NIST

National Institute of
Standards and Technology
Technology Administration
U.S. Department of Commerce

NISTIR 6601
January 2001

Electronics and Electrical Engineering Laboratory

Electromagnetic Technology Division

Programs, Activities, and Accomplishments

NIST CENTENNIAL 1901-2001

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 five programmatic divisions, two matrix-managed offices, and a special unit concerned with magnetic metrology:

- Electricity Division
- Semiconductor Electronics Division
- Radio Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Office of Microelectronic Programs
- Office of Law Enforcement Standards
- Magnetics Group

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

The cover illustrates the variety of work in the Electromagnetic Technology Division. Integrated circuit fabrication underlies all the work of the Division and the large background photograph shows one of our staff members making a circuit in our nanoscale fabrication facility. The left-most micrograph shows a lithographed antenna coupled to a nanometer-sized diode for rectifying visible light. The cellular phone may be receiving a call which passes through a base station which uses high temperature superconductor filters. The complex chip is a Josephson series array ac voltage standard.

Electronics and Electrical Engineering Laboratory

Electromagnetic Technology Division

Programs, Activities, and Accomplishments

NISTIR 6601

January 2001

U.S. DEPARTMENT OF COMMERCE
Norman Y. Mineta, Secretary

Technology Administration
Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Karen H. Brown, Acting Director

Contents

Welcome iv

Josephson Array Technology 1

Nanoscale Cryoelectronics 7

High Performance Sensors, Infrared Detectors, and Mixers 15

High T_c Electronics 19

Nanoscale Fabrication 24

Appendix A: Experimental Systems and Instruments 25

Appendix B: Postdoctoral Opportunities 26

Appendix C: Awards and Recognition...27

Appendix D: Division Staff...30

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 –452 ºF (0 K). This book 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. This year, NIST's director, Ray Kammer, dedicated improved clean room 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, 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.

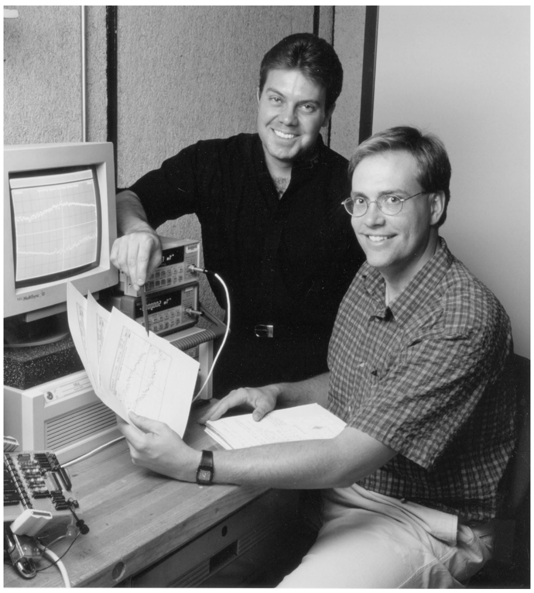
Richard E. Harris
Division Chief

Electromagnetic Technology Division
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80305-3328
(303) 497-3678
http://emtech.boulder.nist.gov

Josephson Array Technology

Project Goal

To develop superconductive electronic circuit and system technology for fundamental, quantum-based dc and ac voltage standard systems; to provide improved standards for fundamental metrology, and support U.S. industry test and measurement applications.



Charlie Burroughs and Sam Benz discuss the operating margins of a pulse-driven Josephson-junction array.

Customer Needs

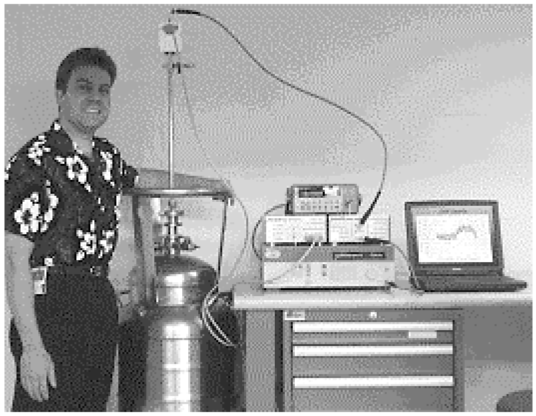
The demands of modern technology for accurate voltage calibrations have gradually exceeded the capability of classical artifact standards. To meet current needs, an international agreement signed in 1990 redefined the practical volt in terms of the voltage generated by a superconductive integrated circuit 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. In contrast to artifact standards in which the value depends upon environmental and physical factors, the voltage developed by each junction depends on frequency and fundamental constants. Thus, a Josephson array circuit never needs to be calibrated. This allows any standards or commercial laboratory to generate highly accurate voltages without the need to transfer 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, and 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 removing 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 and consulting.

Technical Contact:
Samuel P. Benz
benz@boulder.nist.gov

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

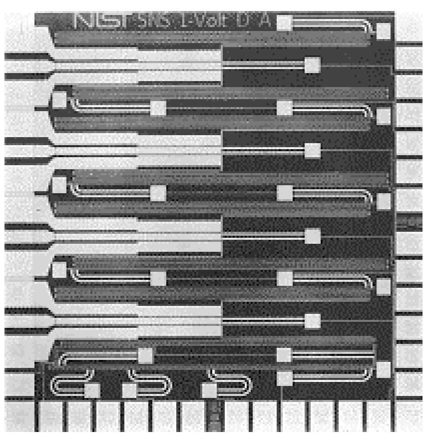


Charlie Burroughs with 1 V programmable voltage standard system consisting of (left to right) low thermal probe, microwave and high speed bias electronics, and computer control.

Technical Strategy

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. This technology has recently been transferred directly to the private sector.

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



A 1 cm × 1 cm superconductive integrated circuit with 32,768 SNS Josephson junctions for the 1 V programmable voltage standard.

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

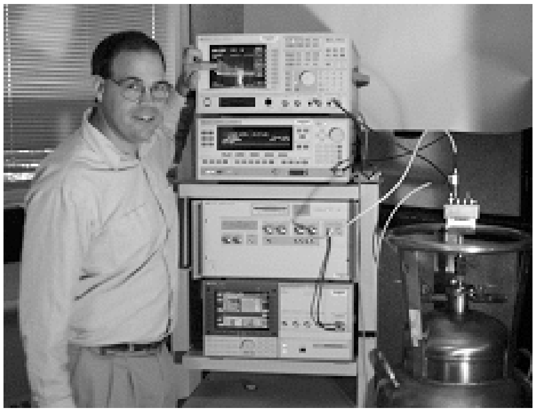
Over the past few years, we have developed a novel superconductor-normal metal-superconductor (SNS) junction technology that adds the features of stability and programmability to the accuracy of conventional Josephson voltage standards. Programmable Josephson voltage standard systems based on these junctions have been delivered 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.

The NIST Electricity Division is interested in improving the internal efficiency of its maintenance and dissemination of NIST-traceable voltage through the development and deployment of an improved 1 V programmable voltage standard. We will work with Electricity Division staff to develop a Josephson voltage standard that can be used more directly in the customer's calibration system.

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

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 standards are detectors based on 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 accurate arbitrary waveform generator would also be useful for calibration of other scientific instruments, such as ac voltmeters, 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 voltage waveform generator with quantum-mechanical accuracy has enabled the possibility of making an electronically 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, we have been awarded a competence grant to develop this new quantum-based electrical thermometer.

