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January 2007

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

QUANTUM ELECTRICAL METROLOGY DIVISION

PROGRAMS, ACTIVITIES, AND ACCOMPLISHMENTS



THE ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

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

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

Semiconductor Electronics Division

Optoelectronics Division

Quantum Electrical Metrology Division

Electromagnetics Division

Office of Microelectronics Programs

Office of Law Enforcement Standards

This document describes the technical programs of the Quantum Electrical Metrology Division. Similar documents describing the other Divisions and Offices are available.

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On the Web: www.eeel.nist.gov

On the cover: Rand Elmquist and the NIST quantum Hall system (upper left); Ray Simmonds with a solid state quantum computing chip (upper right); Kent Irwin testing a superconducting transition edge sensor (lower left); Yicheng Wang performing precision capacitance measurements.

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U.S. DEPARTMENT OF COMMERCE

Carlos M. Gutierrez, Secretary

Technology Administration

Robert Cresanti, Under Secretary of Commerce for Technology

National Institute of Standards and Technology

William Jeffrey, Director



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WELCOME

The Quantum Electrical Metrology Division unites fundamental electrical metrology and leading-edge quantum-based metrology research to create a dynamic organization poised to lead quantum metrology into the future. The Division consists of three groups: Fundamental Electrical Measurements, Applied Electrical Metrology, and Quantum Devices. The first two groups are located in Gaithersburg, MD and boast of a proud 100-year history of precision electrical metrology. The Quantum Devices Group located in Boulder, CO brings a 35-year history of creating world-leading quantum-based standards and measurements. The Division works to provide the world's best electrically-based measurements and standards.

This document is organized into two main sections, Quantum Standards, and Quantum Measurements. Within those sections each Division project is described without reference to its geographical location. Appendix A describes the organizational location of all the research projects in the Division. Appendix B lists all of the measurement services offered by the Division, and Appendix C is a Division staff list for readers wishing to phone or e-mail us to learn more about a topic. We are always interested in new post-doctoral associates, and Appendix D describes many research opportunities in the Quantum Electrical Metrology Division.

We always strive to serve our customer's needs, and I hope that this document provides you with the information you need to better interact with our research staff. We appreciate your interest and welcome your comments. We also invite you to visit our web page at <http://www.eeel.nist.gov/817/>.

Thank you.

James K. Olthoff, Chief
Quantum Electrical Metrology Division
Electronics and Electrical Engineering Laboratory
National Institute of Standard and Technology

QUANTUM STANDARDS

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

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

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

QUANTUM STANDARDS

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

FUNDAMENTAL CONSTANTS

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

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

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

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

QUANTUM VOLTAGE METROLOGY

Technical Contact:
Sam Benz

Staff-Years (FY 2006):
3 professionals
3 guest researchers

GOALS

To meet the nation's voltage metrology needs by developing state-of-the-art voltage standard systems and precision measurement techniques that are founded on quantum-based superconducting circuit and system technology so that internationally consistent, accurate, and reproducible voltage measurements are readily and continuously available for U.S. industrial, governmental, and scientific applications.

CUSTOMER NEEDS

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

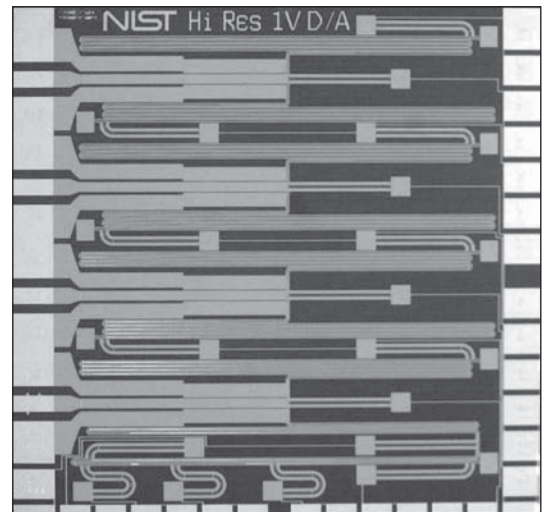
The U.S. electronics instrumentation industry maintains its world position through the development and deployment of increasingly accurate, flexible, easy-to-use instruments. Providing U.S. industry with quantum voltage standard systems gives these customers immediate realization of the highest possible 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 applying quantum-based voltage metrology to new areas and by developing voltage standard systems with new capabilities, including lower cost, increased functionality, and ease of use. This is especially true in the area of ac voltage metrology where we have developed the world's first ac Josephson

voltage standard system for arbitrary waveform synthesis. Other customers are the superconductive electronics community and the U.S. military, which we support through development of novel superconductive circuits, cryogenic packaging, and high-performance systems, and also by providing technical expertise.



Burm Baek, Nicolas Hadacek, Paul Dresselhaus, Charlie Burroughs, Sam Benz, Michio Watanabe, and Yonuk Chong, at NIST-Boulder labs.



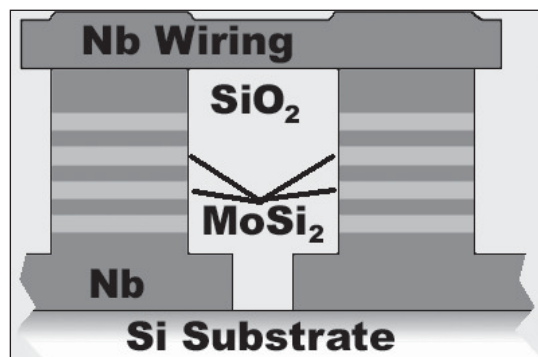
A 1 centimeter \times 1 centimeter superconducting integrated circuit with over 132,000 triple-stacked SNS Josephson junctions for the 5.0 Volt high-resolution programmable voltage standard operating at 18.5 GHz.

TECHNICAL STRATEGY

Over the past 25 years, we have developed superconductive Josephson junction array technology for quantum voltage standard systems. Ground-breaking 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.

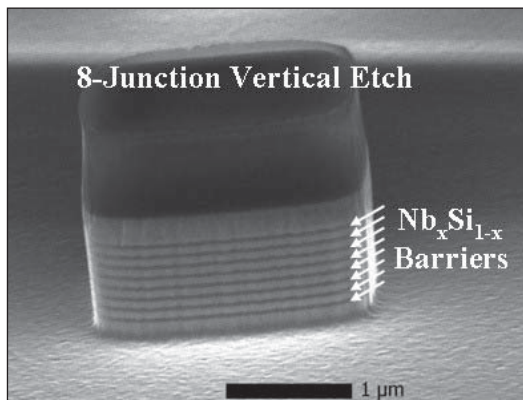
In order to create a new generation of voltage standards, we developed a novel superconductor-normal metal-superconductor (SNS) junction technology that adds the features of stability and programmability to the accuracy of conventional Josephson voltage standards. This gave rise to the first Programmable Josephson Voltage Standard (PJVS) systems with 1 V output voltage. This was the first practical system to have the unique feature that the quantum-defined voltage steps are intrinsically stable, which is essential for some calibrations and many applications. As a result, PJVS systems have been delivered to, and installed in, a number of metrology experiments – namely the Watt-balance experiments at NIST and Switzerland’s Federal Office of Metrology (OFMET), where their accuracy, stability and noise immunity have reduced the uncertainty of the experimental measurements. In order to support the maintenance and dissemination of the Volt, a one-volt programmable voltage standard system is also now in use in the NIST primary voltage calibration laboratory.



Schematic diagram depicting a 4-junction stacked series array with molybdenum-disilicide normal metal barriers, superconducting niobium electrodes, and silicon dioxide insulating dielectric.

In order to increase the junction density of arrays and thereby the output voltage for all our quantum-based voltage standard circuits, we invented a nanoscale junction fabrication technology in which the spacing between junctions is reduced from 7 μm to less than 50 nm. Over many years we explored various fabrication methods and materials before determining the optimal method of verti-

cally stacking the junctions on top of each other in three dimensions. We found a number of useful junction barrier materials, in particular molybdenum-disilicide and niobium-silicide, that could be etched contiguously with niobium electrodes. To form the junction stacks we developed a deep vertical etching process using an inductively coupled plasma etcher to make tall stacks. Stacks as tall as 15 junctions have been demonstrated and uniform electrical characteristics of arrays have been measured using Nb-electrodes as thin as 5 nm. The stacked-junction technology has now matured to the point where we have made useful PJVS circuits with over 130,000 junctions operating uniformly on a single chip. Such nano-stacked junction arrays are now the basis for all of our next generation dc and ac Josephson voltage standard systems.



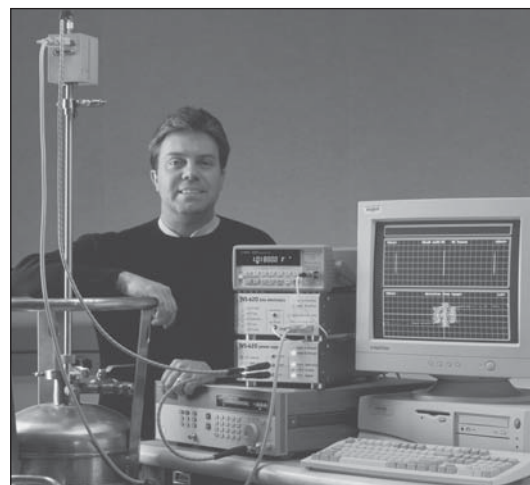
Scanning electron microscope image of an 8-junction stack with niobium-silicide barriers and niobium electrodes. The image shows that the nano-stacked junctions can be vertically etched which is critical for achieving uniformity of the electrical characteristics. (Image by Burm Baek, NIST)

Our present goals are to further improve NIST electrical measurement capabilities by applying quantum voltage standards to both existing and new areas, in particular, in dc and ac metrology, 60 Hz power applications, and electronic-based precision thermometry. Our most challenging and long-term goal is to demonstrate a 10 V PJVS system that is essentially a turn-key system that does not require an expert to operate. Such a system would be preferable for many applications that are not fulfilled using the existing 10 V conventional Josephson voltage standards. This challenging task requires significant development of array technology, microwave integrated circuits, electronic instrumentation, and cryogenic packaging. We have demonstrated circuits that have reached voltages as high as 5 V. This was accomplished by

increasing the number of junctions in each array through the development of new junction barrier materials and nano-stacked junction technology. Achieving 10 V PJVS circuits requires improved microwave designs.

Over the past 10 years we also have been developing the necessary technology to make a practical and automated ac Josephson voltage standard (acJVS) system. We call this same system the Josephson arbitrary waveform synthesizer (JAWS) when it is used to synthesize non-sinusoidal waveforms. The concept for this new device was co-invented by NIST and Northrop-Grumman researchers in 1996, and is essentially a digital-to-analog converter that is capable of synthesizing arbitrary waveforms and, like the previously described dc-only systems, exploits the perfectly quantized pulses of Josephson junctions. Present ac voltage calibrations are done using ac-dc thermal voltage converters, which thermally compare the root-mean-square voltage of an ac signal with a known and accurate dc signal. The new quantum-based acJVS is a perfect voltage source and will provide an entirely new instrument and methodology for ac voltage metrology. The precision, stable and accurate arbitrary waveforms will also be useful for calibrating other scientific instruments, such as ac voltmeters, spectrum analyzers, amplifiers, and filters. The biggest challenge has been to reach practical output voltages of at least one-quarter volt.

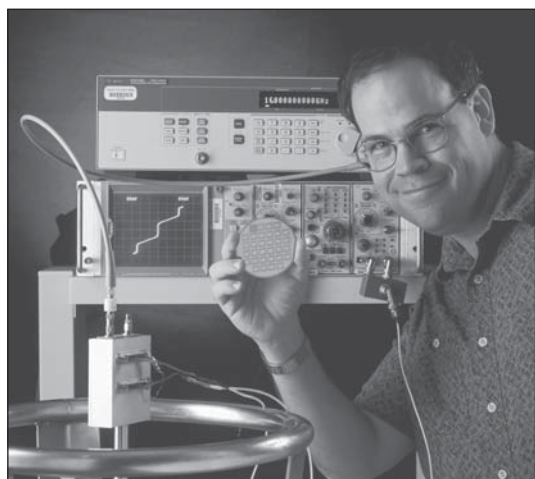
In 2006, we completed the first acJVS system, which is now installed in the NIST Voltage Calibration Lab and can generate arbitrary waveforms up to 100 mV rms and frequencies up to 100 kHz. This is the world's first quantum-mechanically accurate ac voltage standard source with practical output voltage at audio frequencies. Precision measurements with the acJVS demonstrated the accuracy of these synthesized voltage waveforms from dc up to 100 kHz over the full voltage range. This new measurement capability was achieved by using superconducting integrated circuits with nano-stacked Josephson junction arrays, better on-chip filters, and a well-controlled output transmission line. This work was undertaken specifically to improve NIST's low-voltage ac calibration service, and we anticipate a 10- to 100-fold reduction in calibration uncertainties in this 1 mV to 100 mV range.



Charles Burroughs with the Programmable Josephson Voltage Standard system showing (left to right) the low thermal probe, the microwave and high-speed bias electronics, and the computer.

PLANS

- Our present goal is to increase the output voltage and measurement bandwidth of the acJVS to 1 V and 1 MHz. We recently demonstrated 220 mV rms (311 mV peak) output voltage circuits that are even closer to realizing this goal and were possible through the development of high-density arrays and novel tapered transmission line circuits. Future research and creative breakthroughs in electronics and circuit design are required to expand the output range to 1 V and the output bandwidth to 1 MHz. A low-voltage version of the acJVS has also been developed as a precision pseudo-noise voltage source to calibrate the measurement electronics of a novel Johnson noise thermometry system. The thermometry application is described in detail in the Johnson noise thermometry chapter of this book.
- Finally, in order to improve calibrations of 60 Hz power meters, we have renewed our interest in using the PJVS system as an ac standard for frequencies below 1 kHz. Since higher voltages are possible with this system, we can use the PJVS as a multi-bit digital-to-analog converter by rapidly switching array segments to appropriate constant voltage steps. The new quantum-based power standard will use two PJVS systems (one for voltage and one for current) to produce precision 60 Hz sinusoidal reference signals. Using step-wise approximation synthesis, the PJVS systems produce sine waves with calculable rms voltage and spectral content. This work is in collaboration with the Applied Electrical Metrology Group, and they are developing novel divider and amplifier techniques to implement comparison between the 120 V calibration and 1.2 V PJVS signals. Our goal is to reduce all error sources and uncertainty contributions from the PJVS-synthesized waveforms to be a few parts in 10^7 , so that the overall uncertainty in the power standard will be a few parts in 10^6 .



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

ACCOMPLISHMENTS

- Demonstrated accurate 100 mVrms synthesized quantum-based voltage waveforms from dc up to 100 kHz. This new measurement capability was achieved by using superconducting integrated circuits with nano-stacked Josephson junction arrays, better on-chip filters, and a well-controlled output transmission line. This work was undertaken in order to improve our low-voltage ac calibration service.
- Investigated new JJ barriers, WSi_2 , TiSi_2 , $\text{Nb}_x\text{Si}_{1-x}$ which have led to new high-speed Josephson applications.
- Further increased programmable voltage standard output with longer triple-stacked arrays. The record voltage is now 5 V with a useful 1 mA current range. This result gives us confidence that we have a practical path to reach 10 V, which is essential for making a turn-key quantum voltage standard system that will revolutionize voltage metrology.
- Duplicated, automated, and delivered a 100 mVrms acJVS system to voltage calibration lab in Gaithersburg. Performed the first direct quantum-based measurements on the two lowest voltage ranges of a Fluke transfer standard.
- Synthesized and measured 60 Hz 1.5 V rms sine waves with PJVS arrays for quantum-based power calibration EEL Director's Reserve program. Measured harmonic content agrees with the expected quantum-accurate synthesized voltages.
- Demonstrated precision measurements of a commercial analog-to-digital-converter with a record 220 mV rms (311 mV peak) sine waves and arbitrary waveforms.

RECENT PUBLICATIONS

S. P. Benz, C. J. Burroughs, P. D. Dresselhaus, T. E. Lipe and J. R. Kinard, "An AC Josephson Voltage Standard for AC-DC Transfer Standard Measurements," to appear in *IEEE Trans. Inst. Meas.*, vol. 56, no. 2 (in press).

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N. Hadacek, P. D. Dresselhaus, Y. Chong, S. P. Benz, and J. E. Bonevich, "Fabrication and Measurement of Tall Stacked Arrays of SNS Josephson Junctions," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 110-113, June 2005.

C. J. Burroughs, S. P. Benz, P. D. Dresselhaus, Y. Chong, and H. Yamamori, "Flexible Cryo-packages for Josephson Devices," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 465-468, June 2005.

P. D. Dresselhaus, Y. Chong, and S. P. Benz, "Stacked Nb-MoSi₂-Nb Josephson Junctions for ac Voltage Standards," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 449-452, June 2005.

Y. Chong, C. J. Burroughs, P. D. Dresselhaus, N. Hadacek, H. Yamamori, and S. P. Benz, "Practical High-Resolution Programmable Josephson Voltage Standards using Double- and Triple-Stacked MoSi₂-Barrier Junctions," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 461-464, June 2005.

C. J. Burroughs, S. P. Benz, P. D. Dresselhaus, and Y. Chong, "Precision Measurements of AC Josephson Voltage Standard Operating Margins," *IEEE Trans. Inst. Meas.*, vol. 54, no. 2, pp. 624-627, April 2005.

Y. Chong, C. J. Burroughs, P. D. Dresselhaus, N. Hadacek, H. Yamamori, and S. P. Benz, "2.6 V high-resolution programmable Josephson voltage standard circuits using double-stacked MoSi₂-barrier junctions," *IEEE Trans. Inst. Meas.*, vol. 54, no. 2, pp. 616-619, April 2005.

VOLTAGE METROLOGY

GOALS

To maintain the U.S. legal volt and to provide for the dissemination of an internationally consistent, accurate, reproducible, and traceable voltage standard that is tied to the SI units and is readily and continuously available for the U.S. scientific, industrial base and government laboratories.

CUSTOMER NEEDS

All voltage measurements performed in the U.S., whether for the purpose of direct voltage readings or for the determination of another parameter (such as temperature) through the use of a transducer that converts that parameter into a voltage signal, rely on the consistency of traceability to international standards through the U.S. legal volt. Because of the length of the calibration chain that connects measurements by an end user with the U.S. legal volt, it is common for the measurement uncertainty of the end user to exceed the NIST primary uncertainty by a factor of 100 or more. The continued development and deployment by the U.S. electronics instrumentation industry of increasingly sophisticated and accurate instrumentation places ever-increasing demands for higher accuracy voltage metrology both in calibration and testing laboratories and on production lines and factory floors. Consequently, NIST is continuously pressed to reduce measurement uncertainty at the beginning of this chain and to develop improved mechanisms for dissemination to the end user. Through maintenance, development, and dissemination of the U.S. legal volt, this project provides the robust base for voltage metrology that enables the U.S. electronics instrumentation industry to compete successfully in the global market and supports scientific research in high accuracy voltage measurements ever needed.

