Lawrence Berkeley National Laboratory
Recent Work

Title
Summary and Conclusions

Permalink
https://escholarship.org/uc/item/0191756m

Author
Clarke, J.

Publication Date
1991-08-01

eScholarship.org
Powered by the California Digital Library
University of California

LBL-31156

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

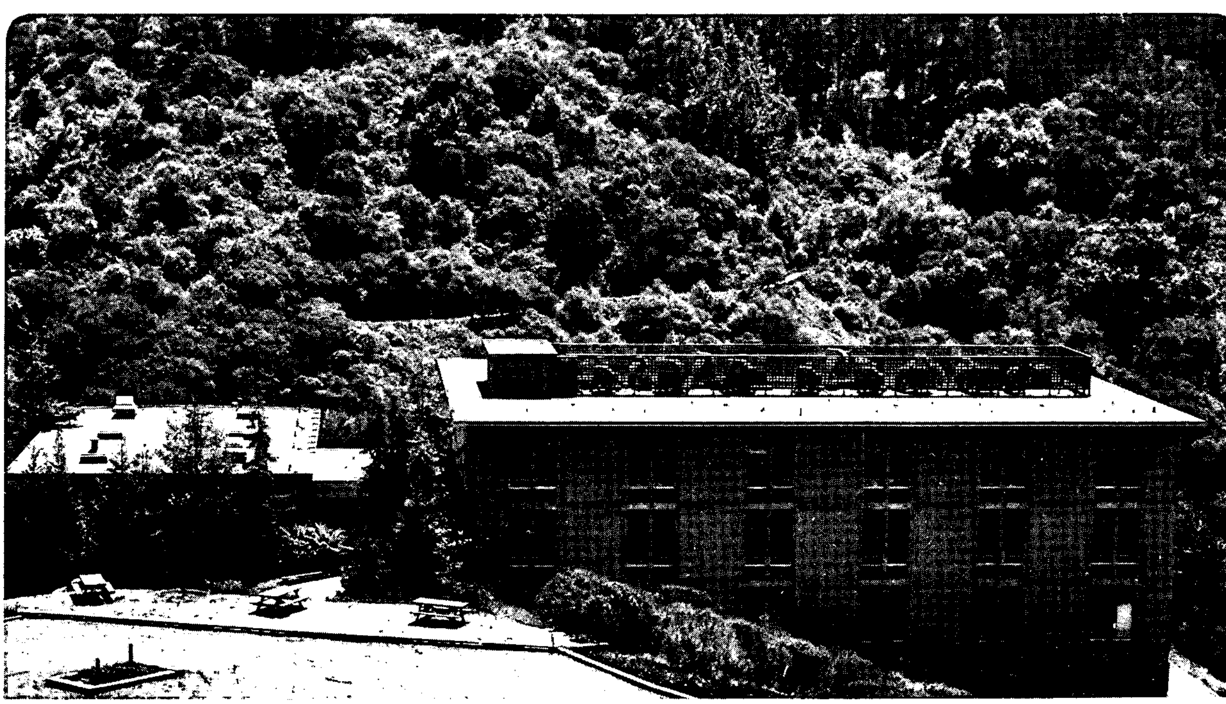
Materials & Chemical Sciences Division

Presented at the SQUID '91 Conference, Berlin, Germany,
June 18–21, 1991, and to be published in the Proceedings

Summary and Conclusions

J. Clarke

August 1991



| LOAN COPY |
|Circulates |
|for 4 weeks| Bldg. 50 Library.
Copy 2
LBL-31156

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-31156

Summary and Conclusions

John Clarke

Department of Physics,
University of California
Berkeley, CA 94720

and

Materials Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

August 1991

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under contract number DE-AC03-76SF00098.

Summary and Conclusions

John Clarke

Department of Physics, University of California, and Materials Sciences Division, Lawrence Berkeley Laboratory, Berkeley, California 94720, U.S.A.

