NIST

National Institute of Standards and Technology

Technology Administration

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NISTIR 6614

January 2002

Electronics and Electrical Engineering Laboratory

Electromagnetic Technology Division

Programs, Activities, and Accomplishments

The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the Federal government as needed to improve efficiency in technical operations, and cooperates with academia in the development and use of measurement methods and scientific data.

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

- Electricity Division
- Semiconductor Electronics Division
- Radio-Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Magnetic Technology Division
- Office of Microelectronics Programs
- Office of Law Enforcement Standards

This document describes the technical programs of the Electromagnetic Technology 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

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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
Arden L. Bement, Jr., Director

Contents

Welcome

The roughly forty staff and guest scientists in the Electromagnetic Technology Division and I take great pride in bringing you this brief report on recent progress of our Division. We have a long history of inventing and disseminating new standards and measurement technology. We focus on exceptional standards and measurement methods using remarkable quantum effects and low noise available only at temperatures close to absolute zero or 0 K (–460 ºF). This publication describes some of our recent successes.

It has always been our goal to provide U.S. industry with the best metrology in the world. We began about thirty years ago to bring the unique capabilities of cryogenic electronic technology to bear on metrology, the science of measurement. In many cases our technology enables measurements that are otherwise impossible. We developed what has become the world's practical standard of voltage, based on integrated circuits containing tens of thousands of superconducting Josephson junctions made in our own fabrication facility. We demonstrated the first capacitance standard based on counting of single electrons. For materials analysis, we perfected an X-ray spectrometer that combines the best features of two types of existing detectors and promises to be critical in defect analysis of future semiconductor devices. We have also improved our cleanroom facilities, which are critical to all of our efforts and enable us to produce microfabricated structures smaller than 100 nanometers.

We have a long tradition of excellence dating back to the formation of our organization in 1969. Our world-leading work has resulted in many prestigious awards to our staff, some of which are listed in Appendix C.

Whether you are our customer and use the results of our efforts, or are simply interested in the remarkable progress our technology brings to measurements, we hope you will find this report exciting. You will find descriptions of our recent work, lists of our publications, and descriptions of our postdoctoral research opportunities. For the most up-to-date information, please visit our Web site, http://emtech.boulder.nist.gov. Our website also contains a searchable bibliography of all of our publications.

Thank you for your interest in NIST's Electromagnetic Technology Division.

Richard E. Harris
Division Chief

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Josephson Array Technology

Technical Contact:
Sam Benz

Staff-Years (FY 2001):
3 NIST staff
1.25 Other staff

Goals

To develop superconducting electronic circuit and system technology for fundamental, quantum-based DC and AC voltage standard systems; to provide improved standards for fundamental metrology; and to support U.S. industry's test and measurement applications.

Clark Hamilton operating one of the 10 V conventional Josephson voltage standard systems developed at NIST and used throughout the world for calibration of Zener voltage references.

Customer Needs

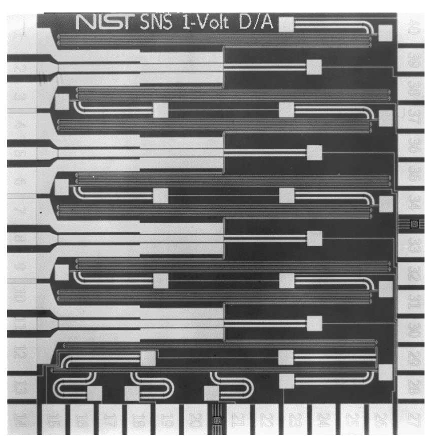
The demands of modern technology for accurate voltage calibrations have gradually exceeded the capability of classical artifact standards. To meet current needs, an international agreement signed in 1990 redefined the practical volt in terms of the voltage generated by a superconductive integrated circuit 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 position through the development and deployment of increasingly accurate, flexible, easier-to-use instruments. Providing U.S. industry with quantum voltage standard systems gives these customers, with appropriate oversight from the NIST Electricity Division, immediate realization of the highest possible in-house accuracy. These customers also benefit dramatically by eliminating their dependence on less accurate reference standards that require frequent calibration.

We also 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.

Over the past 20 years, this project has 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 traveling Josephson voltage standard system that is compact, of 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.

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



A 1 centimeter × 1 centimeter superconductive integrated circuit with 32 768 SNS Josephson junctions for the 1 volt programmable voltage standard.

A few years ago, we developed a novel superconductor-normal metal-superconductor (SNS)

Groundbreaking work at NIST led to commercialization of the first practical DC Josephson voltage standard system.

junction technology that adds the features of stability and programmability to the accuracy of conventional Josephson voltage standards. Programmable Josephson voltage standard systems based on these junctions have 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 features should reduce the uncertainty of the experimental measurements.

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

Our present primary goal is to develop the world's first quantum mechanically accurate voltage source for both AC and DC metrology.

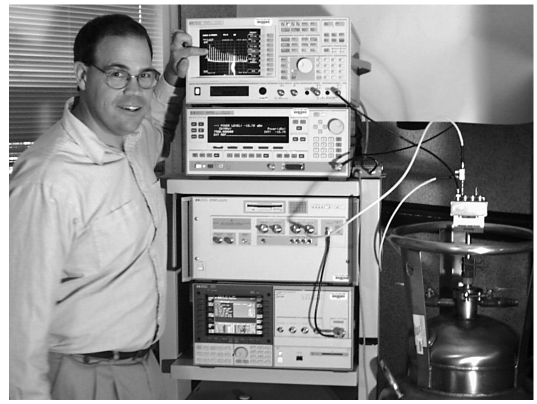
The NIST Electricity Division (811) is interested in improving the internal efficiency of its maintenance and dissemination of the volt through the development and deployment of an improved one-volt programmable voltage standard. This year we collaborated with Electricity Division staff to develop a Josephson voltage standard to be used directly in the customer calibration chain. This system has been completed and delivered to the calibration lab in Gaithersburg, MD.

We provide systems and support to NIST and other national metrology laboratories for Josephson voltage standard systems.

Technical Strategy

Our present primary goal is to develop the world's first quantum-mechanically accurate voltage source for both ac and dc metrology. The device is effectively a digital-to-analog converter capable of synthesizing arbitrary waveforms using 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 source would provide an entirely new instrument and methodology for ac 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. The major challenge of this technology is to achieve practical output voltages by developing improved broadband circuits and novel submicrometer junctions.

We will develop an ac voltage source with an output voltage of 1 volt.



Paul Dresselhaus demonstrates a waveform synthesized with the Josephson arbitrary waveform generator.

The concept of an arbitrary-waveform generator with quantum mechanical accuracy has enabled the possibility of making a quantum-based thermometer. The quantum-based waveform generator can be used to synthesize an equivalent noise voltage with a known, calculable noise spectrum. This quantized noise source can be used to calibrate the correlator measurement electronics of a Johnson noise thermometry system. In collaboration with the Chemical Science and Technology Laboratory's Process Measurements Division (836), we have begun development of this new quantum-based electrical thermometer.

We will develop a quantized voltage noise source for calibration of a Johnson noise thermometer.

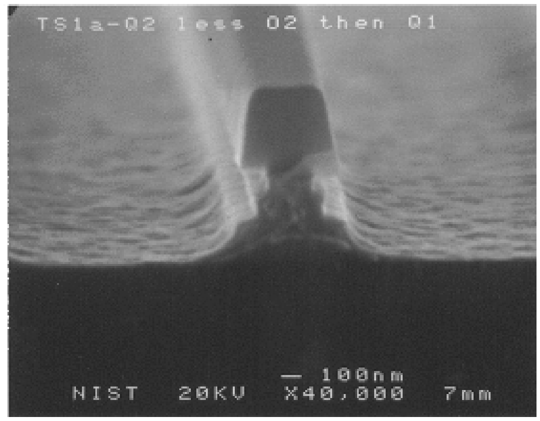
Accomplishments

- NIST operates 1 V Josephson chip on a cryocooler — In collaboration with Sandia National Laboratories and NASA, NIST researchers have successfully operated a 1 V conventional voltage standard chip on a 4 K cryocooler. Guest researcher Clark Hamilton designed a cryopackage that was compatible with the Josephson voltage standard. The cryostat was built by Cryo Industries of America, Inc. Dr. Hamilton installed 75 GHz waveguide and dc wiring for biasing the superconducting chip. Hypres, Inc. provided a 1 V array chip that was mounted on a copper block for efficient cooling. All the components were assembled and cooled to 4 K using Leybold's Coolpower 4.2 LAB cryocooler, which includes a two-stage Gifford-McMahon cryocooler and a CTI 8200 2.1 kW compressor. The cryocooler provides 0.25 W of cooling power at 4.2 K. The chip was successfully cooled to 4 K, where the Josephson junctions produced the appropriate zero-crossing constant-voltage steps that are necessary for conventional voltage standard operation. The cryocooler and cryopackage are in use at Sandia National Laboratories.

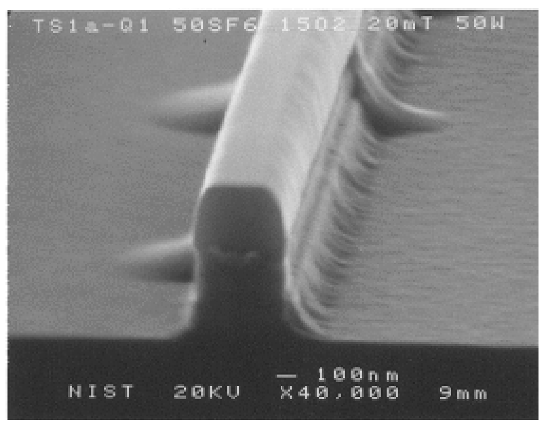
The concept of an arbitrary voltage waveform generator with quantum-mechanical accuracy has enabled the possibility of making an electronically based thermometer.

■ NIST demonstrates remote operation of 10 Volt Josephson voltage standard system — At the June 2001 Combined Calibration Group (CCG) meeting, Charles Burroughs demonstrated the new Windows version of the control software for the conventional 10 Volt Josephson Voltage Standard (JVS) system. This software is the first to provide remote operating capability of JVS systems. A laptop computer with a modem connection in a conference room in Gaithersburg was used to dial-up the 10 V JVS in the Josephson Array Technology Lab in Boulder. Complete remote control of the system was demonstrated by performing a number of calibrations. The new software will replace older DOS-based software, making the system compatible with current computer hardware and software. Remote operation will reduce operating costs of JVS systems by allowing an operator (or repair expert) to monitor, control, and diagnose JVS systems from any location. Additional enhancements will allow JVS operators to collect statistics and perform all the capabilities of the earlier DOS-based software. VMetrix, LLC (Clark Hamilton) and Universal CADD (Rich Jones) have been contracted to do most of the programming.

■ Uniform Ti-barrier Josephson junction arrays for ac Josephson voltage standard — We have made the first uniform arrays of Josephson junctions using titanium as a junction barrier material. We have focused on using Ti because it can be reactive ion etched with the superconducting Nb electrodes. Paul Dresselhaus and Jelle Plantenberg have made a considerable effort experimenting with different etch chemistries to improve the etch anisotropy for etching pentalayer Nb-Ti-Nb-Ti-Nb junction stacks. For example, the figure below shows both isotropic (right, top) and anisotropic (right, bottom) etch processes for a 2-junction pentalayer. The stepped pyramid (right, top) is undesirable compared to the nearly vertical walls (right, bottom) for the anisotropic etch. Two vertically stacked junctions fabricated with this process should have nearly identical areas that very closely match the dimensions of the photoresist. The closely matched areas of the two junctions are essential to ensure that their electrical characteristics are similar.