TECHNICAL STRATEGY

A representation of the SI unit of voltage has been established via the Josephson effect, to maintain and disseminate the U.S. legal volt. The measurement systems required to measure and transfer that voltage to other electronic systems and to chemical or electronic standards have been developed. To continually achieve the lowest possible uncertainty, project members: 1) perform regular checks for subtle systematic errors in the Josephson voltage standard systems and the subsequent transfer systems, 2) perform regular direct or indirect

comparisons between NIST systems, 3) maintain long-term observations of well-characterized check standards, and 4) periodically verify our consistency with the international community through very careful international comparisons. Research continues on the physical and statistical limitations of metrology equipment and protocols both presently in use and under development in order to support future technological advances.

In recent years, an increasing number of Josephson voltage standards have been deployed both around the world and throughout the U.S. It has proven very difficult to verify in the field the performance of voltage metrology systems based upon Josephson standards because the accuracy of these measurements is limited by the performance of the Zener voltage references used as transfer standards. Because the ultimate performance of Josephson voltage systems should be much better than that which can be verified using these standards, a traveling compact Josephson voltage standard (CJVS) has been developed, along with measurement protocols appropriate for its use in comparisons between Josephson voltage systems in geographically separated locations. The elimination of the problems associated with traveling Zener standards has reduced the uncertainty of Josephson voltage comparisons by an order of magnitude compared to that using a Zener MAP. Direct array comparison will be used to further improve the uncertainty of JVS comparisons. NIST is collaborating with the National Research Council, Canada and private industry to develop an alternative protocol for making JVS comparisons available to other NMIs and industry labs.

The NIST voltage calibration service has implemented a programmable Josephson voltage standard (PJVS) to replace the cell banks and incorporated it into the daily calibration service. This implementation has reduced the number of transfers necessary to link the calibration bench to the Josephson voltage standard. The PJVS can be used to verify other NIST JVS systems operation by providing a stable voltage up to 2.5 V with an uncertainty of a few parts in 10^{10} . Further improvement of the programmable voltage standard by using a newly designed array with a higher current and voltage margin is in progress. The final goal is to deliver a system with better specifications for applications such as direct array comparison, the electronic mass and the metrology triangle.

Technical Contact:
Yi-hua Tang

Staff-Years (FY 2006):
1 professional

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

PLANS

- Establish the viability of using the 1 V programmable JVS for regular calibrations.
- Perform a series of comparisons using the NIST compact Josephson voltage standard with other national metrology institutes and with high-level industrial metrology laboratories.
- Upgrade the hardware and software of the compact Josephson voltage standard to develop an alternative protocol for direct array comparisons.
- Continuous improvement of programmable array design and fabrication for applications in volt maintenance, the electronic mass and the metrology triangle.

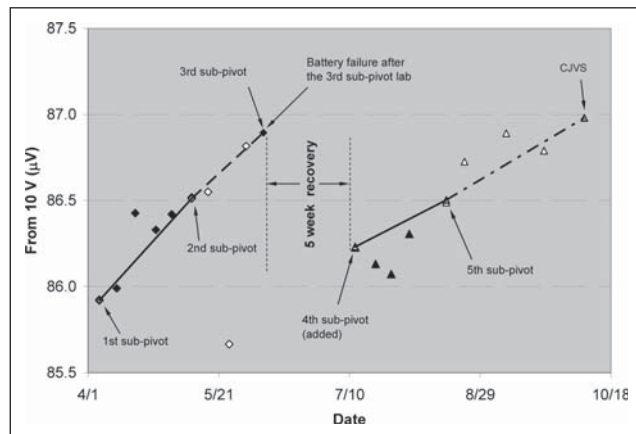
ACCOMPLISHMENTS

■ The 7th interlaboratory comparison (ILC) of Josephson Voltage Standards (JVS) at 10 V, sponsored by the National Conference of Standard Laboratories International (NCSLI), took place from April to October 2005 with 15 participating labs. NIST was the pivot lab and implemented the CJVS in the JVS ILC. A traveling NIST JVS system and NIST protocol were used to make five comparisons with the sub-pivot labs. The use of the CJVS in the ILC 2005 improved the uncertainty of the sub-pivot comparisons by about an order of magnitude to 2 to 3 parts in 10^9 and also provided a more direct link between NIST and the other nine participants in the ILC. Because the sub-pivot comparisons are made *in-situ*, uncertainty from

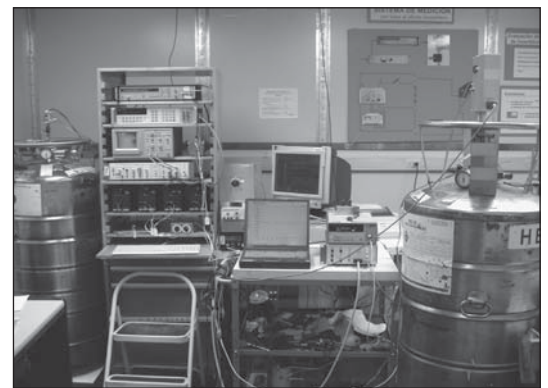
non-linear drift, transportation and environmental effects is largely eliminated. Small system errors of a few parts in 10^9 can be detected and corrected with a CJVS comparison. The discovery of system problems at three of the fifteen laboratories in the ILC 2005 demonstrates the value of intercomparisons of Josephson voltage systems.

■ The National Research Council's (NRC) Josephson voltage standard (JVS) has been directly compared with the compact, transportable Josephson array standard of the National Institute of Standards and Technology (NIST) at 10 V. A simplified biasing technique for both arrays has been developed for this direct comparison. The difference between the NRC JVS and the NIST CJVS at 10 V was found to be 0.3 nV with an expanded uncertainty of 3.8 nV or 3.8×10^{-10} at 95% confidence. This is a substantial reduction over comparisons using Zener references. The results of this comparison augment the confidence and traceability of the 7th interlaboratory comparison (ILC) of Josephson Voltage Standards (JVS) at 10 V sponsored by the National Conference of Standard Laboratories International (NCSLI).

■ A bilateral JVS comparison was carried out in March 2006 with CENAM. This is the first time that the NIST CJVS has been used in a *Sistema Interamericano de Metrologia* (SIM) comparison. A request to list the result in the SIM key comparison database SIM.EM.BIPM-K11.b has been submitted to SIM. The result of the comparison was very satisfying. The difference between the CENAM JVS and the NIST CJVS at 10 V was found to be -38 nV with an expanded uncertainty of 42 nV at 95% confidence or 4.2×10^{-9} . This is a factor of 9.7 improvement compared to the uncertainty that CENAM achieved in the NCSLI JVS ILC 1999, the last intercomparison that CENAM participated in. This is the first time a CENAM JVS intercomparison reached an uncertainty of few parts in 10^9 .



NCSLI JVS ILC 2005 results.



SIM.EM.BIPM-K11.b comparison between NIST and CENAM JVS.

■ A JVS Working Group (JVSWG) consisting of 15 NCSLI JVS ILC participants and other interested labs was formed after the NCSL JVS ILC 2005 to address common issues within the JVS community and to promote collaboration among the group members. Two group meetings have been held; one at the MSC 2006 and the other at NCSLI 2006. One teleconference was accomplished in February. At these meetings the results of the recent JVS ILC 2005 and issues concerning the new WINDOWS JVS software were reported and discussed. The JVSWG has proved to be a useful forum that is beneficial to its members by promoting guidelines and assistance with the maintenance and healthy operation of member JVS systems.

CALIBRATIONS

■ Voltage calibrations (17 calibration reports, 50 outputs) were performed from October 1, 2005 to August 30, 2006. The generated division income was approximately \$41K.

COLLABORATIONS

- NRC, Collaboration in developing an alternative protocol for JVS direct comparison
- NRC, Peer review of NRC dc voltage metrology to meet ISO 17025 technical requirements
- NCSLI, Implementation of NIST compact JVS for ILC to improve uncertainty
- CENAM, Bilateral JVS comparison using NIST CJVS for SIM.EM:BIPM-K11.b
- CENAM, Peer review of CENAM's dc voltage metrology to meet ISO 17025 technical requirements
- INMETRO, Training its staff to prepare for INMETRO-BIPM JVS comparison
- NPL-India, Host a guest researcher for training in JVS operation and volt dissemination

STANDARDS COMMITTEE

PARTICIPATION

- Yi-hua Tang, coordinator of the NCSLI JVS JVS Working Group
- Yi-hua Tang, participant in NCSLI Intrinsic / Derived Standards Committee for revising the Recommended Practice of Intrinsic and Derived Standards (RISP) catalog.

RECENT PUBLICATIONS

Y. Tang "An Overview of Josephson Voltage Standard Interlaboratory Comparison," Proc. 2006 Natl. Conf. of Standards Laboratories Intl. Workshop and Symp. (NCSLI), Aug.6-10, 2006, Nashville, TN (Aug. 2006).

B. Wood, Y. Tang and C. A. Hamilton, "Direct Josephson Array Voltage Comparison between NRC and NIST," Digest of Conf. on Precision Electromagnetic Measurements (CPEM2006), July 9- July 14, 2006, Torino, Italy, pp. 14-15 (July 2006).

Y.Tang , C. A. Hamilton, D. Deaver, H. Parks, and B. Wood, "The Seventh Intercomparison of Josephson Voltage Standards in North America," Digest of Conf. on Precision Electromagnetic Measurements (CPEM2006), July 9- July 14, 2006, Torino, Italy, pp. 188-189 (July 2006).

J. Sims and Y. Tang, "Implementation of Programmable Josephson Voltage Standard to NIST Voltage Dissemination System," NCSLI MEASURE, Vol. 1, No. 2, 42-46, June 2006.

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Y. Tang, "Applications of the Programmable Josephson Voltage Standard in Voltage Metrology," Proc. VI SEMETRO, Sep. 21-23, 2005, Rio de Janeiro, Brazil.

J. Sims and Y. Tang, "Implementation of Programmable Josephson Voltage Standard to NIST Voltage Dissemination System," Proc. 2005 Natl. Conf. of Standards Laboratories Intl. Workshop and Symp. (NCSLI), Aug.7-11, 2005, Washington D.C., (Aug. 2005).

Y. Tang, C. Hamilton, H. Parks, D. Deaver and B. Wood, "Experimental Design of NCSLI 2005 Josephson Voltage Standard Interlaboratory Comparison," Proc. 2005 Natl. Conf. of Standards Laboratories Intl. Workshop and Symp. (NCSLI), Aug.7-11, 2005, Washington D.C., (Aug. 2005).

Y. Tang , S.L. Kupferman and M. T. Salazar, "Interlaboratory Comparison Using a Transport Josephson Voltage Standard System," *IEEE Trans. Instrum. Meas.* Vol.54, pp. 398-403, February 2005.

T. J. Witt and Y. Tang, "Investigations of Noise in Measurements of Electronic Voltage Standards," *IEEE Trans. Instrum. Meas.* Vol.54, pp 567-570, April 2005.

AC-DC DIFFERENCE STANDARDS AND MEASUREMENT TECHNIQUES

Technical Contact:
Thomas E. Lipe

Staff-Years (FY 2006):
3 professionals

GOALS

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

CUSTOMER NEEDS

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

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

- US military and industrial laboratories require highly accurate calibrations of thermal converters at frequencies greater than 1 MHz. Potential discontinuation of the RF-dc calibration service because of funding concerns would mean that NIST customers would no longer have ready access to required calibrations.

- The U. S. Army primary standards laboratory uses the same primary standards for ac current metrology as NIST. New standards are required to replace these aging, failing, devices. In addition, the U. S. Air Force primary standards laboratory is seeking improved thermal converters for measurements at frequencies up to 100 MHz.

- The U.S. Air Force primary standards laboratory calibrates 100 A current amplifiers for their secondary laboratories. Although these amplifiers

are specified to 100 kHz at 100 A, NIST presently supports only 100 A measurements to 10 kHz. The Air Force requires an expansion of the frequency range for high-current calibrations. The Air Force also requires improved devices for measuring ac voltages from 100 mV to 2 V with smaller uncertainties than existing devices.

- NIST's international obligations include assisting other National Metrology Institutes (NMIs) improve their metrology capabilities. For example, the National Institute of Standards in Egypt requires significant improvements in their measurement service for ac-dc difference in order to be recognized in the international arena.

- In 2008, the Quantum Electrical Metrology Division will host the 2008 Conference on Precision Electromagnetic Measurements. This is an extremely important and visible international conference on electrical metrology. Members of the staff will serve as guest editors for the IEEE Transactions on Instrumentation and Measurement special issue for CPEM 2008. This task is vital to the success of the conference.

Research and development are required to maintain and to expand NIST calibration and special test services for thermal converters and shunts, especially for calibrating high current shunts and high voltage converters. In addition, research and development of an intrinsic standard for ac voltage is required to successfully address the problem of maintaining extremely accurate calibrations at voltages below 100 mV.

TECHNICAL STRATEGY

To address manufacturer's requirements for highly accurate calibrations of thermal transfer standards at voltage levels below 100 mV, NIST is developing the world's first intrinsic standard for ac voltage. This system, based on pulse-driven Josephson arrays, will allow us to calibrate thermal converters at voltages down to 2 mV with unprecedented accuracy. Linking with our existing multijunction thermal converter (MJTC) standards at 100 mV, the combination of ac JVS and MJTCs will provide standards for thermal converter calibrations from 2 mV to 2 V without requiring the scaling techniques that increase the uncertainties at these low voltage levels. Combined with the inclusion of Fluke 792A calibrations at all voltage levels into the AC-DC Difference Project, this ac Josephson Voltage Stan-

dard (ac JVS) will give us the ability to span the entire voltage range of 2 mV to 1000 V in a single calibration service, leading to significantly reduced uncertainties and greater efficiency (and therefore reduced turnaround time and lower costs) for our calibration customers.

To maintain the ability to support the US military and industrial calibration laboratories at frequencies greater than 1 MHz, we are transferring the RF-dc calibration service from NIST Division 818 in Boulder, CO to the AC-DC Difference Project in Gaithersburg. In addition to maintaining the service, having both the low-frequency (up to 1 MHz) and high-frequency service in the same project will strengthen the link between the services at 1 MHz, resulting in lower uncertainties and costs, and better customer support. We will also undertake the documentation of the RF-dc service to bring it into compliance with the NIST ISO 17025 self-declaration. In addition, development work has begun on high-frequency MJTCs.

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

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

To support NIS, a collaboration has been formed between NIST scientists and National Institute of Standards, Egypt (NIS) personnel. An exchange of standards and personnel is required for this collaboration.

To support IEEE publication of metrology-related information, staff in the AC-DC Difference Project will serve as guest editors for the IEEE Transactions on Instrumentation and Measurement, in Torino, Italy, July 8-14, 2006.

PLANS

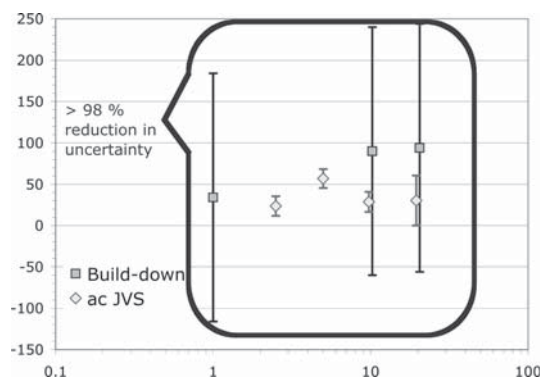
- Bring the ac JVS online and integrate it into the ac-dc difference calibration service as a metrology tool.
- Transfer the RF-dc difference calibration service from NIST Division 818 in Boulder, CO to the AC-DC Difference Project in Gaithersburg, MD. Produce plans for fabricating high-frequency thin-film MJTCs.
- Continue fabrication of thin-film, high-current MJTCs and multiconverter modules for currents up to 10 A.
- Begin calibration service for ac current shunts at 100 kHz up to 100 A.
- Acquire approval for reduced ac current calibration uncertainties.
- Begin documentation of RF-dc calibration service, in anticipation of uncertainty reductions
- Exchange thermal transfer standards with NIS, and visit NIS in Cairo, Egypt.
- Provide personnel for Associate Guest Editor for the CPEM 2006 Special Issue of the IEEE Transactions on Instrumentation and Measurement.
- Begin an interlaboratory intercomparison of MJTC voltage converters, fabricated by NIST and Sandia National Laboratories, and including the DoD laboratories, Kennedy Space Center, and Sandia National Laboratories. NIST will be the pilot laboratory.

ACCOMPLISHMENTS

■ The ac JVS being used as a research tool in Boulder, CO, was duplicated, tested in Boulder, and delivered to NIST in Gaithersburg, MD for development into a metrology system. The system has been tested at voltages down to 2 mV, and at frequencies up to 1 MHz at 100 mV and 50 mV. Measurements on a thermal transfer standard using the ac JVS at 100 mV indicate that the ac JVS agrees with traditional measurement techniques to well within the uncertainty of the traditional measurements. In fact, these measurements are probably serving more as a check on the voltage scaling methods than a check on the ac JVS.

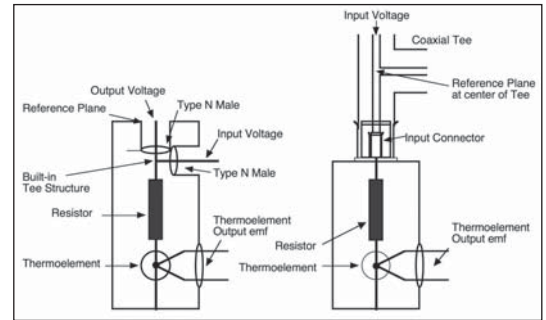


Photograph of the ac JVS System.



Comparison of a thermal transfer standard measured using the ac JVS (in grounded and floating modes) and a calibration made by traditional methods. The uncertainty bars are the expanded uncertainties of the traditional calibration.

■ The RF-dc difference calibration service was successfully transferred from NIST in Boulder, CO to Gaithersburg, MD. The increased efficiency of including this service in the AC-DC Project has already resulted in lower calibration prices. George Free, Thomas Lipe, and Joseph Kinard began documentation of this calibrations service with the CPEM 2006 paper “Characterization of RF-DC Transfer Difference for Thermal Voltage Converters with Built-in Tees in the Frequency Range 1 MHz to 1GHz.” In addition, we provided a calibrated TVC for development of a peak-to-peak detector calibration service using the NIST Sampling Waveform Analyzer.



Comparison of traditional 100 MHz thermal converter (right) with a TVC with an integrated tee structure.

■ Thomas Lipe and Joseph Kinard were trained on the Denton sputtering machine in the NIST Nanofab facility. We will use this tool to deposit the thermocouple metals for high current MJTCs, before they are completed in the Quantum Devices facility in Boulder, Co. In addition, we are planning to host a guest scientist, Luciana Scarioni from Venezuela, to collaborate on fabricating additional MJTCs. She has extensive experience in MJTC fabrication, and is an expert in clean room operations.

