FINAL TECHNICAL REPORT

U. S. Office of Naval Research Contract #N00014-83-K-0383

April 1, 1983 to December 31, 1988

Contract Title: Fundamental Processes in Superconducting Weak Links

Contractor:

The President and Fellows of Harvard College
Office of Sponsored Research
Holyoke Center
1350 Massachusetts Avenue
Cambridge, MA 02138

Principal Investigator:

Prof. M. Tinkham
Physics Department
Harvard University
Cambridge, MA 02138

Total funding: $696,873 (over 5 3/4 years)

TABLE OF CONTENTS

I. SUMMARY OF WORK ACCOMPLISHED

The work accomplished under this contract largely concerns the properties of superconducting weak links, in the form of either small area oxide-barrier tunnel junctions or of SNS weak links, both of which form Josephson junctions. The four major thrusts of the work are reported in ~~detail in the~~ four ~~Technical~~ reports Reports listed in section II of this report. The first two concern the response of tunnel junctions to far-infrared radiation, #22 elucidating the response under conditions suitable for mixer and detector applications, and #25 identifying the regimes in which chaotic noise makes the driven junction unusable for applications. The second two reports concern the static properties of junctions: #26 dealing with the effect of geometric disorder in large arrays of Josephson junctions, and #27 elucidating the properties of oxide barrier junctions that are so small that the charging energy of a single electron dominates the behavior, causing quantum effects which greatly modify the usual semi-classical Josephson junction properties. Although no Technical Report has yet been issued on the subject, in the last year of the contract, work on high temperature superconductivity was also initiated. In the following pages, our accomplishments in all of these areas are summarized.

A. Far-Infrared Response and Chaos in Small-Area Tunnel Junctions

The pioneering work of Danchi in this laboratory on the response of Josephson junctions fabricated out of thin films of lead and tin to far-infrared (FIR) laser radiation showed that they performed in a way that could be understood theoretically even at frequencies as high as the superconducting energy gap. (The actual frequencies used ranged from 200-600 GHz.) To couple the FIR radiation into the junction, it was necessary to fabricate thin-film antenna structures as an integral part of the junction fabrication process. Another crucial requirement was the reduction of the junction area to the order of 1 μm^2 to minimize their capacitance, since this capacitance shunts the FIR current around the nonlinear electronic element. It was found that junctions with impedance high enough for good coupling to incident free-space radiation had, of necessity, sufficiently low critical current and corresponding phase-coupling energy that noise effects play a major role in shaping the dc I-V curve and the consequent response to the FIR radiation. Of the various noise sources, shot noise was shown to be usually the dominant one. This is a consequence of the high voltages of steps induced by radiation at FIR frequencies compared to those at microwave frequencies, since the shot noise is proportional to the level of quasiparticle current and hence the bias voltage. Taking account of this shot noise, as well as other noise sources, we were able to give a quantitative account of the complex shapes of the dc I-V curves, including Josephson steps, photon-assisted tunneling steps, and noise-induced premature switching out of the zero-voltage state as the dc bias current is increaded. This work showed that these junctions were capable of giving detection sensitivities near to the quantum limit of one electron of current change per photon.

The major difficulty impeding further pursuit of these promising results was that these junctions were fabricated from soft metals (Sn and Pb) and so were unable to withstand the strains associated with repeated cycling between room temperature and helium temperature; rather their characteristics would degrade, precluding their use in practical devices and making difficult even their study in the laboratory. To address this problem, we organized a collaboration with Dr. L.N. Smith, then of the Sperry Research Laboratories, in which he fabricated some devices using the material and fabrication method, the configuration of these devices was similar to those studied by Danchi, having broadly-resonant antennas and small junction area. Because of their lower resistance (a few ohms rather than 100-200 ohms), noise-rounding effects were minimal compared to those in the higher resistance Pb-Sn junctions, giving sharper features for detector purposes. However, the low impedance also gave poorer coupling to the incident radiation, limiting the number of steps that could be induced by the available laser source. Subsequently, we obtained another batch of SNAP junctions from Dr. Cornell Chun of Sperry Labs in Minnesota. These were deliberately fabricated so as to have higher impedance, and indeed they showed the expected better coupling to radiation.

In the process of exploring the properties of the low-impedance junctions, we discovered that merely reducing the FIR laser frequency from 604 GHz to a line at 419 GHz caused us to observe I-V curves of an entirely different character from those seen earlier and so well understood; these radical changes are due to the onset of "chaotic motions" when the junction is driven at a frequency near the plasma frequency, which is estimated at about 400 GHz in these junctions. The observed hallmarks include extremely high levels of low-frequency noise, subharmonic step structures accompanied by missing integer steps, and meandering voltage levels in the I-V curve on otherwise well-defined and flat steps.