Nb-Ti-Nb-Ti-Nb pentalayer with photoresist on top, etched with standard SF_6 process resulting in an undesirable stepped pyramid profile. The pentalayer thicknesses from bottom to top are 250 nm, 40 nm, 140 nm, 40 nm, and 140 nm.



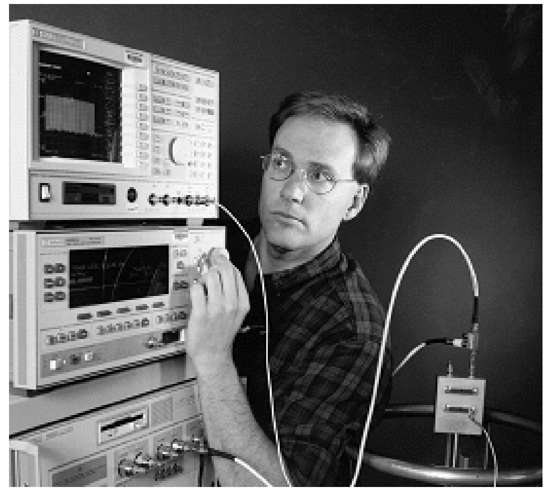
Nb-Ti-Nb-Ti-Nb pentalayer with photoresist on top, etched with SF_6 + O_2 process yielding a desirable nearly vertical sidewall. Same thicknesses as above.

Improved operating margins and a new circuit design have enabled us to perform the first ac metrology measurements of the Josephson arbitrary-waveform synthesizer.

Using this new process we fabricated arrays of single (unstacked) Nb-Ti-Nb junctions in microwave circuits designed for arbitrary waveform synthesis. These junction arrays are embedded in microwave circuits that are used to evaluate the junction uniformity. We successfully generated constant-voltage steps in 1000- and 4100-junction series arrays. This result is encouraging because it demonstrates that the correct voltage is generated over a significant current range for a broad range of frequencies for this large 4100-junction array. This indicates good junction uniformity as well as good microwave uniformity for the Ti normal-metal barrier. This result allowed us to attempt a stacked 2-junction pentalayer (described below).

■ First quantum voltage steps demonstrated in an array of stacked Josephson junctions — We have measured the first constant voltage steps in stacked Ti-barrier Josephson junctions. This is a significant milestone toward creating lumped arrays of Josephson junctions for ac voltage standards. In order to achieve higher output voltage for future standards, all of the junctions must be tightly packed into a size smaller than one-quarter wavelength of the microwave drive frequency. This lumped-array design ensures that all the junctions see nearly the same microwave power, and it is more efficient than distributed arrays because all of the microwave power is used to drive junctions, not dissipated in a termination resistor. For ac and dc programmable voltage standards, lumped arrays will enable increased output voltage, increased bandwidth, increased operating margins, and operations at lower-power.

One thousand double-junction stacks, for a total of 2000 series-connected junctions, were fabricated for the first time. The 40 nm titanium barriers are separated by only 50 nm of niobium. When a 16 GHz microwave bias is applied, a constant voltage step is measured at the expected quantized value of 66.17 mV. The voltage of the step is constant over a 3.5 mA current range, which is more than sufficient for operation as a programmable voltage standard array. This observation of constant voltage steps demonstrates that the stacked junctions are sufficiently uniform for application in voltage standard circuits. For each increase in the number of junctions per stack, we expect to see an improvement in operating margins. Adding a third and fourth junction to each stack will be the next step toward our goal of fabricating and observing steps in 50-junction stacks in order to create a lumped array 2 mm long with a 50 ohm impedance.



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

■ Broadband operation of Josephson synthesizer circuits — Progress has been made toward the development of improved circuits for the Josephson arbitrary-waveform synthesizer. A number of filter designs were found that allow operation at higher frequency and wider broadband compared to previous designs. This has led to a circuit with the largest dc output voltage per junction to date using two series-coupled 3750-junction arrays (for a total of 7500 junctions). Constant voltage steps were measured on this circuit across a broad range of frequencies from 3 to 18 GHz. Also as a result of the improved filters, another circuit with 1000 junctions was driven at a bit-stream data rate by more than a factor of two higher than any previous Josephson array circuit; the bit-stream data rate was successfully increased from 5 gigabits per second to 12 gigabits per second (the maximum data rate of the HP bit-stream generator) while maintaining operating margins for a kilohertz synthesized sine wave. This result gives us confidence that we will be able to fabricate circuits that can be used with the fixed-speed low-cost bit stream generator at 10 gigabits per second that is currently under construction.

■ Constant voltage steps in Josephson junction series arrays at 10 K — NIST is collaborating with Dr. Shoji at Japan's Electrotechnical Institute (ETL), [which has recently become part of the National Institute of Advanced Industrial Science and Technology (AIST)] to develop a higher-temperature programmable voltage standard, so that this system can operate with an economical cryocooler. We have provided fabrication development advice, circuit designs and circuit testing. After considerable improvements in their fabrication process over the last two years, including the addition of 2 planarization steps and the addition of NbN wiring, Dr. Shoji's group has made the first all-NbN arrays with useful operating margins. Arrays of 4096 junctions have sufficient uniformity at an operating temperature of 10 K to generate constant voltage steps. An array circuit was designed with different numbers of junctions in a binary sequence to demonstrate operation as a programmable dc standard. The data show that each segment has a common current bias range of 3 mA for the n=1 step. The total array voltage when all segments are on the n=1 step is 135.5 mV. This circuit can be used as a 10 K programmable standard operating over a range of ±135 mV. The uniformity is also good enough to begin designing circuits with 33,000 (unstacked) junctions for 10 K programmable voltage standard circuits. We hope to continue this collaboration with AIST and begin stacking the junctions for lumped arrays.

Collaborations

- We are collaborating with Dr. Shoji and Dr. Yamamori at Japan's AIST to develop cryocooler-compatible Josephson junctions for programmable voltage standards. The latest results are described above in the accomplishments.

- We are collaborating with Ian Robinson of the National Physical Laboratory (NPL), England, to provide a programmable 1 V probe and chip for their Watt-balance experiment. NPL will purchase the probe from NIST and construct their own bias electronics and computer control.

- We are collaborating with Northrop-Grumman on the development of a pulse-quantized arbitrary waveform generator for radar applications. This application uses the same pulse-quantized AC synthesis techniques as the NIST metrology application except at radar frequencies. We have designed and fabricated SNS junction circuits using Northrop-Grumman designs and demonstrated multiple-tone waveforms at megahertz frequencies.

Recent Publications

S.P. Benz, F.L. Walls, P.D. Dresselhaus, C.J. Burroughs, "Low-distortion Waveform Synthesis with Josephson Junction Arrays," Proc. 8th Int'l Superconductive Electronics Conf. (ISEC '01): 115-116; 19-22 June 2001, Osaka, Japan.

R.H. Hadfield, G. Burnell, M.G. Blamire, P.D. Dresselhaus, S.P. Benz, "Nanofabricated SNS Junction Series Arrays in Superconductor-Normal Metal Bilayers," Proc. 8th Int'l Superconductive Electronics Conf. (ISEC '01): 391-392; 19-22 June 2001, Osaka, Japan.

H. Yamamori, M. Itoh, H. Sasaki, A. Shoji, S.P. Benz, P.D. Dresselhaus, "Fabrication of all-NbN digital-to-analog converters for a programmable voltage standard," Proc. 8th Int'l Superconductive Electronics Conf. (ISEC '01): 219-220; 19-22 June 2001, Osaka, Japan.

S. P. Benz, J. M. Martinis, S. W. Nam, W. L. Tew, D. R. White, "A new approach to Johnson noise thermometry using a Josephson quantized voltage source for calibration," to appear in Proc. of TEMPMEKO 2001, 8th Int'l Symp. on Temperature and Thermal Measurements in Industry and Science, April 2001 (in press).

C.A. Hamilton, S.P. Benz, "Broadband Josephson voltage standards," submitted to the Microwave Conf. Digest of the 2001 Int'l Microwave Symp., to appear in the Special Symposium Issue of the IEEE Trans. on Microwave Theory and Techniques, December 2001 (in press).

S.P. Benz, C.J. Burroughs, P.D. Dresselhaus, "AC coupling technique for Josephson waveform synthesis," IEEE Trans. Applied Superconductivity **11**(1): 612-616 (June 2001).

B. Jeanneret, A. Rüfenacht, C.J. Burroughs, "Comparison Between the SNS and SIS Josephson Voltage Standards at OFMET," IEEE Trans. Instrumentation and Measurement, **50**(2): 188-191 (April 2001).

S.P. Benz, C.J. Burroughs, P.D. Dresselhaus, L.A. Christian, "AC and DC Voltages from a Josephson Arbitrary Waveform Synthesizer," IEEE Trans. on Instrumentation and Measurement, **50**(2): 181-184 (April 2001).

S.P. Benz, P.D. Dresselhaus, C.J. Burroughs, "Nanotechnology for next generation Josephson voltage standards," Proc., Symp. on Microtechnology in Metrology and Metrology in Microsystems: 127-132; 31 August-1 September 2000, Delft University of Technology, Delft, The Netherlands; also to appear in IEEE Transactions on Instrumentation and Measurement, December 2001 (in press).

The larger voltage has enabled 10 times lower uncertainty for ac-to-ac comparisons as compared to previous measurements using lumped arrays.

Nanoscale Cryoelectronics

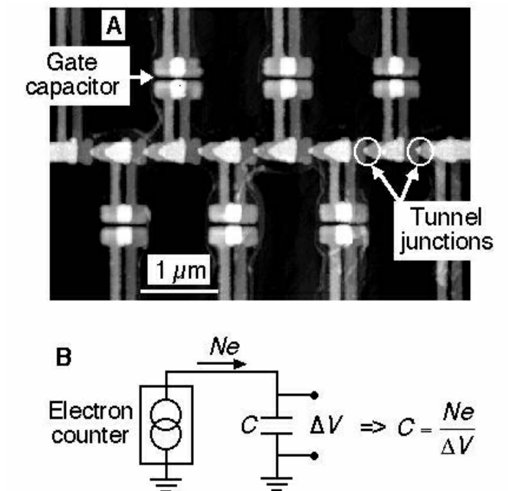
Technical Contact:
David Rudman

Staff-Years (FY 2001):
10 NIST staff
8.25 Other staff

We have already demonstrated a prototype capacitance standard based on counting electrons one at a time.

Goals

To develop novel integrated circuits for metrology based on the unique properties of electronic devices operating at temperatures below one Kelvin.



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 a error rate of less than 1 electron in 10^8.