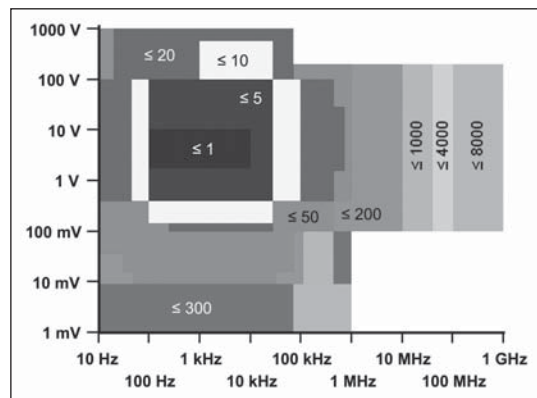
■ To support the collaboration with NIS, we sent two sets of thermal transfer standards to Egypt for an intercomparison with NIS. Joseph Kinard then traveled to NIS to evaluate their methodology, and to present several technical talks on ac-dc difference. Considerable improvement in the NIS capability in the ac-dc difference area has resulted from this collaboration. The equipment purchases and travel was made possible by a grant from the State Department. Mamdouh Halawa from NIS will visit NIST in September to collaborate in modeling transmission line structures for MJTCs and the ac JVS.

■ We began evaluating candidates for the interlaboratory comparison (ILC) of MJTCs. Since these devices are among the most accurate thermal converters in the world, this ILC will enable the participants to check their calibration systems and methodologies to unprecedented accuracies. The participants (the U.S. military primary laboratories, Sandia National Laboratories, and Kennedy Space Center) were chosen because all possess MJTCs of the NIST/Sandia type. NIST will serve as the pilot laboratory for the ILC, and will contribute one of the traveling standards. The U.S. Air Force will contribute the other. This is very likely the first ILC of MJTCs outside of NMIs.

- Thomas Lipe served (with Yi-hua Tang) as co-Associate guest editor for the CPEM 2006 Special Issue of the IEEE Transactions on Instrumentation and Measurement, in Torino, Italy, July 8-14, 2006. He will serve as co-Guest Editor of the CPEM 2008 Special Issue (Boulder, CO).

- Draft B of CCEM-K11 (international inter-comparison of thermal transfer standards at 10 mV and 100 mV) was made available in 2006. The results show that NIST is exceptionally close to the reference value at both voltage and at all frequencies.

- The addition of the RF-dc calibration service and calibrations below 100 mV has significantly expanded the parameter space for voltage calibrations. It is now among the largest parameter spaces in the world serviced by one calibration laboratory.



Parameter space for ac-dc transfer measurements of thermal voltage converters, including the RF-dc calibration service, and expanded service at low voltage.

COLLABORATIONS

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

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

- During 2006, Thomas Lipe served as NVLAP assessor to Southern California Edison, and acted as NVLAP technical reviewer for Fluke 5790A wideband calibration accreditation for John Fluke Manufacturing Company.

CALIBRATIONS

As of August 20, the AC-DC Project had completed 20 calibration jobs of 589 points, with revenues of about \$78,000, with another \$28,000 in process.

SELECTED PUBLICATIONS

George M. Free, Thomas E. Lipe, and Joseph R. Kinard, "Characterization of RF-DC Transfer Difference for Thermal Voltage Converters with Built-in Tees in the Frequency Range 1 MHz to 1 GHz," CPEM 2006 Conference Digest, Torino, Italy, July 8-14, 2006, pp. 248-249.

Samuel P. Benz, Charles J. Burroughs, P. D. Dresselhaus, T. E. Lipe, and J. R. Kinard, "100 mV AC-DC Transfer Standard Measurements with a Pulse-Driven AC Josephson Voltage Standard," CPEM 2006 Conference Digest, Torino, Italy, July 8-14, 2006, pp. 678-679.

Thomas E. Lipe, Joseph R. Kinard, and June E. Sims, "Improvements in the NIST Calibration Service for Thermal Transfer Standards," Proceedings of the 2006 NCSLI Workshop and Symposium, August 7-10, 2006, Nashville, TN, on CD-ROM.

Thomas E. Lipe, Joseph R. Kinard, Charles J. Burroughs, Paul D. Dresselhaus, and Samuel P. Benz, "Improvements in the NIST Calibration Service for Low-Voltage Thermal Transfer Standards," Proceedings of the 2005 NCSLI Workshop and Symposium, August 7-11, 2006, Washington, DC, on CD-ROM.

Charles J. Burroughs, Paul D. Dresselhaus, Samuel P. Benz, Thomas E. Lipe, and Joseph R. Kinard, "100 mV AC-DC Transfer Standard Measurements Using an AC Josephson Voltage Standard," Proceedings of the 2005 NCSLI Workshop and Symposium, August 7-11, 2006, Washington, DC, on CD-ROM.

Joseph R. Kinard, Thomas E. Lipe, and Svetlana Avramov-Zamurovic, "Determination of Frequency Coefficients for Thermal Voltage Converters and Digital Voltmeters by Comparison to Inductive Voltage Dividers," CPEM 2004 Conference Digest, London, UK, June 26-30, 2004, pp. 463-464.

Hector Laiz, Thomas F. Wunsch, Joseph R. Kinard, Thomas E. Lipe, "1 A and 120 mA Thin-Film Multijunction Thermal Converters," IEEE Trans. Instrum. Meas. Vol. IM-54, no. 2, pp. 803-806, April, 2005.

Hector Laiz, Thomas F. Wunsch, Joseph R. Kinard, Thomas E. Lipe, "1 A and 120 mA Thin-Film Multijunction Thermal Converters," CPEM 2004 Conference Digest, London, UK, June 26-30, 2004, pp. 457-458.

Joseph R. Kinard, Thomas E. Lipe, and Svetlana Avramov-Zamurovic, "Determination of Frequency Coefficients for Thermal Voltage Converters and Digital Voltmeters by Comparison to Inductive Voltage Dividers," Proceedings of the NCSLI Workshop and Symposium, Salt Lake City, UT, July 12-16, 2004.

Hector Laiz, Thomas F. Wunsch, Joseph R. Kinard, Thomas E. Lipe, "1 A and 120 mA Thin-Film Multijunction Thermal Converters," Proceeding of the NCSLI Workshop and Symposium, Salt Lake City, UT, July 12-16 2004.

SINGLE ELECTRONICS FOR STANDARDS AND METROLOGY

Technical Contact:

Mark Keller
Neil Zimmerman

Staff-Years (FY 2006):

3 NIST staff
2 post-docs
1 guest researcher

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.

Portions of this project are located in both Boulder, Colorado, and Gaithersburg, Maryland.

CUSTOMER NEEDS

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

For the first need: NIST is working on the development of intrinsic standards based on fundamental physical principles, such as the volt, based on the Josephson effect, and the ohm, based on the quantum Hall effect. The present representation of the SI farad is through silica-based artifact capacitors. Although these capacitors are of high quality, they are susceptible to drift in time and they may depend on other parameters such as temperature, pressure, and frequency. The metrology community, including both the national standards laboratories and domestic secondary calibration laboratories, needs a capacitance representation that is based on fundamental physical principles and not on properties of individual physical artifacts.

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

For the third need: Various classes of future nano-electronics beyond CMOS are projected to work with one or a few electrons. These include molecular electronics, semiconductor-based integrated circuits using single-electron memory or logic, and

quantum computing (QC). For example, in QC, we are using our expertise to elucidate properties of transfer of superconducting “Cooper pairs,” which are the basic mechanism for one realization of QC circuits. As another example, one endemic problem in single-electron logic is the “charge offset” phenomenon, which makes it difficult or impossible to integrate multiple SET-based devices together; again, we are using our expertise to attack this problem. In all three cases, our project has the capability to offer early guidance to these burgeoning fields, to assist companies in pursuing productive areas, and rejecting problematic ones. Because these fields are not yet mature, our relatively small efforts can yield large payoffs for the customers as they progress.

TECHNICAL STRATEGY

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

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

CAPACITANCE STANDARD

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

A prototype of the ECCS has been demonstrated with repeatability on the order of 1 part in 10^7 and a relative standard uncertainty of 1 part in 10^6 . The major tasks remaining are to continue to reduce the uncertainty and to develop a robust system for possible widespread use.

CURRENT STANDARD

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

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

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

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

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

ULTRA-SENSITIVE CHARGE ELECTROMETRY FOR MOLECULAR ELECTRONICS/BIOLOGICAL APPLICATIONS

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

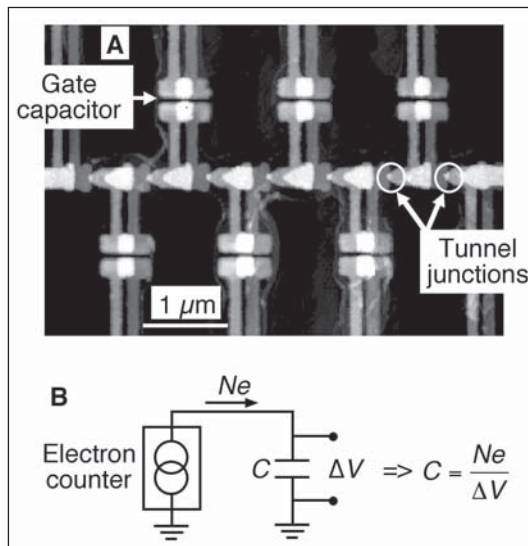
We are pursuing the study of electrostatic charge reconfiguration of self-assembled monolayers (SAM) by fabricating and assembling a “nano-gap” capacitor. This device, made using Si microma-

chining, allows us to make a capacitor with a gap of only 50 nm, but an area of $(80 \text{ nm})^2$; this area is large enough to give us a measurable signal, while the gap is small enough to measure charge motion over 1 nm or less.

PLANS

- Combine a new generation of electron counting devices with various other improvements to allow the ECCS to reach an uncertainty of 1 part in 10^7 .
- Use the improved ECCS to test for possible corrections to the basic formulae relating SET current and Josephson voltage to the fundamental constants e and h .
- Quantify and evaluate the differences in charge offset between metal-based and Si-based SET devices; suggest ways of improving the performance of the metal-based ones.
- Produce a prototype device with parallel SET electron pumps.
- Verify Cooper pair pump operation. This involves studies of individual elements, including eliminating quasiparticle poisoning, verifying the suppression of the Josephson coupling energy in a high impedance environment.
- Produce prototype passive counting device with 10 MHz bandwidth. Determine practical limits of passive counting bandwidth and suggest strategies for multiplexing for larger currents.
- Pursue individual elements, including larger-current SET-based current source, resistor, null detector, and control/monitoring electronics.
- Close metrology triangle to within 0.02 ppm via the current-through-a-resistor method.
- Develop a robust repeatable nano-gap capacitor.
- Verify or refute the belief in the molecular electronics field that nonlinearities in the transport are due to charge motion in the molecules.

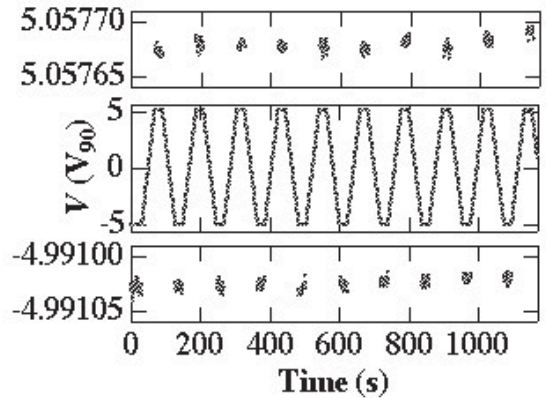
ACCOMPLISHMENTS



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 .

■ **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. A prototype of an Electron Counting Capacitance Standard (ECCS) has been demonstrated, with a repeatability of 1 part in 10^7 and a relative standard uncertainty of 1 part in 10^6 . This brings to fruition a decade of research aimed at creating this standard and shows the way toward even better performance in the future. The components of the standard are an electron counter, a capacitor, and an electrometer to monitor the process, as illustrated in the figure below. The electron counter, shown in the Atomic Force Microscope image below, is based on seven nanometer-scale tunnel junctions in series. It can “pump” electrons onto the capacitor with an error rate of less than one electron in 10^8 . The electron pumping is monitored with an SET-based electrometer fabricated on the same chip as the pump, with a charge sensitivity better than 10^{-2} electrons. The capacitor operates at cryogenic temperatures and uses vacuum as the dielectric, resulting in a frequency-independent capacitance. To operate the ECCS approximately

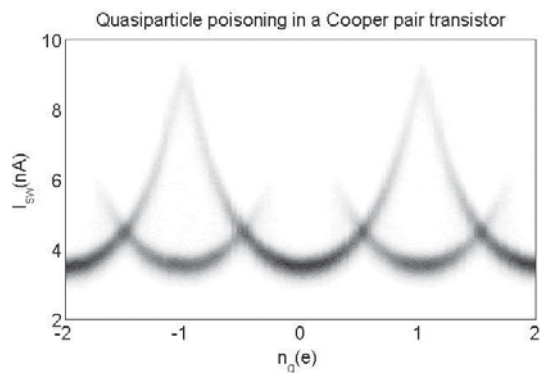
100 million electrons are placed, one at a time, on the capacitor. The voltage across the capacitor is then measured, resulting in a calibration of the cryogenic capacitor. This capacitance can then be transferred to room temperature using a standard ac bridge measurement technique. The figure below 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 in terms of the charge of the electron.



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

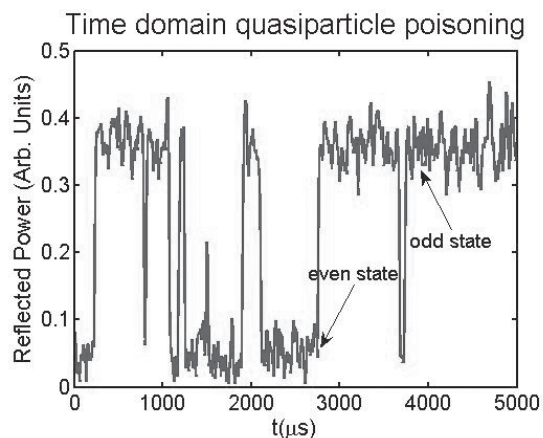
■ **Quasiparticle Poisoning in Cooper Pair Transistors Elucidated** – In collaboration with Professor Michel Devoret (Yale), we have performed a number of experiments which verified a model for erratic quasiparticle tunneling in superconducting Cooper pair transistors (these are the superconducting versions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

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



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

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



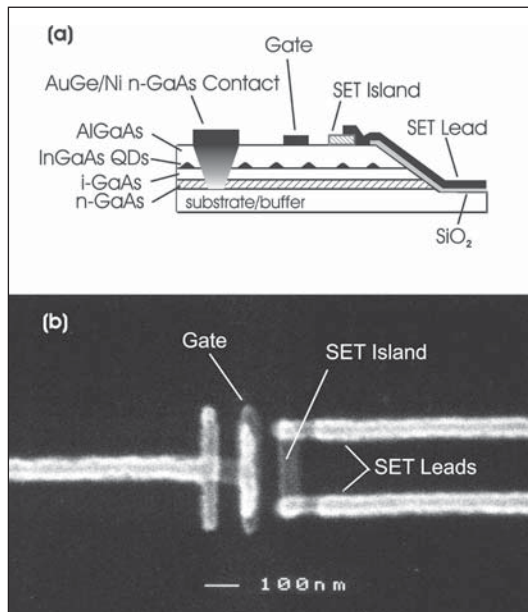
Using techniques similar to the rf-SET measurement, we have measured the modulation of the Josephson inductance of a Cooper pair transistor while biased on the supercurrent branch. In this example, when a quasiparticle enters the transistor island, the Josephson inductance shifts causing a change in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

■ Real-Time Observation of Quasiparticle Poisoning Using a Novel rf Measurement Mode

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

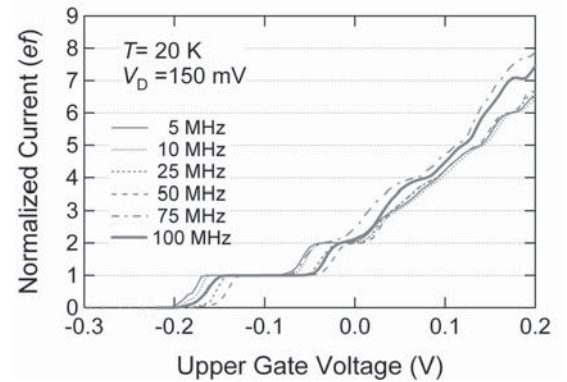
■ SET Electronics Developed to Probe GaAs Quantum Dots for Single Photon Source

– The past two years have produced significant progress towards the development of a single-photon turnstile, a device designed to generate single photons on demand using semiconductor quantum dots (QD) and single-electron principles. A key step towards this goal is to measure the tunneling of single electrons onto individual quantum dots. We have succeeded in making these measurements by integrating an SET electrometer over a low density field of GaAs quantum dots (grown by Rich Mirin of the Optoelectronics Division). A schematic cross-section of the device is shown below, along with a scanning electron micrograph of the SET electrometer. Such nanoscale device integration is difficult and required extensive process development. Using these devices, we have clearly identified the addition of single electrons onto single quantum dots located below the SET. We have counted up to 3 electrons added to a single dot, and have measured the energy spectrum associated with adding electrons on this dot. This work has led to a recent publication showing how adding a gate electrode to the QD structure can improve its performance as a source of single photons for quantum cryptography.



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

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



The pumping current in a CCD versus control voltage. The plateaus correspond to pumping $1e$, $2e$, ..., per cycle; note that the plateaus are at the same level for frequencies between 5 and 100 MHz.

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

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

COLLABORATIONS

■ NIST/JILA, passive electron counting for current standard

- NIST Semiconductor Electronics Division, Si-based SET devices
- NIST Optoelectronics Division, single-photon competence project
- Nippon Telegraph and Telephone, Si-based SET devices
- Center for Integrated Nanotechnologies, Sandia National Laboratory, single-photon devices

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METROLOGY OF THE OHM

Technical Contact:
Randolph Elmquist

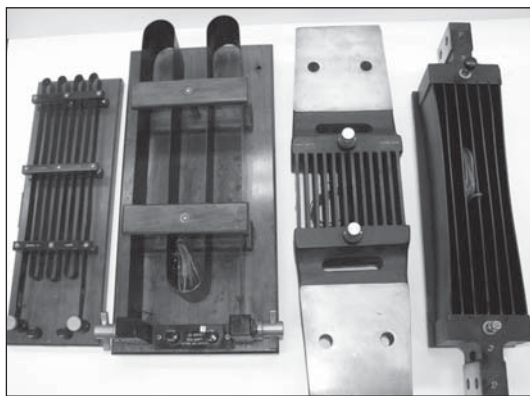
Staff-Years (FY 2006):
3 professionals
1 technician

GOALS

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

CUSTOMER NEEDS

The U.S. electronics instrumentation industry, along with military and aerospace industries, maintains a position of world leadership through the development and deployment of increasingly sophisticated multi-function, high-precision and low-maintenance instruments. To meet the present challenging needs, and in anticipation of the increasingly strict demands of advanced scientific processes, this project develops instruments and standards that enable the dissemination of over 20 decades of resistance values. Resistance standards provide references for electrical measurements at very high and low current levels and are used to support a wide variety of impedance, temperature, strain, and power measurements, over a wide range of frequency, at very high levels of accuracy. Through this very broad customer base, the activities of this project support innovation and enable U.S. industry to demonstrate and verify in a cost-effective way the accuracy of electrical measurements and the performance of high-precision instrumentation in a competitive world environment.



