision electrical measurements, high voltage, and power, in support of U.S. industry for such applications as the transmission and distribution of electric power. Assess and develop new measurement technologies for the increased reliability and quality of the U.S. electric power system.



J. Chandler adjusts the NIST ac power bridge.

Customer Needs

The fair and reliable transmission and distribution of electric power requires accurate and traceable measurements of electrical quantities. Electrical energy metering throughout the U.S. is traceable to NIST calibrations and results in annual revenues exceeding $280 billion. To ensure the accurate measuring and monitoring of electric power, U.S. industry requires traceable calibration services of dc high voltages, Digital Multimeters (DMM), and power and energy. To maintain reliable delivery of electric power and to compete in an international market, U.S. utilities and industry require support in developing technically sound international standards governing the use of technologies related to electric power.

With deregulation of the electric power industry, new diagnostic technologies are needed to ensure the reliability of the increasingly complex U.S. electric power infrastructure. New web-based sensor technologies raise questions of security and access to power system information and control by unauthorized persons. Additionally, economic and environmental pressures are motivating the drive toward more efficient electrical devices. Activities in this project provide the support required by the electric power and electric equipment industries to maintain reliability while utilizing new cost-saving measurement technologies related to the transmission, distribution, and use of electric power. To support industry efforts to protect this critical infrastructure, computer security vulnerabilities of power-grid control systems are being identified, and the standards affected by these vulnerabilities are being reviewed. A testbed was built to develop more secure control system communication techniques and to verify that they still meet the real-time requirements of the standards.

Technical Strategy

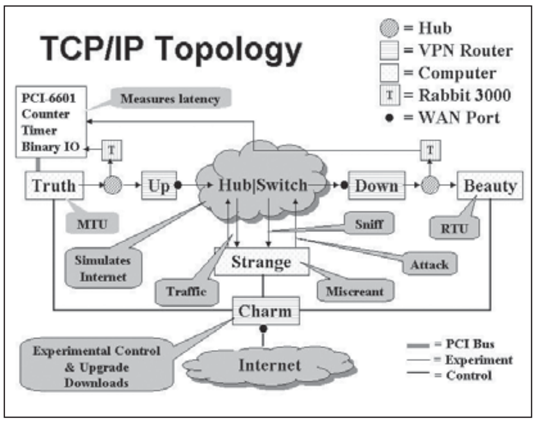
This project supports the electric power industry by maintaining calibration services in the areas of high voltage, digital multimeters (DMMs), and power and energy. These services are continually improved to meet the changing measurement needs of U.S. industry. The technical expertise utilized in providing these services is applied to the development of key national and international standards.

This project maintains the U.S. standard for power and energy, which is used by utilities and meter manufacturers to ensure the accurate sale of electric power in the U.S. In order to improve NIST's ability to support manufacturers and utilities in their measurements in power systems containing harmonics, a new automated sampling test system is being constructed and will be used to participate in an international comparison of harmonic power measurements.

International comparisons are essential for the validation of measurement techniques used at National Metrology Institutes (NMIs). To ensure the accurate measurement of power throughout the Americas, NIST will serve as the pilot lab for an intercomparison among SIM countries. SIM is the regional organization of NMIs for North and South America. Electric power generation, transmission, and distribution comprise an infrastructure that enables the motor of modern society to run. Any interruption of electric power creates at a minimum an inconvenience, but can also be life-threatening to people in hospitals or in very cold weather. There has been a proliferation of modem- and web-connected sensors and actuators used to control the operation of electric power systems. Because they are designed to meet functional specifications such as speed, and not security considerations, the communications among them may be vulnerable to attack or to inadvertent or malicious misoperation.

NIST is identifying the security weaknesses of these process-control systems in an attempt to raise industry awareness of the potential vulnerabilities and to establish a set of security requirements for power system controls and communications.

In an effort to reduce the consumption of electric power, the U.S. Department of Energy (DOE) designates minimum efficiencies of electrical equipment. Distribution power transformers and electric motors are two categories of equipment for which DOE is developing efficiency standards. NIST is advising DOE by developing technically sound sampling strategies and instrumentation for the testing of these devices.



Topology of testbed for evaluating security of serial electric power control systems.

PLAN

- Develop a harmonic power calibration system and participate in an international comparison of harmonic power and provide calibrations to instrument manufacturers
- Complete SIM energy comparison and publish the results
- Provide support for the National Supervisory Control and Data Acquisition (SCADA) Testbed and Department of Homeland Security control system reliability programs
- Perform field testing with portable transformer efficiency measurement system
- Support the DOE in the development of compliance testing for distribution transformer efficiencies
- Provide special tests of on-site multifunction calibrators using a traveling DMM

ACCOMPLISHMENTS

■ *Participated in a bilateral ac shunt comparison with NRC-Canada* — In order to compare harmonic power measurement capabilities, a bilateral comparison of measurements using a harmonic distortion test setup was made with NRC-Canada. A NIST-developed thermally stabilized ac shunt was used to reduce the variation of the resistance from over 60 ppm for currents up to 10 A to less than 1 ppm. The comparison of the shunt measurements at currents between 300 mA and 10 A, and at frequencies from 50 to 10 000 Hz, showed an agreement of better than 10 ppm.