Customer Needs

We work in two principal areas: single-electron devices and microcalorimeter-based detectors. The goal of the single-electron project is to use the unique capabilities of single-electron tunneling (SET) devices to create new quantum standards based on the manipulation of single electrons and to develop measurement techniques applicable to new generations of electronics that will operate with very few electrons. The goal of the microcalorimeter detector project is to use the unique low-noise, high-sensitivity properties of cryogenic electronics to create new generations of detectors for high energy-resolution measurements of radiation, from infrared through X ray.

We have also begun two new programs: work to significantly improve Johnson noise thermometry using state-of-the-art room temperature electronics and Josephson junction voltage standards, and work on quantum computing and quantum coherence.

Single Electron Devices for Electrical and Photonic Standards

The U.S. electronics industry continues to seek improved and more accessible standards for maintaining instrument calibration. NIST is working to support this need through 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. For capacitance, NIST's primary standard (the calculable capacitor) is a unique instrument that is difficult to replicate, and it currently provides the best accuracy at only one fixed frequency.

We are focused on producing a capacitance standard based on counting electrons. This standard will provide accurate calibrations over a wide range of frequencies and will be more easily replicated to meet customers' needs. This same technology is being explored as a way to create new optical calibration devices based on the production of single photons.

Technical Strategy

The creation of electronic devices capable of manipulating and detecting individual electrons has opened the door to the development of entirely new standards and metrology tools. SET devices are made possible by a combination of state-of-the-art nanolithography to create the nanometer-scale devices, millikelvin cryogenics to cool the devices to their operating temperature, custom low-noise electronics to operate and measure the devices, and fundamental physics, to understand and diagnose the operation of the devices. Maintaining expertise and capabilities across these fields represents the core technical strategy of this effort.

We will compare measurements on SET devices to theoretical models to understand the performance and operating margins of the capacitance standard.

At present, the main application for SET devices within the project is to create a new capacitance standard based on the fundamental definition of capacitance: capacitance is stored charge per unit voltage, $C=Q/V$. By placing a known number of electrons on a capacitor, and measuring the voltage across the capacitor, C can be determined. A prototype of such a standard has been demonstrated with repeatability on order of 1 part in 10^7. In order to confirm the accuracy of the standard, a portable version must be taken to NIST in Gaithersburg for direct comparison with the calculable capacitor.

Using a new variable-frequency capacitance bridge and capacitance artifacts calibrated against the calculable capacitor, we will perform improved accuracy measurements on the SET standard in Boulder.

To evaluate the electron counting capacitance standard, we will compare it with the present calculable capacitor.

In collaboration with the Electricity Division, we will build a new copy of the SET capacitance standard in a portable millikelvin refrigerator to allow transport to Gaithersburg and direct comparison with the calculable capacitor.

With the availability of electron pumps, it may be possible to perform unique comparisons of the three intrinsic electrical standards: the volt (based on the Josephson junction), the ohm (based on the quantum Hall effect) and now the ampere (based on counting electrons). This test, known as the quantum-metrology triangle, will provide new understanding and confidence in these quantum standards. The experiments will require a significant increase in current from the electron pump.

We will develop a superconducting version of the electron pump with a goal of providing sufficient current for the metrology triangle experiments.

SET devices can also be used as tools to measure the performance of other devices that operate with individual electrons. Work has begun on creating a new class of electronic devices designed to produce single photons on demand. These devices will be based on quantum dots of semiconductor materials. To understand their behavior, it will be necessary to measure the electrical currents into the dots at the single electron level. This can be done only using SET technology.

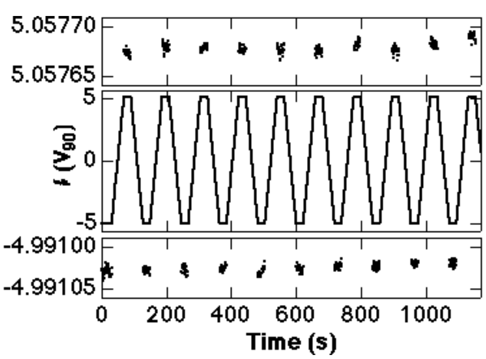
Work has begun on creating a new class of electronic devices designed to produce single photons on demand.

In collaboration with the Optoelectronics Division, we will integrate SET devices into a single photon circuit and confirm the electrical operation of the photon source.

Accomplishments

■ The past few years have brought to fruition the results of a decade of research into SET electronics. The goal of this work has been to develop a capacitance standard based on counting electrons. A thorough understanding of the physics of SET devices has been necessary to count electrons with metrological accuracy. The fundamental error mechanisms in the electron pump have been the subject of theoretical and experimental investigations in the project for several years. The development of an experimental technique for characterizing individual junctions in the pump made possible the first quantitative comparison between experiment and theory in the regime of very rare errors. This comparison showed that the pump was not performing nearly as well as the standard theory predicted. Experiments and theoretical work on the effect of photon-assisted tunneling, which is not included in the standard theory, have shown that this is probably the origin of the discrepancy. This expanded theory remains a powerful tool for predicting and diagnosing the performance of the electron pump.

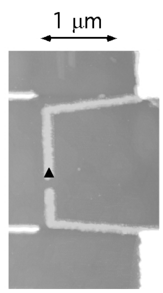
■ A prototype of a capacitance standard based on counting electrons has now been demonstrated. The components of the standard are an electron counter, a capacitor, and an electrometer to monitor the process. The electron counter is based on seven nanometer-scale tunnel junctions in series. It can "pump" 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, fabricated by Neil Zimmerman in the Electricity Division (811), operates at cryogenic temperatures and uses vacuum as the dielectric, resulting in a frequency-independent capacitance.



Demonstration of pumping electrons on to and off a prototype capacitance standard.

To operate the standard, approximately 100 million electrons are placed, one at a time, 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 using a standard ac bridge measurement technique. The figure above shows the result of pumping electrons on and off the capacitor, with a 20 second pause when fully charged to measure the voltage. The result is a value of capacitance with a repeatability of one part in 10^7.

Recently the dependence of pump errors on voltage across the pump has been measured for the first time. This directly gives the operating margin for the feedback that must be maintained during operation of the capacitance standard, a critical design parameter for the next generation of the standard. It has also been determined that the pump can be cycled to temperatures in the range of 50 K without affecting the noise performance. This will allow the standard to be operated in an adiabatic demagnetization refrigerator, a much simpler cryogenic system than the current dilution refrigerator.



An AFM image of electron-beam lithographically-written contact to a single QD. The black triangle indicates where the QD is located. The lead that approaches the QD from the bottom is used to capacitively couple the QD to a single-electron transistor structure. The white lines coming in from the left side of the micrograph are alignment marks.

■ 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 quantum dots (QD) and single-electron principles. The first step towards this end requires the development of a process to allow electrical contact to individual quantum dots. The process uses a combination of photolithography, electron-beam lithography, atomic-force microscopy, etching, and film deposition to allow individual QD, which are only a few tens of nanometers in diameter, to be located and connected to microscopic leads on the same chip. Each of the 12 steps in the process has been executed individually with good yield, and fabrication of a completed chip with contact to four separate quantum dots will be pursued next. An AFM image of electron-beam lithographically-written contacts to a single quantum dot is shown at left.

Cryogenic Detectors

Our detectors will help the semiconductor industry to improve yield by identifying small contaminant particles.

The ability to detect photons with high energy resolution and near-unity quantum efficiency will enable new generations of spectroscopic tools to be created. Improved energy-dispersive X-ray spectroscopy will be used to solve a wide range of problems in materials analysis. For example, the semiconductor manufacturing industry needs improved X-ray materials analysis to identify small contaminant particles on wafers and to evaluate very thin layers used in current device structures.

To make this technology available to the materials analysis community, NIST has licensed several patents to two U.S. companies for commercialization. Additionally, NIST's Chemical Science and Technology Laboratory will use this spectroscopy to improve its own materials-analysis capability. The National Aeronautics and Space Administration (NASA) also needs improved instruments for imaging at wavelengths from infrared to X-ray. We are working with NASA to bring this technology into use.

The same devices can also be used to detect single optical photons such as are conceived to be used in the future for quantum information and communication systems. We are working to apply this technology to the measurement of these entangled photons.

Technical Strategy

Introducing a radically new technology such as cryogenic microcalorimeters to a large community requires creating and demonstrating an entire measurement instrument, not just the detector. In this case, we have developed superconducting electronics to read the detectors, compact adiabatic demagnetization refrigerators to simplify cooling the detectors to millikelvin operating temperatures, and room-temperature electronics to process the output signals. The resulting system makes a much more compelling case for the technology than the performance specifications of the detector alone. Thus, our goal is to develop new detector systems and to apply those systems to problems of interest to our customers.

We will provide technology transfer support to the NIST licensees commercializing this technology.

In the area of X-ray spectroscopy, the performance target depends on the application. For materials analysis, further improvements in energy resolution are not as important as an increase in the maximum count rate and collection area. 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 current approach to the electronics is to develop a superconducting quantum interference device (SQUID) multiplexer (MUX) circuit to read the array, and room-temperature digital signal processing (DSP) to process the MUX signals.

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.

The application of X-ray detectors to materials-analysis problems represents a test bed for this technology. With a focus towards the semiconductor manufacturing industry, problems in characterization of small particles and very thin layers of material are very important. The ability of the detector to differentiate overlapping X-ray lines at low energies enables analysis of previously inaccessible systems.

We will provide the Chemical Science and Technology Laboratory (CSTL) of NIST with a complete prototype system for collaborative use in studying problems of interest to our customers.

For some materials-analysis applications and for astronomical observations, improvements in the energy resolution at relatively high X-ray energies (6000 eV) are still needed. In addition, large-format, densely packed arrays of detectors are required for imaging. These are ambitious goals that will require improved understanding of the limitations on performance of microcalorimeter detectors. Novel fabrication techniques will need to be developed to make densely packed arrays, and SQUID MUX and DSP circuitry will be required to read out the arrays.

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 develop improved bulk and/or surface micromachining techniques to allow fabrication of dense packed arrays of detectors.

These detectors also provide remarkable performance at lower energies, from infrared through visible. In the visible, single-photon microcalorimetry is still possible, opening a range of interesting applications. In the field of quantum information and communication, the detection of single photons is a key measurement requirement. In a new program funded through DARPA, we are working to develop a multichannel single-photon detection system that will allow detection and analysis of correlated photons. A similar system is also being developed for optical imaging spectroscopy.

We will develop a single-photon microcalorimeter system, and in collaboration with Boston University, use it to analyze correlated photons.

With Stanford University, we will develop a 32 pixel optical imaging microcalorimeter instrument.

For infrared applications, the goal is clearly to develop large-format imaging arrays with high sensitivity and energy resolution. The present application for these arrays is in astronomy, both ground-based and in space.

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

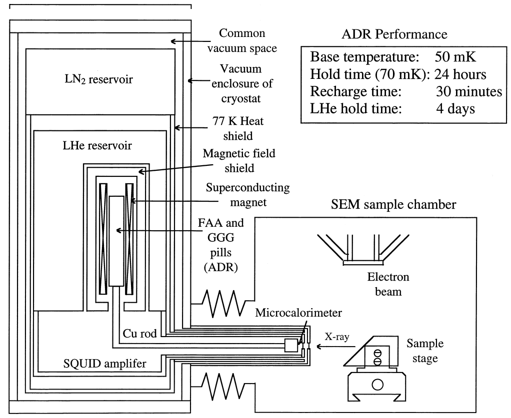
■ The success of the microcalorimeter detector project has been made possible by broad expertise within the Division in such fields as physics superconductivity, device fabrication including Si micromachining, superconducting electronics, cryogenic engineering, and low-noise, room-temperature electronics. 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. As an example, the schematic on the next page shows a microcalorimeter energy-dispersive spectrometer (EDS) X-ray detector system inserted into a scanning electron microscope to allow chemical microanalysis of materials.