Precision shunt resistors provide high-current capability for power and industrial applications.

TECHNICAL STRATEGY

Highly directed research and involvement with our customers demonstrates our interest in performing

at levels that exceed expectations. These customers value NIST calibrations because of our reputation as a “science foremost” and “customers first” institution, and the Division 817 technical strategy reflects these values.

As part of a National Measurement Institute (NMI), we pursue scientific breakthroughs in quantum metrology to maintain an accurate local representation of the unit of resistance. We pursue collaboration with other NMIs, and participate in international metrology comparisons to ensure consistency of electrical measurements.

In FY 2006 we initiated and piloted a regional comparison of dc resistance between laboratories of SIM nations. NIST developed methods to analyze data and link the SIM results to CCEM Key Comparison results through NIST and NRC (Canada). The comparison package traveled first to South America and will complete another three circuits of laboratories, each time returning to NIST for the pilot lab measurements, before the comparison is completed in February 2007.

We are conducting tests on two new Cryogenic Current Comparator (CCC) systems for resistance scaling. A four-decade CCC developed for and in collaboration with Sandia National Labs will allow Sandia to provide ratios accurate to 1 part in a hundred million in support of automated resistance bridges and to maintain their very low uncertainty levels. Sandia engineers developed and produced multi-layer circuit boards for this system, which helped lower the development cost for this and future CCC systems built by NIST. A second, new design of high-resistance (HR) CCC bridge has been tested at 1 megohm, and electronics is being developed for scaling from the QHR standard to 10 megohm and other high resistance levels.

Non-commercial CCC systems have replaced room-temperature current comparators in many NMIs because they allow much lower uncertainty in resistance scaling. Commercialization of CCC systems has ceased for the time being after the first few such systems failed to operate successfully over the long term at NMIs. We are working to initiate a collaboration to construct a number of NIST-design HR CCCs, which could be used at NMIs as well as U.S. DoD primary calibration facilities.

PLANS

- Prepare and pilot the first Regional Metrology Organization (RMO) Key Comparison of dc resistance within SIM, at resistance ranges of 1 ohm, 1 megohm, and 1 gigaohm. SIM constitutes the RMO for major NMIs in the Western Hemisphere
- Using new capabilities to monitor and measure characteristics of large numbers of precision 1 ohm resistance standards, determine how the different construction methods and materials contribute to more stable, predictable behavior under many different conditions and stresses encountered in the laboratory and in transport.
- In order to accommodate customer requests to calibrate higher resistance values, Construct new standards, upgrade detection systems, and complete automated fully-guarded switching systems to enable 100 teraohm measurements with 0.05% or better uncertainty.
- Initiate collaborations with several NMIs to develop CCC systems to compare high value standard resistors directly against the QHR standard with lower noise, better uncertainty, and at a wider range of resistance levels. These methods will test our theoretical models of cryogenic current comparators, and help reach the Johnson noise level of 1 megohm and 10 megohm room-temperature resistors.



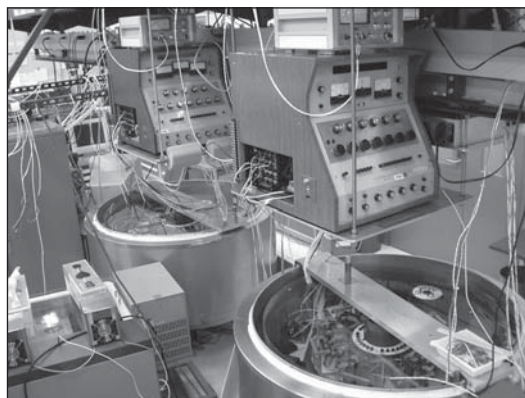
Visit by M. Kraft and R. Elmquist to Navy NAVAIR facility, which this year has installed a new QHR standard.

ACCOMPLISHMENTS

■ At this year's NCSL conference we presented three papers on: 1) the major role of NIST in international comparisons, 2) how to make precise and repeatable tests using high-current shunts, and 3) the effects of changes in temperature and pressure on precision one ohm resistance standards. Staff members also visited the Army Metrology lab at Redstone Arsenal and the Navy NAVAIR Calibration lab in San Diego to observe and offer help on metrology problems. These activities not only serve our customers but also help them to make informed decisions about how to use NIST calibration services and to improve their programs.

■ The Electronic Kilogram Experiment laboratory required more frequent 100 ohm CCC transfers in order to support final results for CPEM-2006. These measurements allowed the EKE lab to maintain two 100 ohm standards on-site with 5 parts in 10^9 uncertainty, in order to cross-check the standards after transfers. These represent the lowest uncertainty dissemination of resistances presently available.

■ With other researchers in Division 812 and 817, we are updating and expanding our calibration service check-standard database and testing this resource in the Ohm and Power & Energy projects. Development will provide more search features, better security, and more control of data by researchers.

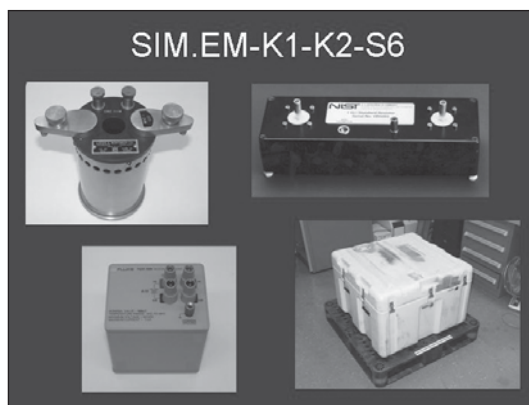


Two automated 1 ohm measurement systems allow precise customer tests and characterization studies.

■ Fifteen Thomas 1 ohm resistors and five newer 1 ohm resistors of similar quality were characterized using controlled, variable temperature and pressure chambers. These standards are calibrated by NIST as references for low resistance DCC and CCC bridges, and for international comparisons. Two oral papers on this study have been presented: CPEM'06, "Recent Investigations into the Temperature and Pressure Characteristics of Precision 1 Ohm Resistors at the National Institute of Standards and Technology," and NCSLI'06, "Temperature and Pressure Coefficients of Thomas 1 Ohm Resistors." George Jones received the "Best Paper Award" at NCSLI'06 for this contribution.

CALIBRATIONS

Over 250 calibrations were performed with approximately \$325,000 division income received (October 1, 2005 to September 30, 2006).



2006 SIM resistance comparison standards and transport package.

COLLABORATIONS

- Argentina, Brazil, Canada, Mexico, Uruguay, and the U. S. are participating in the SIM resistance regional comparison.
- A project to build, test, and install a 10-to-1 ratio CCC for DoE's Sandia Primary Standards laboratory is near completion.
- Studies of 1 ohm precision resistors have been broadened to include Evanohm standards constructed by B. Pritchard of NMI Australia. Pritchard will be a guest Researcher at NIST beginning in February, 2007.
- A program to construct HR CCC systems is being arranged with INTI (Argentina), NMI (Australia). Several other NMIs have been invited to participate.

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FARAD AND IMPEDANCE METROLOGY

GOALS

To provide the world's best basis for accurate impedance measurements. To achieve this by maintaining the Farad and tying the U.S. legal Farad to the international system of units, supporting and improving NIST's impedance measurement services, and ensuring the critically needed access of the U.S. industrial base to internationally consistent, reliable, reproducible, and traceable electrical measurements.



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

CUSTOMER NEEDS

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

TECHNICAL STRATEGY

The primary facility for connecting the U.S. legal system of electrical units to the international system of units is the NIST calculable capacitor, in which the measurement of capacitance is effectively

achieved through a measurement of length. Both the calculable capacitor and the chain of high precision measurements that transfers the SI unit to the calibration laboratories must be maintained, improved, and compared with other national metrology laboratories to ensure measurement consistency on an international level.

Over the last few decades, NIST has successfully invested in two key quantum representations of electrical quantities: both the Quantum Hall Resistance (QHR) and Josephson Voltage standards have now achieved measurement uncertainties approaching parts in 10^9 . These quantum standards, however, represent only a few points in a multi-dimensional world of electrical measurements. The crucial link between the fundamental electrical standards and commercial electronic instrumentation is provided by precision AC measurement standards. The current NIST expertise of AC measurements centers on transformer-based analog bridges and circuits and is largely limited to a single frequency at 1592 Hz, which has been achieved through a long, focused effort to realize the SI electrical units of the farad and the ohm. A combination of well-established transformer techniques and the AC signal generation and detection based on modern Digital Signal Processing (DSP) techniques has the potential to extend our expertise to provide best-in-the-world measurement capability over the frequency range from DC to 100 kHz.

AC measurements linking the calculable capacitor to the set of standards that comprise the National Farad Bank have been performed only at 1592 Hz and 1000 Hz. However, customer standards are often calibrated at other frequencies; as a result, the uncertainty provided for customer calibrations was significantly increased to account for differences in the capacitance unit due to frequency dependence. In order to better support customers' needs in the broader frequency range from 50 Hz to 20,000 Hz, the frequency dependence and dissipation factor of the Farad Bank need to be determined.

Consistency between resistance and impedance measurement services from NIST is expected by the instrumentation industry and DoD laboratories. An improved RC link is also needed to realize the farad from the QHR standard, if the proposed redefinition of the SI occurs in the near future, and to advance basic research such as closing the quantum metrology triangle. The current strategy

Technical Contacts:
Yicheng Wang

Staff-Years (FY 2006):
2.6 Professionals
1.5 Technicians
0.8 Contractor

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

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

for closing the metrology triangle via an electron counting capacitance standard requires an accurate link between the Farad Bank and the QHR standard.

Development of wideband impedance measurement services requires reference standards that can be characterized over the impedance and frequency ranges of interest. NIST has developed a system to characterize commercial four-terminal-pair (4TP) capacitance standards from 1 pF to 1 nF over the frequency range from 1 kHz to 10 MHz. This system is being used to offer special tests for 4TP capacitors as well as provide reference standards for general impedance measurements using a commercial LCR meter. A bootstrapping technique using the LCR meter and an inductive voltage divider (IVD) can be used to extend the characterization from the 1 nF standard to higher-valued capacitance standards up to 10 μ F.

PLANS

- Complete development and characterization of reference standards for, and optimize scaling capabilities for dissemination of, dissipation factor measurements of capacitors from 50 Hz to 20 kHz.
- Complete SIM capacitance comparison report within 6 months of receipt of all participant data.
- Develop a DSP-based ac waveform generator and synchronous detector for applications of precision ac measurements, including ac bridges.
- Demonstrate the applications of DSP techniques to fully automate an existing single frequency, 2-terminal-pair capacitance bridge in the audio frequency range.
- Modernize a quad bridge to link a 1 nF capacitor with a 100 k Ω resistor at 1592 Hz to improve the RC link between the dc QHR and the Farad Bank and provide a foundation for future ac resistance measurement services.
- Implement dissipation factor measurement services for fused-silica capacitors in the audio frequency range.
- Perform regular Farad Bank measurements and calibrations of the Farad Bank against the calculable capacitor.
- Perform calibration and special test workload as well as international inter-comparisons as required. Perform regular calibration and check standard measurements necessary for the maintenance of the present measurement systems and standards.

ACCOMPLISHMENTS

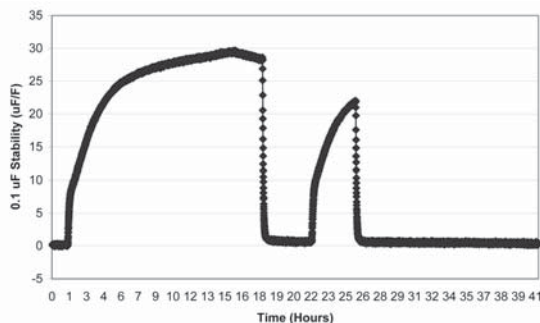
- Major advances have been achieved in determination of frequency dependence of capacitors. Frequency dependences of capacitance standards have to be determined in order to provide traceability

of capacitance calibrations at various frequencies demanded by customers and to enable consistency check among the three fundamental electrical units: the volt, the ohm, and the ampere, by closing the Quantum Metrology Triangle (QMT). Using a combination of a 1 pF “cross capacitor” having a negligible frequency dependence due to surface films and a 10 pF nitrogen dielectric capacitor with a very small residual inductance as references, we have measured the frequency dependence of 10 pF and 100 pF reference fused-silica capacitors from 50 Hz to 20 kHz. This achievement has allowed us to greatly improve and expand the capacitance calibration services at NIST. It has also enabled EEL researchers to set an upper bound on the frequency dependence of a cryogenic vacuum-gap capacitor which is a key component of the QMT experiment and then to close the QMT with uncertainty of 1 ppm.

- We have established references for dissipation factor measurements of 10 pF fused-silica capacitance standards from 50 Hz to 20 kHz, using a toroidal cross capacitor and a 10 pF nitrogen-filled capacitor as the references. Precise dissipation factor measurements for capacitance standards are needed for characterization of dielectric materials, traceability of energy and power measurements, and characterization of precision attenuators (*e.g.*, the input stage of the Agilent 3458A). As commercial instruments become ever more sophisticated, leading manufacturers in the U. S. are demanding better calibration support from NIST.

- Developed and characterized a programmable capacitance standard to provide accurately-known capacitance values over five orders of magnitude from 100 pF to 10 μ F with a resolution of 1 pF. The potential applications of a well-characterized programmable capacitance standard are numerous. NIST measurement support for high-accuracy capacitance calibrations has traditionally been limited to decade values from 1 pF to 1000 pF. The programmable reference capacitor will be used to test the linearity of commercial precision capacitance bridges to support the calibration of non-cardinal and high-valued capacitance standards. Used in conjunction with a programmable resistance standard, presently under construction, the programmable capacitor will be used to synthesize arbitrary impedances to support generalized impedance calibrations. The development of this standard was presented at the 2006 Conference on Precision Electromagnetic Measurements. A plot showing the stability and temperature controller effectiveness of the programmable capacitance

standard over a two-day period is given in the figure below. The two large spikes in the figure correspond to times where the temperature controller was turned off and the flat segments of the curve correspond to times where the controller was turned back on.



Stability data of the programmable capacitor at 0.1 uF and 1 kHz.

- Established a special test for four-terminal-pair capacitance standards of values from 10 nF to 100 uF at frequencies from 100 Hz to 100 kHz. New commercial capacitance bridges and impedance meters are becoming more and more accurate. This capability was established to satisfy the need for U.S. industry to calibrate more accurate impedance meters. An uncertainty analysis has been achieved up to 100 nF. A poster presentation on aspects of this work was given at the 2006 Conference on Precision Electromagnetic Measurements. A complete description of the system has been drafted and will soon be published as a NIST TechNote.



Andrew Koffman performs a special test for a four-terminal-pair capacitance standard.

- Completed the key international comparison for inductive voltage dividers (CCEM-K7). The existing NIST IVD calibration system was used along with the new straddling bridge to determine

the in-phase and quadrature errors of the precision IVD used for a CCEM-sponsored international comparison. Results indicate that agreement between the two systems is better than 3 parts in 10^8 for in-phase error components and better than 5 parts in 10^8 for quadrature error components. The results of the worldwide comparison have been disseminated. NIST measurements agreed well with the reference values to within the NIST uncertainties. NIST was one of only four labs out of the 17 participants whose results agreed with the reference values to within stated uncertainties at all 44 measurement points.

- Served as pilot laboratory for SIM capacitance key comparison SIM-EM.K4 and supplemental comparisons SIM-EM.S4 and SIM-EM.S3, and completed protocol documentation and all measurements. The CCEM K4 key comparison for capacitance standards was completed in 2000 with NIST serving as the pilot laboratory. As the only country with a working calculable capacitor in the Americas, NIST has the obligation to provide the link between SIM and CCEM for capacitance measurements. In partial fulfillment of this obligation, NIST is serving as the pilot lab for an international comparison of capacitance measurements between many of the National Metrology Labs in North, Central, and South America. All measurements have been completed and the traveling standards have been returned to NIST. The final pilot measurements have been completed. When all participating laboratories have submitted measurement results, data evaluation and report generation will follow.

- Documentation of the improved capacitance calibration services is drafted and the MCOM review process will begin before FY06 yearend. NIST low frequency three-terminal fused-silica and nitrogen dielectric standard capacitor calibration services have been improved and expanded in frequency from the previous 100 Hz, 400 Hz, and 1000 Hz to 20 frequencies from 50 Hz to 20 kHz using a commercial automatic capacitance bridge as a transfer standard.

CALIBRATIONS

- 224 tests were performed on 94 artifacts for 54 customers for impedance standards and inductive voltage dividers, providing income to the Division of approximately \$175,000 (October 1, 2005 to August 31, 2006)

COLLABORATIONS

■ Yicheng Wang collaborated with Michael Moldover of CSTL in an SBIR Phase II project to develop an atomic standard of pressure based on capacitance metrology.

■ Andrew Koffman and Bryan Waltrip collaborated with the Measurement Standards Center at Agilent Technologies Japan in the production of the 4TP Capacitance Scaling System.

■ Yicheng Wang collaborated with Rae Duk Lee of KRISS, South Korea on developing transportable capacitance standards for dissipation factor measurements.

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THE ELECTRONIC KILOGRAM

GOALS

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

To enhance NIST's ability to measure and disseminate improved mass standards made of materials suitable for air to vacuum transfers.

CUSTOMER NEEDS

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

The International Committee for Weights and Measures (CIPM), on the recommendation of the Consultative Committee on Units (CCU), has adopted a resolution to the General Committee of Weights and Measures (CGPM), to consider a redefinition of the kilogram in 2011, provided suitable results have been reproduced. Since any new definition of the kilogram will likely involve measurements of mass standards in vacuum, new methods to transfer from and maintain mass standards in vacuum must be explored. Thus the Electronic Kilogram project and the related Alternative Approach to Mass Metrology projects are researching these issues.

