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January 2003

ECTRONICS AND ELECTRICAL
GINEERING LABORATORY

ELECTROMAGNETIC TECHNOLOGY DIVISION

PROGRAMS, ACTIVITIES, AND ACCOMPLISHMENTS

The Electronics and Electrical Engineering Laboratory (EEEL)

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

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

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

This publication 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, http://www.eeel.nist.gov. These publications are updated biennially.

On the cover: Against a background of Jim Beall and Maggie Crews working in our yellow-lit fabrication facility, in the upper left Sae Woo Nam tests room-temperature electronics for fundamental Johnson noise temperature metrology, while in the lower right Paul Dresselhaus displays a wafer of Josephson junction arrays fabricated for a quantum-based arbitrary waveform generator.

Electronics and Electrical Engineering Laboratory

Electromagnetic Technology Division

Programs, Activities, and Accomplishments

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

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

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

Contents

Welcome

The roughly 50 staff and guest scientists in the Electromagnetic Technology Division and I take great pride in bringing you this brief report on recent progress of our Division. We have a long history of inventing and disseminating new standards and measurement technology. We focus on exceptional standards and measurement methods using remarkable quantum effects and low noise available only at temperatures close to absolute zero or 0 K (–460 °F). This publication describes some of our recent successes.

It has always been our goal to provide U.S. industry with the best metrology in the world. We began about 35 years ago to bring the unique capabilities of cryogenic electronic technology to bear on metrology, the science of measurement. In many cases our technology enables measurements that are otherwise impossible. We developed what has become the world's practical standard of voltage, based on integrated circuits containing tens of thousands of superconducting Josephson junctions made in our own fabrication facility. We demonstrated the first capacitance standard based on counting of single electrons. For materials analysis, we perfected an X-ray spectrometer that combines the best features of two types of existing detectors and promises to be critical in defect analysis of future semiconductor devices. We have also improved our cleanroom facilities, which are critical to all of our efforts and enable us to produce microfabricated structures smaller than 100 nanometers.

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

Whether you are our customer and use the results of our efforts, or are simply interested in the remarkable progress our technology brings to measurements, we hope you will find this report exciting. You will find descriptions of our recent work, lists of our publications, and descriptions of our post-doctoral 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
January 2003

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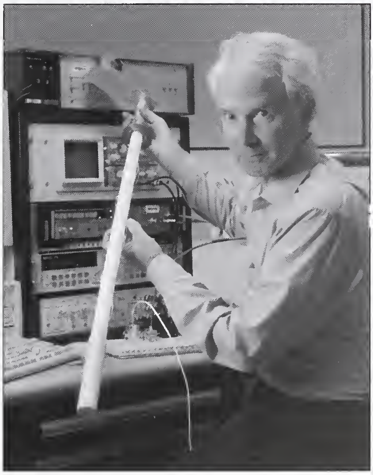
Quantum Standards

Quantum Voltage

Goals

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



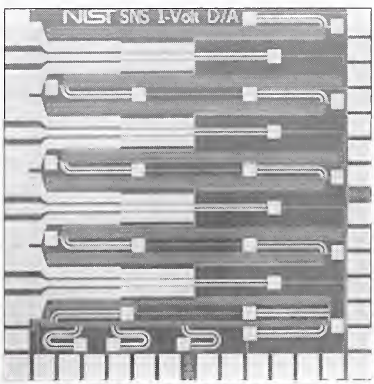
Clark Hamilton showing the probe for the 10 V conventional Josephson voltage standard system developed at NIST and used throughout the world for calibration of Zener voltage references.

Customer Needs

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

The U.S. electronics instrumentation industry maintains its world position through the development and deployment of increasingly accurate, flexible, easy-to-use instruments. Providing U.S. industry with quantum voltage standard systems gives these customers, with appropriate assistance from the NIST Electricity Division, immediate realization of the highest possible in-house accuracy. These customers also benefit dramatically by eliminating their dependence on less accurate reference standards that require frequent calibration.

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



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

Technical Contact:
Samuel Benz

Staff-Years (FY 2003):
4

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

Technical Strategy

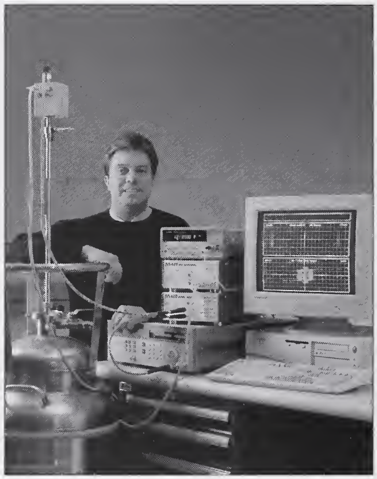
Over the past 20 years, this project has developed superconductive Josephson junction array technology for quantum voltage standard systems. Groundbreaking work at NIST led to commercialization of the first practical dc Josephson voltage standard system. Recent improvements in system design and operation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

A few years ago, we developed a novel superconductor-normal metal-superconductor (SNS) junction technology that adds the features of stability and programmability to the accuracy of conventional Josephson voltage standards. Programmable Josephson voltage standard systems based on these junctions have been delivered to, and installed in, a number of metrology experiments — namely the watt-balance experiments at NIST and Switzerland's Swiss Federal Office of Metrology and Accreditation (METAS, formerly OFMET), and the metrology triangle experiment at France's Bureau National de Métrologie — Laboratoire National d'Essais (BNM-LNE, formerly LCIE), where these features should reduce the uncertainty of the experimental measurements.

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

EEEL's Electricity Division is interested in improving the internal efficiency of its maintenance and dissemination of the volt through the development and deployment of an improved one volt programmable voltage standard. We have delivered a programmable Josephson voltage standard to the Electricity Division's primary voltage calibration lab in Gaithersburg, Maryland and we are collaborating with their staff to integrate the system into the customer calibration chain.

Our present primary goal is to develop the world's first quantum-mechanically accurate voltage source for both ac and dc metrology. This device is essentially a digital-to-analog converter capable of synthesizing arbitrary waveforms and, as for the previously described dc-only systems, exploits the perfectly quantized pulses of Josephson junctions. The concept for this new device was co-invented by NIST and Northrop-Grumman researchers in 1996. Present ac voltage calibrations are done using ac-dc thermal voltage converters. A quantum-based ac voltage source would provide an entirely new instrument and methodology for ac voltage metrology. Its use as a stable generator of accurate arbitrary waveforms would also be useful for calibration of other scientific instruments, such as ac volt-meters, spectrum analyzers, amplifiers, and filters. The major challenge of this technology is to achieve practical output voltages by developing improved broadband circuits and novel nano-meter-spaced junctions.



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

In order to achieve higher output voltages, we have developed a novel ac-coupled technique that allows multiple arrays to be biased in parallel by broadband 10 MHz to 20 GHz drive signals, while connecting the arrays in series for the low-speed, dc-to-10 MHz output voltage waveforms. This technique, as well as improvements in fabrication and microwave circuit design, has enabled us for the first time to increase the peak ac output voltage to about one-quarter volt. This amplitude will enable us during the next year to make some of the first practical calibrations and measurements using the quantum ac voltage source. However, in order to reach our desired 1 V goal we are also pursuing nanoscale junction technology. We can increase the output voltage of an array by decreasing the junction spacing to 50 nm and increasing the number of junctions so that the array remains a lumped microwave element. Stacked junction technology is one possible approach and this year we have found a new junction barrier material, molybdenum di-silicide ($MoSi_2$), that has shown significant uniformity with a slightly modified fabrication process. Development of such nanoscale junction technology is critical for the development of future voltage standard systems.

Accomplishments

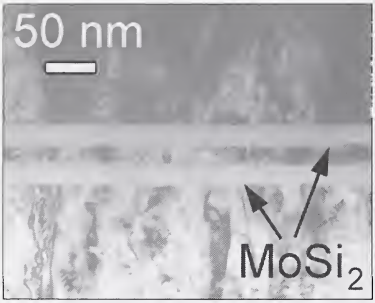
- Record One-Quarter AC Volt – A dc and ac Josephson voltage standard system with output voltages up to one-quarter volt has been demonstrated for the first time. This system, which is capable of synthesizing arbitrary voltage waveforms from dc to 10 MHz, is based on the perfectly quantized voltage pulses of Josephson junctions, making this the first intrinsic quantum standard for ac voltage. The heart of the system is a superconducting microwave integrated circuit in which 8200 junctions are placed in two series arrays to increase the output voltage. The arrays are driven with a 15 GHz sine wave and a high-speed (10 gigabits per second) pulse train to create the desired waveforms. The pulse trains correspond to predetermined digital codes in which the placement of zeros and ones precisely defines all the characteristics (amplitudes, harmonic frequencies and relative phases) of the desired synthesized waveforms. Using the perfectly quantized pulses, the arrays create the desired waveforms with quantum-mechanical accuracy. Recent improvements, such as more junctions, improved on-chip rf circuits, and a lower attenuation cryoprobe, have produced a 2-fold increase in peak output voltage up to one-quarter volt. This larger voltage allows this system to be used for the first time for practical calibrations. DC voltages with ± 0.254 V amplitudes were demonstrated and sine waves at 3.3 kHz and 33 kHz were synthesized with 0.242 V maximum peak amplitudes. Both synthesized sine waves showed excellent operating margins and stability so that harmonic distortion was as low as -93 dBc (93 dB below the fundamental). Precision measurements and comparisons with existing power-detection based ac voltage standards (e.g., ac-dc transfer standards and thermal voltage converters) will be completed in 2003. The ability to synthesize arbitrary waveforms (not just sine waves) with predetermined precision characteristics will enable advanced calibration of other measurement instruments such as spectrum analyzers, ac voltmeters, amplifiers, and analog-to-digital converters.

- Uniform Triple-Junction Stacks Demonstrated – Paul Dresselhaus and Yonuk Chong, a guest researcher from South Korea, have succeeded in making the first 2- and 3-junction stacks using molybdenum di-silicide ($MoSi_2$) as the normal metal and niobium as the superconductor for superconductor-normal-metal-superconductor (SNS) Josephson junctions. Precise three-dimensional control of the junctions during fabrication is critical for achieving uniformity of the electrical characteristics for the junction stacks and large high-density arrays. These new $MoSi_2$ circuits have demonstrated sufficient uniformity for thousands of junctions to display large quantized-voltage steps at frequencies up to 20 GHz. For the past few years the project has been searching for a practical barrier material to allow them to vertically stack junctions in order to make three-dimensional arrays. Higher junction density is required to increase the output voltage as well as the operating bandwidth of both programmable and ac Josephson array circuits. Nanometer control of the barrier thickness, typically 20 to 30 nanometers, is essential because junction electrical characteristics depend exponentially on barrier thickness. Reproducibility and uniformity of the fabrication process make $MoSi_2$ a leading candidate for future lumped-array Josephson voltage standard circuits and systems. We plan to demonstrate a record 5-junction stacked array in 2003.

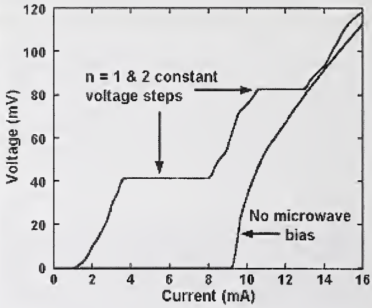
Paul Dresselhaus holds a silicon wafer containing superconducting integrated circuits and shows the current-voltage characteristics of a Josephson junction array.

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

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



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



Two voltage-current characteristics for an array of 1000 stacks, where each stack contains two $MoSi_2$ barriers for a total of 2000 junctions. Good uniformity of the stacked junctions is demonstrated by the sharp voltage onset with no microwave bias and by the flat constant voltage steps when 10 GHz microwave bias is applied.

■ Cryoprobe Technology Transferred – We have transferred the technology for constructing cryoprobes for the 1 Volt programmable Josephson voltage standard (PJVS) to High Precision Devices (HPD) in Boulder, CO. HPD has now delivered a total of seven such probes to NIST and other national metrology labs. Four recent deliveries include 2 probes to the Electricity Division for use in the electronic kilogram experiment and the voltage calibration lab, and 2 probes to the National Institute of Advanced Industrial Science and Technology (AIST) in Japan in support of the AIST-NIST collaboration to develop 10 K voltage standard systems. Charles Burroughs collaborated with HPD to improve the manufacturing precision of the microwave packaging. The improved packaging increased the uniformity of the 16 GHz microwave signals that bias all of the superconducting Josephson junction arrays. This allows the superconducting circuits to be operated with only 25 to 50 mW of rf power, which is 4 to 5 times lower than the power used in previous cryoprobes. The lower power requirements may decrease the total system costs for future PJVS systems by eliminating the need for expensive high-power microwave amplifiers. The cryoprobes have a 30 to 45 day hold time in a 100-liter liquid helium storage Dewar.