■ *Tested two commercial retrofit modules for Supervisory Control and Data Acquisition (SCADA) systems for timing performance* — One method being recommended to improve the security and reliability of the power grid operation is to add encryption to all control loops that pass through public facilities. This requires an analysis of the effects of such a modification on control loop performance. To provide the utilities with the information they need for this purpose, a testbed has been designed to measure the latency and jitter caused by the use of encryption modules in typical control loop communication channels. The equipment for this testbed has been obtained and the testbed is being assembled. The initial testbed design will accommodate RS232 and Ethernet channels, the two most commonly used communications methods currently used by the utilities. Additional channel protocols used by utilities will be added later. Two commercial retrofit modules were tested for participants in the American Gas Association (AGA) Standard 12. The standard is the first one to include security for SCADA systems.

■ *Developed preliminary test procedures for performance evaluation of encryption modules for SCADA systems* — To ensure that everyone can make use of the timing data from the testbed, a standard is needed to describe how the measurements are being made. In collaboration with utility industry associations and encryption module manufacturers, preliminary test procedures have been developed for measuring the impact of encryption technology on performance of control loops. To provide a context for this information, the performance characteristics of typical utility control communications channels without security measures have been analyzed. These characteristics will be used for comparison with measurements of secured channels.

■ *A prototype system for measuring transformer power losses was designed, assembled, and tested* — It is intended to be a low-cost measurement system having measurement uncertainties sufficiently low to be capable of demonstrating the compliance of distribution transformers with energy efficiency regulations now under development by the Department of Energy. The results demonstrated that the design criterion of errors no greater than 0.1 % for power loss measurements was met.

"The aggregate annual economic impact [for not having adequate measurements and standards in place for the electric power industry] range from $3.1 to $6.5 billion."

"Changing Measurements and Standards Needs in a Deregulated Electric Utility Industry,"
NIST Planning Report 00-2

■ *Participated in a bilateral dc High Voltage Comparison with NRC-Canada* — To compare dc high voltage measurement capabilities, a bilateral comparison was made with NRC Canada. A high-voltage Park divider was used to intercompare voltages of up to 100 kV. The measurements showed agreement of better than 100 ppm.

Outputs

Calibrations

Calibrations were performed for 87 companies and government agencies with approximately $275,000 income received.

Standards Committee Participation

IEEE Instrument Transformer Subcommittee (C57.13): T. L. Nelson is the Working Group Chair in charge of the revision of the IEEE Standard on Requirements for Instrument Transformers.

ANSI/NEMA Electricity Metering Committee (C12): T. L. Nelson served as the chair.

IEEE Electricity Metering Subcommittee: T. L. Nelson served as secretary.

IEEE Industrial Applications Society, Electric Machines Committee: K. L. Stricklett chaired the working group updating IEEE P114, the "Draft Standard Test Procedure for Single-Phase Induction Motors."

IEEE Power Engineering Society Surge Protection Devices Committee: F. D. Martzloff served on multiple working groups of this committee, including working groups on Surge Characterization, Multiport Surge Protective Devices, and Secondary Arrestors.

Selected Publications

K. L. Stricklett, O. Petersons, and C. R. Hagwood, "Operating characteristics of the proposed sampling plan for testing distribution transformers," NIST Technical Note 1456 (May 2004).

E. So, D. Angelo, B. Waltrip, T. Nelson, T. Tsuchiyama, and T. Takodoro, "Intercomparison of calibration systems for ac shunts up to audio frequencies," Digest 2004 Conference on Precision Electromagnetic Measurements, pp. 35 (June 2004).

E. So, R. Arseneau, D. Bennett, T. L. Nelson, and B. C. Waltrip, "NRC – NIST intercomparison of calibration systems for current transducers with a voltage output at power frequencies," Conference Digest 2002 Conference on Precision Electromagnetic Measurements, pp. 544-544 (June 2002).

E. D. Simmon, and G. J. FitzPatrick, "High voltage and current metrology at NIST. Precision measurements of the past, present, and the future," Conference on Electrical Insulation and Dielectric Phenomena, 2001 Annual Report, pp. 277-280 (October 2001).

M. Misakian, O. Petersons, J. J. Kasianowicz, and B. Robertson, "Frequency response of alternating currents through the staphylococcus aureus alpha-hemolysin ion channel," Bioelectromagnetics, 22 pp. 487-493 (October 2001).