The ability of the microcalorimeter detector to differentiate overlapping X-ray lines enables analysis of previously inaccessible systems.

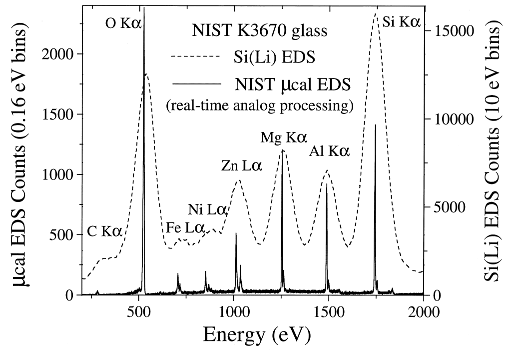
Introducing a radically new technology such as cryogenic microcalorimeters to a large community requires creating and demonstrating an entire measurement instrument, not just the detector.

The key innovation for absolute noise thermometers is a Josephson-junction calculable noise voltage source.

The success of the microcalorimeter detector project has been made possible by the broad expertise within the division in such fields as physics of superconductivity, device fabrication including Si micromachining, superconducting electronics, cryogenic engineering, and low noise, room-temperature electronics.



Schematic of a microcalorimeter energy-dispersive spectrometer (EDS) X-ray detector system inserted into a scanning electron microscope.



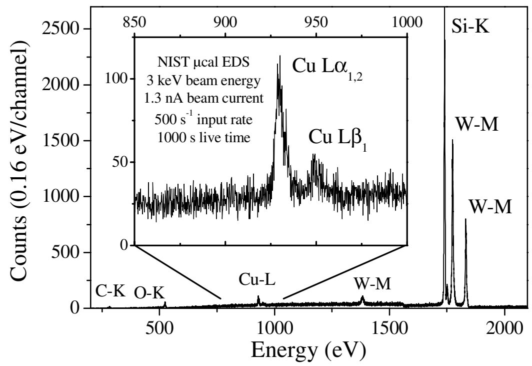
Comparison of resolutions of NIST microcalorimeter EDS to standard semiconductor EDS.

■ The microcalorimeter detector uses a superconducting/normal-metal bilayer to create a superconducting transition-edge sensor (TES). Using the proximity effect, the transition temperature of the bilayer can be selected to match each specific application. We created an accurate model of the proximity effect in this system, which allows the thickness for each layer to be calculated, minimizing trial-and-error fabrication.

■ Originally each TES was individually fabricated using Al/Ag bilayers and a shadow-mask deposition process, but recent advances with Mo/Cu bilayers have allowed whole-wafer photolithographic processing. The TES and appropriate X-ray absorber are fabricated on a Si_3N_4 micromachined membrane to produce the required thermal isolation. The device operates using a current bias and extreme negative electrothermal feedback, so that it self-regulates in temperature. Absorbed X rays produce heat pulses in the device, which are read out as pulses of reduced bias current by a first-stage, single-SQUID amplifier located adjacent to the detector to minimize inductance. The output of the first-stage SQUID is read out by a unique 100-SQUID amplifier invented and fabricated by the Division specifically to allow direct coupling of the signal to room-temperature electronics. The detector is cooled to below 100 mK by a compact adiabatic demagnetization refrigerator, which has unique design features that produce nearly 24 hours of continuous operation, and days of hold time for liquid helium.

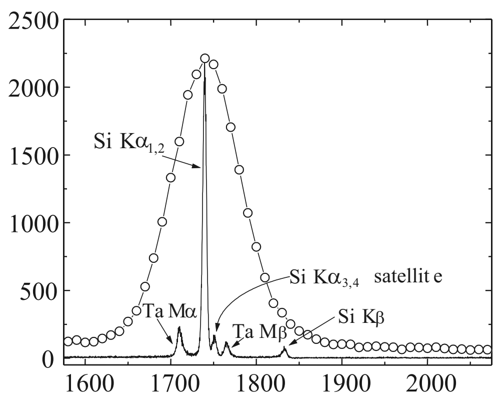
This system holds the world record for energy resolution for an EDS detector of 2.0 eV at 1500 eV, which is over 30 times better than the best high-resolution semiconductor-based detectors currently available. The figure above compares an X-ray spectrum obtained with this system to that from a semiconductor energy-dispersive detector, clearly demonstrating the remarkable improvement in resolution. The specimen was a glass prepared by Dale Newbury of the Chemical Science and Technology Laboratory to use as a test standard for EDS. 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.

Furthermore, we have completed several effective partnerships with companies in the semiconductor industry to demonstrate the usefulness of the microcalorimeter spectrometer for practical analysis. For example, in collaboration with researchers at Lucent Technologies in Orlando, Florida, we critically compared the ability of microcalorimeter-based x-ray analysis to detect trace Cu with that of other industrial analytical techniques, including conventional semiconductor Energy-Dispersive Spectrometry (EDS), Auger Electron Spectrometry, and Secondary Ion Mass Spectrometry (SIMS). Although only SIMS is capable of analysis of trace Cu down to the ~0.02 % atomic level, microcalorimeter EDS fared very well in comparison with the other non-destructive analytical techniques.



A microcalorimeter EDS spectrum of 0.7 % by weight Cu/Al alloy thin film (from Lucent Technologies) demonstrating the sensitivity of microcalorimeter EDS for analysis of trace Cu in the semiconductor industry.

■ In collaboration with the University of Albany (NY), we have used the microcalorimeter EDS to analyze ultra-thin films of TaSiN that are under development as ion diffusion barriers in integrated circuit (IC) interconnect structures smaller than 0.1 micrometer. The figure below compares the spectra taken with the microcalorimeter EDS to that taken with a conventional semiconductor EDS. The high resolution of the microcalorimeter EDS allows unambiguous separation of the Ta M lines from the Si K lines, even for films as thin as 3.5 nm. Such constituent identification is impossible with conventional Si-based EDS detectors.

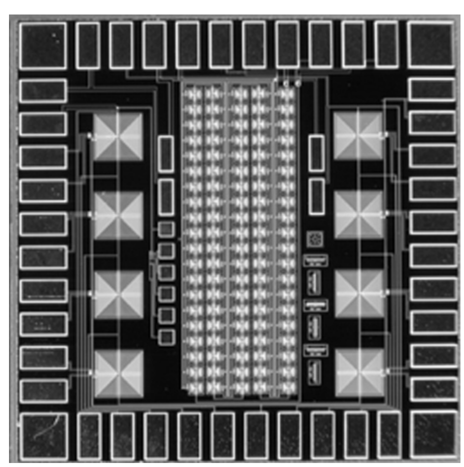


EDS spectra from a 3.5 nm thick TaSiN film on Si taken with a beam voltage of 3 keV. The solid line denotes EDS data taken using a microcalorimeter x-ray detector. Open circles denote EDS data taken using a conventional Si(Li) detector.

Based on these types of results, two U.S. X-ray spectrometer companies have acquired licenses for a suite of patents covering this technology to begin commercialization. Technology transfer to both companies has occurred.

■ To enable more advanced applications of this technology to materials-analysis problems requires coupling the spectrometer to state-of-the-art analytical tools, such as those available in the Chemical Science and Technology Laboratory (CSTL) at NIST-Gaithersburg. To this end, the single-pixel spectrometer used in the above research has been relocated to Gaithersburg. Installation will be completed once a new detector is available, and the system will be used jointly with CSTL to continue microanalytical work on problems of interest to the semiconductor and other materials-intensive industries.

■ In addition to X-ray detection, this microcalorimeter technology is being developed for use at other wavelengths, from optical down through the sub-millimeter. Our TES bolometers have achieved world-record sensitivity for infrared radiation. This impressive result confirms the utility of this technology for this application as well. However, to meet the needs of NASA, large-format arrays of these detectors have to be fabricated, and electronics have to be created to read out the arrays. We have developed the first SQUID-based MUX for this purpose, and have demonstrated it with a 1 x 16 array of TES bolometers. This array and MUX have been delivered to NASA, and were first field-tested in the spring of 2001 on the Cal Tech Submillimeter Observatory located in Hawaii. The devices performed as expected, and will be used for further observations this fall.



A photograph of an 8-channel SQUID multiplexer chip fabricated at NIST. On the 6.4 mm chip are 8 first-stage SQUID amplifiers and one second-stage series-array SQUID amplifier. This chip has been used to multiplex 8 channels at 1 million samples per second.

Our compact adiabatic demagnetization refrigerator has unique design features that produce nearly 24 hours of continuous operation, and days of hold time for liquid helium.

This system holds the world's record for energy resolution for an EDS detector.

The system has demonstrated for the first time EDS energy shifts depending on chemical bonding state.

The ability to read out large arrays of detectors may, in the end, prove as important as the detectors themselves.

This detector technology may provide new capabilities in mass spectrometry.

We have also invented a new SQUID MUX concept that (in models) will have better bandwidth and 2 orders of magnitude lower power dissipation than the present design. The first fabrication run yielded devices that work at the design specifications. High-speed testing and noise analysis will be performed this fall.

■ The ability to handle the data read out from large arrays of detectors may, in the end, prove as important as the performance of the detectors themselves. Even once a multiplexing technology is developed, the huge amount of data acquired from this system will require new room-temperature electronics to collect and process the information. We developed a first-generation digital signal-processing (DSP) system and have successfully interfaced it with the SQUID amplifiers, providing the feedback required for their operation. In collaboration with Stanford University, these electronics have been used with a small array (2 x 2) of optical TES detectors (built by Stanford) to perform astronomical observations at the McDonald Observatory. Using the electronics, real-time data were acquired from the Crab pulsar at higher rates than had been previously achieved. A new 32-channel system is currently being built in collaboration with Stanford.

■ This detector technology has also been explored as a means of providing new capabilities in the field of mass spectrometry. The microcalorimeter can detect the kinetic energy associated with the impact of an accelerated ion on the detector. We have demonstrated the use of this energy measurement to determine the charge of incident ions created using an electro-spray ion source (ESI). ESI is widely used for mass spectrometry of biomolecules because it creates gas-phase ions directly from liquid input. One important drawback of ESI is that it creates ions with a wide range of charge states, leading to many peaks in the measured spectrum of mass-to-charge ratio. This difficulty limits the utility of ESI for complicated samples such as mixtures. The use of an energy-resolving detector can in principle provide a solution to this difficulty by allowing an independent measurement of the ionic charge, which can then be used to deconvolve the spectra. We have demonstrated this technique with a variety of proteins (masses up to 77 kDa), and used this technique to analyze a mixture of calibration proteins. While this technique showed promise, the impact-energy resolution is currently insufficient for widespread application. We have currently suspended work in this area.