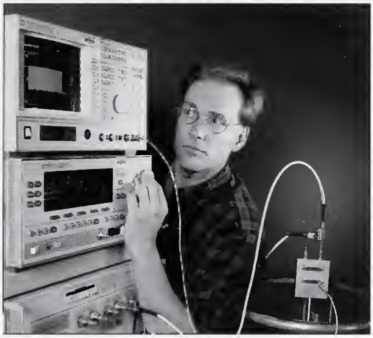
■ Programmable System Delivered to Calibration Lab – Charles Burroughs has delivered a second 1 V programmable voltage standard system to the Electricity Division (the first system is installed in the electronic kilogram experiment). This second system will be used to perform the function of the primary standard cell bank, and could eventually manage much of its workload. He is presently working with Yi-hua Tang to install this system in the primary voltage calibration lab. In the second quarter, Charlie will assist Yi-hua in evaluating the system's ability to perform the function of the primary cell bank. We will fabricate, test and deliver new 1 V chips with improved operating margins by March, 2003.

Collaborations

■ With Dr. Shoji and Dr. Yamamori at Japan's AIST, we are working to develop cryocooler-compatible Josephson junctions for programmable voltage standards. As a result of our collaboration, AIST has successfully demonstrated operation of a 1 V NbN programmable voltage standard at 8.5 K on a cryocooler refrigeration system. This is the first time a programmable 1 V system has been demonstrated on a cryocooler.

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

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



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

Recent Publications

C.J. Burroughs, S.P. Benz, and P.D. Dresselhaus, "AC Josephson voltage standard error measurements and analysis," 2002 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 16-21 June 2002, Ottawa, Canada, pp. 430-431 (June 2002).

S. Nam, S. Benz, P.D. Dresselhaus, and J. Martinis, "A new approach to Johnson noise thermometry using a quantum voltage noise source for calibration," 2002 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 16-21 June 2002, Ottawa, Canada, pp. 438-439 (June 2002).

S.P. Benz, P.D. Dresselhaus, and J. Martinis, "An ac Josephson source for Johnson noise thermometry," 2002 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 16-21 June 2002, Ottawa, Canada, pp. 436-437 (June 2002).

S.P. Benz, P.D. Dresselhaus, and C.J. Burroughs, "Nanotechnology for next generation Josephson voltage standards," IEEE Transactions on Instrumentation and Measurement, Vol. 50, No. 6, pp. 1513-1518 (December 2001).

S.P. Benz, F.L. Walls, P.D. Dresselhaus, and C.J. Burroughs, "Low-distortion waveform synthesis with Josephson junction arrays," Proc. 8th Int'l Superconductive Electronics Conf. (ISEC '01), 19-22 June 2001, Osaka, Japan, pp. 115-116 (June 2001).

R.H. Hadfield, G. Burnell, M.G. Blamire, P.D. Dresselhaus, and S.P. Benz, "Nanofabricated SNS junction series arrays in superconductor-normal metal bilayers," Proc. 8th Int'l Superconductive Electronics Conf. (ISEC '01), 19-22 June 2001, Osaka, Japan, pp. 391-392 (June 2001).

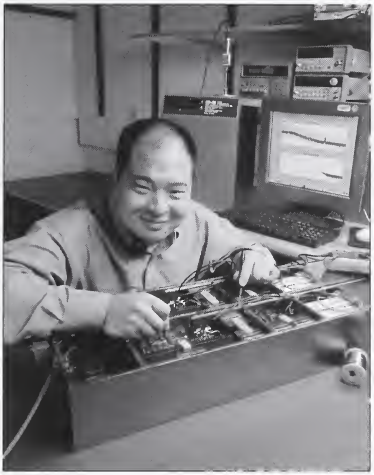
H. Yamamori, M. Itoh, H. Sasaki, A. Shoji, S.P. Benz, and P.D. Dresselhaus, "Fabrication of all-NbN digital-to-analog converters for a programmable voltage standard," Proc. 8th Int'l Superconductive Electronics Conf. (ISEC '01), 19-22 June 2001, Osaka, Japan, pp. 391-392 (June 2001).

QUANTUM STANDARDS

JOHNSON NOISE THERMOMETRY

GOALS

To use a quantum-based voltage source to reduce the uncertainty of Johnson noise thermometers, with the ultimate goal of creating an intrinsic quantum-based electronic temperature standard.



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

CUSTOMER NEEDS

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

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

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

TECHNICAL STRATEGY

In a JNT system, the temperature T is inferred from a measurement of the Johnson noise voltage V_T across a calibrated resistance R. The mean-squared voltage noise is given by the Nyquist formula $\langle V_T^2 \rangle = 4kTR\Delta f$, where Δf is the bandwidth for the measurement and k is Boltzmann's constant. Cross-correlation techniques are typically used to measure these extremely small voltages to remove the error introduced by the noise in amplifiers. In 1999, we realized that the Josephson Arbitrary Waveform Synthesizer being developed within our Division might be able to provide a stable, accurate, pseudo-noise voltage to provide a better means of calibrating the low-noise cross-correlation electronics. A stable, programmable, and intrinsically accurate noise source, such as that provided by the QVNS, would provide the advantages of direct calibration of the cross-correlation electronics, matching of the calibration voltage noise to that of the sense resistor, and matching of the source impedance to both the sense resistance and the output transmission-line impedance. These features reduce the measurement uncertainty, increase the measurement bandwidth, and decrease the measurement time for the entire JNT system.

Technical Contact:
Sae Woo Nam
Samuel Benz

Staff-Years (FY 2003):
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The concept of a Josephson arbitrary voltage waveform generator with quantum-mechanical accuracy has enabled the possibility of making an electronically based thermometer.

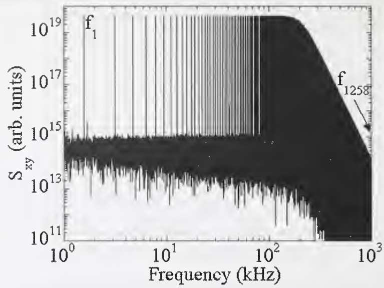
Using a QVNS we hope to achieve uncertainties of better than a few parts in 10^5 for temperatures in the range of several hundred kelvins. At these temperatures the noise signals are small, on the order of 1 nV/Hz$^{1/2}$ for a 100 ohm resistor. However, in order to achieve such small uncertainties for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

This JNT approach to create an "electronic kelvin" is analogous to the watt-balance program to realize an "electronic kilogram."

NIST has constructed custom cross-correlation electronics for the JNT program. Two pairs of voltage leads are measured with separate amplifier channels to perform the cross correlation measurement. Each signal is first measured with an ac-coupled differential FET, followed by an anti-alias filter with a cutoff frequency at 2 MHz. The resulting amplified and filtered signals are digitized at 50 MHz by a 14-bit analog-to-digital converter. Field-programmable gate arrays (FPGAs) at the output of the digitizers then digitally filter the signal with a low-pass frequency of 100 kHz. The digitally filtered data are transmitted via a 50 megabit/s optical link into a custom PCI card installed in a computer. Each channel transmits 2 million samples per second, which is the effective sampling frequency of the signal. In the present system, a dual-CPU computer is used to calculate two 221-point fast Fourier transforms (FFTs) in real-time (less than one second). The cross-correlation and auto-correlation power spectra are then calculated, accumulated, and stored for later analysis.

Accomplishments

- First QVNS-to-Resistor Noise Comparison – Sae Woo Nam, Wes Tew (CSTL), and Sam Benz performed the first comparisons between the Johnson noise voltage of a resistor in a gallium cell and the synthesized pseudo-noise waveforms of the quantum voltage noise source. Measurements were made using the recently completed cross-correlation electronic system. The computer-controlled optically interfaced system demonstrated a 50 MHz sampling rate and stored and processed the waveforms in real time. These correlation electronics are different from other systems because we digitally process the signal in an FPGA before sending it to a computer. This is necessary to reduce the data rate to the computer.



Log-log plot showing the measured spectrum of a QVNS-synthesized pseudo-noise waveform. The spectrum was measured with the JNT cross-correlated electronics and shows the power <V^2> spectrum S_{xy} of the 1258 tones synthesized by the QVNS. Each bin has a width of 1 Hz and is an average of 200 samples. The power spectrum is in arbitrary units.

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

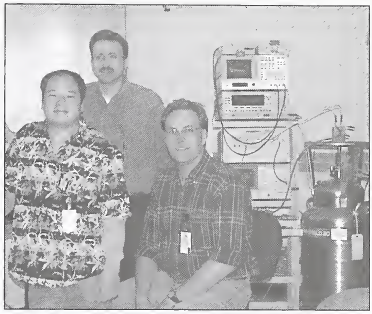
- Improved JNT Uncertainty – Sae Woo Nam, Sam Benz, and Paul Dresselhaus, in collaboration with Wes Tew of CSTL, have continued development of the Johnson noise thermometry system. Unwanted distortion was observed when the Josephson signal was measured with the cross-correlation electronics. Nam and Benz were able to significantly reduce this distortion by using inductive chokes on the input of the electronics. The cause of the distortion appears to be mixing in the first FET amplifier stage of 100-400 MHz delta-sigma modulator tones synthesized by the Josephson array. With this dramatic improvement, direct comparisons were made between the Josephson-synthesized noise waveform and the gallium and water triple point cells. We found agreement to 2 parts in 10^3 with a 1σ uncertainty of 1×10^{-3} between the voltage noise of a 100 Ω resistor in a triple-point gallium cell ($T_{90} = 302.916$) and a pseudo-noise waveform with the same average power that is synthesized by a quantized voltage noise source. We estimate the temperature of the resistor to be 302.5 K ± 0.3 K 1 σ (uncertainty based on the uncertainty from the cross-correlation). With better characterization of our JNT system, we expect to achieve relative accuracies of parts in 10^5 for arbitrary temperatures in the range between 270 K and 1000 K.

■ Novel Ratiometric Method Demonstrated – Wes Tew proposed using a new "ratiometric method" that takes advantage of the linearity of the Josephson waveforms to make independent comparisons between different noise powers. Sae Woo Nam briefly described this approach at the 2002 Conference on Precision Electromagnetic Measurements (CPEM) and it was explained in detail in a paper given at the 8th Temperature Symposium in Chicago in September 2002. The Johnson noise power at a known temperature is first balanced with a synthesized noise power from the QVNS. The process is then repeated by balancing the noise power from the same resistor at an unknown temperature. When the two noise power ratios are combined, a thermodynamic temperature can be derived where the scaling is accomplished by the ratio of the two QVNS spectral densities. Using this method, preliminary results of the ratio between the gallium triple point and the water triple point were used to demonstrate the accuracy of the measurement system with a standard uncertainty of 0.04 %. We are planning to perform more experiments in 2003 and 2004 to understand the limits of this technique.

Collaborations

■ We are collaborating with Weston Tew of the Process Measurements Division in the NIST Chemical Science and Technology Laboratory (CSTL). The JNT development program has been supported by a 5-year NIST competence award as well as with additional funds from both our Division and the Process Measurements Division. In 2003, we expect to deliver a set of JNT correlation electronics to the Project Measurements Division.

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



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

The quantum-based JNT system provides a direct link between temperature and electrical standards.

Recent Publications

S. Nam, S. Benz, P.D. Dresselhaus, and J. Martinis, "Johnson noise thermometry measurements using a quantized voltage noise source for calibration," to appear in IEEE Transactions on Instrumentation and Measurement, Vol. 52, No. 2 (in press).

S. W. Nam, S. P. Benz, J. M. Martinis, P.D. Dresselhaus, W. L. Tew, and D. R. White, "A ratiometric method for Johnson noise thermometry using a quantized voltage noise source," to appear in Proc. of 8th Symposium on Temperature: Its Measurement and Control In Science and Industry, 21-24 Oct 2002, Chicago, IL (in press).

S.P. Benz, P.D. Dresselhaus, and J. Martinis, "An ac Josephson source for Johnson noise thermometry," 2002 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 16-21 June 2002, Ottawa, Canada, pp. 436-437 (June 2002); also to appear in IEEE Transactions on Instrumentation and Measurement, Vol. 52, No. 2 (in press).

S. Nam, S. Benz, P.D. Dresselhaus, and J. Martinis, "A new approach to Johnson noise thermometry using a quantum voltage noise source for calibration," 2002 Conference on Precision Electromagnetic Measurements (CPEM) Digest, 16-21 June 2002, Ottawa, Canada, pp. 438-439 (June 2002).

S. P. Benz, J. M. Martinis, S. W. Nam, W. L. Tew, D. R. White, "A new approach to Johnson noise thermometry using a Josephson quantized voltage source for calibration," to appear in Proc. of TEMPMEKO 2001, 8th Int'l Symp. on Temperature and Thermal Measurements in Industry and Science, 19-21 June 2001, Berlin, Germany, pp. 39-44 (Apr 2001).

Quantum Standards

Technical Contact:
Mark Keller
David Rudman

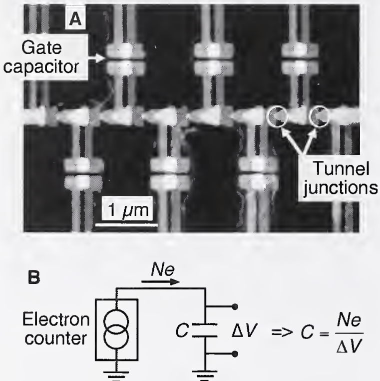
Staff-Years (FY 2003):
5

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

Single Electronics for Standards and Metrology

Goals

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



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

Imagine what you could do if you could build circuits that precisely manipulate and detect individual electrons. Single electronics represents a new class of electronics that does exactly that. At the core of this new electronics are nanoscale devices (dimensions less than 100 nm) operating at cryogenic temperatures, usually below 1 K. These new devices offer unique capabilities that impact electrical standards, fundamental metrology and industrial instrumentation. The goal of this project is to use our world-leading expertise in this field to create new quantum-based electrical standards and new measurement techniques applicable to emerging electronics that will operate with very few electrons.