Because time-resolved measurements of these chaotic motions are impossible at 400 GHz, we have had to rely heavily on simulations to interpret our experimental observations. We have done this using an RCSJ (resistively and capacitively shunted junction) model. However, in contrast with almost all other work in this field, we have built in the gap structure in the quasiparticle current by using a piece-wise linear resistance, equal to the normal resistance R_N above the gap and a leakage resistance R_1 below the gap. Moreover, we have done this both in <u>digital</u> simulations using either a VAX or an Apollo work station, and in <u>analog</u> simulations using a home-built simulator of the Magerlein design (modified to include the non-linear resistance). Our work has confirmed the expectations that chaos and subharmonic responses are prominent only when the physical situation can be modelled by an ac <u>current</u>-drive at a frequency near or somewhat below the plasma resonance frequency of the junction. We have also shown that the sequence of subharmonic steps observed is critically dependent on the ratio of the drive frequency to the plasma frequency, and that our simulations model this well enough to be able to determine the junction plasma frequency within a few percent just from the step pattern at the (fixed) laser frequency. A particularly elegant demonstration of this excellent modeling is made possible by using a small magnetic field to depress the junction critical current and hence its plasma frequency, allowing one to "tune" through different step sequences, exactly as predicted in the simulations.

Another result of this work has been a rather quantitative verification of the importance of genuine thermal and shot noise in modifying the results of noiseless simulations to bring them into agreement with the experimental I-V curves. When the motion is already chaotic in the noiseless simulation, as when it is governed by a "strange attractor", the addition of noise to the simulation produces little qualitative effect on the Poincare' section of the motion, or on the experimentally observable noise. However when the dc and ac bias is such that two different periodic attractors are both locally stable, noise plays a crucial role in inducing noisy switching between the two. Thus, where a noiseless simulation shows hysteresis between, say, the $n = 1/2$ and the $n = 2$ steps, while the experiment shows none, we find that addition of an appropriate amount of noise to the simulation closes the hysteresis loop. The "appropriate" amount is based on the voltage-dependent shot noise modification of the usual Johnson noise. Despite the fact that our photon energy exceeds kT, we are able to use the low-frequency limit of the frequency-dependent quantum noise formula because the finite voltage term (shot noise) already enhances the Johnson noise, and because we have empirically found that noise at frequencies below half the plasma frequency dominate the reduction of hysteresis. This is an interesting and surprising result, since one would think that noise would be most effective at the resonant plasma frequency. In fact, our simulations show that the sensitivity to noise reaches a broad maximum at the 1/3 subharmonic of this frequency in the case of switching between the 2/3 and 2nd step. Further work will be required to explore the generality of this interesting observation.

In our study of these noise-induced switching effects, we have also shown that, in simulations it is necessary to use a fictitious temperature T^* which is larger than the physical one (the thermal-shot noise T_{eff}) by the ratio of the logarithm of the number of drive cycles in the real experiment ($\sim 10^{12}$) to the logarithm of the number of drive cycles in the real experiment ($\sim 10^4$). This correction is based on the critical importance of rare peak noise pulses (as opposed to typical rms values) in triggering switches from one attractor to another. Although only logarithmic, this correction typically implies a 3-fold increase of T^*; just such an increase is found to be required to obtain simulations that agree with the experimental data. Suprisingly, this important quantitative point in making realistic predictions of the effect of noise in real situations by means of simulations running for drastically fewer cycles seems not to have been identified in previous work, except in the work of Danchi et al. on the noise-reduction of the zero-voltage critical current.

B. Josephson Junction Arrays with Positional Disorder

Josephson junction arrays with positional disorder were studied using both experiments and Monte Carlo simulations. We fabricated 50 x 50 arrays of Pb/Cu proximity-effect junctions, with controlled positional disorder characterized by a parameter Δ^*. The zero-field resistive transitions of these samples are well described by the Kosterlitz-Thouless-Halperin-Nelson vortex-unbinding theory. Measurements of resistance vs. magnetic field reveal rich strucutre, with pronounced minima at integer fields, as well as higher-order structure. In samples with disorder the principal oscillations are found to decay linearly with field, after accounting for the effect of the magnetic field on the critical currents of the individual junctions. The destruction of phase-coherence on length-scales of order q times the lattice parameter can be quantified by defining critical fields, $f_c(q) \propto 1/\Delta^*$, by the disappearance of structures at fields $f_o = p/q$, where f_o is the average number of flux quanta per plaquette, and p and q are integers. Extrapolation to $q = \infty$ yields an estimate of the critical field, f_c, for the destruction of quasi-long-range phase coherence which is in good agreement with the theoretical prediction of Garanato and Kosterlitz. However, our experiments show no evidence for the predicted reentrant phase transition.