New Projects

The technical expertise in the project lends itself to the creation of new projects. Over the past two years two new efforts have been started: Johnson Noise Thermometry and Quantum Computing. Both are in the early stages, but significant results are expected within the next few years.

Technical Strategy

The development of DSP electronics for the detector project stimulated interest in applying this technology to other metrology problems. Electronic thermometers based on Johnson noise have been limited by electronic measurement capabilities. In collaboration with the Josephson Array Technology Project and the Chemical Science and Technology Laboratory, we have begun work to develop Johnson noise thermometers using state-of-the-art analog and digital electronics. The key innovation will be the creation and use of a Josephson junction-based Arbitrary-Waveform Synthesizer to generate a calculable-noise voltage source to provide accurate calibration of the amplifiers and correlators needed to make the thermometer. The goal is to make a highly accurate noise thermometer that can be easily replicated for use in a wide variety of applications.

We will develop and test the analog and digital electronics needed to realize a new generation of Johnson noise thermometers.

There has been considerable worldwide interest in using coherent quantum states as a new type of "bit" (qubit) in a computer. To date the most successful demonstration of this concept has used a few trapped ions as the qubits. There has also been research into using superconducting devices to establish the required coherent quantum states. However, it has proved difficult to create devices with coherence times long enough to be considered useful.

John Martinis has conceived of a new way of using Josephson junctions (JJ) to create qubits for a potential quantum computer. Extensive modeling of the behavior of JJ suggested that a practical qubit could be built using superconducting circuits. The modeling, which included noise sources such as 1/f noise, led to a conclusion that large, rather than small, junctions should improve performance of the qubit.

Under funding from the NSA preliminary devices have already been fabricated based on this model. Three iterations of the initial design have been made and tested. Significant attention (modeling and testing) has been paid to the microwave properties of the inductor. The results have been encouraging: energy relaxation times are now compatible with the design values.

We will design, fabricate and test Josephson junction devices as potential qubits.

Recognition

- Presidential Early Career Award for Scientists and Engineers to Mark Keller, 2000.
- NIST Condon Award, for excellence in writing, 2000.
- NIST Applied Research Award, Cryogenic X-ray Detector, 1999.
- Department of Commerce Gold Medal, Cryogenic X-ray Detector, 1999.

Patents

- "Particle Calorimeter with Normal Metal Base Layer," issued June 1997.
- "Mechanical Support for a Two Pill Adiabatic Demagnetization Refrigerator," issued August 1999.
- "Superconducting Transition-Edge Sensor," issued March 1999.
- "Microcalorimeter X-ray Detectors with X-ray Lens," issued March 1999.
- "Superconducting Transition-Edge Sensor with Weak Links," filed November 1998.
- "The Use of Superconductor-Insulator-Normal (SIN) Tunnel Junctions in Superconducting Quantum Interference Device (SQUID) Multiplexers," disclosure submitted, April 2000.

Recent Publications

Single Electron Devices

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Cryogenic Detectors

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K.D. Irwin, M.E. Huber, "SQUID Operational Amplifier," IEEE Trans. Appl. Supercond. 11, 1265 (2001).

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K.D. Irwin, G.C. Hilton, J.M. Martinis, S. Deiker, N.F. Bergren, S.W. Nam, D.A. Rudman, D.A. Wollman, "A Mo-Cu superconducting transition-edge microcalorimeter with 4.5 eV energy resolution at 6 keV," Nuclear Instruments and Methods in Physics Research A 444, 184 (2000).

Terahertz Technology

Technical Contact:
Erich Grossman

Staff-Years (FY 2001):
2 NIST staff
3 Other staff

Goals

To develop and apply electronic technology, especially cryogenic electronic technology, in the terahertz spectral range to measurements and standards in support of other NIST organizations and U.S. industry.

Customer Needs

The U.S. aerospace and defense industries are being pushed toward both higher performance and faster, less expensive systems. Devices originally developed for cryogenic electronics, in particular cryogenic bolometers and tunnel diodes, are often useful in a wide variety of metrological applications, as well as in other scientific or commercial applications, not always at cryogenic temperatures. Atmospheric scientists use satellite-based spectrometers to monitor the worldwide distribution of species relevant to climate change. Security equipment manufacturers are developing millimeter-wave imagers for concealed weapons detection. And submillimeter spectroscopy is being developed as a diagnostic tool—monitoring species concentrations and temperatures—for plasma processes in semiconductor manufacturing. The activities of this project focus on adapting millimeter-wave to IR technology for the benefit of these industries, either directly through collaborative research and development programs, or indirectly, by improving the metrological capabilities of other NIST Divisions, which in turn make the results available to U.S. industry.

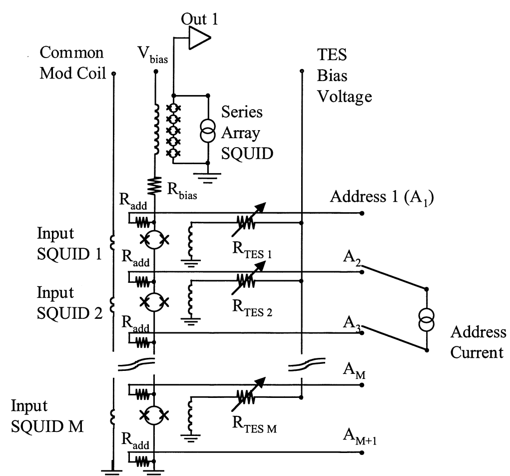
Technical Strategy

The work of this project focuses particularly 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. Work on improving the sensitivity or precision of power measurements exploits the low noise properties of thin-film bolometers.

One focus is the development of bolometers with ever-higher sensitivity, and their incorporation into imaging systems based on large focal-plane arrays. Depending on engineering tradeoffs we make during the design phase, (i.e. between sensitivity and other characteristics such as operating temperature), these imagers are applicable to remote sensing of the Earth, atmospheric spectroscopy, or astronomy. Some of this work is supported by the National Aeronautics and Space Administration (NASA), and its contractors in the aerospace industry.

We will develop a high-sensitivity bolometer for far-IR wavelengths with an noise equivalent power (NEP) of less than 10^{-18} watts per root hertz.

Because readout is a critical element in any array technology, a SQUID-based cryogenic multiplexer is being developed to provide the front-end processing of the bolometers' outputs. The bolometers are superconducting films biased on their transition edge, and operated in an electrical substitution mode.



Monolithic SQUID multiplexer circuit. A 1 × 8 prototype has been demonstrated at pixel rates of 1 megahertz.

Far-infrared spectroscopy at the highest levels of sensitivity and spectral resolution has traditionally been accomplished with heterodyne techniques, in which the weak signal to be measured is combined with a strong "local oscillator" and focused onto a detector or "mixer." The signal at the difference frequency is then measured with an ultra-low-noise detection system. A program is underway to develop ultra-sensitive mixer elements based on superconducting hot-electron bolometers (HEBs). Like the transition-edge bolometer arrays, a major application for these mixers lies in space-based, remote sensing. HEBs formed of thin films of niobium and niobium nitride have already demonstrated sensitivities within a factor of 5 of the fundamental quantum limit. The focus of our research, and of the most

Our large arrays of bolometers are applicable to remote sensing of the earth, atmospheric spectroscopy, and (by NASA) astronomy.

Recent advances in nanoscale fabrication make the vision of direct rectification of sunlight much more realistic.

recent progress in the state of the art, lies in extending the frequency coverage of this measurement technique above 2 THz, allowing measurement of a wider variety of species, and in developing integrated heterodyne arrays.

By 2002, we will demonstrate a 2 x 2 element heterodyne mixer array operating at 2.5 THz, with noise temperature within a factor of 10 of the quantum limit.

Our millimeter wave imaging is being evaluated for concealed weapons detection.

We also use superconducting bolometers to standards-related metrology, both for audio frequencies (where they are known as AC-DC thermal transfer standards) and for IR frequencies (where they are known as electrical substitution radiometers). This project is collaborative with the Electricity Division, which is responsible for AC electrical calibration and metrology.

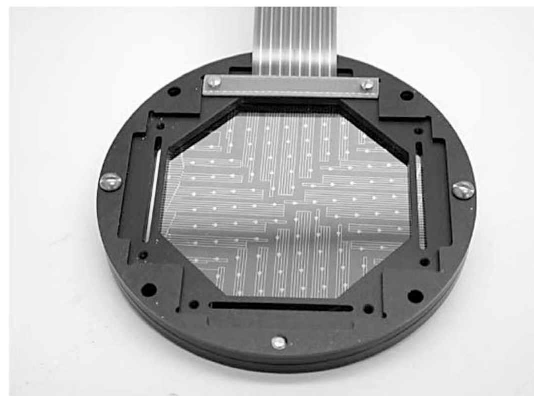
For audio frequencies, we will achieve precision better than 1 part in 10^6 in AC voltage transfer at microwatt power levels.

In addition, we are working on the application of uncooled terahertz bolometer arrays to analyze and diagnose problems in the etching plasmas used for semiconductor manufacturing. These plasmas typically contain a number of molecular and ionic species, whose concentrations and temperatures can be accurately monitored by spectroscopy on their pure rotational transitions, which lie in the terahertz spectral region. A collaborative program with the Physics Laboratory, funded by the NIST Advanced Technology Program (ATP), was started in FY 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. A key part of this program is the development of bolometer arrays with sufficient sensitivity to perform the spectroscopy, but which are not cryogenically cooled, and are therefore practical for industrial use. Based on prior work done for other programs, a detector system based on uncooled Nb bolometers has been designed and built; an example device is shown in the next figure.

By 2002,we will integrate an uncooled THz bolometer with the Physics Lab 's Gaseous Electronics Conference (GEC) plasma reactor and backward-wave oscillator sources, and perform spectroscopy on a CF_2 plasma.

We also develop thin-film bolometers, coupled to antennas and operated at room temperature, in applications where the very highest sensitivity is not required. An example is millimeter-wave imaging for the detection of concealed weapons (clothing is transparent at millimeter wavelengths). In collaboration with the Electricity Division and the Office of Law Enforcement Standards, we are developing an actively illuminated imaging system for this application, based on a full wafer-scale array of several hundred antenna-coupled bolometers. The technical emphasis in this case is on development of a practical system, rugged enough and low enough in cost to allow for field deployment, for example with mobile police units or in airports.

We will develop an imaging system with reflectivity contrast less than 5 % at a range of 5 meters in a 120-element array.



First version of a 120-element antenna-coupled bolometer array for detection of concealed weapons.

In most of these programs, the lithographic antenna forms an important component of the system, frequently requiring as much development as the bolometer or tunnel diode, although its only function is the efficient coupling of radiation to the device. We therefore perform significant development work on lithographic antennas themselves. These are ubiquitous in wireless telecommunications systems (e.g. cellular phones) at lower, microwave frequencies. The relentless drive for greater bandwidth in such telecom systems is driving a push to raise the operating frequencies to the millimeter-wave range or beyond, where our present antenna development effort is focused. Moreover, the polarization-specific nature of antennas can frequently be exploited to provide our devices with additional functionality. For example, the emittance or reflectance properties of a surface differ for *s* and *p* polarizations of obliquely incident radiation. This can be exploited to resolve the ambiguity inherent in noncontact thermometry or materials analysis due to unknown specimen emissivity. In collaboration with a commercial semiconductor metrology manufacturer, we are exploring the potential of this technique.