Customer Needs

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 a few fixed frequencies. In this project we have already produced a prototype capacitance standard based on counting electrons. This standard will provide accurate calibrations over a wide range of frequencies and can be replicated to allow customers direct access to the standard.

This same technology is also being explored for a variety of other applications. Single electron devices can be used to produce single photons on demand by the recombination of single electrons and holes in a semiconductor quantum dot. Such a single photon source would be used for new optical calibration devices, and could become part of a quantum communications system. Molecular electronics is another class of electronics that operate with few or single electrons. The remarkable charge sensitivity of single electron devices makes them unique measurement tools to explore the electrical properties of single molecules. Finally, the superconducting analog of these devices can also be built. These devices manipulate electrons that are bound into "Cooper pairs" of charge 2e. These single Cooper pair devices can in principle be operated at higher speeds to produce large currents with metrological accuracy. They are also being considered for application to quantum computing.

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. The basic electronic device used to create these circuits is the Single Electron Tunneling (SET) transistor. This device consists of a nanoscale metal island coupled to two leads through very small tunnel junctions. This allows single electrons to be controllably put on and off the island, as long as thermal fluctuations are small. 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.

At present, the most advanced 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 the order of 1 part in 10^7. In order to confirm the accuracy of the standard, it must be compared to the SI farad as determined by the calculable capacitor at NIST-Gaithersburg. Using a new variable-frequency capacitance bridge and capacitance artifacts calibrated against the calculable capacitor by researchers in EEEL's Electricity Division, we will first perform this comparison indirectly in Boulder in early 2003. At the same time, a portable version of the standard is being developed to allow a direct comparison at NIST-Gaithersburg. This version will use a commercially available adiabatic demagnetization refrigerator to cool the SET electronics, and will represent a significant step towards making a "user friendly" system that could be duplicated for use in any number of laboratories.

SET devices can also be used as tools to measure the performance of other devices that operate with individual electrons. Currently we are focusing on two different applications utilizing the measurement capabilities of SET devices: single photon production and molecular electronics. In collaboration with Richard Mirin from EEEL's Optoelectronics Division, work has begun on creating a new class of electronic devices designed to produce single photons on demand. The principle of operation for the source is fairly straightforward: individual electrons and holes are alternately injected onto a single semiconductor quantum dot (QD) using single-electron tunneling principles. Once on the dot, a single electron and hole recombine to produce a single photon. To understand the behavior of these devices, it will be necessary to measure the electrical currents into the dot at the single electron level. This can be done only using SET technology. The first step towards this end requires the development of a process to allow electrical contact to individual QDs, and fabrication of SET devices on the same substrate as the quantum dots. In 2003 we will integrate these components on a single chip with QDs to measure the properties of the QDs and the neighboring tunnel barriers to learn how to tunnel single charges onto semiconductor QDs.

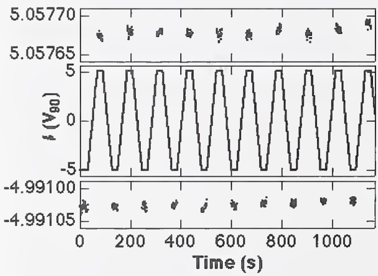
We have also begun a collaboration with the Departments of Physics and Chemistry at the University of Colorado at Boulder (CU) to apply SET devices to the measurement of single molecules having interesting electronic properties. Molecules have been synthesized at CU with large dipole moments that can rotate on the top of a molecular "shaft." Work is underway at the university to measure the properties of films made from these molecules. Our goal in 2003 will be to place a single molecular dipole rotor near an SET electrometer to allow direct measurement of the properties of a single molecule.

We are currently developing the superconducting analogs of the various single electron devices described above. Superconducting Single Cooper Pair Tunneling (SCPT) devices combine the physics of single electron devices and Josephson junctions. Our first application of this new technology will be to develop a SCPT charge pump. Because superconducting tunneling is a coherent process, in principle the SCPT pump should be able to operate at significantly higher frequencies, allowing larger currents to be produced with metrological accuracy. If larger currents are available, 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 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. To build the SCPT pump will require significant advances in the fundamental understanding of how these devices work. In 2003 we will continue our research into SCPT devices. This work will also have direct impact on worldwide progress towards using these devices for quantum computing.

Accomplishments

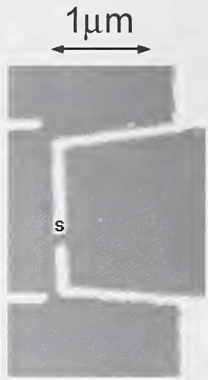
- Electron Counting Capacitance Standard Demonstrated – At present, the most advanced application for SET devices within the project is a new capacitance standard based on the fundamental definition of capacitance. The past few years have brought to fruition the results of a decade of research aimed at creating this standard. A prototype of an Electron Counting Capacitance Standard (ECCS) has now been demonstrated. The components of the standard are an electron counter, a capacitor, and an electrometer to monitor the process, as illustrated in the figure at the beginning of this section. The electron counter is based on seven nanometer-scale tunnel junctions in series. It can "pump" electrons onto the capacitor with an error rate of less than one electron in 10^8. The electron pumping is monitored with an SET-based electrometer fabricated on the same chip as the pump, with a charge sensitivity better than 10^{-2} electrons. The capacitor, fabricated by Neil Zimmerman from the Electricity Division, operates at cryogenic temperatures and uses vacuum as the dielectric, resulting in a frequency-independent capacitance. To operate the ECCS 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 below shows the result of pumping electrons on and off the capacitor, with a 20 second pause when fully charged to measure the voltage. The result is a value of capacitance with a repeatability of one part in 10^7.

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



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

■ Improved Model of SET Devices Helps Predict Error Rates – 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. Recently, the dependence of pump errors on voltage across the pump has been measured for the first time. This directly gives the operating margin for the feedback that must be maintained during operation of the capacitance standard, a critical design parameter for the next generation of the standard. This work has led to a new understanding of the variation in electron temperature within the pump, improving our ability to model SET device performance. This expanded theory is a powerful tool for predicting and diagnosing the performance of the electron pump.

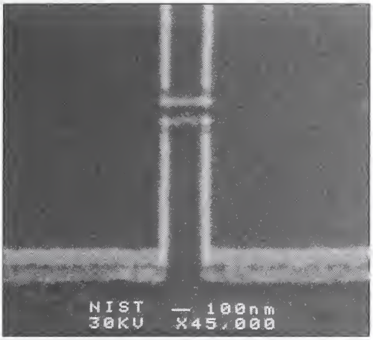


An AFM image of electron-beam lithographically-written contact to a single QD. The 'S' indicates where the QD is located. The lead that approaches the QD from the bottom is used to capacitively couple the QD to a single-electron transistor structure. The white lines coming in from the left side of the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

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

■ SET Electronics Developed to Probe GaAs Quantum Dots for Single Photon Source – The past two years have produced significant progress towards the development of a single-photon turnstile, a device designed to generate single photons on demand using semiconductor quantum dots (QD) and single-electron principles. 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 nanoscale leads on the same chip.

An Atomic Force Microscope (AFM) image of electron-beam lithographically written contacts to a single quantum dot is shown above. We have also fabricated SET electrometers on GaAs substrates in preparation for probing the electronic states of the quantum dot, shown in an SEM image below.



Two SET electrometers separated by 60 nm on a GaAs substrate without quantum dots. This device will be used to probe the electronic states of a quantum dot located between the SET devices and a buried conducting layer in a GaAs-based heterostructure.

■ Superconducting Single Cooper Pair Devices Under Investigation as Current Source – Superconducting Single Cooper Pair Tunneling (SCPT) devices represent a new class of single electronics that operate on single Cooper pairs with charge 2e. Our first efforts to construct a seven-junction SCPT pump (shown above right) produced only limited success. The device did pump Cooper pairs with charge 2e per cycle, but only against a significant background of events due to unpaired electrons, an effect known as "quasiparticle poisoning." In recent years several groups worldwide have been investigating SCPT devices as possible elements for quantum computing. These groups have also reported unexplained quasiparticle poisoning in their devices, which is highly detrimental to their performance. To investigate the origin of these unwanted quasiparticles, we constructed much simpler SCPT devices. We have determined that the quasiparticle poisoning arises from unintentional (and usually uncontrolled) differences in the superconducting energy gap between the two Al layers used to make the tunnel junctions. By intentionally varying the gap in the two layers, we have been able to create devices with either no quasiparticle poisoning or excessive poisoning. These results, which may also explain the results from other groups, point the way to a robust recipe for devices that can realize the promise of superconducting charge transfer for both metrology and quantum computation. We are currently studying the behavior of these devices further, and will then attempt to construct an improved SCPT pump as a current source for metrology triangle and other experiments.

SEM micrograph of our first 7-junction SCPT pump. The junctions, which are less than 50 nm on a side, are too small to be seen in this picture but are located on the central line near each gate electrode.

Recent Publications

S. Anders, C. S. Kim, B. Klein, Mark W. Keller, R. P. Mirin, and A. G. Norman, "Bimodal size distribution of self-assembled InxGa1-xAs quantum dots," Phys. Rev. B 66, 125309 (2002).

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

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. Physics 188, 317 (2000).

R.L. Kautz, M.W. Keller, and J.M. Martinis, "Noise-induced leakage and counting errors in the electron pump," Phys. Rev. B 62, 1588 (2000).

N.M. Zimmerman, M.W. Keller, "Dynamic input capacitance of single-electron transistors and the effect on charge-sensitive electrometers," J. Appl. Phys. 87, 8570 (2000).

M. Covington, M.W. Keller, R.L. Kautz, J.M. Martinis, "Photon-assisted tunneling in electron pumps," Phys. Rev. Lett. 84, 5192 (2000).

M.W. Keller, N.M. Zimmerman, A.L. Eichenberger, J.M. Martinis, "A capacitance standard based on counting electrons," Proc. 2000 Conf. on Precision Electromagnetic Measurements (CPEM), 14-19 May 2000, Sydney, Australia, pp. 317-318 (2000).

R.L. Kautz, M.W. Keller, 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, N.M. Zimmerman, "A capacitance standard based on counting electrons," Science, 285, 1706 (1999).

Quantum Standards

Physics of Quantum Hall Resistance Standards

Technical Contact:
Richard Harris

Staff-Years (FY 2003):
0.1

Goals

To develop applications to metrology of recent advances in the physics of quantum Hall devices and to fabricate optimized devices for metrology.

Customer Needs

The quantum Hall effect has been the basis of resistance metrology for a number of years. Metrology laboratories around the world use it routinely as a practical standard, although the ultimate knowledge of resistance continues to be based on a calculable capacitor. Quantum Hall devices produce very precise values of resistance of the order 10 parts per billion.

Even though the quantum Hall effect was discovered more than two decades ago, there has not been a focused effort to produce optimized quantum Hall devices for metrology. The worldwide lack of a fabrication effort aimed specifically at quantum Hall devices has resulted in a lack of technological progress similar to major advances with the Josephson array voltage standard over the same period.

The Electromagnetic Technology Division is therefore initiating a program to remedy these limitations.

Technical Strategy

With the support of the EEEL a program was initiated in 2001. The program will consist of two staff members and the capability of fabricating two-dimensional electron gas (2DEG) samples using a dedicated molecular beam epitaxy (MBE) machine, followed by characterizing them at appropriate temperatures and magnetic fields.

The approach to the program will range from relatively straightforward tasks to the development of new fundamental knowledge that will enhance future electrical metrology. Following that order, the following are the objectives we foresee at the present time:

Fabrication of optimized conventional quantum Hall samples – We will undertake a collaborative program with EEEL's Electricity Division to produce optimized quantum Hall samples for that Division's use in resistance calibrations. Using an iterative approach we will optimize the samples for this application. We hope to reduce occasional unintended noise, to increase the operating temperature, and to reduce the required magnetic field strength. Ultimately we hope to produce metrology-quality samples that operate at 4.2 kelvin in magnetic fields of one tesla or less. At this level the systems would be inexpensive enough that they could be used by many more laboratories than can afford quantum Hall resistance standards at present. Series arrays will be particularly important in EEEL's pursuit of closing the metrology triangle (described elsewhere in this publication).