N. Oldham, T. Nelson, R. Bergeest, G. Ramm, R. Carranza, A. Corney, M. Gibbes, G. Kyriazis, H. Laiz, L. Liu, Z. Lu, U. Pogliano, K. Rydler, E. Shapiro, E. So, M. Temba, and P. Wright, "An international comparison of 50/60 Hz Power (1996-1999)," IEEE Trans. Instrum. Meas. 50, (2), pp. 356-360 (April 2001).

E. So, D. Angelo, T. Nelson, and L. Snider, "NRC – NIST intercomparison of power meter calibrations at 60 Hz and ranges up to 600 V, 100 A," IEEE Trans. Instrum. Meas., 50, (2), pp. 353-355 (April 2001).

E. D. Simmon, G. J. FitzPatrick, and O. Petersons, "A users' guide to the NIST capacitance ratio bridge," NIST Technical Note 1442 (April 2001).

K. L. Stricklett and J. Baker-Jarvis, "Electrical properties of biological materials": A bibliography survey, Natl. Inst. Stand. Technol. NISTIR 6564 (October 2000).

K. L. Stricklett, "Electrical coupled hydrodynamic flows," Proc. 2000 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Canada (October 2000).

Appendix A: Topics Covered by Organizational Units

The following table shows which organizational unit(s) work on each of the research topics covered in this book. For information on the staff of the organizational units, please see Appendix C.

Topic	Group Name	Project Name	Project Leader
QUANTUM STANDARDS			
Quantum Voltage	Fundamental Electrical Measurements	Voltage Metrology	Yi-hua Tang
	Quantum Devices	Quantum Voltage	Samuel Benz
AC-DC Difference Standards and Measurement Techniques	Fundamental Electrical Measurements	AC-DC Difference Standards and Measurement Techniques	Thomas Lipe
Single Electronics	Fundamental Electrical Measurements	Single Electron Tunneling	Neil Zimmerman
	Quantum Devices	Nanoscale Cryoelectronics	Robert Schwall
Metrology of the Ohm	Fundamental Electrical Measurements	Metrology of the Ohm	Rand Elmquist
Farad and Impedance Metrology	Applied Electrical Measurements	Farad and Impedance Metrology	Yicheng Wang
Electronic Kilogram	Fundamental Electrical Measurements	Electronic Kilogram	Richard Steiner
Noise Thermometry	Quantum Devices	Quantum Voltage	Samuel Benz
	Quantum Devices	Quantum Information and Terahertz Technology	Robert Schwall
QUANTUM MEASUREMENTS			
Quantum Computing	Quantum Devices	Quantum Information and Terahertz Technology	Robert Schwall
Quantum Communication	Quantum Devices	Quantum Information and Terahertz Technology	Robert Schwall
Quantum Sensors	Quantum Devices	Quantum Sensors	Kent Irwin
Terahertz Technology	Quantum Devices	Quantum Information and Terahertz Technology	Robert Schwall
Pulse Metrology and Time Domain Measurements	Applied Electrical Measurements	Pulse Metrology and Time Domain Measurements	Nicholas Paulter
Electric Power Metrology	Applied Electrical Measurements	Electric Power Metrology	Thomas Nelson

Appendix B: Quantum Electrical Metrology Division Calibration Services

The Quantum Electrical Metrology Division provides a number of for-fee calibration services of electrical standards. Below is an abbreviated listing of those services. More information, including a fee schedule can be found in the NIST Calibration Services Users Guide SP250 available from the Calibration Program at NIST, (301) 975-2002, calibrations@nist.gov, or on the Web at: http://ts.nist.gov/ (click on "Calibrations," then "Electromagnetic").

Information about the availability and shipping requirements for the Quantum Electrical Metrology Division services listed below may be obtained by contacting Denise D. Prather, (301) 975-4221, denise.prather@nist.gov. Technical information may be obtained by contacting the specific technical representatives listed below for each service.

A. Resistance Measurements

A.1	DC Resistance Standards and Measurements	Randolph E. Elmquist (301) 975-6591
A.2	High-Voltage Standard Resistors	Kenneth L. Stricklett (301) 975-3955 Gerald J. FitzPatrick (301) 975-8922

B. Impedance Measurements (Except Resistors)

B.1	Low-Frequency Capacitance and Inductance Measurements and Standards	Andrew D. Koffman (301) 975-4518 Yicheng Wang (301) 975-4278

C. Voltage Measurements

C.1	DC Voltage Measurements and Standards	Yi-hua Tang (301) 975-4691
C.2	AC Voltage Measurements	Mark E. Parker (301) 975-2413 Nile M. Oldham (301) 975-2408
C.3	AC-DC Thermal Voltage and Current Converters (to 1 MHz)	Thomas E. Lipe (301) 975-4251

D. Precision Ratio Measurements

D.1 Inductive Dividers .... Andrew D. Koffman (301) 975-4518

D.2 Resistance Dividers .... Kenneth L. Stricklett (301) 975-3955

E. Phase Meters and Standards and .... Mark E. Parker (301) 975-2413
VOR Measurements .... Nile M. Oldham (301) 975-2408

F. Power and Energy Measurements .... Thomas L. Nelson (301) 975-2986
Low-Frequency .... Joseph W. Chandler (301) 975-2868