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

Accomplishments

- First operating margins and record voltage — We have demonstrated operating margins and a record 127 mV peak-to-peak (pp) voltage for ac waveforms with the Josephson arbitrary waveform synthesizer. This device is capable of digitally synthesizing any waveform from dc to 100 MHz. We also measured record low harmonic distortion, demonstrating the importance of perfect quantization from superconducting Josephson junctions. We measured –95 dBc distortion for a 2.8 kHz sine wave and less than –80 dBc intermodulation at 5 MHz. The improvement in operating margins (previously zero for ac waveforms) and output voltage (previously 52 mV pp) are a result of improved broadband on-chip filters and a larger array of 4,096 Josephson junctions.

- First ac metrology measurements — Improved operating margins and a new circuit design have enabled us to perform the first ac metrology measurements of the Josephson arbitrary waveform synthesizer. Comparisons were made between ac and dc voltages synthesized by the Josephson synthesizer. New circuits utilizing lumped arrays of 250 junctions with on-chip filtering and a grounded circuit design enabled direct connection of the array output voltage to a thermal transfer standard. Direct connection to measurement instrumentation is required for optimum performance in calibrations because it avoids gain and distortion errors that can be induced by intermediate amplifiers. From the ac-to-dc comparisons we concluded that the repeatability of the ac voltages is good and that thermal voltages are not a significant source of error. We also concluded that we have precise control of synthesized rms voltages and their harmonic content.

- New coupling method promises higher voltages — We have developed a new ac-coupled input technique that allows us to use large distributed arrays of more than 4,000 junctions and simultaneously maintain the directly coupled output that is necessary for metrological measurements. The larger distributed arrays have larger output voltage as compared to the previously used lumped arrays with only 250 junctions. Larger voltages (127 mV pp) can now be used for both precise arbitrary waveform synthesis with low harmonic distortion as well as for precise rms voltage synthesis for ac metrology. The larger voltage has enabled 10 times

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

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

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

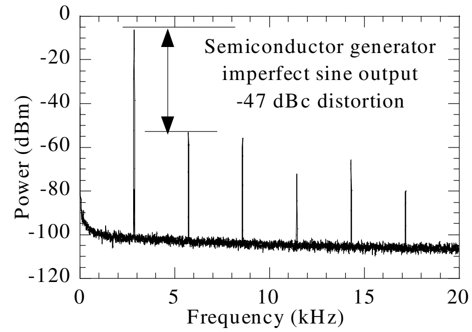
lower uncertainty for ac-to-ac comparisons as compared to previous measurements using lumped arrays. This technique also has the potential for significantly higher output voltage by enabling multiple arrays to be connected in series.

- Titanium nitride junctions — Junctions with titanium nitride barriers are being developed for use in lumped arrays. Lumped arrays, in which a large number of junctions are spaced within a very short distance, are necessary for increasing the output voltage of the ac voltage source as well as its range of output frequencies. TiN was chosen to replace PdAu as the junction barrier because it allows us to stack multiple junctions on top of each other with very close spacing of a few hundred nanometers. We have successfully fabricated our first junctions using TiN as a barrier material.

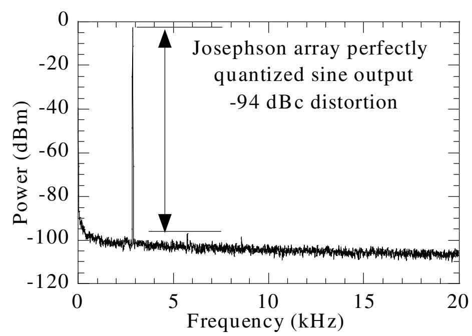
Collaborations

- We are collaborating with Blaise Jeanneret of OFMET, Switzerland. We have delivered a 1 V chip and a cryoprobe with low-thermal voltages for their programmable voltage standard system. The system is being used in OFMET's novel watt balance experiment. To test the system's functionality, a comparison was made between their conventional Josephson voltage standard and our programmable circuit. The two systems agreed to 0.5 parts in 10^9 with an uncertainty of 1 part in 10^9.

- We are collaborating with Gerard Geneves of LCIE, France. We have delivered a complete NIST-developed programmable-voltage standard system, which they will use as one corner of a quantum-based metrology triangle experiment comparing resistance, current and voltage.



Digitally synthesized 2.86 kHz sine wave from a semiconductor generator showing harmonic distortion at 47 dB below the fundamental frequency. High harmonic distortion indicates an imperfectly synthesized waveform.



Synthesized 2.86 kHz sine wave from a 4,096 junction array. The undesired harmonics are reduced to 94 dB below the fundamental frequency because of perfect quantization by the superconducting Josephson junctions.

- We have begun a collaboration 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 Mark Blamire at the University of Cambridge, England, on the development of nanoscale junction fabrication techniques for lumped arrays. Superconductive integrated circuits have been exchanged for fabrication and testing. Constant voltage steps were demonstrated in arrays of 10 bilayer Nb-PdAu SNS junctions where the 50 nm long junctions were defined by focused ion-beam etching.

- We are collaborating with researchers at Japan's Electrotechnical Laboratory (ETL) to develop cryo-cooler-compatible Josephson junctions for programmable voltage standards. Using NIST designed circuits and masks, ETL has fabricated uniform arrays of 4096 NbN-TiN-NbN junctions. Next year, effort will be focused on implementing NbN wiring, increasing the circuit yield, and demonstrating operation at 10 K.

- We are collaborating with Northrop Grumman, Inc. 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 the output signals are at radar frequencies. We have demonstrated multiple-tone waveforms at megahertz frequencies and designed and fabricated SNS junction circuits using designs from Northrop Grumman.

Recent Publications

S.P. Benz, P.D. Dresselhaus, and C.J. Burroughs, "Nanotechnology for next generation Josephson voltage standards," Proceedings of the Symposium on Microtechnology in Metrology and Metrology in Microsystems, 31 August-1 September 2000, Delft University of Technology, Delft, The Netherlands, pp. 127-132.

S.P. Benz, C.J. Burroughs, and P.D. Dresselhaus, "Low harmonic distortion in a Josephson arbitrary waveform synthesizer," Applied Physics Letters Vol. 77, No. 7, pp. 1014-1016 (14 August 2000).

C.A. Hamilton, "Josephson voltage standards- a review," 2000 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 14-19 May 2000, Sydney, Australia, pp. 335-336.

S.P. Benz, L.A. Christian, C.J. Burroughs, and C.A. Hamilton, "DC voltage synthesis using a pulse-quantized Josephson voltage source," 2000 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 14-19 May 2000, Sydney, Australia, pp. 339-340.

C.J. Burroughs, S.P. Benz, T.E. Harvey, and H. Sasaki, "1 volt Josephson fast reversed DC source," 2000 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 14-19 May 2000, Sydney, Australia, pp. 341-342.

B. Jeanneret, A. Rüfenacht and C.J. Burroughs, "Comparison between the SNS and SIS Josephson voltage standards at OFMET," 2000 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 14-19 May 2000, Sydney, Australia, pp. 389-390.