Our Monte Carlo simulations of XY spin systems with positional disorder reveal reentrant behavior in the helicity modulus Y, which is the analog of the effective superfluid density in a junction array, in a narrow range of magnetic fields near the theoretical critical field. As the temperature decreases, Y first increases, then decreases over a narrow temperature range, and finally increases again at low temperatures. We suggest that the complete reentrance proposed theoretically is prevented by either finite-size effects or pinning of vortices due to the disorder.

C. Novel Quantum Phenomena and Charging Effects in Very Small Tunnel Junctions

During the contract period, we have made remarkable progress in exploring new types of quantum effects that occur in ultra-small Josephson junctions at very low temperatures. This research was made possible by our recently developed clean room facility and e-beam writing capability for patterning very small thin-film structures, developed with the motivation of studying the properties of low capacitance junctions for detectors and mixers in the submillimeter wave region. It also requires the use of our helium dilution refrigerator (purchased with NSF and Harvard funds) to reach the millidegree temperature range where the quantum effects most clearly dominate over the classical thermally activated processes. Although these experiments are aimed purely at elucidating basic device physics, in some recent experiments a variation of the configuration used for them has shown potential as a 3-terminal device.

The junctions studied were Sn-SnOx-Sn tunnel junctions, with areas of 0.1 $(\mu m)^2$ or less, so that their intrinsic capacitance is of order 1 femtofarad (fF). With such small capacitances, the charging energy $e^2/2C$ associated with a single electron imbalance between the electrodes is comparable with kT at 1 K, with the energy gap in the Sn banks, and with the Josephson coupling energy $E_J = hI_c/2e$. This is a regime never before explored, especially when the temperature is lowered by a factor of ~150 to ≈20 mK, where the thermal processes are almost completely frozen out.

The most striking observation is the temperature dependence of the critical current shown in Figure 1 (note the logarithmic scale). Focusing on the higher resistance junctions in the figure, as

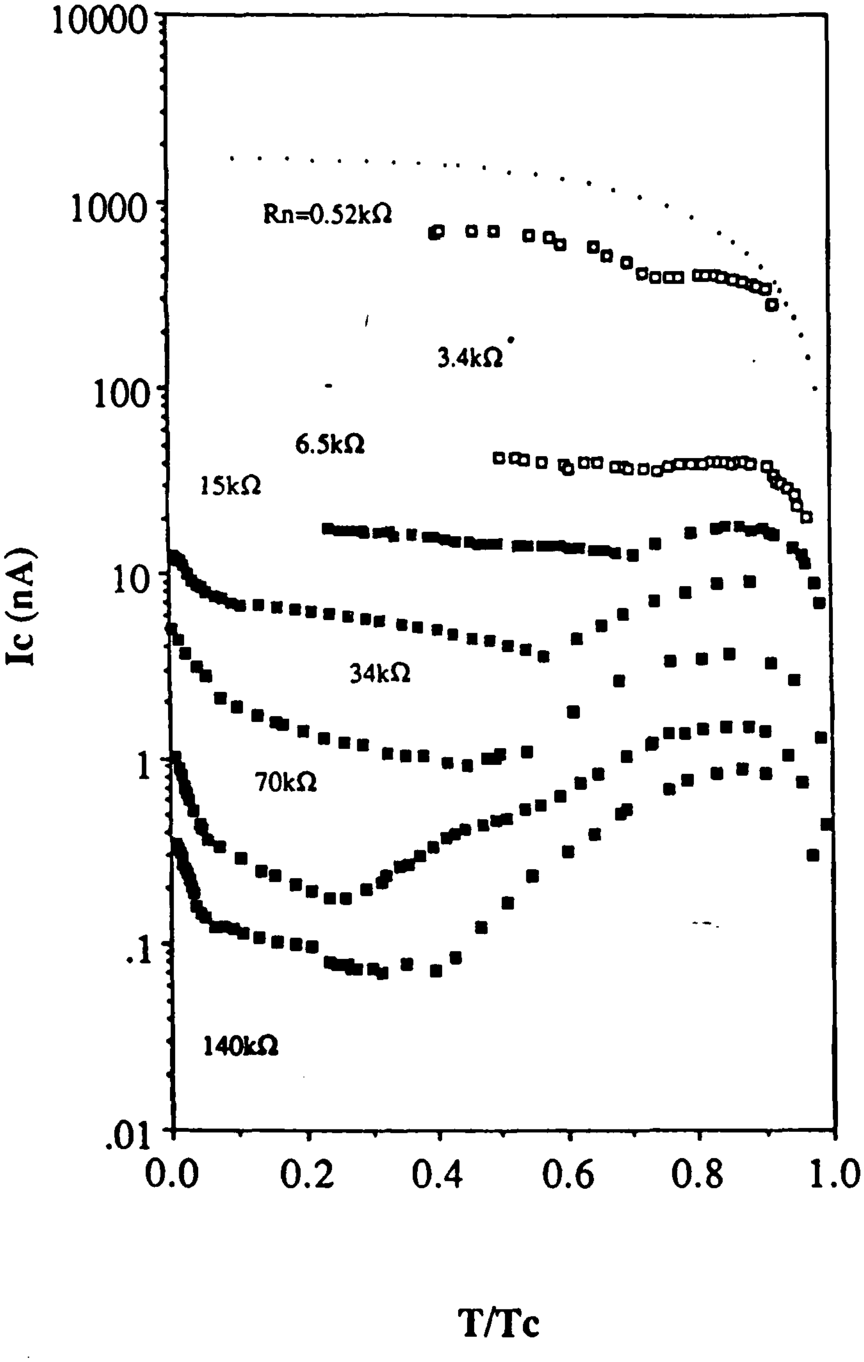
10000
1000
100
10
1
.1
.01
Ic (nA)
Rn=0.52kΩ
3.4kΩ
6.5kΩ
15kΩ
34kΩ
70kΩ
140kΩ
0.0
0.2
0.4
0.6
0.8
1.0
T/Tc