Dramatic changes have occurred since SQUID '85. I think all of us visiting here have been moved by the disappearance of the Berlin Wall – earlier this week, I was fascinated to be able to walk unimpeded past the Brandenburg Gate into what used to be East Berlin. And in superconductivity, of course, the emergence of the high-T_c materials has lent an unprecedented impetus to our field that none of us dreamed about six years ago. Progress in high-T_c technology is rapid, and devices operating immersed in liquid nitrogen are already a reality. Nonetheless, the organizers of SQUID '91, wisely I believe, resisted the temptation to allow high-T_c to dominate, instead choosing to keep a wide range of topics – indeed broadening the meeting to include, for example, 1- and 2-D electron gas devices. Needless to say, it is impracticable for me to mention let alone review all 48 talks and 115 posters, and I shall simply attempt to summarize those areas that interested me most.

There were two papers that I greatly admired for their thoroughness. The first was an update by Niemeyer (PTB) of the Josephson voltage standard which involves about 20,000 Nb tunnel junctions in series. Irradiated with microwaves, the arrays exhibit a very large number of constant-voltage steps crossing the zero current axis, extending up to 10V or more. The precision of the comparison of an external voltage with the voltage of one of the steps is limited by noise in the room temperature system to a few parts in 10^{10}. Although a standard operating at 77K would obviously be very convenient, the lack of high-T_c junctions with hysteretic current-voltage (I-V) characteristics implies that an array cannot be operated in the zero-current regime, and that such a standard is unlikely soon. The second long-term experiment is Soulen's noise thermometer (NBS), which consists of a resistively shunted junction. The junction converts Nyquist voltage noise across the resistor into frequency fluctuations at about 83kHz that are measured with a counting technique to give the absolute temperature with a typical accuracy of 0.1%. Over a period of 2 months, Soulen could detect no drift in the thermometer, and over a period of *nine years*, the overall reproducibility was about 0.15%. Incidentally, there is still a good deal of innovation in these two fields. In the poster session, Kohlmann described the use of the voltage standard to compare resistors to very high precision, and Seppä discussed the use of a low-noise dc SQUID amplifier to read out a noise thermometer.

Perhaps the most exciting new physics at the conference was described in a series of talks on submicron junctions. Mooij (Delft) reminded us that effects arising from single electron tunneling (SET) go back more than 20 years; however, systematic studies have become possible only recently with the emergence of electron-beam lithographic techniques capable of routinely producing junctions with areas $\leq 10^{-2}$ μm^2 and capacitances $C \lesssim 1fF$. The requirements to observe charging effects are $e^2/2C >> k_BT$ and R_t (tunnel resistance) $>> h/e^2$. Likharev (Moscow) and his colleagues provided much of the theoretical framework for this field, both for single electron effects and also for Bloch oscillations involving Cooper pairs. Fulton and Dolan performed an early key experiment on single electron effects when they coupled two small normal state junctions in series and passed single electrons on and off the island between the two junctions. This configuration produced a striking example of the "Coulomb blockade" – the fact that the current through the junctions is significantly reduced at voltages $< e/2C$ – and demonstrated that the blockade could be offset by means of a gate voltage applied to the island via a tiny capacitance.

Urbina described a beautiful series of experiments at Saclay in which the passage of single electrons is synchronized with radiofrequency gate voltages. These experiments, which include the 4-junction turnstile (in collaboration with Delft) and the 3-junction single electron pump, yield (nearly) constant current steps at $I = \pm nef$ and $\pm ef$, respectively, and offer the possibility of a current-frequency standard. At present, the accuracy is limited to about 0.1% by processes that are well understood, and improvements seem likely. Delsing (Göteborg) described, amongst other devices, a 25-junction array turnstile in which constant current steps were induced by a radiofrequency signal. Kuzmin (Göteborg and Moscow) described experiments on superconducting junctions in which peaks were observed in dV/dI at currents of $\pm 2ef$. These peaks, together with the shape of the I-V characteristic, were explained by the theory of Bloch oscillations which is based on the charging of the junction capacitance by single Cooper pairs.