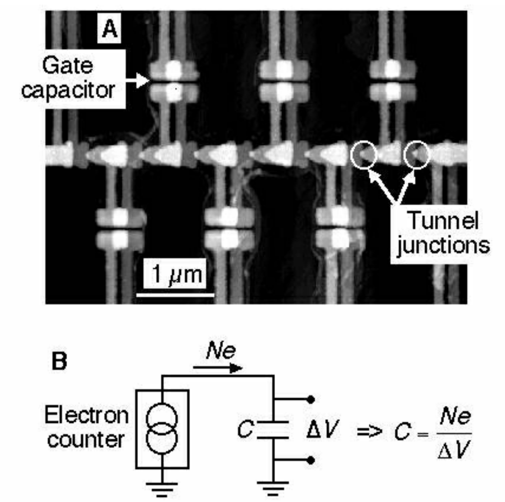
R.H. Ono and S.P. Benz, "Optimum characteristics of high temperature Josephson junctions for "lumped" array applications," in Proceedings of the 7th International Superconductive Electronics Conference (ISEC'99), 21-25 June 1999, Berkeley, pp. 301-303.

S.P. Benz, C.A. Hamilton, and C.J. Burroughs, "Operating margins for a superconducting voltage waveform synthesizer," in Proceedings of the 7th International Superconductive Electronics Conference (ISEC'99), 21-25 June 1999, Berkeley, pp. 115-117.

Nanoscale Cryoelectronics

Project Goal

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 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, and for mass spectrometry of large molecules.

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.

Technical Contact:
David A. Rudman
rudman@boulder.nist.gov

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

We will continue to develop theoretical models for the effect of noise on SET devices and test specific predictions for the performance of electron pumps in the presence of such noise.

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.

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 capacitance standard in a transportable dilution refrigerator. We will confirm its operation and take it to Gaithersburg for comparison against 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, which will pump much faster than the conventional version used thus far for the capacitance standard.

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

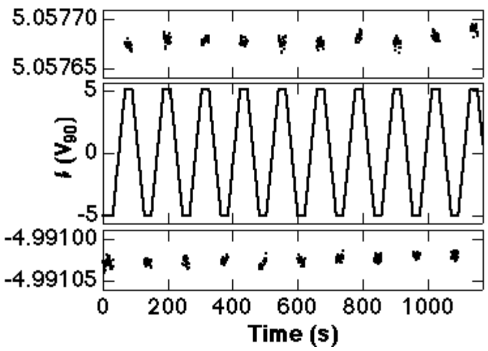
SET devices can also be used as tools to measure the performance of other devices that operate with individual electrons. Under a new NIST-funded program, work has begun on creating a new class of electronic devices designed to produce single photons on demand. These devices will be based on quantum 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.

In collaboration with the Optoelectronics and Semiconductor Electronics Divisions, 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. The likely source of the photons is fluctuating background charges in the substrate or in the pump itself, which produces 1/f noise even at the very high frequencies (GHz) needed to affect pump performance.

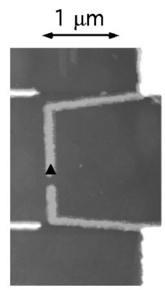
- A prototype of a capacitance standard based on counting electrons has now been demonstrated. The components of the standard are an electron counter, a capacitor, and an electrometer to monitor the process. The electron counter is based on seven nanometer-scale tunnel junctions in series. It can "pump" electrons onto the capacitor with an error rate 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, operates at cryogenic temperatures and uses vacuum as the dielectric, resulting in a frequency-independent capacitance.



Demonstration of pumping electrons on 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 (shown in expanded view above). The result is a value of capacitance with a repeatability of one part in 10^7.

▪ The past year has 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 macroscopic 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 below.



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.

Cryogenic Detectors

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.

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

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, in principle, to greatly enhance mass spectrometry of high-mass biomolecules such as DNA that will be of great importance to the biotechnology community.

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

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.

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 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 develop a small array of microcalorimeter detectors for X-ray analysis and read them out using SQUID MUX and DSP circuitry.

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.

In collaboration with the Chemical Science and Technology Laboratory, we will install the microcalorimeter spectrometer on state-of-the-art microanalysis tools at NIST-Gaithersburg to further demonstrate the capabilities of the system for analysis of particles and thin films.

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 small, densely packed arrays of detectors and instrument them with appropriate read out electronics.

These detectors also provide remarkable performance at lower energies, from infrared through visible. Here 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.

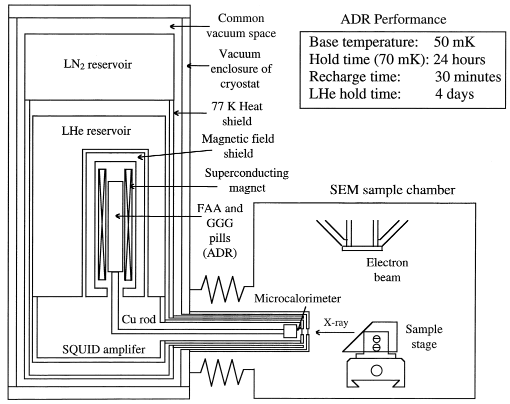
We will develop arrays of microcalorimeter detectors optimized for infrared astronomy along with the necessary wiring, SQUID MUX *and room-temperature DSP electronics to read the array.*

The development of digital signal-processing 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 other members of the Division and the Chemical Science and Technology Laboratory, we have been awarded a NIST grant 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 calculable noise voltage source to provide accurate calibration of the amplifiers and correlators needed to make the thermometer.

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

Accomplishments

- The success of the microcalorimeter detector project has been made possible by 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. 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 above right shows a micro-calorimeter energy-dispersive spectrometer (EDS) X-ray detector system inserted into a scanning electron microscope to allow chemical micro-analysis of materials.



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

- 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, dramatically improving yield. 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

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

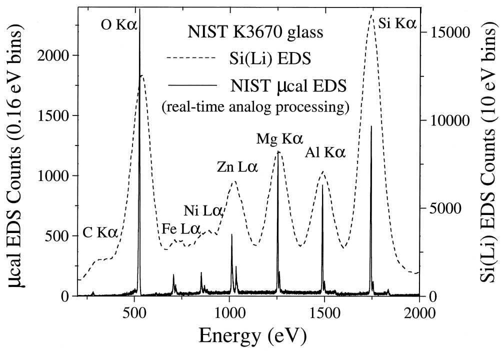
The success of the microcalorimeter detector project has been made possible by the broad expertise within the division in such fields as physics of superconductivity, device fabrication including Silicon micromachining, superconducting electronics, cryogenic engineering, and low noise, room-temperature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

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.

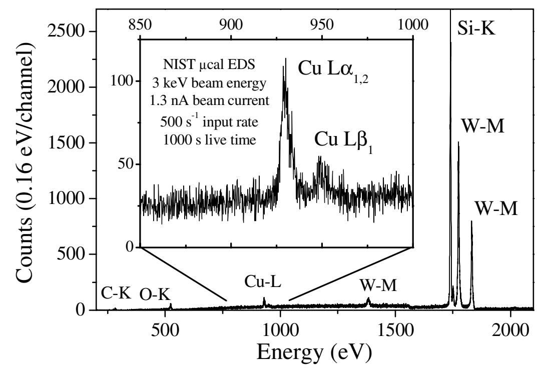
adiabatic demagnetization refrigerator, which has unique design features that produce nearly 24 hours of continuous operation, and days of hold time for liquid helium.



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

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.