Figure 1.

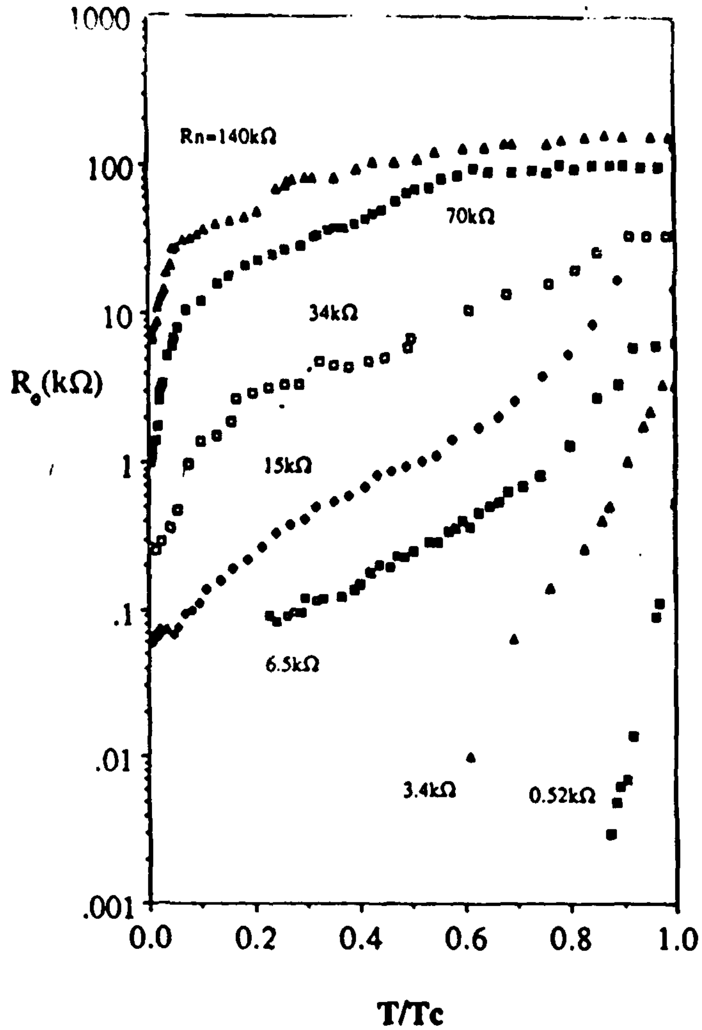

Figure 2.