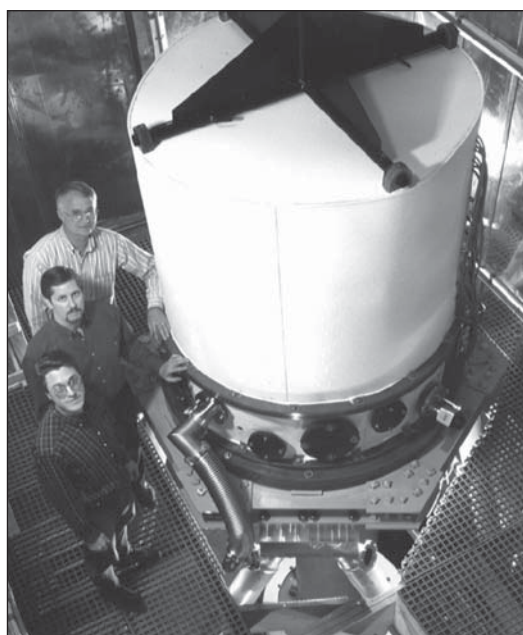
TECHNICAL STRATEGY

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

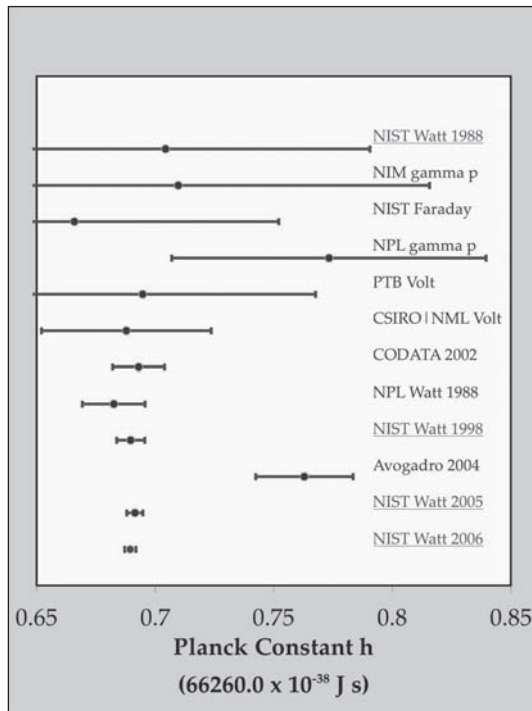
The entire experiment is a complex mesh of mechanical and electronic components controlled by computer. The systems are not only for watt data acquisition but also include reference standards, servo control, and environmental monitoring. All systems need to perform accurately and consistently 24 hours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

Technical Contact:
Richard L. Steiner

Staff-Years (FY 2006):
2.0 professionals



Ed Williams, Richard Steiner, and Dave Newell with the NIST watt balance.



Laboratory Values of the Planck Constant.

are recognized as necessary for better instrument performance, easier operational use, and as preventative maintenance. The work in 2006 is expected to maximize and report on the performance of the present system. Future years envision the design of a new system, enhanced and user friendly, for use as the U.S. kilogram mass standard, located in the Advanced Metrology Laboratory.

PLANS

- Better values of the Planck constant at about 0.02 $\mu\text{W/W}$ uncertainty, to meet the conditions specified in Recommendation 1 (CI-2005), adopted by the International Committee for Weights and Measures (CIPM), calling for preparative steps towards new definitions of the kilogram, the ampere, the Kelvin and the mole in terms of fundamental constants, for possible adoption by the 24th General Committee of Weights and Measures (CGPM) in 2011.
- A new electronic kilogram system in the Advanced Metrology Laboratory, designed for use as the next generation U.S. national mass standard.

ACCOMPLISHMENTS

- *Electronic Kilogram* – A result for the Planck constant was published in March 2005, reporting a combined standard relative uncertainty (CSRU) of 52 $\mu\text{W/W}$, the first result since 1998, after completely rebuilding the apparatus.

- Improved analysis of the Type B systematic error sources led to a better result with a CSRU of 36 $\mu\text{W/W}$ (see figure at left), presented and submitted for publication in July 2006 at the Conference on Precision Electromagnetic Measurements (CPEM-2006). The two results are both within the lower of the two combined uncertainties, and agree with the 1998 result.

- Two publications by Mills, *et al.*, presented arguments for redefining several SI units: the kilogram, ampere, Kelvin, and mole. The first, calling for immediate redefinition of the kilogram, initiated Recommendation 1 (CI-2005) of the CIPM for redefining and linking these units to fundamental constants as early as 2011. The second called for completely redefining these units in terms fundamental constants. Both papers sparked major international discussions within the various Consultative Committees that are concerned with these units.

- R. Steiner, E. Williams, and D. Newell were awarded a Gold Medal in 2006 by the Department of Commerce, for their research work on the Electronic Kilogram.

- *Alternative Mass Metrology* – A vacuum-to-air mass balance has been designed. It involves magnetically suspending a mass inside a vacuum chamber and measuring its mass against one in air. The initial magnetic suspension has been achieved.

COLLABORATIONS

R. Steiner and E. Williams are collaborating via periodic workshops with NPL-UK, METAS-Switzerland, and LNE-France, and the BIPM as part of the Consultative Committee for Electricity and Magnetism (CCEM) group on the watt balance realization of the kilogram.

E. Williams is scheduled to go on a 6 month sabbatical to LNE in November 2006.

Edwin Williams is collaborating with the Mass Group of the Manufacturing Engineering laboratory on the Alternative Mass Metrology competence project.

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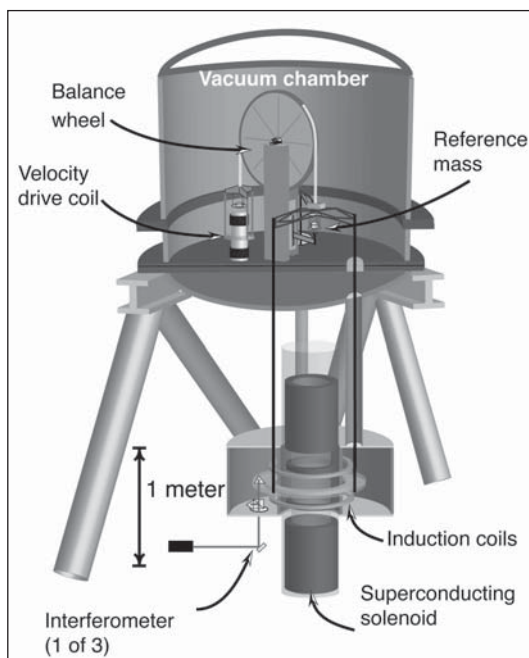
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Schematic diagram of the NIST watt balance.

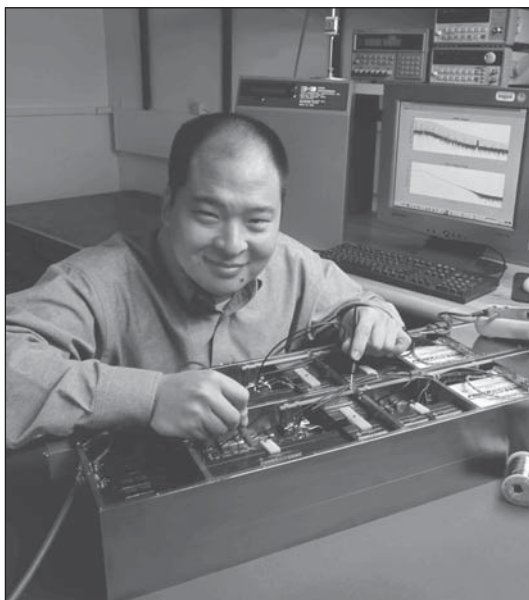
QUANTUM-BASED NOISE THERMOMETRY

Technical Contact:
Sam Benz

Staff-Years (FY 2006):
1 professional
1 guest researcher

GOALS

To create an intrinsic quantum-based electronic temperature standard to support the NIST Chemical Science and Technology Laboratory efforts toward reducing uncertainty in the ITS-90 temperature scale and to develop a novel method for determining the Boltzmann constant.



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

Existing precision thermometry methods use gas-based and fixed-point methods to achieve the lowest uncertainties below parts in 10^5 . Unfortunately, these methods are limited to specific fixed temperatures and require considerable effort. Another method that compares electrical and thermal noise power, called Johnson noise thermometry (JNT), would provide a novel approach to precision thermometry and, through the use of quantum-based voltage standards, has the potential to improve the realization of the Kelvin Thermodynamic Temperature Scale, especially with regard to linearity.

In addition, a quantum-based JNT system would also provide a novel route to a re-determination of the Boltzmann constant, k . This latter goal is particularly timely because there are plans to redefine in 2011 four of the SI units (including the Kelvin in terms of k) in terms of fundamental physical constants so that they are universal, permanent,

and invariant in time. The NIST quantum-based JNT approach to create an “electronic Kelvin” is analogous to the watt-balance program to realize an “electronic kilogram,” which compares electrical and mechanical power for the determination of Planck’s constant, h .

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

In order to meet these customer needs and fundamental metrology goals, we created a quantum-based electronic temperature standard that is unique in the world by developing new technology in a number of different areas. Most importantly, we constructed the world’s first quantum voltage noise source (QVNS) as well as state-of-the-art low-noise cross-correlation electronics, which is calibrated by the QVNS. We developed pseudo-noise voltage waveforms and synthesis techniques for comparison with the voltage noise of resistors in triple point cells of both gallium and water. We also devised a novel ratiometric method that uses the QVNS to compare the voltage noise of resistors at different temperatures.

TECHNICAL STRATEGY

The goal of the NIST Johnson noise thermometry program is to build an electronic temperature standard based on the quantized voltage pulses of superconducting Josephson junctions.

In a JNT system, the temperature T is inferred from measurement of the Johnson noise voltage V_T across a calibrated resistance R . The mean-squared voltage noise is given by the Nyquist formula $\overline{V_T^2} = 4kTR\Delta f$, where Δf is the measurement bandwidth. Cross-correlation techniques are typically used to measure these extremely small voltages to remove the error introduced by amplifier noise. In 1999, John Martinis realized that the Josephson Arbitrary Waveform Synthesizer being developed by the Quantum Voltage Project might be able to produce a stable, accurate, pseudo-noise voltage to provide a better means of calibrating the low-noise cross-correlation electronics. A stable, programmable, and intrinsically accurate noise source, based on the quantum accuracy of Josephson junctions, would provide a number of key

advantages: (1) direct calibration of the cross-correlation electronics, (2) matching of the calibration voltage noise to that of the sense resistor, while (3) simultaneously matching the source impedance to both the sense resistance and the output transmission-line impedance. These features, which are mutually exclusive using conventional methods, reduce the measurement uncertainty, increase the measurement bandwidth, and decrease the measurement time for the entire JNT system.

During the JNT development program, the Quantum Voltage Project developed a QVNS that is ideally suited for these measurements and is based on digital-to-analog waveform synthesis techniques. The QVNS superconducting integrated circuit is based on technology and research developed for ac Josephson voltage standards. However, development of the QVNS also provided new insights and precision measurement expertise that improved and benefited the ac Josephson program.

Our goal is to achieve uncertainties of better than a few parts in 10^5 for temperatures in the range of a several hundred Kelvin. At these temperatures the noise signals are small, on the order of $1 \text{ nV/Hz}^{1/2}$ for a 100 ohm resistor. In order to achieve small measurement uncertainties for such low-voltage signals, the noise power spectral density must be integrated for a long time and over a wide bandwidth. Thus the QVNS must be stable for long integration times but does not need to generate large voltages. We 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 is to obtain the highest possible voltages.

We also constructed custom cross-correlation electronics for the JNT program. Two pairs of voltage leads are measured with separate low-noise amplifier channels. 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 to a custom PCI card installed in a computer. Each channel transmits 2.08333 million samples per second which is the effective sampling frequency of the signal. In the present system, a dual-CPU computer is used to calculate two 2^{21} point fast Fourier transforms (FFTs) in real-time

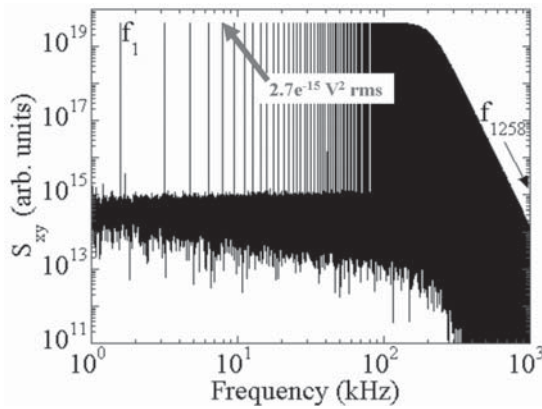
(less than one second). The cross-correlation and auto-correlation power spectra are then calculated, accumulated, and stored for later analysis.



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

ACCOMPLISHMENTS

■ Sae Woo Nam, Wes Tew (NIST Chemical Sciences and Technology Laboratory), and Sam Benz have performed many comparisons between the Johnson noise voltage of resistors at known temperatures and the synthesized pseudo-noise waveforms of the quantum voltage noise source. The resistor temperatures are controlled using either a gallium fixed-point cell or a water triple point cell. Measurements are made using the custom built cross-correlation electronics system. The computer-controlled optically interfaced system correctly samples, stores, and processes the waveforms in real time. This correlation electronics is different from other systems because it digitally processes 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-correlation 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 based on the digitizer bins.

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

■ Nam, Benz, Dresselhaus, and Charlie Burroughs, in collaboration with Wes Tew of the Chemistry Laboratory, have continued development of the Johnson noise thermometry system, especially with regard to improvements in the measurement circuits and electronics. Unwanted distortion was observed when the accurate QVNS signal was measured with the cross correlation electronics. This distortion was significantly reduced by using inductive chokes on the input of the electronics. The cause of the distortion appeared to be mixing in the first FET amplifier from the high-frequency, 100-400 MHz, quantization tones in the QVNS waveform. Other major sources of distortion that were uncovered through measurements of the accurate QVNS synthesized waveforms were due to

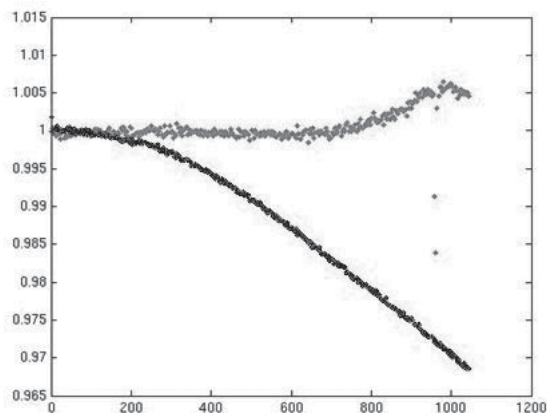
poor contacts and interconnections between the signal sources and the amplifiers; poor interfaces rectify the waveform and produce measurable harmonic distortion. Unique waveforms, with either odd-only or even-only harmonics, were developed to elucidate and remove these errors. By constructing a second QVNS system, and making comparisons between them using both inputs to the JNT electronics, we were able to remove all distortion within the dynamic range of the electronics.

■ Comparisons between different QVNS cryo-probes also increased our understanding of the high-frequency transfer function characteristics. Calculations showed that small differences in the transfer functions of the QVNS probes were caused by different transmission line leads. Calculations showed that this effect could not account for the transfer function differences between the QVNS and noise resistor probes. We finally realized, and confirmed through further calculations, that there is a fundamental difference between the QVNS and resistor output circuits that results in a significantly higher effective capacitance in the resistor circuits that progressively mismatches the two transfer functions at high higher frequencies. By increasing the QVNS output resistance by about 65%, we successfully matched the transfer functions of the QVNS and resistor circuits up to about 600 kHz. This truly matches the transmission lines for the first time, contrary to our original assumptions about impedance matching at the start of this program.

■ Having greatly reduced the errors from distortion and transmission lines, we can now investigate voltage noise over a much wider frequency range. In preliminary measurements we've demonstrated that we can closely match the two transmission lines of the Josephson and triple-point resistor sources, causing the ratio to remain flat over most of the measurement bandwidth. Control of the ratio's frequency dependence is shown in Figure 4, where the grey data points show the ratio when the transmission lines are nearly matched. In this measurement, the absolute error in measuring temperature or determining " k/h " was approximately 50 ppm. This is 3-times better than previous temperature measurements. These preliminary results suggest that with only a 10-fold further improvement in the measurement uncertainty, we can have an impact on Boltzmann's constant at a few parts per million.

■ The next step toward lower uncertainty involves improving the measurement electronics to reduce intrinsic nonlinearities, lower the noise

floor, and extend battery lifetime. These improvements will allow the measurement electronics to complete much longer integration times (>2 days). We also must perform extensive measurements and calculations to model the transmission line effects. We also plan to investigate improvements in common mode rejection of the front amplifier stage and in the switching network.



Measured power spectral density ratios vs. frequency (kHz) showing control of the frequency dependence. The black points show the large frequency dependence in the ratio when the transmission lines (between the noise sources and the correlation electronics) are mismatched. The gray points show a nearly constant ratio up to 600 kHz with matched transmission lines.

■ In FY04 we delivered cross correlation electronics to the CSTL temperature calibration laboratory. This system is in use for making high temperature JNT measurements with the goal to reduce uncertainty in the ITS-90 temperature scale in the range 273 K to 1000 K through comparisons with a calibrated platinum resistance thermometer

■ In FY05 significant improvements in the JNT system were discovered by comparing two different Josephson systems. Poor contacts and interconnects were the primary culprit causing undesirable distortion. Unfortunately, this competence program ended before water/gallium comparisons could be obtained using the improved system.

■ In September of FY06 we installed the Quantum Voltage Noise Source in CSTLs Thermometry Lab and performed record-breaking Johnson Noise Thermometry measurements at temperatures above 500 K.

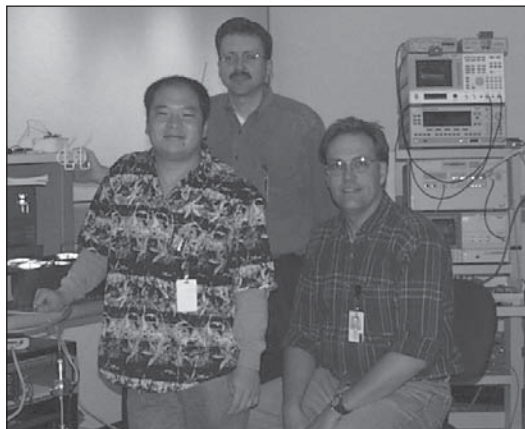
PLANS

- This year we plan to make significant improvements to the cross correlation electronics, including better preamplifiers and battery chargers that allow us to make longer continuous measurements.

- With further improvements and removal systematic errors for the electronics, transmission lines and measurement circuits, we hope to reduce our measurement uncertainty to less than 20 parts per million.

COLLABORATIONS

We are collaborating with Weston Tew and John Labensky of the Process Measurements Division (836) in the NIST Chemical Science and Technology Laboratory.



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

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

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S.P. Benz, P.D. Dresselhaus, and J. Martinis, "An ac Josephson source for Johnson noise thermometry," IEEE Transactions on Instrumentation and Measurement, Vol. 52, No. 2, pp. 545-549 (April 2003).

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QUANTUM MEASUREMENTS

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

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

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

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

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

ELECTRIC POWER METROLOGY

Technical Contact:
Thomas Nelson

Staff-Years (FY 2006):
3.5 NIST staff
1 NIST associate
1 technician

GOALS

Our goals are to provide the electric power industry with the world's best basis of precision electrical measurements in power and energy to ensure fair and accurate revenue billing; to provide electrical standards, tests, and services that underpin the reliable operation of the electrical power grid; and to assess and develop new measurement technologies for the increased reliability and quality of the U.S. electric power system.



PMUs – a key component of electric power grid modernization. The figure shows the NIST Calibration System for PMUs. The PMUs are the two instruments on top of the cabinet.

CUSTOMER NEEDS

The major needs of the U.S. electric power industry supported by this project are the equitable sale of electric power and energy, and reliable transmission and distribution of high quality electric power. Both require accurate and traceable measurements of electrical quantities.