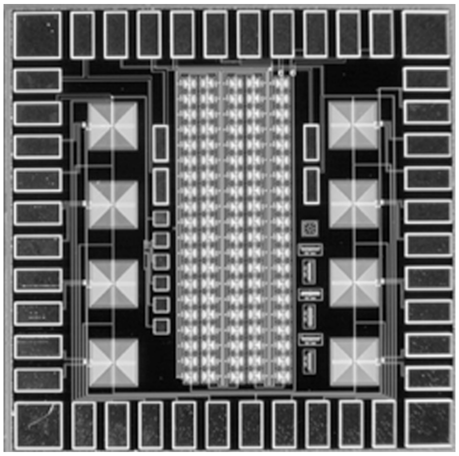
Furthermore, we have completed several effective partnerships with companies in the semiconductor industry to demonstrate the usefulness of the microcalorimeter spectrometer for practical analysis. For example, in collaboration with researchers at Lucent Technologies in Orlando, Florida, we critically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

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, and both are planning to have an initial system available soon.

- 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 are available in the Chemical Science and Technology Laboratory at NIST-Gaithersburg. To this end, the single-pixel spectrometer used in the above research has been relocated to Gaithersburg. Installation and qualification is nearly complete, 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.



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.

- 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 × 16 array of TES bolometers. This array and MUX have been delivered to NASA, which intends to install it in the spring of 2001 on the Cal Tech Submillimeter Observatory located in Hawaii.

- 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 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.

- This detector technology is also being 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 recently 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 may 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 use this technique to analyze a mixture of calibration proteins. While this technique shows promise, the impact-energy resolution is currently insufficient for widespread application. We are exploring the factors limiting the energy resolution.

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.

This detector technology may provide new capabilities in mass spectrometry.

Recognition

- Presidential Early Career Award for Scientists and Engineers to Mark Keller, 2000.

- NIST Condon Award, for excellence in writing, 2000.

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

Eichenberger, A.L.; Keller, M.W.; Martinis, J.M.; Zimmerman, N.M., "Measurement of the Frequency Dependence of a Single-Electron Tunneling Capacitance Standard", Proc., Conf. on Precision Electromag. Meas. (CPEM) 2000, 16-17 (2000).

Keller, M.W.; Zimmerman, N.M.; Eichenberger, A.L.; Martinis, J.M., "A Capacitance Standard Based on Counting Electrons", Proc. Conf. on Precision Electromag. Meas. (CPEM) 2000, 317-318 (2000).

Abusadi, R.; Akerib, D.S.; Barnes Jr., P.D.; Bauer, D.A.; Bolozdynya, A.; Brink, P.L.; Bunker, R.; Cabrera, B.;Caldwell, D.O.; Castle, J.P.; Clarke, R.M.; Colling, P.; Crisler, M.B.; Cummings, A.; Da Silva, A.; Davies, A.K.; Dixon,R.; Dougherty, B.L.; Driscoll, D.; Eichblatt, S.; Emes, J.; Gaitskell, R.J.; Golwala, S.R.; Hale, D.; Haller, E.E.;Hellmig, J.; Huber, M.E.; Irwin, K.D.; Jochum, J.; Lipschultz, F.P.; Lu, A.; Mandic, V.; Martinis, J.M.; Nam, S.W.;Nelson, H.; Neuhauser, B.; Penn, M.J.; Perera, T.A.; Perillo Isaac, M.C.; Pritychenko, B.; Ross, R.R.; Saab, T.;Sadoulet, B.; Schnee, R.W.; Seitz, D.N.; Shestople, P.; Shutt, T.; Smith, A.; Smith, G.W.; Sonnenschein, A.H.;Spadafora, A.L.; Stockwell, W.; Taylor, J.D.; White, S.; Yellin, S.; Young, B.A., "Exclusion Limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search", Phys. Rev. Lett. **84**, 5699-5701 (2000).

Wollman, D.A.; Nam, S.W.; Hilton, G.C.; Irwin, K.D.; Bergren, N.F.; Rudman, D.A.; Martinis, J.M.; Newbury,D.E., "Microcalorimeter Energy-Dispersive Spectrometry Using a Low Voltage Scanning Electron Microscope", J. Microscopy **199**, 37-44 (2000).

Nam, S.; Wollman, D.A.; Hilton, G.C.; Chervenak, J.; Deiker, S.; Irwin, K.D.; Martinis, J.M., "A Digital Readout Scheme for Arrays of Microcalorimeter X-ray Detectors", Proc. Microscopy and Microanal. 2000, 742-743 (2000).

Wollman, D.A.; Newbury, D.E.; Nam. S.W.; Hilton, G.C.; Irwin, K.D.; Rudman, D.A.; Deiker, S.; Bergren, N.F.;Martinis, J.M., "Microcalorimeter EDS: Benefits and Drawbacks", Proc. Microscopy and Microanal. 2000, 738-739 (2000).

Wollman, D. A., Newbury, D. E., Nam, S. W., Hilton, G. C., Irwin, K. D., Rudman, D. A., Deiker, S., Bergren, N. F., and Martinis, J. M., "Microcalorimeter EDS for low voltage microanalysis", Proc. of the 2nd Conf. Int. Union Microbeam Analysis Societies, pp. 125-126 (2000).

Newbury, D. E., Wollman, D. A., Hilton, G. C., Irwin, K. D., Bergren, N. F., Rudman, D. A., and Martinis, J. M., "The approaching revolution in X-ray microanalysis: The microcalorimeter energy dispersive spectrometer", Journal of Radioanalytical and Nuclear Chemistry, **244**, 627 (2000).

J.A. Chervenak, E.N. Grossman, K.D. Irwin, J.M. Martinis, C.D. Reintsema, C.A. Allen, D.I. Bergman, S.H. Moseley, R. Shafer, "Performance of multiplexed SQUID readout for Cryogenic Sensor Arrays", Nuclear Instruments and Methods in Physics Research A **444**, 107 (2000).

J.M. Martinis, G.C. Hilton, K.D. Irwin, and D.A. Wollman, D. A., "Calculation of Tc in a normal-superconductor bilayer using the microscopic-based Usadel theory", Nuclear Instruments and Methods in Physics Research A **444**, 23 (2000).

D.A. Wollman, S.W. Nam, D.E Newbury, G.C. Hilton, K.D. Irwin, N.F. Bergren, S. Deiker, D.A. Rudman, and J.M. Martinis, "Superconducting transition-edge-microcalorimeter x-ray spectrometer with 2eV energy resolution at 1.5 keV", Nuclear Instruments and Methods in Physics Research A **444**, 145 (2000).

K.D. Irwin, G.C. Hilton, J.M. Martinis, S. Deiker, N.F. Bergren, S.W. Nam, D.A. Rudman, and 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).

R. L. Kautz, M. W. Keller, and J. M. Martinis, "Noise-induced leakage and counting errors in the electron pump", *Phys. Rev. B* (accepted for publication).

A. L. Eichenberger, M. W. Keller, J. M. Martinis, and N. M. Zimmerman, "Frequency Dependence of a Cryogenic Capacitor Measured Using Single-electron Tunneling Devices," *J. Low Temp. Phys.*, **118**, 317 (2000).

M. Covington, M. W. Keller, R. L. Kautz, and J. M. Martinis, "Photon-assisted Tunneling in Electron Pumps," *Phys. Rev. Lett.* **84**, 5192 (2000).