There were two talks on 2-D arrays of Josephson junctions. Schön (Delft) described charge-vortex duality and introduced us to various novel properties of vortices, for example, their nonzero mass. Van der Zant (Delft) described some beautiful experiments on arrays in which vortices are generated in one region and launched through a channel into a second region. At low temperatures the vortices propagate through the second region ballistically, implying that they have a mass of about 0.01 m_e and behave as quantum mechanical objects.

The future of this field looks very exciting. There are prospects of a precise current standard. As Nazarov (Moscow) explained to us, there are intriguing possibilities of SET digital devices, although some interesting challenges have to be met to eliminate the probability of errors due to thermal activation, charge macroscopic tunneling and the "quantum wind." There will undoubtedly be new and elegant experiments, not least because, as Ingold (Essen) discussed, the effects of the environment on these tiny junctions are now well understood theoretically.

Needless to say, submicron technology has been taken up with great vigor by the semiconductor field. Von Klitzing (Stuttgart) reviewed quantum wells, wires and dots in which quantum states induced by reduced dimensionality play a dominant role in the electrical and optical properties, giving rise to such phenomena as the quantum and fractional quantum Hall effects and resonant tunneling between the states of coupled quantum wells. Van Houten (Eindhoven) described the effects of Coulomb blockade oscillations in quantum dots and wires – for example, the conductance of disordered quantum wires is periodic in the gate voltage (Kastner, MIT). The combination of the Coulomb blockade and quantized energy levels may lead to a variety of novel effects that have yet to be discovered.

Let me now turn to superconducting devices, starting with radio frequency applications. Martens (Sandia) described a high-T_c flux flow transistor, which involves the flow of vortices across a parallel array of weak links patterned in a single layer of YBCO or TBCCO. The critical value of the current flowing through the array is determined by the onset of flux flow. The nucleation of the vortices is controlled by the magnetic field produced by the current in a nearby control-line, enabling one to modulate the voltage across the device by varying the control-current to achieve transistor-like characteristics. The device has achieved 10-12 dB of gain as an amplifier in the 2 to 10 GHz range, and a noise figure of 2 to 4 dB. Other applications include oscillators and phase shifters, raising the possibility of all-high-T_c electronic circuits. In a totally different context, Doderer (Tübingen) described his use of a low temperature scanning electron microscope to image the standing waves induced by self-resonance or external microwaves in a low-T_c Josephson junction. These beautiful images graphically illustrate various modes in both one- and two-dimensional junctions.

Naturally, much of the conference was devoted to the technology of Josephson junctions, SQUIDs, and applications of SQUIDs. Today's low-T_c junction technology is very much focused on refractory trilayers, namely Nb, NbN, NbZr or NbCN with $A\ell_2O_3$ or MgO barriers. A high degree of reproducibility in the critical current and resistance has been achieved by some groups, making the fabrication of SQUIDs (and much more complicated circuits) relatively routine. Ketchen described the IBM edge junction dc SQUIDs that have achieved a noise energy of about $2\hbar$ at 291 mK, and gave us a view of the future by discussing SQUIDs with junctions in the deep submicron regime. With 0.1 x $0.1\mu m^2$ junctions, the projected noise energy is $3\hbar$ at 4.2K. These devices are based on trilayers made by Lincoln Labs. on 5-inch wafers that will be processed on the IBM silicon line, and involve planarization with a chemical-mechanical polishing technique. About 20 posters demonstrated that the technology of low-T_c dc SQUIDs, driven by the needs of applications, is progressing steadily. A number of these posters described damping resistors to eliminate the infamous resonances arising from the parasitic capacitance between the SQUID and the input coil. Undamped, these resonances can be a major source of excess noise, but this problem has now been eliminated. The biggest group of posters, however, was concerned with new methods to read out dc SQUIDs, for example, to simplify multichannel biomagnetic systems. Thus, we saw such schemes as 2f modulation (Furukawa), on-chip digital (Fujimaki), $PI^{3/2}$ (Grönberg), relaxation oscillator (Kawai), additional positive feedback (Drung), adaptive positive feedback (Seppä) and cooled CMOS (Crocoll). The simplicity of the positive feedback schemes is particularly appealing: one uses inductive feedback to skew the voltage-flux (V-Φ) curve and operates the SQUID where $dV/d\Phi$ is large. The signal from the SQUID is coupled directly into a room temperature amplifier, followed by an integrator. On the subject of novelty, I appreciated Cabrera's laser diode switch (Stanford) that modulates the input circuit to a SQUID (as opposed to the SQUID itself), thereby reducing 1/f noise and drift in both input circuit and the SQUID. This is the only method I know that can reduce 1/f flux noise in a SQUID.