G. Pulse Waveform Measurements .... Donald R. Larson (301) 975-2437
Nicholas G. Paulter (301) 975-2405

Appendix C: Quantum Electrical Metrology Division Staff and Phone Numbers

(December 2004)

Division Office

2431 Olthoff, James (Chief)
3776 Harris, Richard (Chief Scientist) (303-497-3776, Boulder)
2400 Grove, Sharon (Secretary)
4044 Tasker, Amy (Administrative Officer)
4221 Prather, Denise
4941 Dorsey, Roy
4222 Belecki, Norman
2406 Parks, Curtis

Fundamental Electrical Measurements (817.01) (Gaithersburg)

4228 Newell, David (Group Leader)
4229 Pastori Weaver, Suzana (Secretary)

Metrology of the Ohm

6591 Elmquist, Randolph (Project Leader)
4241 Jarrett, Dean
4225 Jones, George
4239 Kraft, Marlin

Voltage Metrology

4691 Tang, Yi-hua (Project Leader)
4238 Sims, June

The Electronic Kilogram

6553 Steiner, Richard (Project Leader)
6555 Williams, Edwin
6556 Liu, Ruimin

Single Electron Tunneling (SET)

5887 Zimmerman, Neil (Project Leader)
4690 Hourdakis, Emanouel

AC-DC Difference Standards and Measurement Techniques

4251 Lipe, Thomas (Project Leader)
4250 Kinard, Joseph
4234 Secula, Andrew

Applied Electrical Measurements (817.02) (Gaithersburg)

8922 FitzPatrick, Gerald (Group Leader)
2403 Lainez, Zulma (Secretary)
4015 Martzloff, François

Farad and Impedance Metrology

4278 Wang, Yicheng (Project Leader)
4224 Cage, Marvin
4518 Koffman, Andrew
2441 Palm, Robert
2413 Parker, Mark
4232 Shields, Scott
2438 Waltrip, Bryan
4231 Lee, Lai
2408 Oldham, Nile

Electric Power Metrology

2986 Nelson, Thomas (Project Leader)
2440 Stenbakken, Gerard
2868 Chandler, Joseph
2412 Parker, Mark
3955 Stricklett, Kenneth
2438 Waltrip, Bryan
2412 Laug, Owen
2413 Fulcomer, Michael
2407 Oldham, Nile
2406 Souders, Michael

Pulse Metrology and Time Domain Measurements

2405 Paulter, Nicholas (Project Leader)
4464 Bergman, David
2437 Larson, Donald
2441 Palm, Robert
2438 Waltrip, Bryan
2412 Laug, Owen
2406 Souders, Michael

Quantum Devices (817.03) (Boulder)

5081 Rudman, David (Group Leader)
3678 Repetto, Francesca (Secretary)
4727 Gutierrez, Mary (Secretary)
4641 Hoskins, Mark (Administrative Officer)

Quantum Voltage (817.03-1)

5258 Benz, Sam (Project Leader)
3906 Burroughs, Charlie
5211 Dresselhaus, Paul
4218 Hadacek, Nicolas
3740 Hamilton, Clark

Quantum Sensors (817.03-2)

5911 Irwin, Kent (Project Leader)
4463 Doriese, William
3811 Duncan, William
4391 Ferriera, Lisa
5679 Hilton, Gene
3402 Huber, Martin
4576 Miller, Nathan
5052 Reintsema, Carl
4408 Ullom, Joel
5121 Vale, Leila
4480 Williams, Anthony
7894 Xu, Yizi
4320 Zink, Barry

Quantum Information and Terahertz Technology (817.03-3)

4732 Schwall, Robert (Project Leader)
4429 Beall, Jonathan
5344 Bergren, Norman
4606 Cicak, Katarina
5102 Grossman, Erich
4378 Lang, Kristine
4608 Lita, Adriana
4590 Luukanen, Arttu
4212 Miller, Aaron
3148 Nam, Sae Woo
4318 Salminen, Arto
4403 Simmonds, Ray
4617 Strong, Josh

Nanoscale Cryoelectronics (817.03-4)

4732 Schwall, Robert (Project Leader)
4137 Aumentado, Jose
3391 Kautz, Richard
5430 Keller, Mark
3021 Naaman, Ofer

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Appendix D: Post-Doctoral Research Associateships

The National Institute of Standards and Technology (NIST), in cooperation with the National Research Council, offers awards for postdoctoral research in the fields described in this booklet. These awards provide a select group of scientists and engineers an opportunity for research in many of the areas that are of deep concern to the scientific and technological community of the nation. NIST, with direct responsibilities for the nation's measurement network, involves its laboratories in the most modern developments in the physical, engineering, and mathematical sciences and the technological developments that proceed from them.