Electrical energy revenue metering throughout the U.S. is traceable to NIST calibrations and results in annual revenues exceeding \$280 billion. We provide measurement traceability through calibration services for power and energy meters that ensure accuracy in measuring electric power and in monitoring power grid operation.

In addition, we support the reliable operation of the power grid. The U.S. electric power industry continues to play *the* major role in public safety, economic stability, and quality of life. Because it underpins many other infrastructures, electric power is the infrastructure we most readily notice when a disruption occurs, even if it is only mo-

mentary. In the wake of the major electric power outages in 1996 and 2003, the U.S. Department of Energy (DoE) has sponsored grid modernization efforts that entail a revolutionary change in control of the power grid, with the long-range goal of removing system operators from the control loop and replacing them with completely automatic control systems. This will be achieved through synchronized measurements of system conditions derived from quantities known as phasors (voltage and current amplitudes and phases). The website for the Eastern Interconnect Phasor Project (EIPP) is http://phasors.pnl.gov/EIPP_RT_Resources made using Phasor Measurement Units (PMUs). The major benefits of these efforts will be improved grid reliability and efficiency that lower costs to consumers, and reduced magnitude of the disruptions due to instantaneous location of faults. PMU-based control systems will also promote the use of alternative power generators by ensuring reliability as these new devices are added to the grid. We provide the basis for objective evaluation of PMU performance through the development of standards, test protocols, and measurement services.

TECHNICAL STRATEGY

This project maintains the U.S. standards for power and energy and disseminates them through measurement services for electric meters used by utilities and meter manufacturers to ensure the accurate sale of electric power in the U.S. Improvements in the accuracies we provide to our customers and internal streamlining of our services adds value for our customers. For example, we are developing a power calibration system that is based upon Josephson arrays that will allow us to reduce uncertainties to a few ppm for power calibrations.

International comparisons of measurement capabilities are essential for the equivalence of calibrations at all the National Metrology Institutes (NMIs), allowing customers to use only one calibration to sell their product worldwide. To ensure the accurate measurement of power throughout the Americas, we are serving as the pilot lab for an intercomparison among the member countries of the regional organization of NMIs for North and South America, the Sistema Interamericano de Metrologia (SIM).

The accuracies of power and energy measurement services that we provide depend in part upon accuracies of the digital multimeters (DMMs) we use

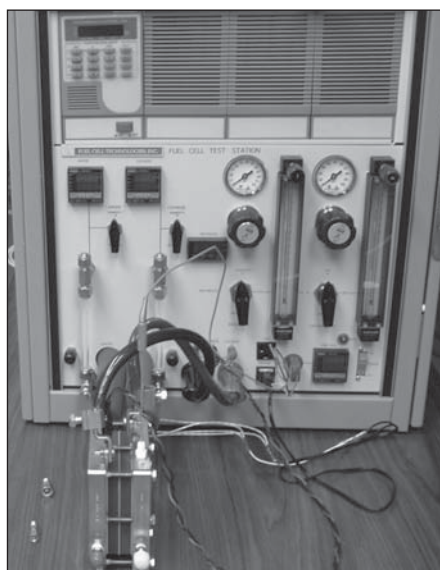
in our measurement systems. To achieve the best accuracies for our own measurement systems and to meet the demands of manufacturers and users for DMM measurements traceable to national electrical standards, we also provide measurement services for DMMs. We will pilot a SIM intercomparison for DMMs in 2007.

To improve power grid monitoring and control, a common calibration reference for devices requiring Coordinated Universal Time (UTC) timing references from GPS sources is required. We have established a SynchroMetrology Laboratory which will serve to calibrate PMUs and to develop and disseminate test procedures for use by manufacturers and utilities to assure interoperability and accuracy of time-coordinated metrology. The initial development of this laboratory is a calibration service for PMUs, to assure compliance of PMUs with the IEEE synchrophasor standard, C37.118. An Interagency Agreement between NIST and the U.S. DoE provides substantial support for this project. In collaboration with the North American Electric Utilities and DoE-sponsored Eastern Interconnect Phasor Project (EIPP), we are leading a working group to develop a testing Guide for PMUs. Future needs of the Electric Power Utilities require the assurance of interoperability of PMUs under dynamic conditions of the electric power grid. In collaboration with utilities and the standards community we are developing testing procedures and providing feedback to PMU manufacturers on the performance of their devices under various dynamic conditions.

Not only is reliability important to utilities and end users of electric power, but the quality of electric power is also important. Our meter measurement services are typically performed at a single frequency, namely the 50 or 60 Hz power frequency. To improve our capability and meet the needs of electrical equipment manufacturers and utilities for measurements of distorted power that contains harmonics of the power frequency, a new sampling test system has been constructed and is being used to participate in an international comparison of harmonic power measurements. The system developed is based upon a NIST-developed sampling waveform analyzer (SWA) with custom probes that make highly accurate measurements of arbitrary waveform parameters from the basic root-mean-square (rms) values to crest factor, signal-to-noise ratio (SNR), harmonic distortion, etc. The SWA has a frequency response flatter than any commercially-available instrument and this allows traceability to the national dc volt standard

and enables accurate waveform sampling from power-line frequencies to 5 GHz. In addition to the distorted power measurements, application areas for the SWA include ac voltage, characterization of voltage pulses, and radiofrequency calibrators. A newly redesigned version of the mainframe unit, SWA II, is now being tested in the laboratory. The new system offers several significant performance improvements including a tenfold increase in sampling time achieved through optimized efficiency in the Markov signal averaging and increased data record length, better accuracy through optical isolation of the digital circuitry, and a considerable decrease in the physical size and cost of the system. The reduced cost is of interest to the primary standards laboratories (PSLs) of the U.S. Air Force, Army, and Navy, and Sandia National Laboratories. We have already delivered SWA systems that give them in-house capability to calibrate their ac measurement standards and they are interested in the improved SWA II. We will also use it to provide dedicated support for another NIST special test measurement service in voltage pulse characterization, the 65250S service, Fast Repetitive Pulse Settling Error.

Fuel cells are used as electrical power sources in many applications from electric vehicles to spacecraft. Much work needs to be done in determining which designs and manufacturing processes result in the best fuel cell performance and lowest cost. To help answer these questions, we have set up a fuel cell testbed to assess fuel cell performance.



The new test stand for performance evaluation of fuel cells. The cells can be evaluated under controlled conditions to assess how manufacturing processes and design affect electrical performance.

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

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

PLANS

PMU Performance Evaluation

- Develop a measurement service for performance testing of commercial PMUs.
- Serve as leader of the EIPP PMU testing working group and complete the Guide for PMU testing under static conditions.
- Develop test methods for measuring performance of PMUs under dynamic conditions.

Improved Measurement Services

- Incorporate the NIST-developed quantum watt source into the power and energy calibration system.
- Complete the SIM energy comparison and publish the results
- Develop the waveform sampling-based calibration system for distorted power sources and other ac waveform standards, such as the Fluke 5790A Automated AC Measurement Standard.

New Project Areas

- Test prototype fuel cell performance to determine influence of design and manufacturing parameters.

ACCOMPLISHMENTS

■ We developed special calibration procedure for PMUs relative to the parameters specified in IEEE Standard C37.118 together with the North American electric utilities and power equipment manufacturers collaborating in the Eastern Interconnect Phasor Project (EIPP). This standard ensures that PMUs from multiple vendors will all interact correctly with the stability monitoring system being developed. In collaboration with the EIPP, we developed a special calibration service to calibrate the PMU parameters specified in the IEEE Standard.

■ We constructed a precision thermally-stabilized calculable shunt for measuring currents from 0.1 to 10 amperes for frequencies up to 1 MHz. This shunt exhibits less than 1 ppm of resistance change with currents between 0.3 and 10 amperes. This shunt was used in a ac shunt comparison with NRC-Canada up to 10 kHz and the agreement was better than 6 ppm.

■ We demonstrated the feasibility of making peak-to-peak waveform measurements up to 500 MHz with uncertainties less than 3 % using a SWA-based waveform sampling system. The Peak-to-Peak Detectors measurement service, 53430S and 53431S, which previously relied upon inferring peak-to-peak from root-mean-square measurement of a pure sinusoidal signal, will soon switch over to a waveform sampling technique using the

NIST SWA, allowing more accurate peak-to-peak measurements to be made.

■ We set up fuel cell test bed for performance testing of single cells and to correlate the impact of variation in manufacturing processes on electrical output.

CALIBRATIONS

Calibrations are typically performed for about 35 companies and government agencies annually, for total fees of nearly \$100,000.

COMMITTEE PARTICIPATION

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

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

Eastern Interconnect Phasor Project - G.N. Stenbakken is a member of the EIPP Performance Requirement Task Team and is the leader of the PMU System Testing and Calibration Guide Task Team.

IEEE Instrumentation and Measurement (I&M) Society TC-10 Waveform Generation, Measurement and Analysis Committee, D.I. Bergman is a member.

IEEE Power Engineering Society Power Systems Instrumentation and Measurement (PSIM) Committee, G.J. FitzPatrick chairs the committee.

SELECTED PUBLICATIONS

D. I. Bergman and G. N. Stenbakken, "Phase-Plane-Derived Distortion Modeling of a Fast and Accurate Digitizing Sampler," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 4, August 2006.

NIST Support of Phasor Measurements to Increase Reliability of the North-American Electric Power Grid, IEEE Power Engineering Society General Meeting, June 18-22, 2006, PESGM2006-000586.PDF.

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E. So, D. Angelo, B. Waltrip, T. Nelson, T. Tsuchiyama and T. Takodoro, "Intercomparison of Calibration Systems for AC Shunts up to Audio Frequencies," Conference Digest 2004, Conference on Precision Electromagnetic Measurements (CPEM 2004), pp. 35 (June 2004)

E. So, R. Arseneau, D. Bennett, T.L. Nelson, and B.C. Waltrip, "NRC - NIST Intercomparison of Calibration Systems for Current Transducers with a Voltage Output at Power Frequencies," Conference Digest 2002 Conference on Precision Electromagnetic Measurements, (CPRM 2002), pp. 544 – 544 (June 2002).

QUANTUM COMPUTING USING INTEGRATED JOSEPHSON JUNCTION CIRCUITS

GOALS

To develop techniques for making highly coherent quantum systems using integrated circuits. This includes developing new high fidelity measurements techniques for quantum systems. Ultimately, we want to make large-scale quantum information processing systems a reality.



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

CUSTOMER NEEDS

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

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

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

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

Technical Contact:
Raymond W. Simmonds

Staff-Years (FY 2006):
1 professional
1 technician
4 post-doc researchers
4 graduate students

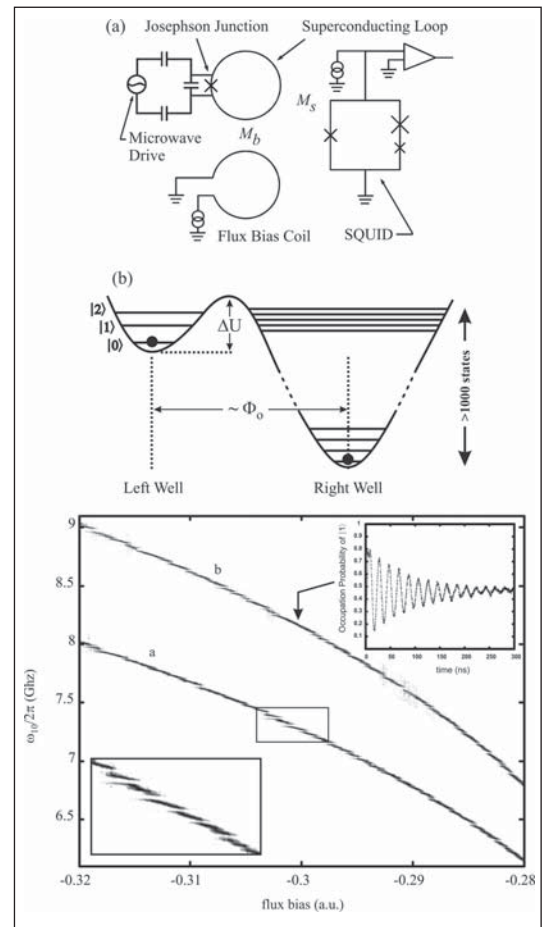
The integrated circuit components of classical computers are rapidly approaching the so-called “quantum limit.” Instead of avoiding quantum effects, we should exploit them as a means for more effective computation. Ultimately our work will produce new knowledge for the precise measurement of quantum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

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

Through the first ever simultaneous measurement of two superconducting qubits, we have witnessed two coupled phase qubits entangle themselves by performing coherent state oscillations.

TECHNICAL STRATEGY

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



(a) The phase qubit schematic circuit. (b) The potential energy at a particular flux bias applied to the qubit loop. An example of qubit spectroscopy for two qubits showing the transition frequency ω_{10} for various flux biases to the qubit loop. Notice the small “splittings” indicative of microscopic quantum systems residing within the tunnel junction coupling to our superconducting quantum bit. Top inset shows Rabi oscillations away from resonators.

The qubit transition frequency ω_{10} , which is directly related to the energy level separation of the $|0\rangle$ and $|1\rangle$ state, is measured spectroscopically as a function of the applied flux bias to the qubit loop. First we prepare the qubit in the $|0\rangle$ (ground) state. If we apply a microwave drive current at frequency ω and $\omega = \omega_{10}$, then the qubit will make a transition to the $|1\rangle$ state, otherwise it will remain in the ground state. If we sweep the value of ω and measure the occupation probability of state $|1\rangle$, we can determine the precise value for ω_{10} at that particular flux bias. We measure the occupation of the $|1\rangle$ state using a “fast” qubit state measurement technique. This is done by applying a quick dc flux pulse to the qubit loop so that the potential barrier ΔU is lowered just enough so that, if occupied, the

$|1\rangle$ state has a high probability for tunneling to the right well and will be detected using the SQUID. This procedure is done for many different values of the flux bias in order to determine the energy level separation or transition frequency ω_{10} as a function of the qubit loop flux bias. If we know the transition frequency ω_{10} , then we are able to fully control the state of the qubit. Varying the flux bias, simply allows us to operate the qubit at different frequencies (typically from 7 to 10 GHz).

An example of “qubit spectroscopy” is shown in the figure below. We find the expected decrease in the transition frequency with flux bias as the current through the junction approaches its critical or maximum current. Notice (in the lower inset) that there are “gaps” or “splittings” in the spectra. We have identified these spurious resonators as nanoscopic two level systems within the junction’s insulating barrier. Away from any spurious resonators, we have applied microwaves on resonance ($\omega = \omega_{10}$) to performed coherent state oscillations, known as “Rabi oscillations”, between the $|0\rangle$ and $|1\rangle$ state (upper inset). Near spurious resonators, we have found coupled interactions between the qubit and the resonator as described briefly in Accomplishments. Although these resonators are undesirable in an ideal qubit, so far they have been useful for testing coupled interactions and estimating the limits of

coherence in solid state nanosystems. An effort is being lead by David Pappas to improve the quality of Josephson junctions by growing epitaxial tunnel barriers to remove these nanoscopic defects.

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

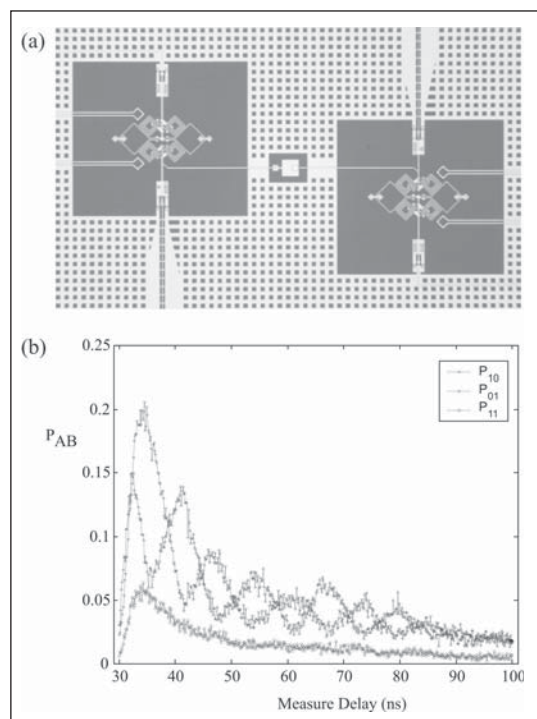
PLANS

- The development of the phase qubit was just a start. This program is interested in understanding decoherence sources and producing high quality superconducting qubits. We plan to study all three types of qubits: charge, flux, and phase as well as harmonic oscillators or microwave resonators which also operate in the quantum regime. We will also extend these investigations to qubits coupled to harmonic oscillators and coupled qubits.

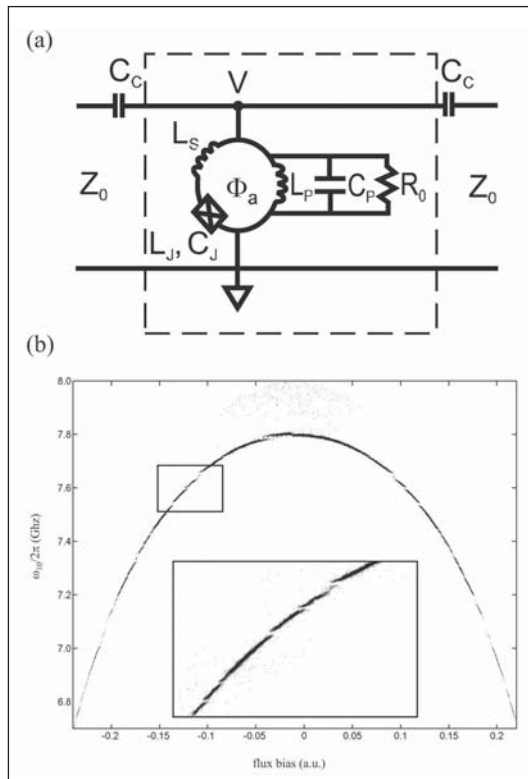
ACCOMPLISHMENTS

Although this project began only four years ago, we have made significant progress over this short period of time. Our work on coupled qubits has shown that two-qubit gates should be feasible. We have developed high quality harmonic oscillators or microwave resonators in order to investigate energy loss from dielectric materials. Our research has led the way to understanding how to improve future qubits by eliminating dielectric materials in the fabrication of qubits. We have managed to improve the materials and design properties of our qubits to more than double their coherence times. Most significantly we have developed a frequency tunable Josephson junction resonator which allows us to asses the quality of Josephson junction in an entirely new way. Many of our accomplishments over the past year are included in the list below.

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



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



(a) The Josephson junction resonator circuit. (b) An example of spectroscopy showing “splittings” from the two-level defects in the single Josephson junction.

■ **Developed a new, faster method to readout the phase qubit.** We have implemented a new qubit state measurement technique that is an order of magnitude faster than our former method. In less than 5 ns, a flux bias pulse is applied to the qubit so that the $|1\rangle$ state, if occupied, rapidly tunnels to the right well. This new advance has allowed us to monitor rapid qubit state variations such as the coupled interactions between phase qubits and other quantum systems.