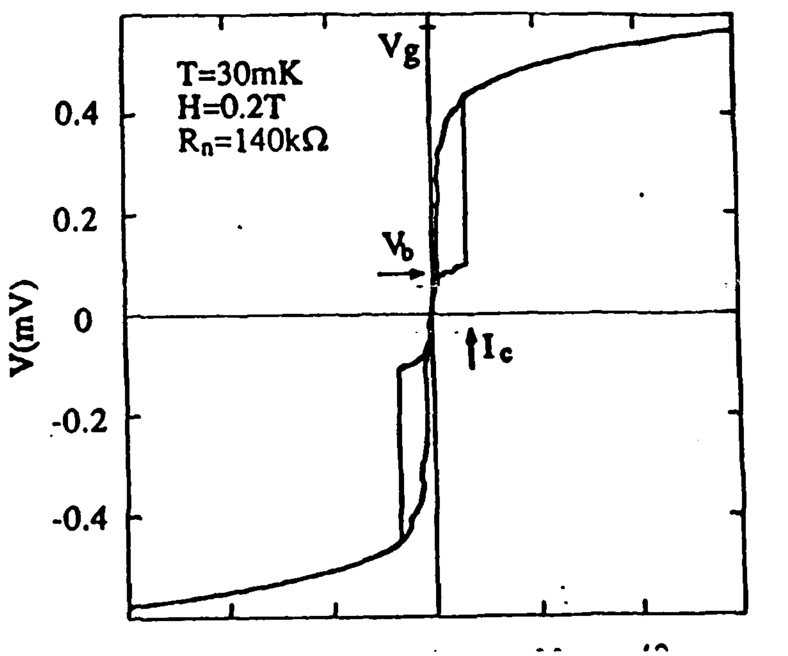

Figure 3.

one cools below the superconducting critical temperature T_c, I_c first rises, then falls by as much as an order of magnitude, and then rises again by a similar amount. The value at T = 0 is typically an order of magnitude less than that of a classical junction of the same resistance, as determined by the Ambegaokar-Baratoff relation, which is known to work well for larger junctions with lower resistance. Moreover, for these small high resistance junctions, the measured $I_c(0)$ scales with R_n^{-2} rather than scaling with R_n^{-1} as in the conventional Ambegaokar-Baratoff regime. We can account for both these facts by invoking the capacitive charging energy, which forces a partial delocalizaton of the phase difference across the junctions by quantum fluctuations because of the quantum conjugate relation between the phase and the number of transferred electrons. Qualitatively, the spread-out probability distribution of the phase φ is less strongly bound to the minimum of the Josephson coupling energy $-E_J \cos \varphi$ than a localized semi-classical phase variable would be, so a smaller current (which acts to "tilt" the cosine potential) is sufficient to cause rapid phase evolution (in the "tilt" direction) and a jump to the high-voltage (gap voltage) state.

Explanation of the entire doubly-reentrant temperature dependence of I_c requires inclusion of thermal activation effects as well as these quantum effects. According to our analysis, the initial rise near T_c and the subsequent fall can be understood as being determined by the "retrapping" critical current, below which the damping is sufficient to cause retrapping in the cosine potential rather than runaway, after an initial activation. Although this reentrance arises from a classical effect, it has never studied before because it only shows up in very high resistance junctions, where thermal activation over the cosine potential barrier is very easy. As one cools further, the retrapping current I_r continues to approach zero as the quasiparticle damping freezes out. However, the I-V curve becomes hysteretic, with I_c bottoming out and rising again as one approaches the lowest temperatures. This rise occurs at temperatures low enough to finally freeze out the thermal activation over the barrier energy E_J.

Another remarkable observation is that these junctions show a finite resistive voltage even below the critical current I_c, indicating a finite rate of phase evolution, again completely contrary to conventional junctions in which there is no phase slip until the jump to the gap voltage at I_c. Our interpretation of this voltage is that it arises from MQT (Macroscopic Quantum Tunneling) of the phase from minimum to minimum, which is prevented from running away because of damping effects. We have been able to give a semiquantitative account of the value of this resistance at T=0. Of course, as T increases, thermally-activated phase motion also plays a role. In this way we can give at least a qualitative description of the temperature dependence of this initial resistance, which is shown in Fig. 2.