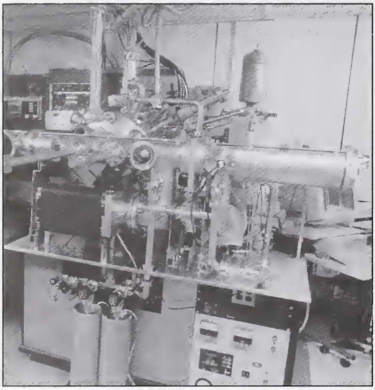
Quantum Hall integrated circuits – We will fabricate quantum Hall integrated circuits for use in metrology or physics studies. Inspired by the report of a French group at the 2002 Conference on Precision Electromagnetic Measurements, we will produce integrated circuits of quantum Hall devices. That group fabricated a parallel/series array of devices to enable lower or higher resistance than the standard resistance of $h/e^2 = 25812.807$ ohms. Their significant accomplishment was to reduce the contact resistance between samples to a low enough value that the overall resistance was accurate to better than 100 parts per billion. In addition we will explore the possibility of combined quantum Hall and superconducting circuits that might permit miniature, or even on-chip, magnetic field generation to eliminate the need for a bulky external magnet, further reducing the cost of the overall system. If this field could be confined to a small region of the chip, it might be possible to fabricate a Josephson array voltage standard on the same chip as the quantum Hall device, creating a monolithic quantum multimeter for the first time. The device would achieve a voltage and resistance having quantum accuracy, with the current derived as the ratio of the two.

..... it might be possible to fabricate a Josephson array voltage standard on the same chip as the quantum Hall device, creating a monolithic quantum multimeter for the first time.

New quantum Hall physics for metrology – Experiments performed over the last few years at the California Institute of Technology (Caltech) by Professor James P. Eisenstein, his students and collaborators demonstrate new physics having potential importance to metrology. In these experiments quantum Hall samples are fabricated with two 2DEGs spaced by less than 100 nm to permit tunneling between the layers. These remarkable experiments demonstrate the quantum Hall effect with a filling factor of 1/2 in each layer, which is not observed in a single layer. Moreover with a current through only one of the layers, a voltage is generated in the other layer that is proportional to the product of the current and the quantum Hall resistance in the first layer. While the metrological utility of the second layer is yet to be explored, this effect suggests opportunities important to practical quantum Hall metrology.

Accomplishments

Taking advantage of the refocusing of another program in EEEL, we have acquired an MBE system of suitable cleanliness to fabricate conventional quantum Hall samples. Based on the experience of researchers at Bell Laboratories, it would also be capable, with modification, of producing very high mobility samples similar to those presently used in the Caltech bilayer experiments. We are also searching for two world-class staff members to initiate and carry out this work.



Molecular beam epitaxy machine prior to shipment to Electromagnetic Technology Division.

Recent Publications

Since this program is still being initiated at NIST, the relevant background is in publications from the work at Caltech. Two are listed below:

M.Kellogg, J.P. Eisenstein, L.N. Pfeiffer and K.W. West, "Double layer two-dimensional electron systems: probing the transition from weak to strong coupling with Coulomb drag," cond-mat/0211502 (2002).

M.Kellogg, I.B. Spielman, J.P. Eisenstein, L.N. Pfeiffer and K.W. West, "Observation of quantized Hall drag in a strongly correlated bilayer electron system," Phys. Rev. Lett. vol. 88, pp. 126804 (2002).

Quantum Information

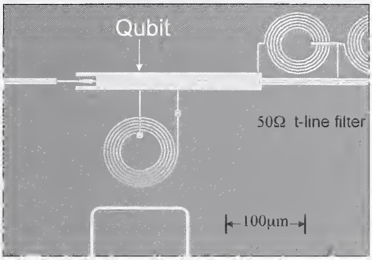
Quantum Computing Using Integrated Circuits

Technical Contact:
John Martinis

Staff-Years (FY 2003):
5

Goals

To develop the physical principles essential to quantum computing and other future electronic technologies.



Photograph of current-biased Josephson junction qubit.

Quantum computing is a radically new approach to computing. A large part of the scientific community is very excited about this possible application of very fundamental physics.

In a conventional computer, information is often stored as an electrical charge on a tiny capacitor. The presence or absence of charge indicates a value of 1 or 0. In a quantum computer, information is stored as a wave function of a quantum bit, or qubit. Theorists project enormous increases in computing power if quantum computing can be made practical.

Many very different quantum systems are being considered worldwide for possible use in quantum computing. At NIST, staff in the Physics Laboratory are pursuing single ions and neutral ions. In EEEL, we are considering superconducting integrated circuits. The potential advantage of our approach is that we are using lithographic fabrication, which can be scaled from a single first qubit to an entire integrated circuit, necessary for any actual quantum computer.

Customer Needs

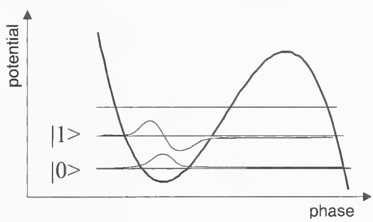
Whether or not quantum computing becomes practical, our work will produce new knowledge of electrical measurements in systems with extremely low energy levels. This is the direction all computing is taking. With the current focus on massively integrated nanoscale devices, energy differences between different states in a computer are reduced because of the ever smaller device sizes, proving the important practical result of lower power dissipation.

In future systems exceptional care must be taken to eliminate both external noise and even self-generated noise. Low temperature operation is essential. While the ultimate success of quantum computing is still unknown, the measurement techniques that we will develop will find application in much advanced electronic technology.

Technical Strategy

Our first demonstration of a qubit uses a current-biased Josephson junction operated at about 20 millikelvin (mK).

Our qubit is based on a current-biased Josephson junction. The energy levels are shown in the following diagram:



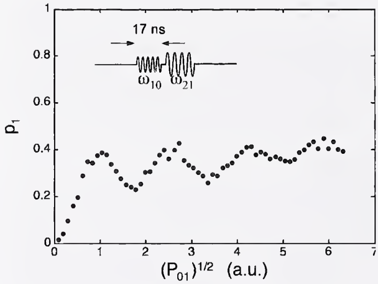
Potential energy of current-biased Josephson junction showing ground and first excited state wavefunctions as a function of junction phase difference.

Using a microwave source we can control the population of the first state above the ground state. Reading out that state is accomplished by applying a second microwave signal to move the system into the highest state (not shown). Adjusting the bias permits the system to tunnel through the right energy barrier into the Josephson voltage state, which is easily detectable using conventional instrumentation.

This very specialized circuit is fabricated in our versatile facility, described elsewhere in this publication.

Accomplishments

- Qubit Demonstrated – One important test of potential qubits is the observation of stimulated transitions between states, called Rabi oscillations. These are demonstrated in the figure on the next page. These and other data reveal a coherence time of about 10 ns. Calculations suggest that times as long as about 1 μs should be possible, which is long enough for experimental quantum communication.



Rabi oscillations demonstrated in plot of measured probability of occupation p1 of first state as function of microwave excitation $(P_{01})^{1/2}$.

Our results demonstrate an operating qubit. The next steps in our work, in 2003, are to find ways to increase the coherence time. Once that is complete it will be necessary in 2004 to develop methods for coupling two or more qubits into a logic gate. Following this step we will have to demonstrate quantum computing, beginning with very simple circuits and learning techniques for increasing the complexity toward circuits, which can perform meaningful computation.

We are vigorously pursuing this fast-moving field of research and invite interested readers to check our web site for our latest results.

Recent Publications

J.M. Martinis, S. Nam, J. Aumentado, K.M. Lang, and C. Urbina, "Decoherence of a superconducting qubit from bias noise," submitted to Physical Review B (in press).

K.M. Lang, S. Nam, J. Aumentado, C. Urbina, and J.M. Martinis, "Banishing quasiparticles from Josephson-junction qubits: why and how to do it," Proc., 2002 Applied Superconductivity Conference, 4-9 August 2002, Houston, TX (2002), IEEE Trans. Appl. Supercon. (in press).

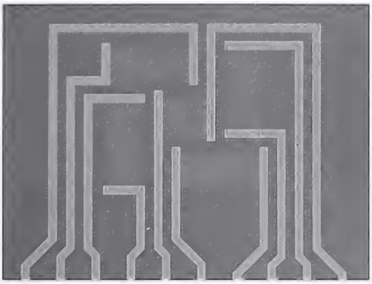
J.M. Martinis, S. Nam, J. Aumentado, and C. Urbina, "Rabi oscillations in a large Josephson-junction qubit," Phys. Rev. Lett. 89(11), pp. 117901 1-4 (9 Sept. 2002).

Quantum Information

Quantum Communication

Goals

To develop and apply single photon detectors (optical/infrared) for metrology and science.



Photograph of a small array of tungsten transition edge sensors (TES) to detect single photons. The active areas are the center square and surrounding rectangular areas. The light colored traces are aluminum wires to bias the detectors. The light colored lines are 2 μm wide.

Customer Needs

New quantum-based communication and measurement systems that use single and correlated photons have been developed. However, the current tools to calibrate the components in these systems are inadequate for the emerging applications. For accurate calibration, a detector capable of determining the number of photons in a single pulse of light is needed. We are developing a high-efficiency detector system with this capability in the three telecommunication windows (850 nm, 1310 nm, and 1550 nm). This new instrument will also aid in the understanding and advancement of new photon sources such as the single photon turnstile (SPT). Our detectors can also be used as a spectroscopic diagnostic tool or characterization tool of optical elements, optical materials, and optical systems at ultra-low light levels. This detector technology will also enable metrology for understanding and evaluating a new class of devices currently being developed for quantum networks.

In collaboration with Stanford University, we are also developing arrays of single photon detectors as spectrophotometers for use in astrophysics and astronomy. The detectors that have been developed are capable of measuring the energy of the photon and time stamp the arrival of a photon to better than 1 microsecond.

Technical Strategy

The technology for counting photons at telecommunication wavelengths or measuring the energy of a single photon is a refinement of superconducting transition-edge sensor (TES) detector technology that was previously developed by the Division and researchers at Stanford University.

These abilities are achievable due to the low operating temperature (100 mK) of the TES devices. The photons are detected by exploiting the superconducting properties of tungsten at these low temperatures. At 100 mK the devices become exceedingly sensitive thermometers capable of measuring the heat deposited into the TES from single optical/infrared photons. The tungsten device absorbs the photons, heats up a very small amount, and produces an electrical output signal that is proportional to the energy absorbed by the device.

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

At the present time, our quantum efficiency of detection is ~18 % and is limited by our optical coupling and intrinsic quantum efficiency of absorption of tungsten. Our goal by the end of 2003 is to develop detectors with a quantum efficiency of at least 80 % in the telecommunication wavelengths.

Conventional semiconductor-based single-photon detectors suffer from high rates of "dark counts" (false positives), especially at the communication wavelengths at 1300 nm and 1550 nm, severely limiting the single-photon applications. In principle, our

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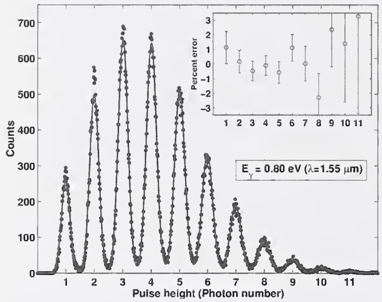
Staff-Years (FY 2003):
2

detectors do not suffer from dark counts at all. This simple fact will allow our instrument to be operated at much lower light levels than any existing metrological instrument. Consequently, these detectors could be a significant tool in the development of quantum-based communication protocols. The multi-photon discrimination metrology will be essential for evaluating the security of such quantum cryptographic systems.



Comparison of the measured pulse-height distribution of a pulsed-laser source using a TES calorimetric photon counter with the expected photon-number distribution. The source was 100 ns wide pulses of 1550 nm laser light at a repetition rate of 500 Hz containing an average photon number of ~4. Total acquisition time was four minutes. Shown are the data and best fit Poisson distribution convolved with the measured device response. Inset shows the difference between measured and fit probability distributions. Error bars show the expected 1-sigma standard deviation due to counting statistics.

Accomplishments

■ Operation of Detectors in a Portable Cryostat – Aaron Miller, Sae Woo Nam, and John Martinis demonstrated the operation of a tungsten TES optical detector in a portable adiabatic demagnetization refrigerator (ADR). Previously, operation of optical TES detectors has been done in refrigeration systems that were difficult to transport.

■ Photon Number Counting Detectors Demonstrated – Aaron Miller, Sae Woo Nam, and John Martinis demonstrated the operation of a tungsten TES optical detector capable of counting the number of photons in a short pulse of light. The initial demonstrations were performed with an attenuated pulsed laser diode.

■ Optical Detectors with Photon Number Counting Capabilities Used with a Twin Photon Source – The NIST group and researchers at Boston University have demonstrated the use of the NIST detectors with a SPDC crystal. Full accounting of the distribution of all the photons from the SPDC in simple optical experiments was done for the first time. The demonstrations included observations of classical interference and quantum interference.

Collaborations

■ Alan Migdall from NIST's Optical Technology Division (Physics Laboratory) is developing a single photon source using SPDCs, and we will be using our detectors to verify the performance of this type of photon source in 2004.

■ With Xiao Tang from the Convergent Information Systems Division (Information Technology Laboratory), Carl Williams from the Atomic Physics Division (Physics Laboratory), and Alan Migdall, we are working on installing one of our detector systems in the quantum communication testbed being developed at NIST by the end of 2004.