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

■ **Dielectric loss reduce energy relaxation times.** Dielectric loss from two-level defects was shown to be a dominant decoherence source in superconducting quantum bits. Depending on the qubit design, dielectric loss from insulating

materials or the tunnel junction can lead to short coherence times. We have shown that a variety of microwave and qubit measurements are well modeled by loss from resonant absorption of two-level defects. Our results demonstrate that this loss can be significantly reduced by using better dielectrics and fabricating junctions of small area and by removing dielectric material completely. Redesigned phase qubits reducing the amount of dielectric and using an improved dielectric have improved energy relaxation rates by a factor of 20.

■ **Josephson junction resonator.** We have developed a unique microwave resonator using a single Josephson junction as a tunable inductance in the circuit. This flux tunable circuit allows spectroscopic measurements for frequencies that vary over a range >1 GHz. Information can be gathered to test the quality of Josephson junctions in terms of individual nanoscopic defects as well as excess energy loss. This device very similar to a phase qubit but is extremely simple to fabricate and operate, and it allows us to obtain a maximum amount of information. Moreover, this device operates as a low loss fluxometer ideal for future qubit readout.

COLLABORATIONS

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

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

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

■ Lev Ioffe – Rutgers University, Theoretical study of two-level systems

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QUANTUM SENSORS

Technical Contact:
Kent Irwin

Staff-Years (FY 2006):
15

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

*Catherine Pilachowski,
President of the American
Astronomical Society*

The development of sensors based on the quantum mechanical phenomenon of superconductivity can dramatically improve the sensitivity of measurements across the electromagnetic spectrum, from dc magnetic fields to microwaves all the way through gamma rays. By operating at temperatures below 1 Kelvin, photon detectors based on superconductivity are achieving unparalleled sensitivity, and they are beginning to bring about a broad revolution in many areas. Superconducting X-ray spectrometers are providing new capabilities in materials analysis for the semiconductor industry. Gamma-ray sensors that can provide more than an order of magnitude better spectral resolution are aiding in analyzing nuclear materials for nuclear non-proliferation, and may be used material to stop them from being smuggled across international borders. In the future, improved detectors for measuring the polarization of microwaves will probe the first moments of the universe by measuring the pattern that gravity waves from the Big Bang imprinted on the cosmic microwave background.

GOALS

The Quantum Sensors Project develops sensors based on quantum phenomena for spectroscopy, imaging, and other precision measurements for wavelengths from dc through gamma rays. We integrate these sensors with custom superconducting and room temperature electronics, cryogenic structures, and software to create complete measurement systems. We work with collaborators in industry, academia, and other government agencies to apply this measurement capability to applications including materials analysis, particle physics, astronomy, cosmology, and homeland defense.

We are developing sensors that operate at extremely low temperatures, and that take advantage of quantum phenomena, including quantum interference (SQUIDS), quantum phase transitions (superconducting transition-edge sensors), and quantum tunneling (normal-insulator-superconductor tunnel junctions).

The Quantum Sensors Project has been a world leader in developing these new detector systems. We have developed transition edge sensors (TES) 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.

Many applications require large arrays of quantum sensors. However, it is difficult to route individual wires from many different pixels to room temperature readout electronics. Practical implementation of large superconducting detector arrays requires that the signals be multiplexed at the cold stage. We have developed large-format superconducting integrated circuits based on SQUID switches that make it possible to read out many pixels in one output channel.

Applications for superconducting detectors include high-resolution X-ray spectroscopy for materials analysis for the semiconductor industry, high resolution gamma-ray spectroscopy to analyze nuclear materials to assist in nuclear non-proliferation and border security, and submillimeter and microwave detector arrays for astronomy and cosmological physics. In each of these areas the Quantum Sensors Project 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 is one of the most important metrology needs for the semiconductor industry. The 2005 International Technology Roadmap for Semiconductors recognize that superconducting X-ray detectors provide important new capability in resolving overlapping X-ray peaks: “Such new X-ray detectors will allow resolution of slight chemical shifts in X-ray peaks providing chemical information such as local bonding environments. These advances over traditional energy-dispersive spectrometers (EDS) and some wavelength dispersive spectrometers can enable particle and defect analysis on SEMs located in the clean room.” The transition-edge sensor (TES) microcalorimeter X-ray detector developed at NIST has been identified as a primary means of realizing these detector advances, which will greatly improve in-line and off-line metrology tools that currently use semiconductor EDS. At present, these metrology tools fail to provide fast and unambiguous analysis for smaller nanoparticles. 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 ranging from solar flares to supernova remnants to the formation of galaxies. The Quantum Sensor project has formed collaborations to transfer our TES technology into astronomical instruments with several institutions, including NASA, Stanford University, the Lockheed-Martin Solar Astrophysics Laboratory and the UK Astronomy Technology Center.

TECHNICAL STRATEGY

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

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

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

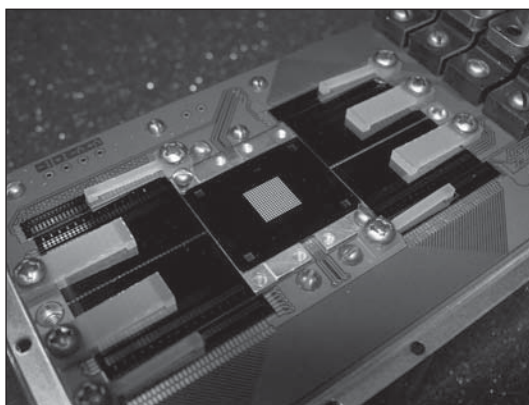
tectors as a means of increasing X-ray collection area and count rate.

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

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

While the performance of the detectors we have made is much better than existing detectors, additional 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, and to develop the nonequilibrium thermodynamic theory of resistive bolometers to better explain measured noise.

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.

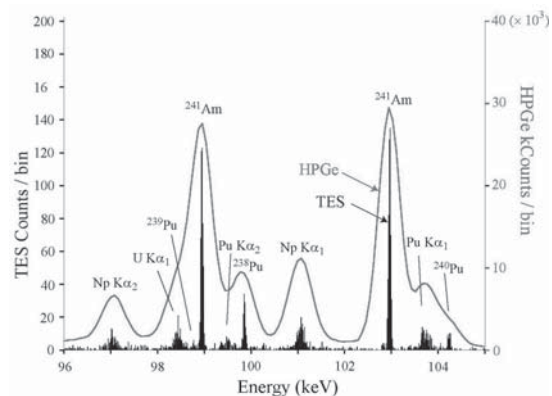


256-pixel TES X-ray calorimeter array and SQUID multiplexer electronics for X-ray material analysis and astronomy.

Another significant focus of the project is the development of gamma-ray detectors for the analysis of nuclear materials. One of the most pressing international priorities is to control the dissemination of nuclear materials that could be used in attacks by terrorists or rogue states. Nuclear materials contain unstable isotopes, which emit X-rays and gamma rays. The characteristic energies of these photons provide a fingerprint of which radioactive isotopes are present. Unfortunately, some isotopes that occur in benign applications emit gamma rays with energies that are very similar to those emitted by materials used in weapons, which leads to ambiguous identifications and false alarms. This problem has been vexing the U.S., which is installing thousands of radiation portal monitors to detect the gamma rays emitted by nuclear materials carried by vehicles crossing the Canadian and Mexican borders. One of our most significant fears is that terrorists might smuggle highly enriched (weapons-grade) uranium into the country to build a crude Hiroshima-style atomic bomb. The primary signature of highly enriched uranium is the 185.7 kiloelectron-volt (keV) gamma ray from uranium-235. This gamma ray, however, has almost the same energy as the 186.1 keV gamma ray emitted from the radium-226 in clay in cat litter and other materials, making it very difficult to distinguish the two. This so-called kitty-litter problem is the largest source of false alarms at the U.S. border.

The Quantum Sensors Project is developing gamma-ray detectors based on TES technology that have more than ten times better energy resolution than conventional detectors. These detectors can resolve more lines in the complicated gamma-ray spectra of nuclear materials such as uranium and

plutonium isotopic mixtures (see figure below). The devices are being developed specifically to help in the verification of international nonproliferation treaties, by determining the plutonium content of spent nuclear fuel. But they can also distinguish between the radium-226 in cat litter and the uranium-235 in highly enriched uranium. If a conventional hand-held detector or portal monitor were to detect a gamma-ray signal, one of the superconducting devices could be used as a follow-up tool to distinguish unambiguously between these two isotopes, thus eliminating many false alarms.



Spectrum taken with NIST gamma-ray detector array. When superconducting detectors are used to measure the spectrum of radiation from a plutonium-uranium isotopic mixture, the photons from the different isotopes are clearly resolved, allowing unambiguous identification of the isotopes that are present (black lines). In a spectrum taken with a conventional high-purity germanium (HPGe) detector (gray line), the lines are not resolved, and the determination of the isotopic composition is more difficult.

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. Finally, quantum sensors will be important for the precision measurement of the polarization of the cosmic microwave background, which will make it possible to measure the signal of gravity waves from the Big Bang itself.

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

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

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

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

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

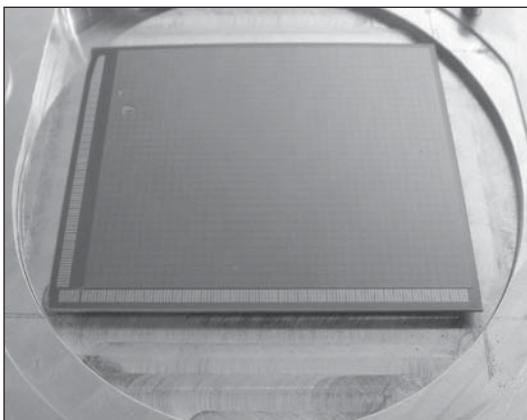
In addition, the Quantum Sensor project, in collaboration with the United Kingdom's Astronomy Technology Center, is developing both sensors and readout technology for the second Submillimeter Common User Bolometer Array (SCUBA-2). The SCUBA-2 instrument is designed to detect radia-

tion 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 over 10,000 individual pixels. It will allow astronomers to map the sky at speeds 100-1000 times faster than previously achieved.

The detector systems discussed above all share a common technical requirement: large arrays of TES detectors. This requirement brings with it the complication of reading out such large arrays. 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 low impedance, which allows them to be read out by superconducting SQUIDS. Because SQUIDS, in their unbiased "off" state, are superconducting, they may be effectively multiplexed without adding the noise of each individual SQUID to the whole.

The Quantum Sensor project has been at the forefront of SQUID multiplexing for several years now. Our first-generation 8-channel SQUID MUX was successfully deployed with the FIBRE far-infrared bolometer array on the CSO telescope on Mauna Kea, Hawaii. We have now built upon that success by developing a second generation, 32-channel SQUID MUX that has better bandwidth and 2 orders of magnitude lower power dissipation than the first design. The first fabrication run yielded devices that work at the design specifications. These MUX chips should have sufficient performance to multiplex X-ray TES detectors, which are much faster than the infrared bolometers in FIBRE. We are now building full 1,280-pixel multiplexed arrays for the SCUBA-2 project.



A hybridized TES subarray for the SCUBA-2 instrument. The array consists of a 1,280-pixel SQUID multiplexer wafer bump bonded to a 1,280-pixel TES bolometer array.

NIST has a long tradition of exploiting physical phenomena that occur at ultralow temperatures to produce electronic devices with properties that cannot be achieved by conventional electronics. For instance, NIST has developed Transition-Edge Sensor (TES) X-ray sensors which operate at temperatures near 100 mK and provide improved analytical capabilities to the semiconductor industry. The 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 begun development of a thin-film refrigerator which is capable of cooling sensors from 300 mK to 100 mK.

The refrigerator consists of Normal-Insulator-Superconductor (NIS) tunnel junction. 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 100 mK temperatures.

PLANS

- We have provided the Chemical Science and Technology Laboratory (CSTL) of NIST with a complete prototype microcalorimeter system for collaborative use in studying problems of interest to our customers. We will continue to provide support and improvements for this system.

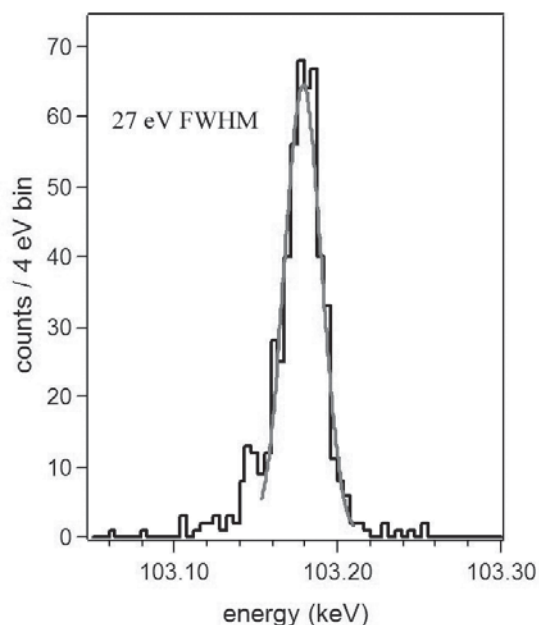
- We will develop models of single-pixel microcalorimeter performance to assist in improving detector sensitivity, and will fabricate and test novel detector designs based on these models.
- We will further develop arrays of X-ray microcalorimeter detectors to demonstrate the increase in collection area and count rate achievable through arrays. We will work with NASA to develop these arrays for use in the Constellation-X project.
- We will develop arrays of detectors optimized for imaging infrared bolometry, along with the necessary wiring, SQUID MUX and room temperature DSP electronics to read the array.

ACCOMPLISHMENTS

■ We have developed an 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.

■ This system holds the world record for energy resolution for an EDS detector of $2.37 \text{ eV} \pm 0.12 \text{ eV}$ at 5900 eV, which is over 30 times better than the best high-resolution semiconductor-based detectors currently available. 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.

■ We have fabricated gamma ray detector arrays with the world record energy resolution for an EDS detector of 25 eV at 103 keV (see figure). This energy resolution was achieved in a 14-pixel multiplexed array. Gamma ray detectors with ultra-high energy resolution will provide superior capabilities for nuclear materials analysis.



World record 25 eV energy resolution achieved with NIST microcalorimeter at 103 keV.

■ We have fabricated the first on-chip, solid-state microrefrigerator using Normal metal-insulator-superconductor (NIS) tunnel junctions integrated with superconducting transition-edge sensors. Presently, cryogenic instruments that operate near 100 mK use complex, expensive adiabatic demagnetization refrigerators and dilution refrigerators. We have fabricated an NIS refrigerator designed to operate at bath temperatures of 300 mK, which is accessible with relatively simple and inexpensive ^3He refrigerators. The normal metal in the junction is an Al thin film doped with ferromagnetic impurities (Mn) in order to suppress superconductivity. These sensors are integrated with TES detectors, making it possible for them to operate from a lower temperature.

■ We demonstrated the first multiplexed readout of an X-ray microcalorimeter array. This breakthrough establishes a clear path to the instrumentation of kilopixel microcalorimeter arrays, which will have wide-ranging implications for fields as diverse as materials analysis and X-ray astronomy. A challenge in the development of large arrays of X-ray microcalorimeters, which measure the energy, or color, of X-rays with high resolution, is that providing an amplifier channel for each detector in the array requires too many wires to be connected to the cryogenic detectors. Time-division SQUID multiplexing, a scheme in which the signals from many detectors are read out through a single amplifier, is one way to conquer this challenge. In the

experiment, we measured the energy resolution of four microcalorimeters, using both conventional and multiplexed readout techniques.

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

■ We have delivered science-grade parts for the first full, 1,280-pixel multiplexed submillimeter bolometer subarrays for the SCUBA-2 project. These parts are now being hybridized, and will lead to a significant step forward for the community.

COLLABORATIONS

UK Astronomy Technology Center, SCUBA2 camera

University of Edinburgh / Scottish Microelectronics Centre, SCUBA2 camera

Raytheon Vision Systems Inc., SCUBA2 camera

University of Cardiff, SCUBA2 camera

NIST Division 837, X-ray microcalorimeter for microanalysis

Intel, X-ray microanalysis using our microcalorimeter system

Lockheed Martin, X-ray detector development for solar physics

Stanford University, X-ray detector development for solar physics

Jet Propulsion Laboratory, SQUID multiplexer for IR detectors

NASA Goddard Space Flight Center, SQUID multiplexer for IR detectors

NASA Goddard Space Flight Center, X-ray microcalorimeter arrays

NASA Goddard Space Flight Center, Magnetic Microcalorimeters

JILA, Microwave SQUID multiplexer

Star Cryoelectronics, X-ray detector development

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

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MAGNETIC SENSORS & QUANTUM MATERIALS

GOALS

This project addresses measurement needs in characterization of magnetic sensors, advanced applications of magnetic sensors, and national security. We are developing magnetoresistive arrays and readout electronics that can image magnetic fields for biomedical research, forensic analysis of magnetic recording media, and current distributions in integrated circuits for nondestructive evaluation. We also develop advanced electron tunneling barriers for superconducting Josephson junctions for future quantum computers.

CUSTOMER NEEDS

Magnetic Sensors — Magnetoresistive magnetic field sensors have wide application in research and industry. Currently, cryogenic superconducting quantum interference devices (SQUIDs) are used for the measurement of ultra-low magnetic fields. They provide important information in many areas of basic research, medical magnetic field monitoring, and security. However, it is necessary to develop devices operating at room temperature that are scalable, linear, and have comparable sensitivity to realize the maximum benefit of such devices. The most promising candidates for development are magnetoresistive technologies. Magnetic noise is a critical problem in the development of these devices; such noise can be two orders of magnitude higher than the intrinsic Johnson, shot, and $1/f$ noise of the device. New materials, measurement techniques, and device architectures are required to characterize and reduce the effect of low- and high-frequency magnetic fluctuations.

Magnetic Forensics — In the late 1990s, in a collaboration with the National Telecommunications and Information Administration, we developed basic magnetic imaging technology to retrieve data from damaged or altered magnetic tapes and computer disks by rastering samples with a single sensor to build up an image. We first demonstrated the approach by recovering data from scraps of aircraft “black-box” tape that were too short to be played in a conventional tape deck. For several years, the Federal Bureau of Investigation (FBI) used a prototype of the magnetic imaging system. Because the system was slow, it was used only for testing and special cases. There has been a need for new, faster methods to authenticate magnetic recording tape.

Quantum Computing — Promising candidates for quantum computing devices are quantum bits (qubits) based on Josephson junctions. These junctions are used in magnetic detectors (SQUIDS), voltage standards, and other superconducting electronic devices; techniques for their fabrication have been investigated in some detail. However, qubits have far more stringent noise requirements that are now only barely satisfied by current fabrication technology. A significant limitation to the performance of these devices is the generation of defects in the oxide interlayers. The structural origin of these defects is not well established, but is likely a consequence of both the amorphous nature of the oxides and the preparation methods.

TECHNICAL STRATEGY

Magnetic Sensors — In 2004 we embarked on a NIST “Competence” program with the Materials Science and Engineering Laboratory, the Physics Laboratory, and the Information Technology Laboratory on low-noise magnetic sensors. The program includes development of new amorphous and nanocrystalline materials, imaging of magnetic domains, noise measurement in sensor devices, and micromagnetic modeling.