J. A. Chervenak, K. D. Irwin, E. N. Grossman, J. M. Martinis, C. D. Reintsema, M. E. Huber, "Superconducting Multiplexer for Arrays of Transition Edge Sensors," Appl. Phys. Lett. **74**, 4043 (1999).

C. K. Stahle, D. McCammon, K. D. Irwin, "Quantum Calorimetry," Physics Today **52**, 32 (1999).

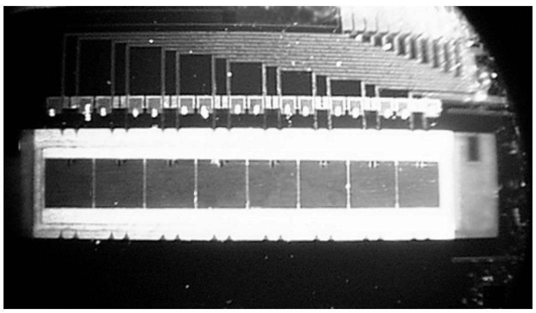
R. L. Kautz., M. W. Keller, and J. M. Martinis, "Leakage and Counting Errors in a Seven-Junction Electron Pump," Phys. Rev. B **60**, 8199 (1999).

M. W. Keller, A. L. Eichenberger, J. M. Martinis, and N. M. Zimmerman, "A Capacitance Standard Based on Counting Electrons," Science, **285**, 1706 (1999).

High Performance Sensors, Infrared Detectors, and Mixers

Project Goal

To develop and apply cryogenic electronic technology in the millimeter wave to infrared (IR) spectral range measurements and standards in support of other NIST Divisions and U.S. industry.



A 1 × 8 array of 300 mK bolometers.

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. 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 infrared 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 two types of devices, bolometers and tunnel junctions. These devices were initially developed for cryogenic electronic applications, but are also useful in the detection or frequency conversion of radiation from millimeter to infrared wavelengths. Our efforts to improve the sensitivity or precision of radiation power measurements exploits the low noise properties of thin film bolometers. Our work on improving the frequency coverage and efficiency of frequency conversion (i.e., rectification and mixing) exploits the low capacitance and nonlinear transport properties of tunnel diodes.

We work on the development of bolometers with ever-higher sensitivity, and their incorporation into imaging systems based on large focal-plane arrays. Depending on engineering trade-offs 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 NEP of less than 10^{-18} W/√Hz.

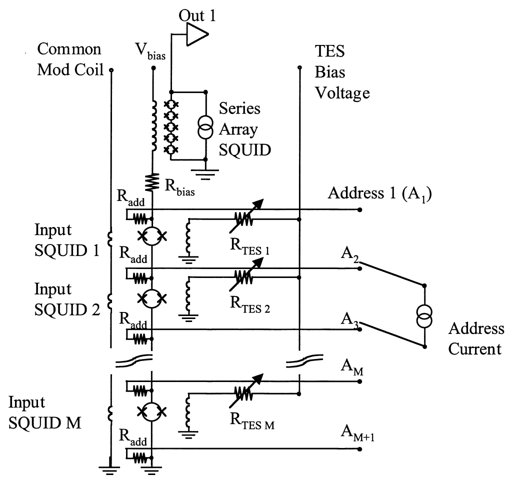
We will develop a 32 × 32 element bolometer array with NEP less than 5×10^{-17} W/√Hz.

Because readout is a critical element in any array technology, a superconducting quantum interference device (SQUID)-based cryogenic multiplexer is being developed to provide the front-end processing of the bolometer outputs. The bolometers are superconducting films

Technical contact:
Erich N. Grossman
grossman@boulder.nist.gov

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

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 MHz.

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

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. We have recently begun a program to develop ultra-sensitive mixer elements based on superconducting hot-electron bolometers. Like the transition-edge bolometer arrays, a major application for these mixers lies in space-based remote sensing. Hot-electron bolometers formed of thin films of niobium and niobium nitride have already demonstrated sensitivities within a factor of five of the fundamental quantum limit. The focus of our research in this area, and of the most recent progress in the state of the art, lies in extending the frequency coverage of this measurement technique to above 2 THz, and in developing integrated arrays of heterodyne mixers.

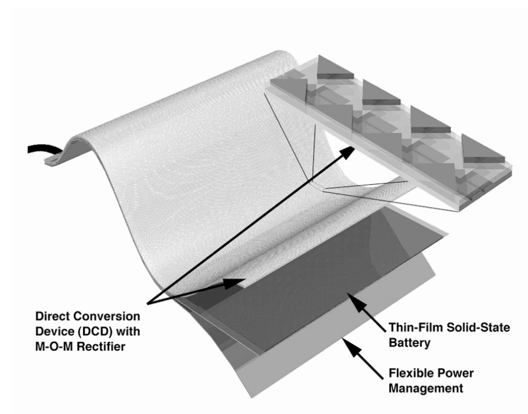
By 2001, we will demonstrate a 2 x 2 element hetrodyne mixer array operating at 2.5 THz, with noise tempertaure within a factor of 10 of the quantum limit.

We also use superconducting bolometers for 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 one part in 10^6 in ac voltage transfer at microwatt power levels.

We apply tunnel junctions, originally developed for cryogenic electronics, to IR rectification and mixing applications. For decades, scientists have envisioned highly efficient generation of solar power by the direct rectification of sunlight in ultra-low-capacitance diodes. Recent advances in nanoscale fabrication make such visions much more realistic; commercial firms and government agencies are now working with NIST to realize them using the nonlinearity of tunneling in uncooled, metal-insulator-metal (MIM) thin-film diodes.

Our goal is to observe photon-assisted tunneling steps in uncooled MIM diodes at 30 THz. By 2001, we aim for operation at above 100 THz with ac to dc conversion efficiency from greater than 20 %.



Direct conversion of solar energy concept showing array of antenna-coupled metal-insulator-metal diode rectifiers on flexible panel.

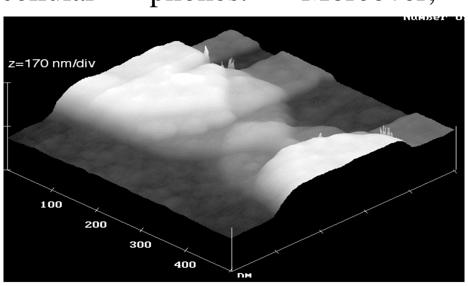
Separately, IR frequency synthesis and metrology have traditionally been performed by harmonic mixing of the output of low-frequency standards in whisker-contacted tunnel diodes, and the same thin film MIM diodes we are developing will enable the creation of frequency-synthesis systems that are much more compact, reliable, and user friendly.

We also develop thin-film bolometers, coupled to antennas and operated at room temperature, for use 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 to radiation 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.

We will develop an imaging system capable of detecting a reflectivity contrast less than 0.5 % at 5 meters range using a 16 x 16 element array.

Nanoscale metal-insulator-metal diode, 40 nm × 40 nm, integrated with a dipole antenna.

In most of these programs, the lithographic antenna forms an important component of the system, and frequently requires 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 at lower, microwave frequencies in wireless telecommunications systems such as cellular phones. Moreover, the



polarization-specific nature of antennas can frequently be exploited to provide our devices with additional functionality. For example, the emittance/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.