These activities, comprising a broad spectrum of interests in basic and applied science, engineering, and technology, involve many disciplines. NIST affords great freedom and an opportunity for both interdisciplinary research and research in well-defined disciplines.

The technical activities of NIST are conducted in its laboratories, which are based in Gaithersburg, a large complex of modern laboratory buildings in a Maryland suburb of metropolitan Washington, DC, and at a modern, equally well-equipped facility in Boulder, Colorado. NIST has a staff of approximately 3,000 people, of which more than 55% are technical personnel.

Included on the following pages are the opportunities available in the Quantum Electrical Metrology Division. They are listed separately for the two locations in the Division, Boulder and Gaithersburg. For each opportunity a reference number is provided as well as the location.

Interested applicants should contact the advisors shown. All opportunities for NIST and application materials can be found at the National Research Council web site at http://www4.nas.edu/pga/rap.nsf/. There are two competitions per year with final applications due by February 1 and August 1. Forty awards are made in the February competition and 20 in August. Please allow at least a month in advance of the deadlines to contact the advisor and prepare the application because a research proposal is required.

Opportunities in Boulder, Colorado

A Capacitance Standard Based on Counting Electrons

50.81.42.B4762 BoulderCO 80303

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Modern metrology is moving toward quantum measurement standards, such as atomic clocks, that provide a natural basis for our system of units. We are currently working toward a method for determining capacitance in terms of the electron charge. We do this simply by placing N electrons onto a capacitor, measuring the resulting voltage V, and thus determining $C = Ne/V$, where e is the electron charge. We use a unique cryogenic, vacuum-gap capacitor, and the electrons are counted using single-electron tunneling (SET) devices operating at temperatures below 1 K. The current version of the standard has an estimated uncertainty of less than 1 part-per-million when compared with NIST's primary standard. Future work in this area will focus on determining the ultimate uncertainty of this method, more direct comparisons with primary standards, and the construction of a robust, automated version of the standard. The development of this new standard is expected to have impacts spanning practical metrology, our knowledge of fundamental constants, and the fundamental basis of electrical units. Facilities include a clean room for fabricating SET devices, a custom cryostat for the capacitance standard, and custom capacitance bridges for making accurate comparisons with other standards.

Applications of Superconducting Integrated Circuits and Josephson Junction Arrays

50.81.42.B4376 BoulderCO 80303

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We are studying and developing Josephson junctions for use in voltage standard and other applications of integrated superconductive circuits. Our project leads the field in their implementation into systems. Some of these systems include voltage standards, digital-to-analog converters, and arbitrary waveform synthesizers. One current focus is on the construction of a pulse-quantized arbitrary waveform synthesizer to be used as an ac and dc voltage standard source and for other applications that require digitally synthesized waveforms with precise control of voltage, frequency, and phase. Another focus is the fabrication and study of lumped arrays of stacked Josephson junctions. These three-dimensional circuits will be implemented in the next generation voltage standard. Applicants should be interested in some or all of the following areas: nanofabrication, superconductive device physics, broadband (dc-20 GHz) circuit design and construction, digital waveform synthesis, and cryogenic packaging.

Characterization of Single-Photon Turnstiles Using Single-Electron Tunneling Devices

50.81.42.B4763 Boulder CO 80303

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NIST is developing a device based on Coulomb blockade in a self-assembled semiconductor quantum dot (QD) that can generate single photons on demand. The turnstile operates by applying bias voltages that inject precisely one electron and one hole into the QD, which then recombine to produce one photon. We are using the unique capabilities of single-electron tunneling (SET) devices to perform electrical characterization of these devices with unprecedented accuracy. We have performed capacitance spectroscopy performed on individual QDs with an SET transistor, revealing the single-particle states for electrons. The accurate current produced by an SET pump can be compared with the current flowing through the turnstile to determine if the turnstile is operating as desired. These measurements allow us to optimize the performance of the turnstile before mastering the relatively difficult task of building microstructures to direct the photons toward an appropriate detector. The QDs are grown by NIST's Optoelectronics Division, and all facilities for making contacts to individual QDs, fabricating SET devices, and measuring electrical properties are available in our project.