Accomplishments

- First electrical substitution radiometer based on superconducting sensors — In 1997, we completed a standards-grade, electrical substitution radiometer for measurement of mid- and far-IR-wavelength blackbody radiation, and delivered it to the Optical Technology Division, which is responsible for optical and IR power calibration and metrology. For an extended series of experiments covering a range of substitution power from 500 picowatts to 5 microwatts, the instrument's noise floor could be approximated as 4 picowatts plus 7×10^{-6} times the measured power. We are now assisting a U.S. manufacturer of cryogenic radiometers with the incorporation of superconducting sensors into its products.

- First ac-dc thermal transfer standard based on superconducting sensors — In 1998, we completed and reported a set of preliminary experiments on ac-dc transfer using similar transition-edge bolometers. These yielded errors varying from 50 to 150×10^{-6} (for frequencies from 100 hertz to 10 kilohertz), limited chiefly by inaccuracy introduced in delivering the ac signal to the cryogenic reference plane.

- First SQUID-based multiplexer for transition-edge bolometers — In far-IR astronomical applications (both imaging and low-resolution spectroscopy), speed, and therefore sensitivity, are both limited by the number of pixels that can be read simultaneously. Present far-IR bolometer arrays are already at the practical limit for low-temperature wire count, so further improvement requires cold multiplexing. Over the last 2 years, a novel SQUID-based multiplexing scheme was conceived and demonstrated in a 1 × 8 channel prototype. It operates at pixel rates up to 1 megahertz, and has noise sufficiently low to multiplex up to about 250 channels without degrading the system noise.

- First monolithic arrays of transition-edge bolometers for space astronomy — These 1 × 8 arrays are prototypes of a new generation of detector arrays for low-background, far-infrared astronomy, and were spotlighted in a recent article in *Superconductor and Cryoelectronics* magazine. The Al-Ag or Mo-Au arrays are fabricated on micromachined Si structures that enable construction of closely packed two-dimensional arrays by folding the "legs" back out of the focal plane. The bolometers operate with a 300 millikelvin base temperature requiring ^{3}He refrigeration, and have a saturation power of about 5 picowatts and a time constant of about 2 milliseconds. Electrical NEP is phonon-noise limited at roughly 2×10^{-17} watts per root hertz, the best ever reported for an IR bolometer operating with ^{3}He refrigeration, and within a factor of six of the best reported for any other IR bolometer.

Our 300 mK infrared bolometers have the best noise equivalent power ever reported.

- A novel slot-ring antenna design for uncooled millimeter-wave bolometer arrays – Imaging applications in the terahertz spectral range require large numbers of pixels, reasonable sensitivity, and reasonable cost. One approach to achieving all three goals simultaneously is use of 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 groundplanes 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.

Our nano-MIM diodes have clearly rectified 10 µm infrared radiation.

- Uncooled antenna-coupled Metal-Insulator-Metal (MIM) junctions for IR rectification and mixing — The ultra-low capacitance, fully lithographic diodes have areas as low as 30 × 30 square nanometers and are fabricated by angled evaporation through a free-standing PMMA resist bridge defined by electron beam lithography. The diodes are coupled to planar dipole antennas designed for resonance at a wavelength of 10 micrometers. We have successfully fabricated and tested diodes from Al-AlO_x-Al, Al-AlO_x-Pd, and Nb-NbO_x-Ag materials. The nonlinear current-voltage characteristics are accurately predicted by the Brinkman-Dynes-Rowell theory of tunneling through trapezoidal barriers, both for the nano-MIMs and for separate, micrometer-sized Nb-NbO_x-Ag MIM diodes. The latter show barrier heights that can be controllably modified by in-situ Ar-ion milling following the barrier growth. The optical response of the nano-MIM diodes to CO_2 laser radiation at 10 micrometers was clearly proven to arise from classical rectification. Previous attempts to develop fully lithographic MIM diodes, on the other hand, all foundered on the difficulty of separating optical signals due to rectification from those due to thermal mechanisms. The nonlinearity observed in the large-area diodes is, according to theory, sufficient to enable observation of photon-assisted tunneling steps, a phenomenon observed at room temperature only recently in GaAs heterostructures.

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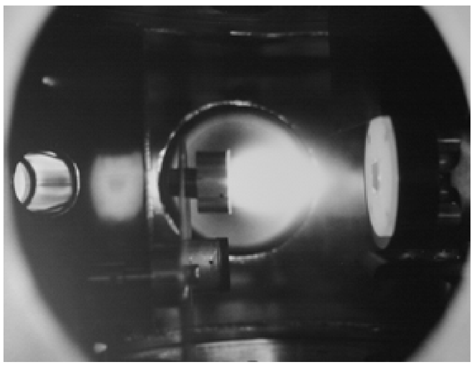
High T_c Electronics

Goals

To aid and accelerate the development of new thin-film materials and devices for electronic applications, especially high temperature superconductors (HTS), thin film oxides, and microelectromechanical systems (MEMS).



Pulsed-laser deposition chamber for oriented growth of complex oxides.

Customer Needs

We support the emerging HTS electronics industry through measurements that enable the development of HTS devices and circuits. Our customers are also those other NIST Divisions responsible for standards and measurement techniques in areas such as voltage; infrared, millimeter wave, and microwave radiation; and time and frequency standards. In addition, we support other government agencies, including the National Aeronautic and Space Administration (NASA), the Office of Naval Research (ONR), the National Security Agency (NSA) and the Defense Advanced Research Projects Agency (DARPA).

Technical Strategy

We consider three criteria when selecting research projects: importance for standards improvement and development; importance but pre-competitive in the commercial sector; and the inclusion of a strong component of innovative science and technology.

To address these criteria, we have developed fabrication processes, testing capabilities, and theoretical competence for advanced cryogenic materials and devices at rf, microwave and millimeter-wave frequencies. We use pulsed laser deposition to grow novel thin-film materials and take those materials through the device design and processing steps to final test. We have also developed techniques for fabricating micro-machined structures to aid in metrology for a number of different technological areas. We actively collaborate with U.S. and international standards laboratories that provide materials and make comparative measurements. Below we describe the efforts in the two major thrusts of our project: cryogenic microwave measurements and devices, and novel micro- and nano-scale devices.

Microwave measurements and devices

We work with the HTS communications industry to measure and improve the capabilities of HTS devices. The rapidly expanding wireless communications industry has begun to adopt HTS components in receiver front-ends. This effort is driven by the need for more efficient use of a limited spectrum in the face of an increasing amount of interference and signal from other providers. The introduction of third- and fourth-generation technology for the wireless Internet has created a new market for improved passive and active devices. Our work is aimed at addressing some of the unresolved issues in HTS devices that affect their ultimate performance. In particular, the nonlinear response of HTS-based microwave devices is not well understood and is a serious problem for communications applications.

We will perform measurements of the microwave-frequency nonlinear signal generation in commercially produced HTS materials for the purpose of determining the source of the nonlinear response in HTS devices.

We will transfer low-frequency measurement techniques for screening unpatterned films for nonlinear response to HTS communication industry partners.

We collaborate with the Radio-Frequency Technology Division to improve both linear and nonlinear microwave measurement and characterization techniques for thin-film materials and devices, particularly at cryogenic temperatures. We also investigate new materials and device structures for achieving low-loss electronically tunable microwave circuits.

We will develop superconducting devices to be used as model nonlinear elements for detailed evaluation using a Nonlinear Network Measurement System in collaboration with the Nonlinear Device Characterization Project in the Radio-Frequency Technology Division.

Technical Contact:
James Booth

Staff-Years (FY 2001):
5 NIST staff
.25 Other staff

The rapidly expanding wireless communications industry has begun to adopt HTS components in receiver front-ends.

We have implemented a cryogenic microwave probe station for broadband (dc to 40 GHz) characterization of temperature-dependent microwave properties.

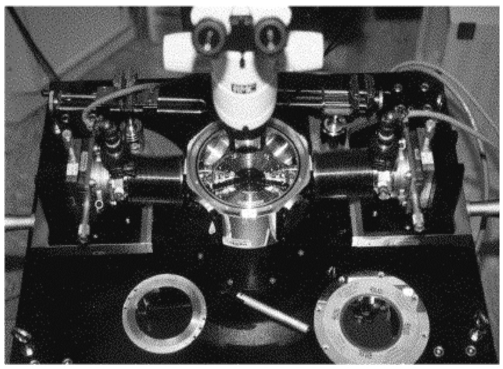
We will improve methods for measuring the broadband permittivity of ferroelectric thin films as a function of temperature and bias voltage.

"Dr. Beall [of the High Tc Electronics Project] has generously helped us with technical advice and processing assistance which in turn has had a significant impact on advancing our prototypes. We hope our relationship with NIST will continue."

- Astralux, Inc., Boulder, CO

We are participating in developing a new standard for measuring the surface resistance R_S of ultra-low-loss superconducting thin films. This is under the auspices of the International Electrotechnical Commission (IEC) and the Versailles Agreement on Advanced Materials and Standards (VAMAS).

We will continue development and improvements in our implementation of the proposed international standard technique for measuring surface resistance at microwave frequencies.



Cryogenic microwave probe station.

Micromachining and MEMS

MEMS and nanoelectromechanical systems (NEMS) are the enabling technology for entire new generations of electronic systems. Novel sensor and metrology technologies benefit from the ability to use integrated-circuit fabrication paradigms in constructing mechanical devices. Our work in this area also includes measurement techniques for evaluation of novel MEMS structures at rf and microwave frequencies.

MEMS and nano-electromechanical systems (NEMS) are the enabling technology for entire new generations of electronic systems.

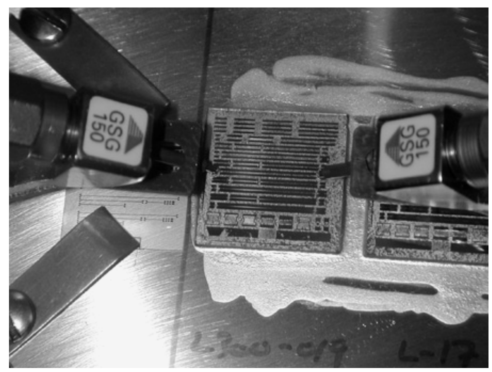
We will continue research efforts in support of the Time and Frequency Division while developing new processes and applications.

We will develop new measurement techniques for characterizing MEMS elements at cryogenic temperatures.

Accomplishments

Microwave measurements and devices

■ Loss and nonlinearity limit the utility of HTS and tunable-dielectric-based components in communications applications. Superconductivity can significantly improve the sharp band edges of filters, reduce insertion loss in most passive components, and eliminate dispersion in transmission lines. HTS materials have been improved to the point that they rival their low-temperature counterparts in surface resistance, R_S; however, power handling and nonlinearity are not yet fully understood or controlled in the manufacturing environment. In contrast, tunable dielectric thin-film materials, which offer the promise of electronic tuning of microwave circuit elements on nanosecond time scales, suffer from excessive loss at microwave frequencies, the origin of which loss is unknown. Our measurements are performed with a unique cryogenic microwave probe station to enable precise characterization of patterned devices. The project has achieved significant technical progress in several areas of study related to microwave measurements and devices implementing HTS materials, tunable dielectric materials, and MEMS structures.