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

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

Recent Publications

S.W. Nam, J. Beyer, G. Hilton, K. Irwin, C. Reintsema, and J.M. Martinis, "Electronics for arrays of transition edge sensors using digital signal processing," to appear in IEEE Transactions on Applied Superconductivity vol. 52 no. 2 (in press).

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

R.W. Romani, A.J. Miller, B. Cabrera, S.W. Nam, J.M. Martinis, "Phase-resolved Crab studies with a cryogenic transition-edge sensor spectrophotometer," Astrophysical Journal 563, pp. 221-228 (2001).

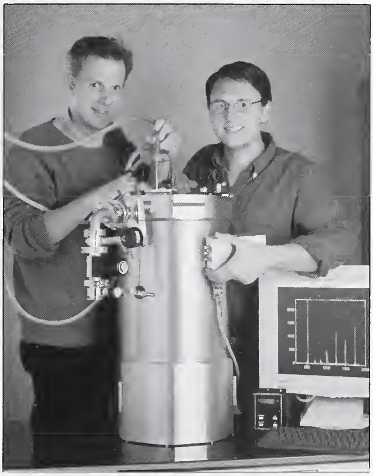
R.W. Romani, A.J. Miller, B. Cabrera, E. Figueroa-Feliciano, S.W. Nam, "First astronomical application of a cryogenic transition edge sensor spectrophotometer," Astrophysical Journal 521, pp. L153-L156 (1999).

Quantum Measurements

Cryogenic Sensors

Goals

To develop devices and systems for the measurement of electromagnetic signals using the unique properties of electronic devices operated at cryogenic temperatures.



Gene Hilton and Steve Deiker standing by an Adiabatic Demagnetization Refrigerator (ADR). The ADR is used to cool our transition edge sensor (TES) x-ray detector down to about 1/10th of a degree above absolute zero. The TES is used to provide extremely sensitive x-ray microanalysis of materials.

By operating at temperatures below 1 kelvin, a new generation of photon detectors is achieving unparalleled sensitivity. Because they operate at such low temperatures, these detectors are able to measure very small differences in the energy of photons. They also are able to take advantage of extremely low-noise superconducting amplifiers such as SQUIDs, further enhancing their performance.

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

Applications include ultra-high-resolution x-ray spectroscopy for materials analysis for the semiconductor industry and the development of large-scale arrays of cryogenic sensors for high-throughput imaging, and spectroscopy of electromagnetic radiation for materials analysis and astronomy. In each of these areas the Division is developing detector systems that will redefine the measurement abilities of currently available technology, often by orders of magnitude. Our goal is to continue developing groundbreaking detector systems for both industry and research groups.

Customer Needs

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

In addition, the astronomy community has an ever-increasing need for instruments capable of supplying extremely high energy sensitivity coupled with large-format arrays for imaging and photon collection. TES detector arrays promise to greatly expand the abilities of astronomers to study objects

Technical Contact:
Kent Irwin

Staff-Years (FY 2003):
14

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

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

ranging from solar flares, to supernova remnants, to the formation of galaxies. The Division has formed collaborations to transfer our TES technology into astronomical instruments with several institutions, including NASA, Stanford University, the Lockheed-Martin Solar Astrophysics Laboratory, and the UK Astronomy Technology Center.

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.

X-Ray Microanalysis

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

To make this technology available to the materials analysis community, NIST has licensed several patents to a U.S. company for commercialization. Additionally, NIST's Chemical Science and Technology Laboratory (CSTL) is using a prototype microcalorimeter system constructed by our group to improve its own materials-analysis capability.

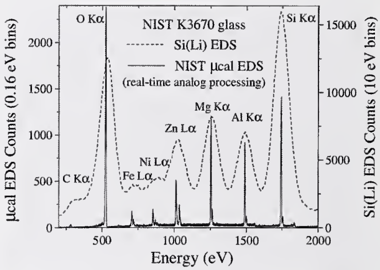
Technical Strategy

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

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

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

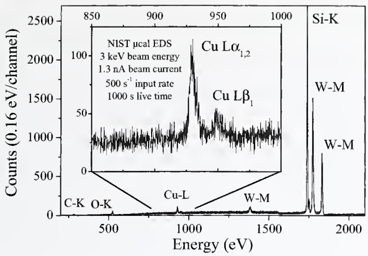
An important part of our effort is providing support to our existing customers, most notably the users of the prototype microcalorimeter system at CSTL in Gaithersburg, MD, and to the current patent licensees. We continue to provide expertise and training in detector and SQUID (readout electronic) operation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



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

While the performance of the detectors we have made is much better than existing energy dispersive detectors, improvements in energy resolution (particularly at higher energies) are both theoretically possible and desirable by the user community. Improvements in energy resolution require new understanding of the limitations on performance of microcalorimeter detectors. We have begun to explore novel detector geometries and materials. These include annular geometries to reduce edge effects that may produce some of the noise in detectors, as well as fabricating detectors using magnetic impurities to suppress the transition temperature of superconductors, rather than the bilayer technique. (The transition temperature of the films in most TES microcalorimeters is adjusted by depositing a think layer of normal metal on top of the superconductor to make a bilayer.)

In addition to improving our understanding by studying new single-pixel designs, we hope to improve and simplify our fabrication methods. One key advantage of the magnetically doped TES microcalorimeter is that the fabrication would require approximately half as many steps as the bilayer TES microcalorimeter. We are exploring this and other means to make TES microcalorimeters cheap and reliable to produce.



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

For many x-ray microanalysis applications, improvements in count-rate and collection area are far more important than further improvements in energy resolution. This can be achieved by the creation of multipixel arrays of detectors. In addition to the fabrication difficulties in making such arrays, the cold- and room-temperature electronics to read out the arrays must also be created. The work on the readout electronics (SQUID multiplexers, high-density wiring and room-temperature signal processing) is discussed in more detail in the section titled "Superconducting Electronics." We are currently exploring two means of developing arrays of Mo/Cu bilayer TES detectors, bulk micromachining and surface micromachining. These two methods require different modifications of our existing process, thus we are exploring both means of making arrays. We will test both concepts by June 2003.

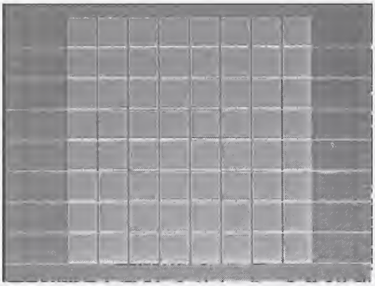
Accomplishments

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

■ World-Leading Energy Resolution Achieved – 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 on the previous page 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 CSTL 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.

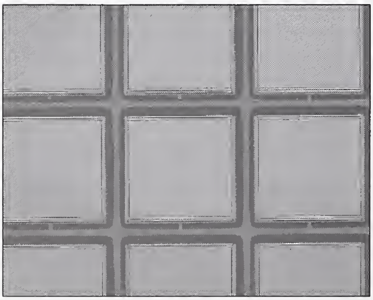
■ Partnerships with Semiconductor Companies Formed – We have completed several effective partnerships with companies in the semiconductor industry to demonstrate the usefulness of the microcalorimeter spectrometer for practical analysis. For example, in collaboration with researchers at Lucent Technologies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

■ Working X-ray Spectroscopy System Delivered to CSTL – To enable more advanced applications of this technology to materials-analysis problems requires coupling the spectrometer to state-of-the-art analytical tools, such as those available in CSTL at NIST-Gaithersburg. To this end, a working single-pixel spectrometer used in the above research has been delivered to Gaithersburg. The system is being used jointly with CSTL to continue microanalytical work on problems of interest to the semiconductor and other materials-intensive industries.



An 8x8 array of TES x-ray detectors fabricated using a surface micromachining technique. Each square pixel is 400 μm on a side.

■ New TES Materials Systems Developed – We have demonstrated two new materials systems suitable for a magnetically doped microcalorimeter: Mo doped with Fe and Al doped with Mn. In both cases we have demonstrated tenability of the transition temperature of the doped superconductivity over the range of interest. The iron doped molybdenum is created by ion-implanting Fe ions into films of Mo. The resulting T_c can be controlled with the ion dose. The Mn-doped Al has been produced in collaboration with the Magnetic Technology Division of EEEL. Here the films are produced by co-sputtering a highly Mn-doped Al target with a pure Al target. When detectors are produced using these methods, they should provide new insight into TES detector physics. Additionally these detectors may be simpler and more reliable to produce than those made by our conventional bilayer methods.



An array of x-ray TES detectors fabricated using a Deep Reactive Ion Etch (DRIE) process. Each square pixel is 400 μm on a side.

■ New Micromachining Capabilities Developed – In order to produce arrays of TES microcalorimeters, we have developed two micromachining methods compatible with our existing fabrication processes. In the first of these, surface micromachining, a sacrificial layer of poly-Si that was fabricated underneath the Si_3N_4 membranes and detectors is removed by a XeF_2 "plasma-less" etching technique. Prototype detectors fabricated by this method are shown at left. The second method, bulk micromachining, removes all of the substrate Si from beneath the Si_3N_4 and pixel using deep-reactive ion etching. A prototype array fabricated using this method is also shown at left.

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

Astronomical Instrumentation

The astronomy community has long been the driving force behind improvements in photon detection systems at all wavelengths. Because of TES detectors' extremely good sensitivity, they are obvious candidates to solve many problems faced by this community. The same x-ray detectors used in our microanalysis efforts, for example, are well suited to analyzing the x-ray spectra of supernova remnants and solar flares. By redesigning these detectors, they may be used as bolometers to measure far infrared and submillimeter radiation on ground-based telescopes, allowing astronomers to probe the evolution of galaxies and search for planets around other stars.

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

Technical Strategy

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

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

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

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

In addition the Division, in collaboration with the United Kingdom's Astronomy Technology Center, is developing both sensors and readout technology for the second Submillimeter Common User Bolometer Array (SCUBA-2). The SCUBA-2 instrument is designed to detect radiation from astronomical sources at wavelengths of 450 μm and 850 μm, and will be installed on the James Clerk Maxwell Telescope (JCMT) in Hawaii. This array will be, by orders of magnitude, the largest bolometer array ever deployed, having 12,800 individual pixels. It will allow astronomers to map the sky at speeds over 1,000 times faster than previously accomplished.

Accomplishments

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

- Deep Reactive Ion Etch Techniques Developed – We have used the Division's newly acquired Deep Reactive Ion Etcher (DRIE) to fabricate closely spaced pixels. This process replaces the anisotropic KOH etch we have used in the past. The KOH etch, while effective, etched along crystal planes in silicon wafers, producing sloped sidewalls and forcing a minimum separation between adjacent pixels. This DRIE etch produces vertical sidewalls, allowing pixels to be more closely spaced, and thus greater spatial resolution

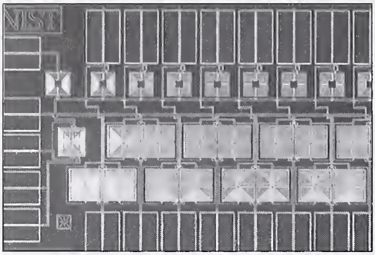
- X-ray TES Detector Delivered to LMSAL – We have delivered a single pixel x-ray detector and SQUID to LMSAL. This detector will be used by LMSAL to develop their own cryogenic facilities and design a rocket payload for solar observations.

- SCUBA-2 Test Pixel Fabricated – We have fabricated a SCUBA-2 test pixel that met or exceeded all of the design specifications for the SCUBA-2 project.

Superconducting Electronics

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

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



A photograph of a 32-channel SQUID multiplexer chip fabricated at NIST. On the chip are 32 first-stage SQUID amplifiers and one second-stage series-array SQUID amplifier. The area shown is 4 mm by 6 mm.

Technical Strategy

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

NIS Microrefrigerators could make cryogenic sensors much more practical to deploy in industrial and analytical laboratory settings.

Accomplishments

- SQUID Multiplexer Deployed at the CSO in Mauna Kea – We have demonstrated an 8-channel multiplexer on the CSO telescope in Mauna Kea, Hawaii. This is the first astronomical use of SQUID multiplexing. The multiplexer performed well, and will be used for further observations.

- Second-Generation SQUID MUX Tested – We have successfully fabricated and tested a second-generation SQUID MUX chip, which has significantly improved speed and performance. This chip will be integrated with a small x-ray detector array by June 2003.

- Room-Temperature Digital Feedback Electronics Developed – We have developed a room-temperature digital feedback system to read out the SQUID MUX. This system is critical for deployment of large multiplexed TES systems.

NIS Microrefrigerators

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

Technical Strategy

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

Accomplishments

- Developed Photolithographic NIS Process – We have recently developed a photolithographic fabrication process for NIS junctions. This process reliably produces junctions whose smallest dimensions are 5 µm – 10 µm. Junction quality is extremely high: the leakage current is 0.3 % of the tunneling current even for barrier transparencies as low as 1,000 Ω (µm)^2. We are currently testing our first set of devices laid out as complete refrigerators.

New Directions

The Division is currently investigating several new cryogenic detector applications and technologies.

Technical Strategy

Large arrays of x-ray microcalorimeters will be able to acquire high-quality spectra in a fraction of a second. This will make it possible for the first time to study the evolution of rapidly changing x-ray spectra at high energy resolution. Such capability would be revolutionary for in-process monitoring in which, for instance, the evolving materials properties of a film are studied during deposition. We are exploring this possibility in conjunction with CSTL at NIST-Gaithersburg.