Magnetic Forensics — We are fabricating linear arrays of 256 sensors to scan magnetic recording tape in a single pass. The sensors make use of the magnetoresistance effect, where their electrical resistance changes in response to magnetic fields detected from the tape. Software converts the sensor resistance measurements to visual images that have a resolution of about 240 dots per square centimeter (1520 dpi). Systems that are of interest include cassette, VHS, and digital audio tapes.

Quantum Computing — State-of-the-art Josephson junctions employing superconducting Al or Nb electrodes and native-oxide tunnel barriers typically are fabricated by use of sputter deposition onto thermally oxidized Si wafers for microelectronics fabrication. However, spurious resonant states arising from microstructural defects in the tunnel barrier promote decoherence in Josephson qubits. These resonances may originate from defects and inhomogeneous oxidation during the tunnel barrier formation. Crystalline oxides contain three to four orders of magnitude fewer defects in the frequency range of interest for Josephson qubits. Our capability to prepare and then process samples in ultrahigh vacuum is critical to the development

Technical Contact:
David Pappas

Staff-Years (FY 2006):
1 professional
3 post-docs

of defect-free, crystalline tunneling barriers. We are now developing a process to grow epitaxial Re on crystalline sapphire (Al_2O_3) substrates.

PLANS

- Install 256 imaging system at FBI Audio Forensics Laboratory in Quantico, VA. Train forensics agents on its use.
- Fabrication low-dielectric Al_2O_3 qubit and investigate measurement fidelity.
- Fabricate V/MgO/V tunnel junctions and optimize for low subgap conductance
- Fabricate NbN thin films with high T_c (>9 K) and investigate efficacy in single photon transition threshold detector.

ACCOMPLISHMENTS

■ **New Zig-Zag Magnetoresistive Field Sensors Developed** — We have developed new “zig-zag” magnetoresistive sensors that, because of their shape, are sensitive to magnetic fields parallel to their axes but insensitive to fields perpendicular. The thin-film devices are also able to distinguish positive and negative fields because their resistance is an odd function of field.

In general, anisotropic magnetoresistive sensors must be biased, with their magnetization at an angle with respect to the current direction. Our new sensors are fabricated in a zig-zag pattern that pins the magnetization at alternating positive and negative 45 degrees to the direction of the current flow (see figure below). This novel approach provides a built-in magnetization bias determined by the corrugation of the edges. Since the angle of magnetization of the magnetic domains is controlled only by the sensor shape, and not by adjacent biasing fields, the devices may be scaled to nanometric dimensions. When the sensor is exposed to a magnetic field oriented in the direction of the current, the angle of magnetization relative to the current in both sets of the domains decreases. This results in an increase of electrical resistance in each domain and in the entire device. For magnetic fields in the negative current direction, the magnetization angle increases and the resistance decreases. For magnetic fields in the perpendicular axis, the magnetization angle increases in one set of magnetic domains and de-



Magnetization of a $10\ \mu\text{m}$ long zig-zag shaped magnetic element.

creases in the other, resulting in no net change in device resistance.

■ **Images of Erased Tapes** — We conducted high-resolution magnetic imaging measurements on erased audio tape for the FBI as part of its participation in a study by the National Archives and Records Administration (NARA) on the feasibility of recovering audio from an 18.5 minute gap in a tape from the Nixon White House.

NARA's 6-millimeter-wide test tapes had been recorded and then erased in a manner similar to that of the Nixon tapes. As described by NARA, the test tapes were “recorded on an original Nixon White House Sony 800B tape recorder, then erased on Rosemary Woods' UHER 5000.” Tests were made of both an erased audio recording and an erased blank section of tape. The FBI could find no trace of the recording or erasure marks using a standard imaging technique with a ferromagnetic fluid. However, we were able to detect an extra noise band on the outside edge of the erased section of the audio tape that was not evident on the erased section of blank tape. The noise band was scanned at high resolution and converted to an audio signal. It consisted of only very low frequency sounds, with no trace of audible speech. In a press release dated May 8, 2003, Archivist of the United States John W. Carlin said, “I am fully satisfied that we have explored all of the avenues to attempt to recover the sound on this tape. The candidates were highly qualified and used the latest technology in their pursuit.”

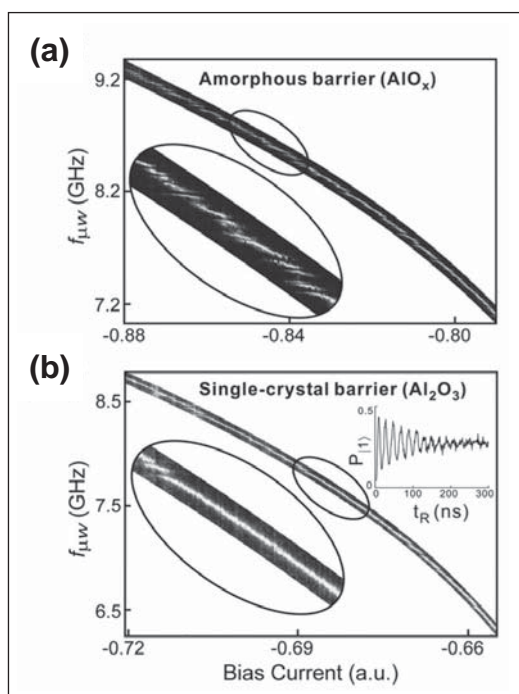
■ **New System Sees Crimes on Audiotape** — We developed a real-time magnetic imaging system that enables criminal investigators to see signs of tampering in audiotapes — erasing, over-recording, and other alterations — while listening to the tapes. An upgraded system was delivered to the FBI in Sept. 2006. The upgrades included increasing the resolution by a factor of 4 (to 256 sensors from 64), the capability to scan both VHS and cassette tapes, on-the-fly image capture, complete computer control of the cassette tape transport, and the capability to digitize the audio directly from the acquired image (either real-time or in post-processing). A sample image is shown below.

Magnetic image of ~ 2 seconds of audio cassette tape where an overrecorded event occurred. On the top left is new data, the top right is old data. The erased gap in center top is the area between the erase head and write head.

At the heart of the technology is a cassette player modified with an array of 256 customized magnetic sensors that detects and maps the microscopic magnetic fields on audiotapes as they are played. The array is connected to a desktop computer programmed to convert the magnetic data into a displayable image. Authentic, original tapes produce images with non-interrupted, predictable patterns, whereas erase and record functions produce characteristic “smudges” in an image that correlate to “pops” and “thumps” in the audio signal. The original markings specific to different types of tape players are not present on tape copies. An examiner can use this new system to help determine the authenticity of a tape and also help determine whether that tape is a copy. The benefits of the system are its speed in correlating sounds with magnetic marks on tape, and the fact that it makes an image without damaging the tape.

■ **Improved Superconducting Tunnel Junctions Using Epitaxial Underlayers** — In collaboration with the Quantum Computing Measurements Project, we studied the growth of tunnel junction base electrodes to investigate the role that crystalline quality plays in device performance. We found that there is a strong correlation between the morphology of oxidized base electrodes and the lowering of subgap currents, and through the use of epitaxial seed layers, junctions with even lower subgap currents were obtained. In order to accomplish this, we engineered Josephson junctions with increasingly improved crystalline quality and were able to correlate the microstructure of the junctions with low-frequency transport measurements. Our data indicate a strong correlation between improved crystallinity of the tunnel barrier and reduced subgap leakage currents.

In order to test the properties of these materials, we have fabricated quantum bits using the crystalline Al_2O_3 as a tunnel barrier. We have found an 80% reduction in the density of the spectral splittings that indicate the existence of two-level fluctuators (TLFs) in amorphous tunnel barriers (see following figure). The residual 20 % TLFs can be attributed to interfacial effects that may be further reduced by different electrode materials. These results show that decoherence sources in the tunnel barrier of Josephson qubits can be identified and eliminated.



Comparison of spectra taken from qubits with amorphous (a) and crystalline (b) barriers.

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APPENDIX A: TOPICS COVERED BY ORGANIZATIONAL UNITS

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

Topic	Group Name	Project Name	Project Leader
QUANTUM STANDARDS			
Quantum Voltage	Fundamental Electrical Measurements	Voltage Metrology	Yi-hua Tang
	Quantum Devices	Quantum Voltage	Samuel Benz
AC-DC Difference Standards and Measurement Techniques	Fundamental Electrical Measurements	AC-DC Difference Standards and Measurement Techniques	Thomas Lipe
Single Electronics for Standards and Metrology	Fundamental Electrical Measurements	Single Electron Tunneling	Neil Zimmerman
	Quantum Devices	Quantum Information And Measurements	Robert Schwall
Metrology of the Ohm	Fundamental Electrical Measurements	Metrology of the Ohm	Rand Elmquist
Farad and Impedance Metrology	Applied Electrical Metrology	Farad and Impedance Metrology	Yicheng Wang
The Electronic Kilogram	Fundamental Electrical Measurements	The Electronic Kilogram	Richard Steiner
Josephson-based Noise Thermometry	Quantum Devices	Quantum Voltage	Samuel Benz
Electric Power Metrology	Applied Electrical Metrology	Electric Power Metrology	Thomas Nelson
QUANTUM MEASUREMENTS			
Quantum Computing Using Integrated Josephson Junction Circuits	Quantum Devices	Quantum Information and Measurements	Robert Schwall
Magnetic Sensors & Quantum Materials	Quantum Devices	Advanced Magnetic and Quantum Materials	David Pappas
Quantum Sensors	Quantum Devices	Quantum Sensors	Kent Irwin



APPENDIX B: QUANTUM ELECTRICAL METROLOGY DIVISION CALIBRATION SERVICES

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

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

A. Resistance Measurements

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

B. Impedance Measurements (Except Resistors)

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

C. Voltage Measurements

- C.1 DC Voltage Measurements Yi-hua Tang (301) 975-4691
and Standards
- C.2 AC Voltage Measurements Mark E. Parker (301) 975-2413
David I. Bergman (301) 975-4664
- C.3 AC-DC Thermal Voltage and Thomas E. Lipe (301) 975-4251
Current Converters (to 1 GHz)

D. Precision Ratio Measurements

- D.1 Inductive Dividers Scott Shields (301) 975-2432
- D.2 Resistance Dividers Gerald J. FitzPatrick (301) 975-8922

E. Phase Meters and Standards and VOR Measurements

- Mark E. Parker (301) 975-2413
- Nile M. Oldham (301) 975-2408

F. Power and Energy Measurements Low-Frequency

- Thomas L. Nelson (301) 975-2986

APPENDIX C: QUANTUM ELECTRICAL METROLOGY DIVISION STAFF AND PHONE NUMBERS

(OCTOBER 2006)

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2400 Grove, Sharon (Secretary)
4044 Tasker, Amy (Administrative Officer)
4941 Dorsey, Roy
4221 Prather, Denise
4223 Belecki, Norman

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4228 Newell, David (Group Leader)
2737 Williamson, Laura (Secretary)

METROLOGY OF THE OHM

6591 Elmquist, Randolph (Project Leader)
4240 Jarrett, Dean
4225 Jones, George
4239 Kraft, Marlin

VOLTAGE METROLOGY

4691 Tang, Yi-hua (Project Leader)
4238 Sims, June
4246 Jaiswal, Shiv Kumar

THE ELECTRONIC KILOGRAM

4226 Steiner, Richard (Project Leader)
6555 Williams, Edwin
6556 Liu, Ruimin

SINGLE ELECTRON TUNNELING (SET)

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

AC-DC DIFFERENCE STANDARDS AND MEASUREMENT TECHNIQUES

4251 Lipe, Thomas (Project Leader)
4250 Kinard, Joseph

APPLIED ELECTRICAL METROLOGY (817.02) (GAITHERSBURG)

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

FARAD AND IMPEDANCE METROLOGY

4278 Wang, Yicheng (Project Leader)
4518 Koffman, Andrew
2441 Palm, Robert
4232 Shields, Scott
2438 Waltrip, Bryan
3922 Avramov-Zamurovic, Svetlana
4237 Chang, Yui-May
4231 Lee, Lai

ELECTRIC POWER METROLOGY

2986 Nelson, Thomas (Project Leader)
4464 Bergman, David
2413 Parker, Mark
2440 Stenbakken, Gerard
2438 Waltrip, Bryan
2412 Laug, Owen
2413 Fulcomer, Michael
2407 Oldham, Nile
2417 Petersons, Oskars
2406 Souders, Michael
2416 Zhou, Ming

QUANTUM DEVICES (817.03) (BOULDER)

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4724 Filla, Mary (Secretary)
3776 Harris, Richard

QUANTUM VOLTAGE

5258 Benz, Sam (Project Leader)
4760 Baek, Burm
3906 Burroughs, Charlie
5211 Dresselhaus, Paul
4218 Hadacek, Nicolas
3740 Hamilton, Clark

QUANTUM VOLTAGE (CONTINUED)

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 5312 Landim, Regis
 5310 Rogalla, Horst
 4853 Veening, Thijs

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 3811 Duncan, William
 4391 Ferreira, Lisa
 5679 Hilton, Gene
 4380 Horansky, Robert
 3402 Huber, Martin
 4834 Mates, Ben
 4576 Miller, Nathan
 4794 O'Neil, Galen
 4983 Rahman, Rezwan
 5052 Reintsema, Carl
 4743 Schmidt, Dan
 4985 Sultan, Rubina
 4408 Ullom, Joel
 5121 Vale, Leila
 7894 Xu, Yizi
 4320 Zink, Barry

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 5430 Keller, Mark
 4378 Lang, Kristine
 3021 Naaman, Ofer
 4325 Osborn, Kevin
 4995 Park, Jae
 4410 Sillanpaa, Mika
 4403 Simmonds, Ray
 4772 Sirois, Adam
 4905 Spietz, Lafe
 4617 Strong, Josh
 4826 Whittaker, Jed

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 3374 Fardi, Hamid
 4651 Halloran, Sean
 4795 Kline, Jeffrey
 4655 Oh, Seongshik
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APPENDIX D: POST-DOCTORAL RESEARCH ASSOCIATESHIPS

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

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

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

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

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

OPPORTUNITIES IN BOULDER, COLORADO A CAPACITANCE STANDARD BASED ON COUNTING ELECTRONS

50.81.42.B4762 Boulder CO 80303

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

room for fabricating SET devices, a custom cryostat for the capacitance standard, and custom capacitance bridges for making accurate comparisons with other standards.

APPLICATIONS OF SUPERCONDUCTING INTEGRATED CIRCUITS AND JOSEPHSON JUNCTION ARRAYS

50.81.42.B4376 Boulder CO 80303

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

HIGH-RESOLUTION MICROCALORIMETERS FOR X-RAY MICROANALYSIS

50.81.42.B3588 Boulder CO 80303

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As the size scale of microelectronics continues to shrink well below 1 μm , current semiconductor-based energy-dispersive spectrometers (EDS) on scanning electron microscopes can no longer provide the resolution needed to evaluate these structures. We are developing a high-resolution microcalorimeter-based EDS that provides revolutionary new capabilities for X-ray microanalysis. Microcalorimeter EDS provides more than an order of magnitude improvement in energy resolution (to 2 eV) compared to commercial semiconductor EDS, with good collection area (4 mm² effective area with the use of an X-ray polycapillary optic lens) and count rate (500 s⁻¹). The spectrometer system consists of a superconducting transition-edge sensor microcalorimeter cooled by a compact adiabatic demagnetization refrigerator and instrumented

by a SQUID current amplifier. These unique superconducting electronics are fabricated in our state-of-the-art clean room. Using our microcalorimeter EDS mounted on a scanning electron microscope, we have resolved closely spaced X-ray peaks in complicated spectra and have made the first energy-dispersive chemical shift measurements. The excellent performance of this system enables a wide range of research opportunities in X-ray microanalysis, including improved particle analysis, chemical bonding state analysis, and synchrotron-based measurements. Work is also underway to dramatically increase the collection area and count rate of the system using arrays of detectors read out with superconducting multiplexer, which will dramatically increase throughput and open new applications in real-time, in-process monitoring and process-stream monitoring.

PHYSICS AND APPLICATIONS OF SINGLE ELECTRON TUNNELING DEVICES

50.81.42.B3586 Boulder CO 80303

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

QUANTUM COMPUTING USING SUPERCONDUCTING DEVICES

50.81.42.B4764 Boulder CO 80303

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A new class of powerful computation algorithms have been proposed based on logic operations using quantum mechanical systems or quantum bits (qbits). Experimental implementation will require qbit coherence times long enough to perform single qbit manipulations, controlled interactions of multiple qbits, and state measurements. While the most dramatic progress to date has been made with trapped-ion systems, solid-state quantum devices should in principle have distinct advantages for the creation of a practical large-scale "quantum computer." Using our state-of-the-art superconducting fabrication facility, we have improved the operation of a Josephson junction based phase qubit by incorporating it into a superconducting loop. This

has allowed us to further decouple the qubit from its environment and has eliminated quasiparticle-heating effects. Recent improvements in the fabrication of the Josephson junctions have produced a dramatic increase in the overall performance of qubits. Research opportunities include materials characterization for Josephson junctions, fabricating novel superconducting qubit devices, exploring the physics of coherence and coupling between qubits, and engineering multi-qubit devices. Our goal is to fabricate high quality Josephson junction based qubits for the eventual use in a 100 to 1000 qubit quantum computer.

SUPERCONDUCTING DETECTORS FOR X-RAY THROUGH MILLIMETER PHOTONS

50.81.42.B3587 Boulder CO 80303

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

SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE DEVELOPMENT

50.81.42.B5189 Boulder CO 80303

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

OPPORTUNITIES IN GAITHERSBURG, MD
"ELECTRONIC KILOGRAM" – THE SI DETERMINATION OF THE RATIO OF THE
MECHANICAL WATT TO THE ELECTRICAL WATT

50.81.11.B1491 Gaithersburg MD 20899

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

CAPACITANCE STANDARDS AND AC MEASUREMENTS

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The Quantum Electrical Metrology Division ties the US legal system of electrical units for capacitance, inductance, and resistance to the SI system of units. First, we realize the SI farad from

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

FUNDAMENTAL CONSTANTS, PRECISION MEASUREMENTS, AND ELECTRICAL UNITS

50.81.11.B1490 Gaithersburg MD 20899

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

PHYSICS OF JOSEPHSON JUNCTIONS AT MICROWAVE FREQUENCIES AND PRECISION VOLTAGE MEASUREMENT

50.81.11.B1494 Gaithersburg MD 20899

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

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

QUANTUM HALL EFFECT

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

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

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

RESISTANCE COMPARISONS FOR FUNDAMENTAL ELECTRICAL STANDARDS

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

50.81.11.B1492 Gaithersburg MD 20899

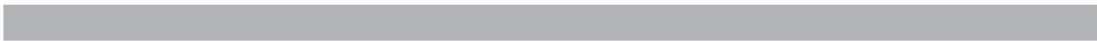
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In nanoscale electronic circuits, we can observe Coulomb blockade or single electron tunneling (SET) effects. For metrological applications, the basic device is the single electron pump, which allows control of electrical flow in units of $1 e$. This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



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