View of two 40 GHz probes and a sample of YBCO devices in the probe station.

■ Intercomparison of nonlinearity – Using the measurement techniques we have developed in collaboration with the Naval Research Laboratory (NRL), we have conducted a study of nonlinearity using four measurement techniques. We have shown that there is a distributed source of geometry-independent nonlinearity that is clearly associated with a current-dependent penetration depth. These measurements span frequencies from 2 kHz to 18 GHz. In addition, the results obtained using our measurement techniques compare well with results obtained from Passive InterModulation (PIM) measurements and Nonlinear Network Measurement System (NNMS) measurements for the same superconducting device, made in collaboration with the Nonlinear Device Characterization Project in the RF Technologies Division. We are now beginning to study devices made from films produced by HTS filter companies, with the goal of comparing our measurements to the performance of the filters made from identical thin films.

■ Nonlinear phase measurements – We have succeeded in measuring for the first time the phase of the nonlinear signal generated by HTS devices at microwave frequencies, also in collaboration with the Nonlinear Device Characterization Project in the Radio-Frequency Technology Division. The value of the phase of the nonlinear signal provides important information on the origin of the nonlinear response in HTS materials. In addition, a superconducting device could be used to calibrate the relative phase of higher harmonics in a nonlinear measurement system. We are currently developing improved circuits with the goal of more accurate nonlinear phase measurements of HTS-based devices.

■ Microwave signal limiter developed – It is possible to build extremely sensitive digital circuits using low-temperature superconducting (LTS) Josephson junction technology. However, such circuits can be vulnerable to transient over-power conditions such as lightening strikes or unintended radar illumination. We have designed, fabricated and tested an HTS microwave signal limiter for the purpose of protecting an ultra-sensitive LTS analog-to-digital converter from such over-power conditions. The device makes use of the microwave current-induced transition from the very low-loss superconducting state to the high-loss normal state, and has been shown to have extremely wide bandwidth (> 40 GHz). Reversible operation has been demonstrated at microwave powers up to 10 watts, and switching speeds for transitions between the limiting and non-limiting states have been measured to be on the order of microseconds. Improved designs and further testing for the signal limiter are currently underway.

■ Measurements of dynamic effects in frequency-dependent permittivity of tunable dielectric thin films – Recent measurements in our project of ferroelectric thin films have revealed large relaxation effects at high microwave frequencies that have not been previously observed. Ferroelectric thin films are potentially valuable because they possess a dielectric permittivity that can be modified by the application of a relatively modest bias voltage. Such a tunable dielectric material would enable very fast tuning of microwave elements such as filters, and would also enable cheaper phased-array antennas. Our measurements have revealed that the high microwave losses that to date have limited the application of ferroelectric thin films are at least in part due to coupling of energy into lattice modes of these materials. We are aggressively pursuing ways to engineer the lattice dynamics in these materials in order to optimize their performance at microwave frequencies.

■ Comparison of tuning and nonlinear response in tunable dielectric thin films – A major issue in the application of tunable dielectric thin films for microwave elements is the response times over which one can vary the permittivity using an applied bias field. We have performed nonlinear harmonic generation measurements as a way of deducing switching times for these materials on the nanosecond scale. By comparing the tuning due to the rf field within the device derived from such harmonic-generation measurements with the tuning induced by a dc bias field, we have been able to show that tuning in these materials is possible on nanosecond time scales or faster. Further nonlinear measurements are being pursued in order to determine tuning times for different materials and also as a way of assessing the detrimental nonlinear properties that might arise in a tunable application.

■ Measurements of MEMS structures at cryogenic temperatures – We have modified our cryogenic microwave probe station to allow for the application of large bias voltages in order to enable measurements of MEMS structures at cryogenic temperatures. So far, several sets of devices, designed and fabricated by the Electrical Engineering Department of the University of Colorado, have been tested at both room temperature and cryogenic temperatures. These initial measurements indicate that the MEMS structures will function at cryogenic temperatures, which will allow for ultra-low-loss MEMS and combination MEMS/superconductor structures to be designed and evaluated.

■ International draft standard for surface resistance – A draft standard for surface resistance R_S using dielectric resonators has been written, and round-robin testing in Japan has begun. We have completed the first set of comparative measurements in our laboratory. Good agreement was observed for values of the superconductor R_S and the sapphire loss tangent in the initial temperature-dependent measurements, and further improvements to the measurement apparatus are underway.

Micromachining and MEMS

We use our new MEMS facilities to fabricate novel structures that enable new measurements and devices in a number of different areas.

We have developed a model system to investigate different HTS structures for nonlinear microwave response, and can test a variety of thin films, fabrication processes, and structure dimensions to achieve improved performance.

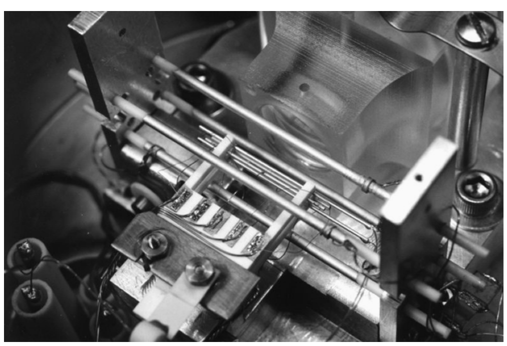
"Working with Jim [Beall, of the High T_c Electronics Project] has been a great help to us. We have benefited in particular from Jim's experience with silicon device fabrication."

-Precision Photonics Corp.

Quantum entanglement of four ions has been demonstrated in a micromachined ion trap.

■ Micromachined structures for ion traps – We have made micromachined structures for use in ion traps, in collaboration with the Physics Laboratory's Time and Frequency Division. They have recently demonstrated quantum entanglement with four ions in one of these traps. Recent traps made with improved surfaces have had much smaller anomalous heating, leading to improved ion-storage times. We are proceeding with development of ion traps fabricated from silicon electrodes, which should have even higher quality.

■ MEMS facility – The new facility for furnace processing of silicon is in routine use by several projects. We have developed improved cantilevers for magnetometers in collaboration with the Magnetic Technology Division. We are presently exploring collaborations to work on MEMS and NEMS devices for new metrological instruments, both internally with the Chemical Sciences and Technology Laboratory (CSTL) and externally with local companies. We have recently added a XeF_2 gas-phase silicon isotropic etch system that allows rapid dry etching of silicon. This is useful for releasing membranes and other delicate structures. This process was used for development of a silicon nitride pop-up-detector structure and a surface-micromachined thermal-isolation platform structure, both of which have applications in detector array technologies.



Cryogenic linear quadrapole Hg ion trap used for atomic frequency standard experiments.

Collaborations

■ We held the first NIST-Boulder MEMS Working Group meeting in December 2000, which was attended by NIST personnel from several laboratories as well as members of the local university and industrial MEMS community. This was an opportunity for researchers across the community to meet become aware of activities in the area.

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Nanoscale Fabrication

Our facilities for fabricating integrated circuits are essential to nearly all of the work in the Division. We maintain a research-class facility for superconductor and MEMS structures. Beginning with computer-aided design, we use electron-beam and optical lithography to make structures smaller than 100 nm and complex circuits containing as many as 32,000 Josephson junctions. Our tools are housed in 200 m^2 of “class 100” cleanroom space, which was improved greatly in 1999. We also added tools for fabricating MEMS that in the past have been essential for many of our ultra-sensitive instruments, and for micromachined ion traps for future clocks. We are applying these techniques to novel magnetic instruments and photon detectors.

Maggie Crews (left), Jim Beall and Jay Koch in the lithography bay of the cleanroom.

Our near state-of-the-art facilities are open-shop. All of our staff, and occasional visitors, can personally use them after appropriate training. To avoid constraining research activities to fixed design rules and to allow maximum creativity our processes are flexible. Our past accomplishments are testimony to the success of our approach.

Computer-controlled research tube furnaces for growth of SiO_2, Si_3N_4, and other CVD materials.

For patterning at the 1 µm scale, we use optical lithography in an I-line stepper and a deep-UV contact aligner. Electron-beam lithography enables patterning at less than 100 nm. Our facilities support fabrication of superconductor integrated circuits and MEMS fabrication, as well as laser ablation of thin films of high-temperature superconductors. We recently installed a set of tube furnace reactors (5" capable), shown above, for wet and dry silicon oxidation, solid-source diffusion of boron, low-stress silicon nitride/polysilicon low-pressure chemical vapor deposition (LPCVD), and LPCVD of low-temperature oxide.

In the past year we have upgraded our optical pattern generator to a modern instrument capable of making masks with feature sizes of 1.5 micrometers. Having an in-house mask-making facility allows very rapid turnaround, which improves productivity and encourages creativity. Our capability in electron beam lithography has been expanded with the addition of a second scanning electron microscope with wafer-scale stages and load lock. We have added a silicon dry-etch tool that uses xenon difluoride gas to isotropically etch silicon without liquids. We have completed procurement of two new sputter-deposition tools that will allow contamination-free systems for depositions of SNS junctions and superconducting bilayers. We are also in the procurement phase for a deep silicon reactive ion etch system.

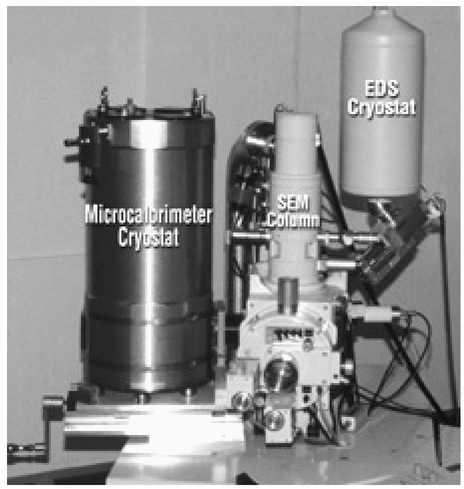
Appendix A:

Experimental Systems and Instruments

A partial list of our measurement facilities and capabilities follows:

Experimental environments include a dilution refrigerator (DR) for temperatures down to 30 mK and adiabatic demagnetization refrigerators (ADR) for cooling to 50 mK. The DR cools the capacitance standard to less than 50 mK and has special filtering to provide a noise-free environment for the standard. See the Nanoscale Cryoelectronics Project section of this publication for more information on the capacitance standard based on counting electrons.

Mark Keller (left) and John Martinis with the dilution refrigerator used for the capacitance standard based on counting electrons.



The microcalorimeter system connected to an SEM for x-ray analysis.

Measurement systems include: high-speed electrical test facilities, an atomic-force microscope, a scanning electron microscope (SEM), high-resolution X-ray materials analysis, X-ray structural analysis, a high-resolution mass spectrometer with electrospray source, variable-temperature microwave probe station, Josephson voltage standards, and tools for characterizating microwave loss in thin films and detailed properties of infrared antennas. The figure on the above right is a photograph of an ADR with an x-ray microcalorimeter spectrometer attached to a commercial SEM.