In addition, two new detector technologies are being investigated. We are developing magnetic calorimeters in conjunction with the Magnetic Technology Division of EEEL. In a magnetic calorimeter, a SQUID is used to measure the change in magnetization of a sample of material when it is heated by an incident x-ray photon. Because this type of calorimetry is non-dissipative, it may offer the possibility of greatly improved energy sensitivity. The expertise available in the Division in fabrication and SQUID readout, combined with the magnetic films expertise in the Magnetic Technology Division, makes us ideally suited for exploring this new technology.

Another promising technology is that of kinetic inductance detectors. In this type of detector, changes in the inductance of a superconductor are created by the energy deposited by an incident photon. This technology has seen a recent revitalization, and may allow for improvements in performance over TES detectors in both speed and array size. Again, the superconducting fabrication skills available in the group make this an attractive project for us.

Patents

- "The Use of Superconductor-Insulator-Normal (SIN) Tunnel Junctions in Superconducting Quantum Interference Device (SQUID) Multiplexers," disclosure submitted, April 2000.

- "Superconducting Transition-Edge Sensor with Weak Links," issued May 2001.

- "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.

- "Particle Calorimeter with Normal Metal Base Layer," issued June 1997.

Recent Publications

K.D. Irwin, "SQUID multiplexers for transition-edge sensors (review)", Physica C, 368, 203 (2002).

R.E. Geer, D. Wu, and D.A. Wollman, "High-resolution energy-dispersive x-ray spectroscopic analysis of ultrathin ion diffusion barriers using microcalorimetery," J. Appl. Phys., 91, 1099 (2002).

K.D. Irwin, L.R. Vale, N.F. Bergren, S. Deiker, E.N. Grossman, G.C. Hilton, S.W. Nam, C.D. Reintsema, and D.A. Rudman, "Time-division SQUID multiplexers," Proc. 9th Int'l Workshop on Low-Temperature Detectors, AIP Conf. Proc. 605, 301 (2002).

R.E. Geer, D. Wu, and D.A. Wollman, "High-resolution EDS analysis of ultra-thin TaSiN diffusion barriers for Cu metallization using microcalorimetry," Proc. IEEE 2001 Int'l Interconnect Tech. Conf., 3-6 June 2001, Burlingame, CA, pp. 192-194 (2001).

S. Deiker, J. Chervenak, G.C. Hilton, K.D. Irwin, J.M. Martinis, S. Nam, and D.A. Wollman, "Transition edge sensor array development," IEEE Trans. Appl. Supercond. 11, pp. 469-472 (2001).

G.C. Hilton, J.M. Martinis, K.D. Irwin, N.F. Bergren, D.A. Wollman, M.E. Huber, and S.W. Nam, "Microfabricated transition-edge x-ray detectors," IEEE Trans. Appl. Supercond. 11, pp. 739-742 (2001).

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, pp. 184-187 (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 2 eV energy resolution at 1.5 keV," Nuclear Instruments and Methods in Physics Research A 444, pp. 145-150 (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).

D.A. Wollman, S.W. Nam, G.C. Hilton, K.D. Irwin, N.F. Bergren, D.A. Rudman, J.M. Martinis, and D.E. Newbury, "Microcalorimeter energy-dispersive spectrometry using a low voltage scanning electron microscope," J. Microscopy 199, pp. 37-44 (2000).

The expertise our group has in cryogenic detectors and superconducting electronics makes us ideal to explore new detector technologies and applications.

Quantum Measurements

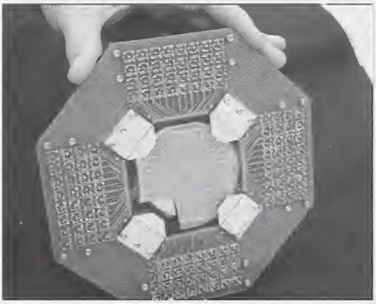
Technical Contact:
Erich Grossman

Staff-Years (FY 2003):
6

Terahertz Technology

Goals

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



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

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

Customer Needs

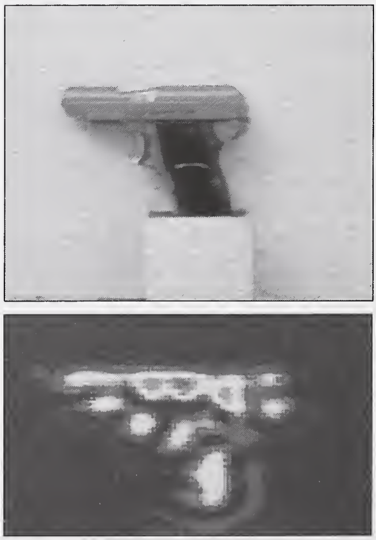
The U.S. aerospace and defense industries are being pushed toward both higher performance and faster, less expensive systems. Devices originally developed for cryogenic electronics, in particular cryogenic bolometers and tunnel diodes, are often useful in a wide variety of metrological applications, 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 IR technology for the benefit of these industries, either directly through collaborative research and development programs, or indirectly, by improving the metrological capabilities of other NIST Divisions, which in turn make the results available to U.S. industry.

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

Technical Strategy

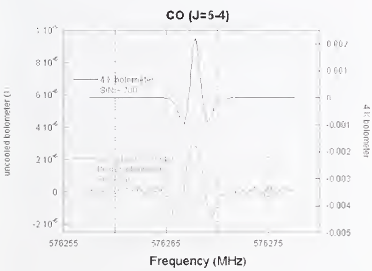
The work of this project focuses particularly on bolometric detectors, initially developed for cryogenic electronic applications, but also useful in the detection or frequency conversion of radiation from millimeter to infrared wavelengths.

Some projects do not require the very highest sensitivity but exploit the same antenna-coupled bolometer strategy. An example is millimeter-wave imaging for the detection of concealed weapons (clothing is transparent at millimeter wavelengths). In collaboration with EEEL's Electricity Division and the Office of Law Enforcement Standards (OLES), we are developing an actively illuminated imaging system for this application, based on a full wafer-scale array of several hundred antenna-coupled bolometers. By early 2003, we will demonstrate real-time readout of our initial 120-element focal plan array. The technical emphasis in this case is on development of a practical system, rugged enough and low enough in cost to allow for field deployment, for example with mobile police units or in airports.



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

In addition, we are working on the application of uncooled terahertz bolometer arrays to analyze and diagnose problems in the etching plasmas used for semiconductor manufacturing. These plasmas typically contain a number of molecular and ionic species, whose concentrations and temperatures can be accurately monitored by spectroscopy on their pure rotational transitions, which lie in the terahertz spectral region. A collaborative program with NIST's Physics Laboratory, funded by the NIST Advanced Technology Program (ATP), was started in 2001 to demonstrate the usefulness of this technique as an industrial plasma diagnostic, and to develop a practical system that can be applied to it. A key part of this program is the development of bolometer arrays with sufficient sensitivity to perform the spectroscopy, but which are not cryogenically cooled, and are therefore practical for industrial use. Based on prior work done for other programs, a detector system based on uncooled Nb bolometers has been designed and built; results from an example device are shown in the next figure. By mid-2003, we will perform a side-by-side comparison of Nb and semiconducting VO_2 based microbolometers at 0.6 THz.



Uncooled antenna-coupled microbolometer and spectra of CO, a low concentration reaction product in an CHF_3 plasma, measured in the Gaithersburg Gaseous Electronics Conference (GEC) reactor.

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

Far-infrared spectroscopy at the highest levels of sensitivity and spectral resolution has traditionally been accomplished with heterodyne techniques, in which the weak signal to be measured is combined with a strong "local oscillator" and focused onto a detector or "mixer." The signal at the difference frequency is then measured with an ultra-low-noise detection system. A program is underway to develop ultra sensitive mixer elements based on superconducting hot-electron bolometers (HEBs). As with transition-edge bolometer arrays, a major application for these mixers lies in space-based remote sensing. HEBs formed of thin films of niobium and niobium nitride have already demonstrated sensitivities within a factor of 5 of the fundamental quantum limit. The focus of our research, and of the most recent progress in the state of the art, lies in extending the frequency coverage of this measurement technique above 2 THz, allowing measurement of a wider variety of species, and in developing integrated heterodyne arrays.

Accomplishments

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

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

Our nano-metal-insulator-metal (MIM) diodes have clearly rectified 10 μm infrared radiation.

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

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

Recent Publications

S. Nolen, C.D. Reintsema, E.N. Grossman, "Slot-ring antennas with a planar backshort designed for millimeter-wave imaging applications," submitted to IEEE Antennas and Propagation Lett. (in press).

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

E. Gerecht, C.D. Reintsema, E.N. Grossman, A.L. Betz, and R.T. Boreiko, "Superconducting Nb DHEB mixer arrays for far-infrared spectroscopy," Proc. 12th Intl. Symp. on Space Terahertz Technology, 12-16 Feb 2001, San Diego, CA, pp. 168-176 (2001).

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

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

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

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., 48(4), 712 (2000).

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, v. 3795, 279 (1999).

C.D. Reintsema, E. N. Grossman, and J.A. Koch, "Improved VO_2 microbolometers for infrared imaging: operation on the semiconducting-metallic phase transition with negative electrothermal feedback," Proc. SPIE v.3698, pp. 190-200 (April 1999).

Quantum Measurements

Emerging Electronic Materials

Goals

To develop measurement techniques that aid and accelerate the incorporation of new thin-film materials and devices in electronic applications.

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

Advances in the microelectronics industry require a continual supply of new materials with unique properties that can be exploited to improve device performance or that enable entirely new devices to be created. To incorporate these materials into new technologies requires knowledge of their electronic properties. Often, full characterization of these materials requires the development of new measurement techniques, data analysis methods and material property modeling. The overall goal of this project is to aid and accelerate the development and incorporation of new thin-film materials and devices for electronic applications. At present the focus of the project is on emerging materials of interest to microwave applications, especially for the telecommunications industry. We are working primarily on new high-temperature superconducting (HTS) thin films, tunable ferroelectric thin films, and microelectromechanical systems (MEMS) structures. The Division has developed standards and new measurement methods to characterize and qualify thin films and devices of these materials for microwave applications, providing the measurement techniques and engineering parameters necessary to design new devices with these materials.

Customer Needs

This research supports the wireless telecommunications industry through the development of measurement techniques for emerging industries that are incorporating new materials (such as high-temperature superconductors and tunable ferroelectrics) into new devices and circuits. For high-temperature superconductor microwave standards development, we actively collaborate with U.S. and international standards laboratories to exchange materials and make comparative measurements. We also work with other NIST divisions that are responsible for standards and measurement techniques in areas such as microwaves and time and frequency standards. We collaborate with EEEL's Radio-Frequency Technology Division to improve both linear and nonlinear microwave measurement and characterization techniques for thin-film materials and devices, particularly at cryogenic temperatures. Our work has attracted the interest of other U.S. government agencies such as NASA and the Office of Naval Research (ONR), and we are providing them with research support and direction to help advance their programs.

Technical Strategy

Microwave measurements and devices

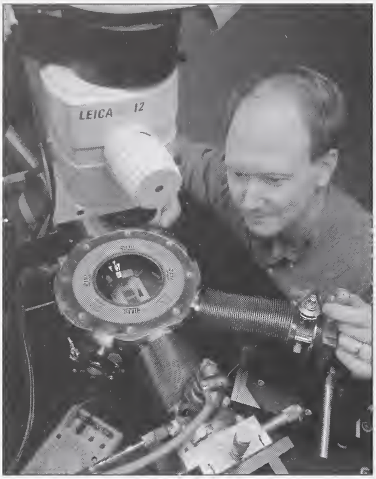
Our research projects are selected for their importance for standards improvement and development and their impact in the commercial sector. We also look for projects with a strong component of innovative science and technology. Our research has resulted in the development of fabrication processes, testing capabilities, and theoretical competence for advanced cryogenic materials and devices at rf, microwave and millimeter-wave frequencies. We use pulsed laser deposition to grow novel thin-film materials and take those materials through the device design and fabrication to final test devices. We have developed microwave measurement capabilities for unpatterned superconducting films using a sapphire-loaded dielectric cavity resonator and for planar devices using a cryogenic microwave probe station (shown on the next page). The probe station allows us to develop temperature-dependent measurement techniques and provide test results on new materials in actual devices, rather than as unpatterned thin films.

Technical Contact:
James Booth

Staff years (FY 2003):
5

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

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



Jim Booth operates the cryogenic microwave probe station that enables rapid temperature-dependent measurements of a variety of emerging materials and devices.

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

By collaborating with EEEL's Radio-Frequency Technology Division, we hope to improve both linear and nonlinear microwave measurement and characterization techniques for thin-film materials and devices. Our research also includes developing superconducting devices to be used as model nonlinear elements for detailed evaluation using a Nonlinear Network Measurement System in collaboration with the Nonlinear Device Characterization Project in the Radio-Frequency Technology Division.