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

Accomplishments

- First Electrical Substitution Radiometer Based on Superconducting Sensors —We completed a standards-grade, electrical substitution radiometer for measurement of mid- and far-IR wavelength blackbody radiation, and delivered it to Division 844, 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 pW to 5 μW, the instrument's noise floor could be approximated as 4 pW plus 7×10^{-6} times the measured power. We are now helping a U.S. manufacturer of cryogenic radiometers incorporate superconducting sensors into its products.

We are helping a U.S. manufacturer of cryogenic radiometers incorporate superconducting sensors into its products.

- First ac-dc Thermal Transfer Standard Based on Superconducting Sensors —We completed and reported a set of preliminary experiments on ac-to-dc transfer using similar transition-edge bolometers. These yielded errors varying from 50 to 150×10^{-6} W (for frequencies from 100 Hz to 10 kHz), limited chiefly by inaccuracy introduced in delivering the ac signal to the cryogenic reference plane.

- First SQUID-Based Multiplexer for Transition-Edge Bolometers — In applications to far-IR astronomy (both imaging and low-resolution spectroscopy), speed, and therefore sensitivity, are limited by the number of pixels that can be read simultaneously. Present cryogenic far-IR bolometer arrays are already at the practical limit for the number of wires connecting the arrays to room temperature, so further improvement requires cold multiplexing. Over the last two 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 MHz, and has sufficiently low noise to multiplex up to about 250 channels without degrading the system noise.

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

- 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. The bolometers operate with a 300 mK base temperature, requiring ^{3}He refrigeration, and have a saturation power of about 5 pW and a time constant of about 2 milliseconds. Electrical NEP is phonon-noise limited at roughly 2×10^{-17} W/•Hz, the best ever reported for an IR bolometer operating with ^{3}He refrigeration, and within a factor of 6 of the best reported for any other IR bolometer.

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 nm^2 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 10 µm wavelength. 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 optical response of the nano-MIM diodes to 10 µm CO_2 laser radiation 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.

Recent Publications

M. E. MacDonald, A. Alexanian, R. A. York, Z. Popovic, and E. N. Grossman, "Spectral transmittance of Lossy Printed Resonant-Grid Terahertz Bandpass Filters," IEEE Trans. Micro. Theory Tech., in press.

J. A. Chervenak, K. D. Irwin, E. N. Grossman, K. D. Irwin, J. M. Martinis, C. D. Reintsema, C. A. Allen, D. Bergman, S. H. Moseley, and R. Shafer, "Performance of Multiplexed SQUID Readout for Cryogenic Sensor Arrays," Nuclear Inst. Methods A, in press.

S. Nolen, J. A. Koch, N. Paulter, C. D. Reintsema, and E. N. Grossman, "Antenna-Coupled Niobium Bolometers for mm-Wave Imaging Arrays," Proc. SPIE, in press.

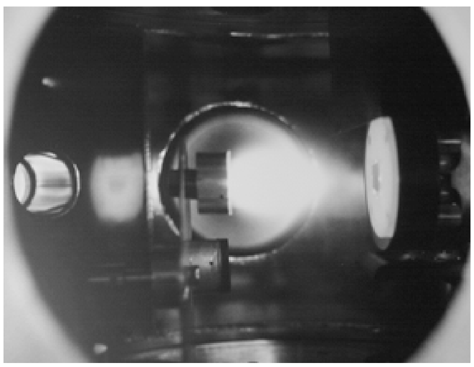
J. A. Chervenak, K. D. Irwin, E. N. Grossman, J. M. Martinis, C. D. Reintsema, and M. E. Huber, "Superconducting Multiplexer for Arrays of Transition Edge Sensors," Appl. Phys. Lett. **74**, 4043-4045 (June 1999).

C. D. Reintsema, E. N. Grossman, J. A. Koch, "Improved VO_2 Microbolometers for Infrared Imaging: Operation on the Semiconducting-Metallic Phase Transition with Negative Electrothermal Feedback," Proc. SPIE **3698**, 190-200 (April 1999).

High T_c Electronics

Project Goal

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 superconducting electronics industry through measurements, which 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 HTS devices in the areas of microwave, millimeter wave and terahertz metrology and technology; high-sensitivity bolo-meters; and Josephson junctions. We use pulsed laser deposition to grow novel thin-film materials and take those materials through processing to final test. We also collaborate with U.S. and international standards laboratories that provide materials and make comparative measurements. Below we describe the efforts in the three major thrusts of our project: microwave measurements and devices, bolometers and Josephson junctions, and novel micro- and nano-scale structures.

Microwave measurements and devices

We work with the HTS communication 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 impact their ultimate performance.

We collaborate with the Radio-Frequency Technology Division to improve microwave measurement and characterization techniques for HTS films and devices. We are participating in developing a new standard for measuring the surface resistance R_s. This

Technical Contact:
Ronald H. Ono
ono@boulder.nist.gov

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

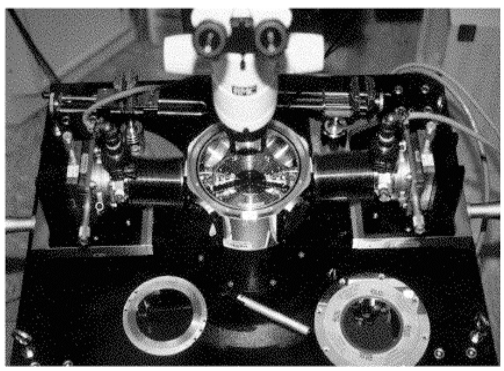
We have implemented a cryogenic microwave probe station for broadband (dc-40 GHz) characterization of temperature dependent microwave properties.

A draft international standard for R_S using dielectric resonators has been written and round-robin testing of HTS films has begun.

is under the auspices of the International Electrotechnical Commission (IEC) and the Versailles Agreement on Advanced Materials and Standards (VAMAS). We are developing new, calibrated measurements of power-dependent effects, especially nonlinearity. We also investigate new materials and device structures for tunable microwave circuits.

Our goals for research on microwave and millimeter wave devices in the next year are to understand the source of undesirable nonlinear behavior in HTS transmission lines and resonators. We will measure materials from companies making HTS filters so that our results can be directly compared to device performance.

We will continue to work on a standard for measuring surface resistance at microwave frequencies.



Cryogenic microwave probe station.

Bolometers and Junctions

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

We collaborate with industry to develop and test HTS bolometers for applications such as calibrated radiometers. We are studying new hot-electron mixing effects for detecting, synthesizing, and frequency-converting THz radiation. Applications include sensitive chemical line spectroscopy, frequency chain experiments in a solid-state system, and specialized communication bands. We are presently working on a long-term effort to develop HTS Josephson junctions for use as active components. These may be used in voltage standards, detectors, and integrated circuits that meet the measurement and application needs of industry.

We will use our existing research base in bolometers on Si membranes and in fabricating of submicrometer structures in HTS films.

We will continue to develop HTS Josephson junctions with controllable characteristic voltages, V_C. High V_C is required for terahertz mixing, detection, and generation, while low V_C is needed for voltage standards.

MEMS

MEMS and nano-electromechanical 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 focus in this area will be on continuing current research efforts in support of the Time and Frequency Division while developing new processes and applications.

Accomplishments

Microwave Measurements and Devices

- Loss and nonlinearity limit the utility of HTS 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.