Appendix B:

Postdoctoral Opportunities

NIST offers postdoctoral associateships in collaboration with the National Research Council (NRC). Research topics and associated advisors for the Electromagnetic Technology Division are listed below. Please see our Web site at http://emtech.boulder.nist.gov for full details on each opportunity. Contact a prospective adviser to discuss details of proposed work and the application process. If you do not find a topic that exactly matches your interest, please contact an advisor in a similar discipline. U.S. citizenship is required for postdoctoral appointments.

Research Topic	Advisor(s)
Superconducting and Nanometer-Scale Devices for Infrared to Millimeter Wave Applications	Erich Grossman
Applications of Superconducting Integrated Circuits and Josephson Junction Arrays	Sam Benz
Functional Materials and Systems for RF/Microwave/mm-Wave Electronics	James Booth
Linear and Nonlinear Microwave Response of Oxide Thin Films and Devices	James Booth
High-T_c Superconductors: Devices, Device Physics, and Circuits	James Booth
Micromachined Materials and Devices for Metrological Applications	James Booth James Beall Richard Harris
Physics and Applications of Single Electron Tunneling Devices	Mark Keller
A Capacitance Standard Based on Counting Electrons	Mark Keller
Characterization of Single-Photon Turnstiles Using Single-Electron Tunneling Devices	Mark Keller
Superconducting Detectors for Photons from the Infrared through X Rays	Kent Irwin John Martinis
High-Resolution Microcalorimeters for X-Ray Microanalysis	Gene Hilton John Martinis David Rudman
Quantum Computing using Superconducting Devices	John Martinis

Appendix C:

Awards and Recognition

***Notes:** * indicates a coworker from outside the Electromagnetic Technology Division*
Medal awards are from the U.S. Department of Commerce

Award	Recipient	Date	Notes
William A. Wildhack Award	Robert A. Kamper	October, 1972	National Conference of Standards Laboratories
Arnold O. Beckman Award (ISA)	Robert A. Kamper	1974	Instrument Society of America, no citation
Gold Medal	James E. Zimmerman and Robert A. Kamper	October, 1975	For innovative contributions to practical precise measurements using superconducting quantum interference devices (SQUIDs)
Industrial Research -100 Award	Clark A. Hamilton, Robert J. Phelan*, Gordon W. Day*, John Geist*, and B. McIntosh*	1975	
NIST Condon Award	Robert A. Kamper	November, 1977	For distinguished achievement in written exposition.
NBS Stratton Award	James E. Zimmerman	1979	
Silver Medal	Clark A. Hamilton, Richard E. Harris, Frances L. Lloyd, and Robert L. Peterson	November, 1980	For creative advancement of the state of the art in ultra-high-speed analog-to-digital conversion.
NIST Condon Award	Donald G. McDonald	December, 1981	For distinguished achievement in written exposition.
Silver Medal	Michael. W. Cromar		
Silver Medal	Richard L. Kautz	1983	For fundamental contributions to the understanding of chaotic behavior in Josephson junction devices.
Gold Medal	Clark A. Hamilton	1983	For outstanding contributions to the development of ultra-high-speed Josephson junction microcircuit technology.
NBS Fellow	James E. Zimmerman	1984	
EEEL Outstanding Paper Award	Richard L. Kautz	1985	"Chaos and Thermal Noise in the rf-Biased Josephson Junction," *Journal of Applied Physics*, Volume 58, Number 1 (1 July 1985).
NIST Stratton Award	Richard L. Kautz and Donald B. Sullivan	December, 1985	For exceptional accomplishments that established the feasibility of a fundamental improvement in the Josephson voltage standard.
Research and Development Magazine Industrial Research -100 Award	Clark A. Hamilton, Richard L. Kautz and Frances L. Lloyd	1986	For development of Josephson series array voltage standards.
NBS Fellow	Clark A. Hamilton	1987	

NIST Gold Medal	Clark A. Hamilton, Richard L. Kautz, Frances L. Lloyd, James A. Beall	October, 1989	For developing the first practical Josephson-junction series array voltage standards, at both 1 V and 10 V levels, including the U.S. primary standard.
IEEE Fellowship	Robert A. Kamper	1989	For leadership and technical contributions to the application of superconductivity in instrumentation, measurement, and standards.
EEEL Outstanding Paper Award	Samuel P. Benz and Charles J. Burroughs	1991	"Coherent Emission from Two-Dimensional Josephson Junction Arrays," *Appl. Phys. Lett.* 58(19): 2162-2164, May 1991
NIST Gold Medal	High Temperature Superconducting Electronics Team: James A. Beall, Todd E. Harvey, Ronald H. Ono, David A. Rudman, etc	October, 1993	For the world's best Josephson junction and associated practical technology to put the U.S. in the lead for superconducting electronics
Department of Commerce Silver Medal	Robert A. Kamper	1993	For leadership of NIST's Boulder Laboratories and for excellent negotiating skills in facilities development.
Harry Diamond Memorial Award (IEEE)	Robert A. Kamper	1993	For pioneering the application of superconducting quantum mechanical principles to metrology, directing development of advanced Cryoelectronics devices, and guiding a metrology program supporting the lightwave industry.
EEEL Outstanding Paper Award	John M. Martinis, Michael Nahum, and Hans Dalsgaard Jensen	1994	"Metrological Accuracy of the Electron Pump," *Physical Review Letters*, Volume 72, Number 6, pp. 904-907 (7 February 1994)]
EEEL Outstanding Paper Award	Mark W. Keller, John M. Martinis, Neil M. Zimmerman, and Andrew H. Steinbach	1996	"Accuracy of Electron Counting Using a 7-Junction Electron Pump," *Applied Physics Letters*, Volume 69, Number 12, pp 1804-1806, 16 September 1996].
NIST Stratton Award	John M. Martinis	December, 1996	For applying new insights into quantum phenomena to establish the fundamental accuracy of Coulomb-blockage circuits for single-electron counting
Silver Medal	John Martinis	December, 1996	For establishing the fundamental accuracy of Coulomb-blockade circuits for single-electron counting, providing the basis for new intrinsic standards
EEEL Measurement Services Award	Clark A. Hamilton	February, 1995	
EEEL Outstanding Authorship Award	Mark W. Keller, John M. Martinis, Neil Zimmerman, and Andrew H. Steinbach	February, 1997	"Accuracy of electron counting using a 7-junction electron pump," *Appl. Phys. Lett.* 69(12), 1804-1806, 16 September 1996.
Allen V. Astin Award (National Conference of Standards Laboratories)	Samuel P. Benz, Clark A. Hamilton, Charles J. Burroughs, Todd Harvey, and Lawrence Christian	1997	Josephson Standards for AC Voltage Metrology
Fellow of American Physical Society, Condensed Matter Physics	John M. Martinis	November, 1997	For his experimental investigations into the fundamental quantum behavior of low-temperature electronic devices

NIST Condon Award	Richard L. Kautz	December, 1997	For his extensive review of the physics of the dc series array voltage standard in the paper "Noise, chaos, and the Josephson voltage standard," which appeared in *Reports on Progress in Physics*, vol. 59, pp. 935-992, Aug 1996.
Fellow of the American Physical Society, Precision Measurements and Fundamental Constants	Richard L. Kautz	1998	For experimental and theoretical investigations of Josephson junctions, particularly the nonlinear dynamics of phase locking and chaos, essential to the development of practical series-array voltage standards.
Fellow of the American Physical Society, Precision Measurements and Fundamental Constants	Donald G. McDonald		
EEEL Outstanding Authorship Award	David A. Wollman, Kent D. Irwin, Gene C. Hilton, Laura L. Dulcie, Dale E. Newbury, and John M. Martinis	1998	"High-Resolution, Energy-Dispersive Microcalorimeter Spectrometer for X-Ray Microanalysis," *Journal of Microscopy*, Volume 188, Pat 3, pp. 196-223, December 1997
NIST Applied Research Award	Gene C. Hilton, Kent D. Irwin, John M. Martinis, and David A. Wollman	December, 1998	For inventing an x-ray detector, demonstrating its potential to revolutionize x-ray microanalysis and developing it to the point of commercialization
Gold Medal	Gene C. Hilton, Kent D. Irwin, John M. Martinis, and David A. Wollman	December, 1998	For inventing a new x-ray detector, showing its potential to revolutionize x-ray microanalysis, and bringing it to the point of commercialization.
EEEL Outstanding Authorship Award	Mark W. Keller, Ali L. Eichenberger, John M. Martinis, and Neil M. Zimmerman	1999	"A Capacitance Standard Based on Counting Electrons," *Science*, Vol. 285, 10 September 1999, pp 1706-1709
Presidential Early Career Award for Scientists and Engineers	Mark W. Keller	October, 2000	
NIST Condon Award	Mark W. Keller, John M. Martinis, Ali Eichenberger, Neil Zimmerman	November, 2000	For distinguished achievement in written exposition.
William H. Wildhack Award	Clark Hamilton	October, 2001	National Conference of Standards Laboratories
Symbols, Units, Nomenclature, Atomic Masses and Fundamental Physical Constants (SUNAMCO) Award	Clark Hamilton	2001	International Union of Pure and Applied Physics (IUPAP)

Appendix D:

Electromagnetic Technology Division Staff

(December 2001)

Division Office

3776 Harris, Richard E. (Chief)
3678 Metz, Sara E. (Division Secretary)
3812 Schump, Jeanne (Admin. Officer)
3988 McCarthy, Sandy (Secretary)
5068 Copeland, Jill (Secretary)

Josephson Array Technology

5258 Benz, Sam (PL)
3906 Burroughs, Charlie
5211 Dresselhaus, Paul
3740 Hamilton, Clark (GR)
4218 Rogalla, Horst (GR)

Nanoscale Cryoelectronics

5081 Rudman, David (PL)
4137 Aumentado, Jose (PD)
5344 Bergren, Norm
4153 Beyer, Joern (GR)
4320 de Korte, Piet (GR)
3461 Deiker, Steven (PREP)
4280 Halford, Forrest (PREP)
5679 Hilton, Gene
3402 Huber, Martin (IPA)
5911 Irwin, Kent
3391 Kautz, Richard (GR)
5430 Keller, Mark
3597 Martinis, John
4212 Miller, Aaron (PD)
3148 Nam, Sae Woo
4325 Osborn, Kevin (PREP)
4319 Ruggiero, Steve (IPA)
5121 Vale, Leila
7457 Wollman, David
7894 Xu, Yizi (Ctr)

Terahertz Technology

5102 Grossman, Erich (PL)
3114 Bhupathiraju, Ashok (IPA)
4199 Gerecht, Eyal (IPA)
5052 Reintsema, Carl
4318 Salminen, Arto (GR)

High T_c Electronics

5989 Beall, Jim
7900 Booth, Jim
5049 Crews, Maggie
7064 Koch, Jay
5113 McDonald, Don (GR)
7213 Schima, Susan

Division website: http://emtech.boulder.nist.gov/

Email addresses for all staff are: firstname.lastname@boulder.nist.gov

Telephone numbers are: (303) 497-XXXX (the four-digit extension as indicated).

Legend:
Ctr = Contractor
GR = Guest Researcher
IPA = Interagency Personnel Agreement
PD = Postdoctoral Appt.
PL = Project Leader
PREP = Professional Research Experience Prog.
PHASE = Practical Hands-on Application to Science Education