High-Resolution Microcalorimeters for X-Ray Microanalysis

50.81.42.B3588 Boulder CO 80303

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As the size scale of microelectronics continues to shrink well below 1 µm, current semiconductor-based energy-dispersive spectrometers (EDS) on scanning electron microscopes can no longer provide the resolution needed to evaluate these structures. We are developing a high-resolution microcalorimeter-based EDS that provides revolutionary new capabilities for X-ray microanalysis. Microcalorimeter EDS provides more than an order of magnitude improvement in energy resolution (to 2 eV) compared to commercial semiconductor EDS, with good collection area (4 mm2 effective area with the use of an X-ray polycapillary optic lens) and count rate (500 s-1). The spectrometer system consists of a superconducting transition-edge sensor microcalorimeter cooled by a compact adiabatic demagnetization refrigerator and instrumented by a SQUID current amplifier. These unique superconducting electronics are fabricated in our state-of-the-art clean room. Using our microcalorimeter EDS mounted on a scanning electron microscope, we have resolved closely spaced X-ray peaks in complicated spectra and have made the first energy-dispersive chemical shift measurements. The excellent performance of this system enables a wide range of research opportunities in X-ray microanalysis, including improved particle analysis, chemical bonding state analysis, and synchrotron-based measurements. Work is also underway to dramatically increase the collection area and count rate of the system using arrays of detectors read out with superconducting multiplexer, which will dramatically increase throughput and open new applications in real-time, in-process monitoring and process-stream monitoring.

Noise Thermometry

50.83.61.B3925 Gaithersburg MD 20899

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The electronic fluctuations in voltage and current that exist in a normal conductor are a fundamental measure of thermodynamic temperature. Many challenging metrology and electronic design problems must be solved in order to exploit fully Johnson Noise as an accurate primary thermometer. Opportunities exist for experimental investigations into advanced techniques in

Johnson Noise Thermometry (JNT). The benchmark for accuracy is 10 ppm in temperature over the range 273 K to 933 K. The topic encompasses areas such as ultra-low noise system design, electromagnetic interference (EMI), digital signal processing, and impedance measurements, as applied to the 20 kHz to 200 kHz band.

Possible research topics with important applications in JNT include development of solid-state tunable noise references, new techniques to improve EMI rejection, signal processing routines for real-time digital Fourier transform and cross-correlation, and network modeling for applying accurate impedance-related corrections. The program involves collaboration between groups with expertise in thermometry, ac voltage standards, and impedance standards. Research that emphasizes and augments state-of-the-art techniques in these areas, as applied to JNT, is most needed.

Physics and Applications of Single Electron Tunneling Devices

50.81.42.B3586 BoulderCO 80303

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Single electron tunneling (SET) devices are based on nanofabricated tunnel junctions operated at temperatures below 1 K, where the charging energy for a single electron dominates thermal fluctuations. By using gate voltages to control the charging energy, individual tunneling events can be manipulated very precisely, allowing control of individual electrons. We have developed and now routinely operate devices in which the error per tunnel event is of order 1 part per billion, a world's best by several orders of magnitude. Our research goals are to understand the fundamental physics of SET phenomena and to construct practical SET circuits for applications in metrology and other areas. Examples include electron pumps for accurate electron counting, new SET transistors for ultrasensitive electrometry, and SET-based direct measurements of the properties of single molecules for use in molecular electronics. Facilities include electron-beam lithography, extensive microfabrication, micromachining and vacuum deposition equipment, and two dilution refrigerators equipped for measurements up to GHz frequencies.

Quantum Computing and Quantum Communication Using Superconductors

50.81.42.B5891 BoulderCO 80303

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Quantum computing offers the possibility of solving certain classes of problems at speeds far in excess of those attainable by any classical computer. Because of their ease of integration and communication to conventional electronics, superconducting qubits based on Josephson junctions offer an attractive approach to quantum computing. Our program seeks to develop superconducting qubits with long coherence times along with methods for defining and reading qubit states and controlling their interactions.

Quantum communication using single photons in fiber or free space offers the potential for completely secure communication. Fully realizing this potential requires the development of fast, highly efficient single photon detectors with essentially no dark counts. We are investigating a variety of superconducting detectors in pursuit of these goals. Superconducting transition edge sensors (TES) operating at 125 mK have achieved broadband photon-number resolving with no dark counts. Work is in progress to increase their quantum efficiency and bandwidth. Other, extremely fast, superconducting detectors are also under investigation.

Quantum Computing Using Superconducting Devices

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A new class of powerful computation algorithms have been proposed based on logic operations using quantum mechanical systems or quantum bits (qbits). Experimental implementation will require qbit coherence times long enough to perform single qbit manipulations, controlled interactions of multiple qbits, and state measurements. While the most dramatic progress to date has been made with trapped-ion systems, solid-state quantum devices should in principle have distinct advantages for the creation of a practical large-scale "quantum computer". Using our state-of-the-art superconducting fabrication facility, we have improved the operation of a Josephson junction based phase qubit by incorporating it into a superconducting loop. This has allowed us to further decouple the qubit from its environment and has eliminated quasiparticle-heating effects. Recent improvements in the fabrication of the Josephson junctions have produced a dramatic increase in the overall performance of qubits. Research opportunities include materials characterization for Josephson junctions, fabricating novel superconducting qubit devices, exploring the physics of coherence and coupling between qubits, and engineering multi-qubit devices. Our goal is to fabricate high quality Josephson junction based qubits for the eventual use in a 100 to 1000 qubit quantum computer.