What of the applications? Cabrera told us about his elegant experiments to determine the Cooper pair mass, the absolute Aharonov-Bohm effect, the distribution of flux quanta trapped in a superconducting loop, the pinning force on a trapped vortex and the kinetic inductance, all using a SQUID and a laser switch. Awschalom (IBM) investigated quantum tunneling and spin dynamics in nanometer-scale magnets, and Benoit (Grenoble) described his efforts to look for persistent currents in a normal metal ring. Posters discussed nondestructive testing of steel structures and the testing of multilayer electronic cards. Other applications included SQUID-readout for a noise thermometer and a transition-edge thermometer. However, the applications were dominated by biomagnetic measurements, nicely reviewed by Foglietti (Rome). I am impressed by the progress being made with multichannel systems. No fewer than four groups – Helsinki, PTB, Twente and Rome – and four companies – BTi, Siemens, Phillips and Dornier – make systems with between 28 and 37 channels. Indeed, the Helsinki group has a 122 channel system under construction. These systems are usually operated in a magnetically and electrically shielded room, and electronic cancellation of background noise is standard. Schneider reported a magnetoencephalogram study of 20 epileptic subjects in whom the focus was localized; of these, 17 were treated with a γ-knife and 14 were cured. Both the diagnosis and treatment are entirely noninvasive. Other potential studies include brain infarction, migraines and the recovery of areas of the brain damaged by a stroke. Matlashov (Moscow) discussed his modular system with each sensor in a very small dewar, a cluster of which can be arranged as needed around the subject. Drung described the PTB system consisting of axial first-order gradiometers in which the signals from two planar multiloop magnetometers are subtracted. This arrangement offers both simplicity and flexibility, since a single SQUID can be used as a reference for an array of sensors, and one can operate a given array as both axial and planar gradiometers simultaneously. The system is usually operated inside a shielded room, but has sufficient dynamic range to operate in an unshielded environment.

The impressive performance of the biomedical systems is a double-edged sword. They have progressed to the point where serious clinical studies are now feasible, and are being undertaken. But will magnetic measurements be accepted by the medical community as a standard diagnostic tool? The pros and cons of magnetic vs. electrical measurements remain unclear, and there is the ever present threat of "cost containment" that may make it difficult to launch yet another expensive clinical instrument. I know of no other application of SQUIDs remotely approaching the commercial potential of biomedicine; success in this endeavor will provide a tremendous boost to the whole field, while failure may, I fear, lead to serious reductions in funding.

Let me turn finally to progress in HTSC technology, reviewed by Braginski (Jülich). Many groups now grow epitaxial films of YBCO, mostly with *in situ* laser or single-target sputtering processes. Photolithographic processing of these films and the fabrication of multilayer structures are progressing rapidly. Both Braginski and Okabe (Tokyo) stressed the lack of HTSC tunnel junctions with hysteretic I-V characteristics. Indeed, in the light of the experiments reported by Yoshida (Toshiba) and many others on SN interfaces and Kupriyanov's theoretical work (Moscow) on electron scattering at the surface of HTSC, the prospects of achieving such junctions seem to be fading. However, the field has made a lot of mileage from grain boundaries, although I can only echo Okabe's question "Why are natural grain boundaries so good?" A fair degree of control of parameters has been achieved with grain boundaries grown at steps, on bicrystals or with a bi-epitaxial process. Other promising structures include proximity effect junctions involving, for example, normal metal (d'Iorio, BTi) or PBCO (Rogalla, Twente) barriers making contact with the YBCO along the a-b plane.