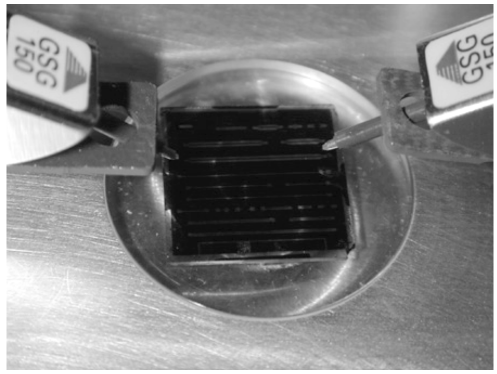
The project has achieved significant technical progress in three areas of study. Working with international standards organizations we are working towards a standard for the measurement of R_s. New, calibrated measurement techniques for power dependent effects, especially nonlinearity, have been developed. We have studied novel devices for tuning microwave circuits by investigating new materials and structures. Our measurements are performed with a unique cryogenic microwave probe station to enable precise characterization of patterned devices.

- International Draft Standard – A draft standard for 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 in the preliminary tests, and further improvements to the measurement apparatus are underway.

- Measurement of nonlinearity in HTS devices – We have developed a model system to investigate the nonlinear microwave response of HTS structures. By measuring dimensions and microwave properties of thin films fabricated for a variety of purposes, we are able to assist industry to improve device performance. In particular, calibrated power-dependent measurements have been made using a specially modified vector network analyzer

- Intercomparison of nonlinearity – Using the measurement techniques we have developed in collaboration with the Naval Research Laboratory (NRL), we have conducted a study of non-linearity using four measurement tech-niques. 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. 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.

- Calibrated Measurements of Ferroelectric Films – Using the cryogenic probe station, we have studied ferroelectric thin films for tunability and loss. We have developed new and fully calibrated measurement techniques that will enable other groups to better compare materials and devices.



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

Bolometers and Junctions

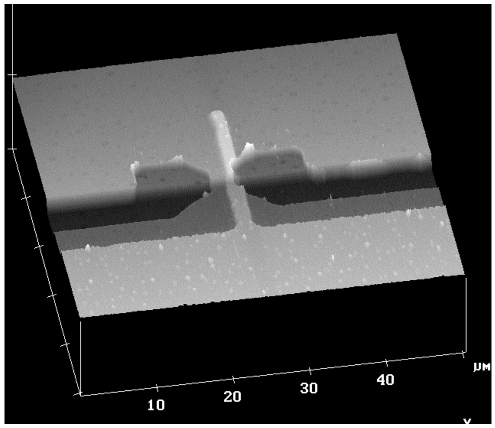
Bolometric applications use the sharp transition to zero resistance at temperatures accessible by inexpensive cryocoolers. The project developed the first sensitive, composite, infrared bolometer and demonstrated the lowest noise temperatures for devices on sapphire and silicon substrates. Our recent work has been in developing fabrication processes for terahertz mixers and detectors. Josephson junction research has focused on this area, as well as working towards devices suitable for use in arrays.

- HTS Devices on Si – We have fabricated new HTS devices on Si for testing of hot-electron mixing. Narrow transition widths have been obtained in 1 μm to 2 μm structures; submicrometer devices will be made.

- We have developed new HTS Josephson junctions using a barrier-modification process. Record-high V_c values (> 5 mV at 4 K) have been achieved in narrow edge junctions. We are also collaborating with several groups in trying to develop junctions capable of producing technologically interesting arrays, such as needed for a Josephson Arbitrary Waveform Generator.

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.

We have developed new HTS Josephson junctions using a barrier-modification process with record high characteristic voltages and frequency response.



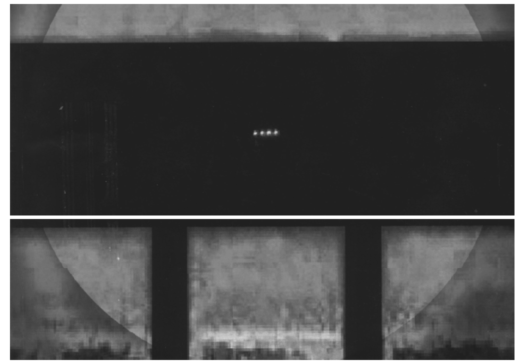
HTS Josephson junction with large characteristic voltage. The edge junction is 0.9 µm wide

Micromachining and MEMS

Quantum entanglement of 4 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 (847). Division 847 has recently demonstrated sub-dekahertz resolution in the measurement of Hg low resonance. Quantum entanglement has been demonstrated with four ions in one of these traps, as seen in the figure on the above right.

- MEMS Facility – A new facility for furnace processing has been completed and is in routine use. The Nanoscale Fabrication section of this book contains a photograph of the tube furnaces. We have developed improved cantilevers for magnetometers in collaboration with the EEEL Magnetics Group. We are presently exploring collaborations to work on MEMS and nano-electro-mechanical systems (NEMS) devices for new metrological instruments.



Photograph of the central region of an alumina micro-trap. The four trapped ions are seen in the center of the image.

Recent Publications

H. Shimakage, R. H. Ono and L.R. Vale, "Interface Engineered Josephson Junctions Optimized for High Jc, IEEE Transaction on Applied Superconductivity (in press).

L.R. Vale and R. H. Ono, "Small Area, "Thin Films of YBCO for Applications in Hot Electron Bolometers," IEEE Transaction on Applied Superconductivity (in press).

J. C. Booth, L.R. Vale, and R. H. Ono, "On-Wafer Measurements of Nonlinear Effects in High Temperature Superconductors," IEEE Transaction on Applied Superconductivity (in press).

J. C. Booth, L.R. Vale, R.H. Ono, and J.H. Claassen, "Power Dependent Impedance of High Temperature Superconductors Thin Films: Relation To Harmonic Generation," James C. Booth, L.R. Vale, R.H. Ono, and J.H. Claassen, J. Supercond. (in press).

J. C. Booth, Leila R. Vale, and R. H. Ono, "Broadband Determination Of Microwave Permittivity and Loss in Tunable Dielectric Thin Film Materials," in Materials Issues for Tunable RF and Microwave Devices, Proceedings, Materials Research Society Symposium,Vol. 603, 253-264, Q. Jia, Ed., Warrendale, PA (2000).

J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, and R. H. Ono, "Geometry Dependence of Nonlinear Effects in High Temperature Superconducting Transmission Lines at Microwave Frequencies," J. Appl. Phys. **86**, 1020-1027 (July 1999).

J. C. Booth, and C. L. Holloway, "Conductor Loss in Superconducting Planar Structures: Calculations and Measurements," IEEE Trans. Micro. Theory Tech. **47**, 769-773 (June 1999).

J. H. Claassen, J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, R. H. Ono, "Nonlinear Inductive Response of High Temperature Superconducting Films Measured by the Mutual Inductance Technique," Appl. Phys. Lett. **74**, 4023-4025 (June 1999).

H. Shimakage, R.H. Ono, J.C. Booth and L.R. Vale, "Third Harmonic Generation in Bicrystal Junctions," Superconductor Science and Technology 12, 830-832 (1999).

L.R. Vale, R.H. Ono, D.G. McDonald and R. Phelan, "Large area YBCO Bolometers on Si," Superconductor Science and Technology 12, 856-858 (1999).