We are participating in developing a new standard for measuring the surface resistance R_S of ultra-low-loss superconducting thin films. This is under the auspices of the International Electrotechnical Commission (IEC) and the Versailles Agreement on Advanced Materials and Standards (VAMAS). Development and improvements in our implementation of the proposed international standard technique will continue in 2003.

In addition, the Division is investigating new materials and device structures for advance microwave applications. Our development of a superconducting microwave power limiter is of interest to a variety of military applications. We continue to characterize and model low-loss electronically tunable microwave materials (ferroelectrics). Of particular interest for these materials are improved broadband permittivity measurements. We will work with the Radio-Frequency Technology Division to take advantage of their new 100 GHz network analyzer capabilities for these measurements. In 2003 we will begin exploring microwave MEMS structures.

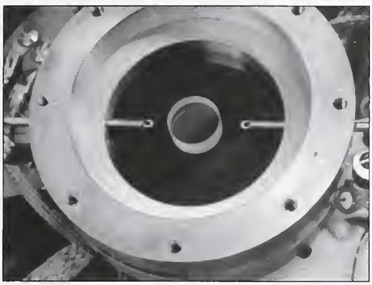
Micromachining and MEMS

MEMS and nanoelectromechanical systems (NEMS) are the enabling technologies for entire new generations of electronic systems and measurement devices. Novel sensor and metrology technologies benefit from the ability to use integrated-circuit fabrication paradigms in constructing mechanical devices. Our work in this area also includes measurement techniques for evaluation of novel MEMS structures at rf and microwave frequencies. We will continue our research efforts in support of the NIST Time and Frequency Division's work to develop a fully micromachined ion trap for time standards and quantum computing. We will also collaborate with other projects in the Division to apply MEMS technology to a variety of problems.

Accomplishments

Microwave measurements and devices

- International Standard for HTS Surface Resistance Measurement — Sapphire-loaded dielectric cavity resonators (shown on the next page) are under consideration by the IEC as a possible standard for the measurement of the surface resistance R_S of HTS thin films. Previously we have participated in round-robin testing of this technique with Japan, and good agreement was observed for values of the superconductor R_S and the sapphire loss tangent. In the past year we have made two significant improvements in NIST's capability for determining R_S by this technique. We have completed new measurements of the microwave loss tangent of sapphire at cryogenic temperatures using the HTS resonator with two different length sapphire rods. While the losses in sapphire are extremely small, the surface resistance of HTS films is so low that losses in the sapphire are a major source of error in the current measurement. We have also implemented an improved method for determining Q_o of the resonator, the Transmission-Mode Q Factor (TMQF) technique. The accuracy of R_S depends almost exclusively on the uncertainty in Q_o, making improvements in Q_o determination critical. The TMQF method can provide better than 1 % accuracy in Q_o, an improvement by a factor of 2 over previous methods.



Sapphire-loaded dielectric resonator for measuring R_s of HTS films. The sapphire puck is sitting on a black YBCO thin film.

- Calibration Devices for Nonlinear Phase Measurements — In collaboration with the Nonlinear Device Characterization Project in the Radio-Frequency Technology Division, we have succeeded in measuring for the first time the phase of the nonlinear signal generated by HTS devices at microwave frequencies. The lack of appropriate nonlinear test devices has made it difficult to characterize the new Nonlinear Network Measurement System, and this superconducting device is being evaluated for this application. In addition, the value of the phase of the nonlinear signal provides important information on the origin of the nonlinear response in HTS materials, a limiting problem in HTS microwave devices. In 2003 we plan on developing improved circuits with the goal of more accurate nonlinear phase measurements of HTS-based devices.

View of two 40 GHz probes and a sample of YBCO devices in the probe station. Devices such as these are used for the nonlinear phase measurements and the microwave power limiter.

- Superconducting Microwave Power Limiter Developed — We have designed, fabricated and tested an HTS Superconducting Microwave Power Limiter (SMPL) for the purpose of protecting ultra-sensitive analog-to-digital electronics in very-high-performance receivers (such as on military platforms) from over-power conditions such as lightning strikes. The device makes use of the microwave current-induced transition from the very-low-loss superconducting state to the high-loss normal state, and has been shown to have extremely wide bandwidth (> 40 GHz) with constant impedance over the entire band. Reversible operation (self-resetting) has been demonstrated at microwave powers up to 10 watts, and switching speeds have been measured to be less than 1 microsecond. Since no other power limiter exists with this remarkable performance, this device is of interest for a variety of military applications.

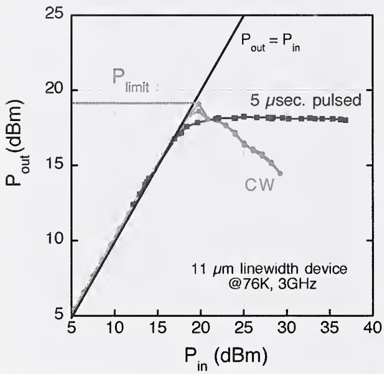
- Dynamic Effects in Tunable Dielectric Thin Films — Recent measurements in our project of ferroelectric thin films have revealed large relaxation effects at high microwave frequencies that have not been previously observed. Ferroelectric thin films are potentially valuable because they possess a dielectric permittivity that can be modified by the application of a relatively modest bias voltage. Such a tunable dielectric material would enable very fast tuning of microwave elements such as filters, and would also enable cheaper phased-array antennas. Our measurements have revealed that the high microwave losses that to date have limited the application of ferroelectric thin films are at least in part due to coupling of energy into lattice modes of these materials, and are thus intrinsic to the class of ferroelectrics being studied (e.g.. $SrTiO_3$). In collaboration with Radio-Frequency

"Dr. Beall has generously helped us with technical advice and processing assistance which in turn has had a significant impact on advancing our prototypes. We hope our relationship with NIST will continue."

- Astralux, Inc., Boulder, CO

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

Technology Division we will be extending the frequency for these measurements to above 100 GHz in early 2003 in an effort to further understand this behavior.



Pulsed and CW power through a Superconducting Microwave Power Limiter operating at 76 K and 3 GHz. Onset of limiting behavior is near 20 dBm.

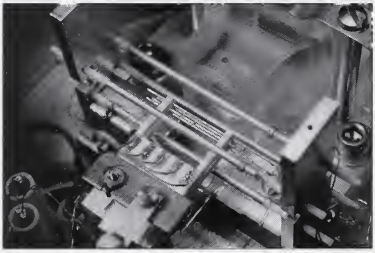
■ Tuning Time for Ferroelectric Films — A major issue in the application of tunable dielectric thin films for microwave elements is the response times over which one can vary the permittivity using an applied bias field. We have performed nonlinear harmonic generation measurements as a way of deducing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

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

Micromachining and MEMS

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

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



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

■ Surface Micromachining for Cryogenic Detectors — Large arrays of cryogenic detectors have applications to a variety of x-ray and infrared detector projects. One option for creating such large arrays is to use surface micromachining. Using the recently developed MEMS capability in the Division, we have demonstrated 64-element thermal isolation platforms above a Si substrate, and have begun integrating these devices with detectors. Further details on this project are described elsewhere in this publication.

Recent Publications

J.C. Booth, S.A. Schima, and R.H. Ono, "A self-attenuating superconducting transmission line for use as a microwave signal limiter," to appear in IEEE Trans. Appl. Supercon. Vol. 13 (in press).

J.C. Booth, S.A. Schima, and D.C. DeGroot, "Phase-sensitive measurements of the nonlinear microwave response in YBCO thin film devices," to appear in IEEE Trans. Appl. Supercon. Vol. 13 (in press).

J.C. Booth, S.Y. Lee, K.T. Leong, J.H. Lee, J. Lim, H.N. Lee, S.H. Moon, and B. Oh, "Microwave surface impedance and nonlinear properties of MgB_2 films," to appear in IEEE Trans. Appl. Supercon. Vol. 13 (in press).

K.T. Leong, J.C. Booth, and S.Y. Lee, "Influence of impedance mismatch effects on measurements of unloaded Q factors of transmission mode dielectric resonators," to appear in IEEE Trans. Appl. Supercon. Vol. 13 (in press).

G.C. Hilton, J.A. Beall, S. Deiker, L.R. Vale, C.D. Reintsema, and K.D. Irwin, "Surface micromachining for arrays of transition-edge sensor based detectors," to appear in IEEE Trans. Appl. Supercon. Vol. 13 (in press).

J.C. Booth, R.H. Ono, I. Takeuchi, and K.-S. Chang, "Microwave frequency tuning and harmonic generation in ferroelectric thin film transmission lines," Appl. Phys. Lett. 81: pp. 718-720 (2002).

J.C. Booth, L.R. Vale, R.H. Ono, "Comparative studies of the microwave nonlinearities in high temperature superconducting films and devices," Physica C Vol. 357-360, pp. 1516-1520 (2001).

H. Shimakage, R.H. Ono, L.R. Vale, "Interface engineered Josephson junctions optimized for high Jc," IEEE Trans. Appl. Supercon. 11(2), pp. 4032-4035 (2001).

J.C. Booth, L.R. Vale, R.H. Ono, "On-wafer measurements of nonlinear effects in high temperature superconductors," IEEE Trans. Appl. Supercon. 11(1), pp. 1387-1391 (2001).

J.C. Booth, L.R. Vale, R.H. Ono, J.H. Claassen, "Power dependent impedance of high temperature superconductors thin films: relation to harmonic generation," J. Supercond. 14(1), pp. 65-72 (2001).

R. Rafac, B. Young, J. Beall, W. Itano, D. Wineland, J. Bergquist, "Sub-Dekahertz ultraviolèt spectroscopy of $^{199}Hg^{+}$," Phys. Rev. Lett. vol. 85, pp. 2462-2465 (2000).

J.C. Booth, J.A. Beall, D.A. Rudman, L.R. Vale, R.H. Ono, "Geometry dependence of nonlinear effects in high temperature superconducting transmission lines at microwave frequencies," J. Appl. Phys. vol. 86, pp. 1020-1027 (July 1999).

Nanoscale Fabrication

Technical Contact:
James Beall

Staff-Years (FY 2003):
2

Our facilities for fabricating integrated circuits are essential to nearly all of the work in the Division. We maintain a research-class facility specialized in the fabrication of complex superconducting circuits, nanoscale electronics and MEMS structures. Beginning with computer-aided design, we use electron-beam and optical lithography to make structures smaller than 50 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 have recently added tools for fabricating MEMS that are essential for the creation of many of our ultra-sensitive instruments, and for micromachined ion traps for future clocks.

Maggie Crews inspects a mask generated in our new Optical Pattern Generator.

Our facilities are available as an "open-shop" operation. After appropriate training, all of our staff can personally use them to fabricate the devices needed for their research. We keep the facility and the processes flexible and under the control of each individual user to avoid constraining research and to allow maximum creativity. Our past accomplishments are testimony to the success of our approach.

In the past year we have upgraded our optical pattern generator (shown above) to a modern instrument capable of making masks with feature sizes of 1.5 micrometers. Having an in-house mask-making facility allows very rapid turnaround, which improves productivity and encourages creativity. 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 50 nm. Our capability in electron beam lithography is currently being expanded with the addition of a second scanning electron microscope with wafer-scale stages and load lock.

Our thin-film deposition and etching tools are similar to those found in a semiconductor fabrication facility, but they have been optimized for normal and superconducting metal fabrication. We have general purpose and dedicated sputtering and e-beam systems to deposit multilayers of metals. We use electron cyclotron resonance (ECR) plasma-enhanced chemical vapor deposition (CVD) of SiO_2 for circuit insulation. Dry etching is performed in standard RIE and plasma etching tools.

Leila Vale examines a 76 mm $Nb/Al_2O_3/Nb$ trilayer wafer that will be used for Josephson junction circuit fabrication.

We have recently installed the tools necessary to fabricate MEMS structures. We use a set of research-scale tube furnace reactors (5" capable), for wet and dry silicon oxidation, solid-source diffusion of boron, low-stress silicon nitride/polysilicon low-pressure chemical vapor deposition (LPCVD), and LPCVD of low-temperature oxide. We have added two silicon dry-etch tools for micromachining of Si. We use xenon difluoride gas to rapidly and isotropically etch silicon. This year we have also acquired a deep silicon reactive ion etch system to allow highly anisotropic etching of Si.

Topics Covered by Organizational Units

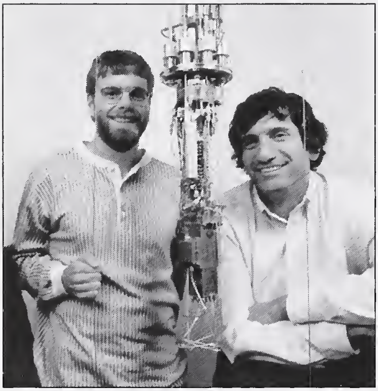
The following table shows which organizational unit(s) work on each of the research topics covered in this book. For information on the staff of the organizational units, please see Appendix D.