High-T_c SQUIDs are a growth industry, with 18 papers – 13 on dc and 5 on rf devices. Koch (IBM) showed that the performance of YBCO SQUIDs grown on bicrystals is in very good agreement with computer simulations of the transfer functions and white noise, implying that the junctions were at least reasonably close to the resistively shunted junction model. As with all HTSC SQUIDs, the level of l/f noise remains high: possible sources are fluctuations in the critical current or resistance of the junctions, which can be reduced by appropriate double-modulation bias schemes, or flux noise due to the thermally activated motion of vortices pinned in the SQUID, which cannot be so reduced (except by Cabrera's scheme). Koch reported that attempts to reduce l/f noise by double modulation had sometimes been successful, but often not, for reasons still under investigation. It appears that flux noise, described by Ferrari (Berkeley), is generally lower than junction noise, except perhaps, at the highest operating temperatures. Ironically, the mechanism of flux noise is much better understood than that of junction noise, and can even be used to determine pinning energies. Wellstood (Berkeley) described SQUIDs involving bi-epitaxial junctions (made by Char *et al.*, Conductus). These junctions involve 45° grain boundaries grown at the edge of a seed layer, and can be placed at will on a chip. Several groups have achieved white noise energies comparable with or even exceeding the performance of commercially available Nb hybrid SQUIDs; the best at 77K so far is 3×10^{-31} $JHz^{-1/2}$ at 71kHz, (Kawasaki, IBM). However, the l/f noise energy, at best 10^{-28} JHz^{-1} at 1Hz, remains high, and its reduction is a major challenge for the future.

Wellstood also described the development of epitaxial YBCO-insulator-YBCO multilayers that provide the essence of an interconnect technology –

insulating crossovers and superconducting vias. Both he and Koch reported flip-chip magnetometers in which a SQUID on one chip is pressed against the multiturn input coil of a flux transformer on a second chip. The best magnetic field sensitivity yet achieved at 77K and 1Hz is about $1pTHz^{-1/2}$ (Berkeley/Conductus). Koch also reported a flip-chip first-order gradiometer, and Char (Conductus/Berkeley) an integrated magnetometer, involving 7 epitaxial layers, in which the SQUID and flux transformer were grown on a single chip. Two groups showed magnetocardiograms taken with HTSC SQUIDs at 77K: Vasiliev (Dubna) with a bulk rf SQUID, and the Berkeley/Conductus group with their flip-chip magnetometer.

Thin-film high-T_c devices have made great strides in the last year or so. SQUIDs have progressed to the point where real-life applications – geophysics, nondestructive evaluation and even magnetocardiology – are only a year or two away. One might hope for commerically available SQUIDs on a similar time-scale. The whole field of superconducting and quantum devices is progressing more rapidly now than at any time in the past that I can recall, and there is every reason to believe that the next Berlin SQUID conference – maybe in 1995? – will be just as exciting as this one.

In concluding, I should like to express the thanks of us all to the sponsors and organizers of SQUID '91. The conference was supported by the European Physical Society, the Physikalish-Technische Bundesanstalt and the Dr. Wilhelm Heinrich Heraeus and Else Heraeus Foundation, to all of whom we express our grateful thanks. The superb organization followed in the tradition of Drs. H.D. Hahlbohm and H. Lübbig who originally conceived the SQUID conferences and organized the first three. They passed the helm to Dr. Hans Koch who, supported by Dr. R. Cantor, D. Drung and S.N. Erné and by a wonderfully able group of helpers, worked so hard to make the conference run smoothly and be such a resounding success. We thank you all very much.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720