J. C. Booth, L. R. Vale, R. H. Ono, J. H. Claassen, "Predicting Nonlinear Effects in Superconducting Microwave Transmission Lines from Mutual Inductance Measurements," Superconductor Science and Technology 12, 711-713 (1999).

J. H. Claassen, J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, and R. H. Ono, "Comparison of Microwave and Mutual Inductance Measurements of the Inductive Nonlinearity of HTS Thin Films," Superconductor Science and Technology 12, 714-716 (1999).

C. Weber, J.C. Booth, L. R. Vale, R. H. Ono, A.M. Klushin, H. Kohlstedt, and R. Semerad, "Coplanar Transmission Lines with Meandering Center Conductors in YBCO/Au Bilayers Superconductor Science and Technology 12, 998-1000 (1999).

Distributed Nonlinear Effects In Planar Transmission Lines, James C. Booth, J.A. Beall, L.R. Vale, and R.H. Ono, 53rd Automated RF Techniques Group (ARFTG) Digest, 31 - 40, June 1999.

D. A. Rudman, F. J. B. Stork, J. C. Booth, J. Y. Juang, L. R. Vale, G. J. Beatty, C. I. Williams, J. A. Beall, R. H. Ono, S. B. Qadri, M . S. Osofsky, E. F. Shelton, J. H. Classen, G. Gibson, J. L. MacManus-Driscoll, N. Malde, and L. F. Cohen, "Role of Oxygen Pressure during Deposition on the Microwave Properties YBCO Films," IEEE Trans. Appl. Supercond. **9**, 2460-2464 (June 1999).

D. G. McDonald , R. J. Phelan, Jr., L. R. Vale, R. H. Ono, and D. A. Rudman, "Passivation, Transition Width, and Noise for YBCO Bolometers on Silicon," IEEE Trans. Appl. Supercond. **9**, 4471-4474 (June 1999).

J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, R. H. Ono, C. L. Holloway, S. B. Qadri, M. S. Osofsky, E. F. Shelton, J. H. Classen, G. Gibson, J. L. MacManus-Driscoll, N. Malde, and L. F. Cohen, "Simultaneous Optimization of the Linear and Nonlinear. Microwave Response of YBCO Films and Devices," IEEE Trans. Appl. Supercond. **9**, 4176-4179 (June 1999).

H. Q. Li, R. H. Ono, L. R. Vale, D. A. Rudman, and S. H. Liou, "Interactions Between Bicrystal Josephson Junctions in a Multilayer Structure," IEEE Trans. Appl. Supercond. **9**, 3417-3420 (June 1999).

L. R. Vale, R. H. Ono, J. Talvacchio, M. G. Forrester, B. D. Hunt, M. S. DiIorio, K-Y Yang, and S. Yoshizumi, "Long Term Stability of YBCO Based Josephson Junctions," IEEE Trans. Appl. Supercond. **9**, 3382-3385 (June 1999).

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, which have been essential in the past 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.

Jim Beall, Maggie Crews, 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. Our processes are flexible to avoid constraining research activities to fixed design rules and to allow maximum creativity. 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.

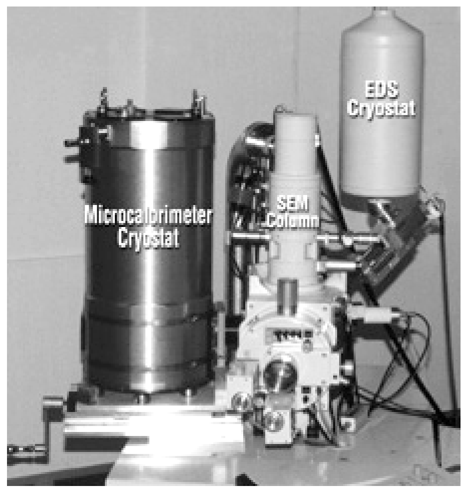
For patterning at the 1 µm scale, we use optical lithography in an I-line stepper and a deep-UV contact aligner. Electron-beam lithography enables patterning at less than 100 nm. Our facilities support fabrication of superconductor integrated circuits and MEMS fabrication, as well as laser ablation of 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 boron diffusion, low-stress silicon nitride/polysilicon low pressure chemical vapor deposition (LPCVD), and LPCVD of low-temperature oxide.

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 book 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)
Applications of Superconducting Integrated Circuits and Josephson Junction Arrays	Sam Benz
DNA Sequencing Using a Cryogenic-Detector-Based Mass Spectrometer	Gene Hilton John Martinis
High-Resolution Microcalorimeters for X-Ray Microanalysis	John Martinis Dave Rudman Gene Hilton
High-Tc Superconducting Thin Films for Devices	Ron Ono Dave Rudman
High-Tc Superconductors: Devices, Device Physics, and Circuits	Ron Ono
High-Tc Superconductors: Microwave Properties and Devices	Ron Ono
Physics and Applications of Single Electron Tunneling Devices	Mark Keller
Superconducting and Nanometer-Scale Devices for Infrared to Millimeter-Wave Applications	Erich Grossman
Superconducting Detectors for Photons from the Infrared through X Rays	Kent Irwin 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	"For his pioneering work in applying single-electron tunneling (SET) quantum mechanical principles to fundamental electrical metrology, realizing the first SET pump having parts per billion accuracy, and demonstrating the feasibility of a SET-based capacitance standard."
NIST Condon Award	Mark W. Keller, John M. Martinis, Ali Eichenberger, Neil Zimmerman	November, 2000	For distinguished achievement in written exposition.

Appendix D:
Electromagnetic Technology Division Staff

(January to December, 2000)

Division Office

3776 Harris, Richard E. (Chief)
3678 Metz, Sara E. (Division Secretary)
3812 Schump, Jeanne (Admin. Officer)
3811 Majack-Sweet, Kate (Admin. Asst.)
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)
4153 Takada, Akio (GR)

Nanoscale Cryoelectronics

5081 Rudman, David (PL)
5557 Anders, Solveig (GR)
4137 Aumentado, Jose (PREP)
5344 Bergren, Norm
7644 Chervenak, Jay (Prep)
7457 Chiu, John (PHASE)
3461 Deiker, Steven (PD)
3418 Eichenberger, Ali (GR)
5679 Hilton, Gene
3402 Huber, Martin (IPA)
5911 Irwin, Kent
3841 Jehl, Xavier (GR)
3391 Kautz, Richard (GR)
5430 Keller, Mark
3597 Martinis, John
3148 Nam, Sae Woo (PD)
3021 Rabin, Michael (PD)
5221 Urbina, Cristian (GR)
7457 Wollman, David
7894 Xu, Yizi (Ctr)

High Performance Sensors, Infrared Detectors, and Mixers

5102 Grossman, Erich (PL)
5102 Featherstone, Kelly (PHASE)
4199 Gerecht, Eyal (IPA)
3340 Harvey, Todd
3114 Nolen, Shalva (PD)
5052 Reintsema, Carl

High T_c Electronics

3762 Ono, Ron (PL)
5989 Beall, Jim
7900 Booth, Jim
5049 Crews, Maggie
7064 Koch, Jay
5113 McDonald, Don (GR)
7213 Shimakage, Hisashi (GR)
5121 Stevensen, David (PHASE)
5121 Vale, Leila

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

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

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

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

January 2001

For additional information contact:
Telephone: (303)497-3678
Facsimile: (303)497-3066
On the Web: http://emtech.boulder.nist.gov/