Topic	Project Name	Project Leader
Quantum Standards:		
Quantum Voltage	Quantum Voltage	Samuel Benz
Noise Thermometry	Quantum Voltage	Samuel Benz
	Quantum Information and Terahertz Technology	Richard Harris (acting)
Single Electronics	Nanoscale Cryoelectronics	David Rudman
Physics of Quantum Hall Resistance Standards	Nanoscale Cryoelectronics	Richard Harris (acting)
Quantum Information:		
Quantum Computing	Quantum Information and Terahertz Technology	Richard Harris (acting)
Quantum Communication	Quantum Information and Terahertz Technology	Richard Harris (acting)
Quantum Measurements:		
Cryogenic Sensors	Cryogenics Sensors	Kent Irwin
Terahertz Technology	Quantum Information and Terahertz Technology	Richard Harris (acting)
Emerging Electronic Materials	Nanoscale Cryoelectronics	David Rudman

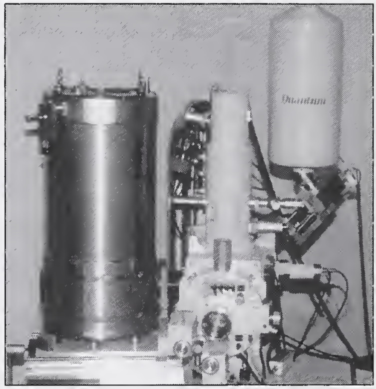
Appendix A: Experimental Systems and Instruments

A partial list of our measurement facilities and capabilities:

Experimental environments include two dilution refrigerators (DR) for temperatures down to 30 mK and 7 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. These refrigerators are used to provide cooling for much of the experimental work that takes place in the Division.



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 characterizing 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: Post-Doctoral Opportunities

NIST offers post-doctoral associateships in collaboration with the National Research Council (NRC). Research topics and associated advisers for the Electromagnetic Technology Division are listed below. 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 post-doctoral appointments.

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

Adviser: Erich N. Grossman

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

Applications of Superconducting Integrated Circuits and Josephson Junction Arrays

Advisers: Samuel P. Benz, Paul D. Dresselhaus

We are developing superconducting integrated circuit technology and systems using Josephson junction arrays. These are the most practical applications of single-flux-quantum-based superconductive electronics, and our project leads the field in their implementation into systems. Some of these systems include voltage standards, digital-to-analog converters, and arbitrary waveform synthesizers. We currently focus on the construction of a pulse-quantized arbitrary waveform synthesizer to be used as an ac and dc voltage standard source and for other applications that require digitally synthesized waveforms with precise control of voltage, frequency, and phase. Applicants should be interested in some or all of the following areas: nanofabrication, broadband (dc to 20 GHz) circuit design and construction, digital waveform synthesis, and cryogenic packaging.

Functional Materials and Systems for Radio Frequency/ Microwave/Millimeter-Wave Electronics

Advisers: James C. Booth, James A. Beall, David A. Rudman

Functional materials and systems have key electronic properties that can be manipulated by changing external variables. Examples are voltage-tunable dielectric/ferroelectric films (for application to electronically tuned microwave filters and delay lines), high-Tc superconductor Josephson junctions (for application to THz-frequency mixers), and microelectromechanical systems (for application to radio-frequency and microwave switches and circuit elements). These materials and systems hold promise for a new generation of high-performance electronics, enabling new applications because of their inherent functionality. For all these materials and systems, the key to optimizing device performance is to understand the intricate connections between material growth and device fabrication processes and electronic performance of the resulting structure(s). We exploit our thin-film growth and fabrication facilities to create novel device structures that either possess unique properties or allow for the extraction of the relevant electronic properties of the constituent materials. A vital part of this effort is the development of new measurement techniques (such as cryogenic microwave wafer-probing techniques) to evaluate device performance and obtain fundamental material properties (such as relative permittivity or conductivity) as a function of frequency, temperature, and applied power. We are also developing novel device concepts that exploit the unique properties of these materials and systems, individually, or in combination with each other and with other materials and systems.

Linear and Nonlinear Microwave Response of Oxide Thin Films and Devices

Advisers: James C. Booth, David A. Rudman

Thin-film oxide materials and devices possess extraordinary properties that could revolutionize many different areas of modern electronics. For example, the low microwave surface resistance R_s of the high-T_c superconductors makes them ideal for a wide variety of high-performance devices and circuits. However, fundamental questions still remain with regard to the origins of losses in these materials at microwave frequencies, as well as to the origin of the nonlinear response that is observed under large signal conditions. We address these fundamental questions with measurements of the linear properties (surface resistance) as well as the nonlinear response (third-order intercept and intermodulation) of unpatterned thin films and also patterned devices at low to moderate power levels. Other measurements (such as inductive critical-current measurements and high-power microwave transmission measurements) address the response of these materials under high-power conditions. In all of the above measurements, special attention is paid to the relationship between the electronic properties of interest and film growth and device fabrication processes. Our goals are to understand the physical origins of both the losses and nonlinearity in these systems while simultaneously developing processes to optimize performance of microwave devices incorporating these materials.

High-T_c Superconductors: Devices, Device Physics, and Circuits

Advisers: James C. Booth, David A. Rudman

A major challenge to the development of high-temperature superconducting (HTS) electronics is the reproducible active device, which is either a Josephson junction or a three-terminal "transistor" analog. Another hurdle is the difficulty in fabricating multilayer circuits where level-to-level epitaxy is required for insulators and wiring, as well as the device layers. We have worked on several HTS Josephson junction approaches and developed techniques for fabricating multilayer circuits that incorporate these junctions. Applications of interest include high-frequency mixers and detectors, voltage standards, and high-speed switching. Integration of active devices into microwave and millimeter-wave monolithic circuits can take advantage of our research on passive applications of HTS circuits.

Micromachined Materials and Devices for Metrological Applications

Advisers: James C. Booth, David A. Rudman, James A. Beall

Recent advances in silicon micromachining techniques have made possible a host of new metrological applications based on microelectromechanical systems. We are currently employing Si micromachining technologies to fabricate devices and structures for use in applications such as ion traps, radiation detectors, bolometers, magnetometers, and microfluidic devices. The breadth of our Division resources allows metrology solutions involving high- or low-temperature superconductors, ultra-low-temperature measurements, SQUID readouts, as well as room-temperature thin-film electronics. Our fabrication facilities include high-temperature furnaces for oxidation, diffusion and LPCVD of low stress silicon nitride, polysilicon, and low-temperature oxide as well as optical and electron beam photolithography, deposition, and etching equipment (including a deep RIE). In addition to the applications above, we are interested in applying our Si micromachining technology to a number of different areas, including radio-frequency and microwave devices.

Physics and Applications of Single Electron Tunneling Devices

Adviser: Mark W. Keller

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

A Capacitance Standard Based on Counting Electrons

Adviser: Mark W. Keller

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

Characterization of Single Photon Turnstiles Using Single Electron Tunneling Devices

Adviser: Mark W. Keller

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

Superconducting Detectors for X-Ray through Millimeter Photons

Advisers: Kent D. Irwin, Carl D. Reintsema, Gene C. Hilton

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

High-Resolution Microcalorimeters for X-Ray Microanalysis

Advisers: Gene C. Hilton, Kent D. Irwin, Carl D. Reintsema

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

Superconducting Quantum Interference Device (SQUID) Development

Advisers: Kent D. Irwin, Carl D. Reintsema, Gene C. Hilton

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

Thin-Film Refrigeration Using Normal-Insulator Superconductor Tunnel Junctions

Adviser: Carl D. Reintsema

We are developing a miniature, solid-state refrigerator using superconducting thin-film technology. In particular, we use the quantum-mechanical tunneling of electrons through a Normal-Insulator-Superconductor (NIS) junction to produce cooling. Our goal is to build a refrigerator that can cool a payload of cryogenic detectors from 0.3 to 0.1 Kelvin. An integrated package of refrigerator and detectors is desirable for commercial microanalysis. In order to design devices, candidates will acquire a solid understanding of electronic and thermal transport at very low temperatures. In order to fabricate devices, candidates will master conventional lithographic techniques, the preparation of unusual substrates, and, possibly, MEMS technology. We are also interested in pursuing the potential of NIS junctions as superconducting transistors.

Quantum Computing using Superconducting Devices

Adviser: John M. Martinis

A new class of powerful computation algorithms have been proposed based on logic operations in quantum mechanical systems. Experimental implementation will require a coherence time of the quantum bits of information (qubits) long enough to perform calculations, a state measurement of the qubits, and a method to sequence controlled interactions of qubit pairs. While the most dramatic progress to date has been made with trapped-ion systems, solid-state quantum devices should in principle have distinct advantages for the creation of a practical large-scale "quantum computer". The superconducting state represents a rich system to explore for this purpose because of its inherently low dissipation. Using our state-of-the-art superconducting fabrication facility, we have made single qubit devices based on Josephson junctions. Research opportunities include fabricating novel superconducting qubit devices, exploring the physics of coherence and coupling between qubits, and engineering multi-qubit devices. Our goal is to build a 100 to 1000 qubit quantum computer that can perform 1000 to 10000 logic operations.

Appendix C: Awards and Recognition

Note: * 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 device (SQUIDs)
Industrial Research-100 Award	Clark A. Hamilton, Robert J. Phelan*, Gordan W. Day*, John Geist*, and B. McIntosh*	1975	
NBS 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
NBS 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)
NBS 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

Award	Recipient	Date	Notes
EEEL Outstanding Paper Award	Samuel P. Benz and Charles J. Burroughs	1991	"Coherent Emission for 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
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 Electon Pump," *Physical Review Letters,* Volume 72, Number 6, pp. 904-907 (7 February 1994)
IEEE Electrotechnology Transfer Award	Clark A. Hamilton	1995	For providing services that collectively have resulted in the practical introduction of a new voltage standard based on Josephson-junction arrays into industry and the general metrology community of measurement systems.
IEEE Fellow	Clark A. Hamilton	1995	For his key role in developing the Josephson voltage standard & other novel superconducting circuitry.
EEEL Measurement Services Award	Clark A. Hamilton	February 1995	
EEEL Outstanding Paper Award	Mark W. Keller, John M. Martinis, Neil M. Zimmerman, and Andrew H. Steinbach	1996	"Accuracy for Electron Counting Using a 7-Junction Electron Pump," *Appl. Phys. Lett.* 69 (12), 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-blockade circuits for single-electron counting
Silver Medal	John M. Martinis	December 1996	For establishing the fundamental accuracy of Coulomb-blockade circuits for single electron counting, providing the basis for new intrinsic standards
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

Award	Recipient	Date	Notes
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, Part 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, pp 1706-1709, 10 September 1999
Presidential Early Career Award for Scientists and Engineers	Mark W. Keller	October 2000	In recognition for his research on using the fundamental quantum properties of nature to create new standards and tools for measurement science
NIST Condon Award	Mark W. Keller, John M. Martinis, Ali Eichenberger, Neil Zimmerman	November 2000	For distinguished achievement in written exposition
William A. Wildhack Award	Clark Hamilton	October 2001	National Conference of Standards Laboratories
NIST Fellow Award	John M. Martinis	December 2001	In recognition for his excellence as a scientist and for the contributions he has made in both science and technology
Symbols, Units, Nomenclature, Atomic Masses and Fundamental Physical Constants (SUNAMCO) Award	Clark Hamilton	2001	International Union of Pure and Applied Physics (IUPAP)
2001 Best Paper Award ASME International, Heat Transfer Division	David Rudman and Leila Vale	2001	"Far-infrared transmittanee and reflectance of $YBa_2Cu_3O_{7-\delta}$," *J. Heat Transfer,* vol. 121, p. 844 (1999)

Award	Recipient	Date	Notes
Kurt F.J. Heinrich Award	David Wollman	August 2002	Given by the Microbeam Analysis Society in recognition of his work supporting the microcalorimeter project in the Electromagnetic Technology Division to develop a high-resolution microcalorimeter energy-dispersive X-ray spectrometer and demonstrate its usefulness for low-voltage X-ray microanalysis
Gold Medal	Samuel Benz and Charles Burroughs	September 2002	In recognition for developing an original quantum-based dc voltage reference system that is now being applied to improve the accuracy and reliability of NIST's fundamental electrical measurement systems, upon which all U.S. electrical measurements are based

Appendix D: Electromagnetic Technology Division Staff

(December 2002)

Division Office

3776	Harris, Richard E. (Chief)
3678	Metz, Sara E. (Division Secretary)
3812	Schump, Jeanne L. (Admin. Officer)
3811	Copeland, Jill V. (Admin. Asst.)
3988	McCarthy, Sandra E. (Secretary)
5068	Novik, Kristen E. (Secretary)

Quantum Voltage

5258	Benz, Samuel P. (Project Leader)
3906	Burroughs, Charles J.
5543	Chong, Yonuk
5211	Dresselhaus, Paul D.
3740	Hamilton, Clark A.

Cryogenic Sensors

5911	Irwin, Kent D. (Project Leader)
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4153	Beyer, Joern
4409	Clark, Anna
3461	Deiker, Steven
4463	Doriese, William (Randy)
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5679	Hilton, Gene C.
3402	Huber, Martin E.
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4319	Ruggeiro, Steve
4408	Ullom, Joel N.
5121	Vale, Leila R.
7894	Xu, Yizi
4320	Zink, Barry L.

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5344	Bergren, Norman F.
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3148	Nam, Sae Woo
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4464	Rosenberg, Danna
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