Superconducting and Nanometer-Scale Devices for Infrared to Millimeter-Wave Applications

50.81.42.B1533 BoulderCO 80303

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Our goal is to explore the physical mechanisms and limitations of devices operating in the frequency range from 0.1 to 100 THz, and to develop novel devices and measurement techniques. For the short wavelength end, we use electron-beam lithography to fabricate the submicron structures required to minimize parasitic impedances. One specific research area includes mixers and harmonic mixers for frequency synthesis and high-resolution spectroscopy; another research area involves IR to millimeter-wave imaging radiometry. Our main focus is on high-sensitivity bolometers and superconducting multiplexers based on SQUIDS. Other devices of interest include high-Tc superconducting bolometers; room-temperature, thin-film bolometers; lithographic and/or micromachined coupling structures, particularly antennas and integrating cavities; superconducting mixers/rectifiers; and room-temperature mixers/rectifiers (*e.g.*, lithographic metal-insulator-metal diodes).

Superconducting Detectors for X Ray through Millimeter Photons

50.81.42.B3587 BoulderCO 80303

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Cryogenic detectors and electronics provide unprecedented sensitivity and energy resolution for the detection of photons. We are developing novel low-temperature (100 mK) superconducting microcalorimeters and bolometers for the detection of photons from X rays to millimeter waves. These devices, fabricated in our state-of-the-art clean room, consist of superconducting transition-edge sensors on micromachined structures. They are read out using unique high-speed, low-noise SQUID preamplifiers designed and fabricated here. Using these devices, we have demonstrated the highest energy resolution achieved with an energy-dispersive X-ray detector, and one of the most sensitive detectors of incident infrared/submillimeter power. We are employing these detectors in a system for X-ray microanalysis of materials on a scanning electron microscope. We are also developing arrays of X-ray microcalorimeters and infrared/submillimeter bolometers for astronomy and other applications. Research opportunities include improving our understanding of the nonequilibrium superconducting processes underlying the performance of superconducting detectors, developing novel micromachined structures to integrate detector arrays, developing and testing detector arrays, developing multiplexed superconducting integrated circuits for the readout of large arrays, and developing the first uses of these detectors in astronomy and other applications.

Superconducting Quantum Interference Device Development

50.81.42.B5189 BoulderCO 80303

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We are developing superconducting electronics for applications in the measurement of electromagnetic signals. Our main focus is on the development of superconducting quantum interference device (SQUID) circuits to multiplex signals from superconducting microcalorimeters and bolometers. SQUID multiplexers are a practical requirement for the successful deployment of large-format cryogenic detector arrays for X-ray microanalysis and X-ray through millimeter-wave astronomy. We are also investigating other novel directions including the SQUID operational amplifier and the development of susceptometers for magnetic calorimeters. Research opportunities involve improving the noise and bandwidth of these devices, fabricating SQUID circuits in our state-of-the-art superconducting fabrication facility, developing high-performance room-temperature electronics to drive our superconducting circuits, and exploring the device physics of SQUID circuits.

Opportunities in Gaithersburg, MD

"Electronic Kilogram" - The SI Determination of the Ratio of the Mechanical Watt to the Electrical Watt

50.81.11.B1491 Gaithersburg MD 20899

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This experiment uses an electromagnetic force balance to measure the unit of power, the Watt, with a 0.01 ppm uncertainty, by determining the practical relation of the units Volt (Josephson effect) and Ohm (Quantum Hall effect) in terms of their theoretical representations in the SI units Meter (laser), Second (atomic clock), and Kilogram (artifact standard). This determines the Planck constant and the electron mass and has the potential to electronically monitor and redefine the Kilogram, the last artifact-based unit. Monitoring the Kilogram is a significant goal pursued by only a few of the best international standards laboratories. The broad range of precision measurements involves force and mass (mechanical design, local gravity determination), velocity and position (optical interferometry), and voltage and current (electromagnetism, superconductivity). Applicants need a strong familiarity in classical electromagnetism, mechanics, electronics, and optics, while experience with superconductivity, electromagnetic interference, vibration isolation, and instrumentation programming is also useful.

Capacitance Standards and AC Measurements

50.81.11.B5185 Gaithersburg MD 20899

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The Quantum Electrical Metrology Division ties the US legal system of electrical units for capacitance, inductance, and resistance to the SI system of units. First, we realize the SI farad from the SI meter through the calculable capacitor whose capacitance depends on only one length. We then realize the SI henry from a Maxwell-Wien bridge and the SI ohm from a quadrature bridge. However, routine calibrations demanded by the evolving industry call for research beyond these classical experiments used for the realization of the electrical units. Current research focuses on the frequency dependence, in the audio frequency range from 50 Hz to 20 kHz, of capacitance standards including the calculable capacitor, toroidal cross capacitors, and fused-silica capacitors. In close collaboration with other staff, we are also pursuing two alternative representations of the farad: (1) an ac Quantum Hall Resistor with a quadrature bridge and (2) a single electron pump with a cryogenic capacitor. To fully take advantage of these quantum effects, classical precision ac bridge methods must be re-examined and automated whenever possible.

Fundamental Constants, Precision Measurements, and Electrical Units

50.81.11.B1490 Gaithersburg MD 20899

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The Division is engaged in research on methods to improve accuracies of fundamental physical constants and to develop better and more accurate techniques for measuring and maintaining basic electric units. Research includes developing nuclear magnetic resonance-based current and voltage standards, and measurements of absolute ampere, absolute volt, absolute farad and ohm, quantized-Hall resistance, and fine-structure constant. We are particularly interested in refining our current techniques and/or initiating new experiments to increase knowledge of these quantities or other constants of comparable importance, especially those involving the electrical units.

Fundamental Constants, Precision Measurements, and Electrical Units

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The Division is engaged in research on methods to improve accuracies of fundamental physical constants and to develop better and more accurate techniques for measuring and maintaining basic electric units. Research includes developing nuclear magnetic resonance-based current and voltage standards, and measurements of absolute ampere, absolute volt, absolute farad and ohm, quantized-Hall resistance, and fine-structure constant. We are particularly interested in refining our current techniques and/or initiating new experiments to increase knowledge of these quantities or other constants of comparable importance, especially those involving the electrical units.

Physics of Josephson Junctions at Microwave Frequencies and Precision Voltage Measurement

50.81.11.B1494 Gaithersburg MD 20899

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The physics of Josephson junctions, driven at microwave or millimeter wave frequencies of 15-20 and 70-95 GHz, has important applications to ultrahigh precision voltage measurements in support of several other experiments. Adversely affecting the desired voltage stability are behaviors such as complex frequency response in series-array Josephson junctions, noise induced instability of the quantized voltage steps, and the generation of Shapiro voltage steps at fractional values. Related applications in voltage measurement include the characterization of noise or externally induced (pressure, humidity) effects in electronic, Zener-diode based, instrumentation at nanovolt levels for normal measurement frequencies (10 mHz-1 kHz), and nonlinear, unpredictable behavior for longer times (1 mHz and below).

Research facilities include several Josephson array voltage calibration systems; temperature and humidity test chamber; low noise, phase-locking microwave sources; a high-resolution spectrum analyzer; an assortment of high-precision voltage, frequency, and electrical reference instrumentation; and various waveguide-equipped probes and magnetically shielded Dewars for cryogenic measurements.

Quantum Hall Effect

50.81.11.B1496 Gaithersburg MD 20899

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The Quantum Electrical Metrology Division is involved in a continuing research program on the quantum Hall effect, with emphasis placed on using it to maintain the US legal unit of resistance and to determine the fine structure constant to the highest possible accuracy. Any experiments that would further the understanding of the quantum Hall effect or explore its limitations would be of interest. Such experiments could include temperature and current dependence, current distribution (edge and bulk effects), voltage quantization (breakdown effect), and ac quantized Hall resistance measurements that lead to ac impedance standards. Theoretical studies are also needed in all of these areas.

The apparatus consists of two 16-T persistent-current superconducting magnets, a top-loading He-3 refrigerator, a variable temperature insert, and automated quantized Hall resistance measurement systems with parts-per-billion uncertainties.

In support of this research, a clean-room sample preparation facility has been installed that is equipped with a micrometer photo-mask aligner, wire bonder, annealing oven, and probe test station as required for the definition, mounting, ohmic contracting, and room-temperature testing of semiconductor samples for quantum Hall experiments.

Resistance Comparisons for Fundamental Electrical Standards

50.81.11.B5186 Gaithersburg MD 20899

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Converting single-electron tunneling (SET) devices into next-generation usable precision electronic will require precise cryogenic current-multiplication and a better understanding of highly resistive thin films. Our work would be aided by fabrication of improved thin-film resistance-material devices and studies of mesoscopic processes contributing to resistive noise at low temperature. This research would contribute to development of a precision three-way comparison of the SET current, lead to better measurements of Planck's constant, and improve the uncertainty of precision SET-based current sources.

Single Electron Effects

50.81.11.B1492 Gaithersburg MD 20899

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In nanoscale electronic circuits, we can observe Coulomb blockade or single electron tunneling (SET) effects. For metrological applications, the basic device is the single electron pump, which allows control of electrical flow in units of 1 e. This device enables accurate measurements of electrical current or charge. The Quantum Electrical Metrology Division studies such effects and their implications for precision metrology of the electrical units. We are pursuing two goals, both in close collaboration with our Boulder location. The first involves using the electron pump to charge up a cryogenic capacitor. Then, by comparison to the Calculable Capacitor and Josephson Volt experiments, we will make metrological measurements of the electrical charge, e, or the fine structure constant, . Our second goal is to investigate ways to increase the value of the current, for use as a direct current standard. Our current approach is to use Si-based SET pumps, which hold the potential to be parallelized.

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