Subsequently, we have studied an even more extreme quantum regime, obtained by application of a magnetic field, in which the charging energy greatly exceeds the Josephson energy. In this case, the charge variable is almost classically well defined, and the phase almost entirely washed out by the effect of the quantum fluctuations. In this regime, we obtain I-V curves (see Fig. 3) which show a remarkable coexistence of the "Coulomb blockade" associated with single electron tunneling, together with a finite "critical supercurrent", albeit one that occurs at a substantial voltage level ($\approx e/2C$) associated with the blockade. At present there is no available theory that can account in any detail for our observations, which are quite unexpected. However, we have developed phenomenological models which can account for most of the features. Because these phenomena are sensitive to the charging energy associated with a single net electronic charge on the electrodes, they have potential applications for very sensitive electronic devices.

In summary, these phenomena: the severe reduction of $I_c(0)$, the remarkable temperature dependence of $I_c(T)$, the existence and the temperature-dependence of the resistance $R_0(T)$ below I_c, and coexistence of Coulomb blockade and Josephson effects in a single junction are to the best of our knowledge new observations first made by our group and our interpretations involve new theoretical considerations.

D. High Temperature Superconductivity

We have made significant progress in understanding the phenomenology of the unusually broad resistive transition of the new superconductors, as summarized below.

In 1987, Müller, Takashige, and Bednorz demonstrated the existence of an "irreversibility line" in high temperature superconductors which separates the region of reversible magnetization near T_c from the irreversible region in which measurable (and useful) persistent irreversible supercurrents can exist. The form of this line was found to be

$$1 - t \propto H^{2/3}$$

where $t=T/T_c$. They interpreted this result in terms of a spin-glass analogy, but in 1988 Yeshurun and Malozemoff proposed an attractive alternative interpretation in terms of more conventional thermally-activated flux creep ideas. In their model, they introduce a field-dependent activation energy $U_o \propto H_c{}^2\xi\ /B \propto (1 - t)^{3/2}/B$, and interpret the irreversibility line as the condition for this U_o to be so large compared to kT that nonequilibrium currents decay sufficiently slowly to give apparently persistent currents.

In our work, we have extended this model to the regime where U_o/kT is not so large. In that case, instead of persistent currents, there is measurable resistance because of flux motion. We argue that the resistance should follow the form derived in 1969 by Ambegaokar and Halperin for the resistive transition in a heavily-damped Josephson junction. In this way, we are able to give a natural explanation of:

1) the fact that the resistive transition of high-T superconductors gets increasingly broad in the presence of magnetic flux (in fact, $\Delta T \propto B^{2/3}$);
2) the fact that the resistively determined upper critical field $H_{c2}(T)$ appears to vary as $(1\text{-}t)^{3/2}$ rather than the expected (1-t), and also that it greatly underestimates the true thermodynamic H_{c2};
3) the actual shape of R(T;H) and its dependence on the quality of the material as measured by $J_{co}(0)$.

From these successes of the model, we extrapolate to the inference that it will be hard to avoid the existence of appreciable resistance in flux-containing high temperature superconducting materials except at temperatures far below the nominal T_c.

In addition to the analytical work described above, we have also written a more general review of the physical properties of the new superconductors for publication as a chapter in the Solid State Physics series, edited by Ehrenreich and Turnbull.

II. INDEX OF TECHNICAL REPORTS

Tech. Report # 22: "A Far-Infrared Laser Study of Small-Area Superconducting Tunnel Junctions", William C. Danchi, October 1983.

Tech. Report #25: "Noise and Chaos in Driven Josephson Junctions", Qing Hu, March 1987.

Tech. Report #26: "Josephson Junction Arrays With Positional Disorder: Experiments and Simulations", Martin G. Forrester, February 1988.

Tech. Report # 27: "Quantum Phenomena in Mesoscopic Superconducting Tunnel Junctions", Marco Iansiti, December 1988.

III. PUBLICATIONS

1. RESEARCH OPPORTUNITIES IN SUPERCONDUCTIVITY: M. Tinkham, M.R. Beasley, D.C. Larbalestier, A.F. Clark, and D.K. Finnemore, Copper Mountain Workshop Report, November, 1983; Cryogenics 24, 378-388 (1984).

2. SUBHARMONIC ENERGY GAP STRUCTURE AND EXCESS CURRENT IN NIOBIUM POINT CONTACTS: J. Bindslev Hansen, M. Tinkham, and M. Octavio, Proc. LT-17 Conf., Karlsruhe, W. Germany, August, 1984, North Holland Press, p. 435-6 (1984).

3. EFFECTS OF NOISE ON THE DC AND FAR-INFRARED JOSEPHSON EFFECT IN SMALL-AREA SUPERCONDUCTING TUNNEL JUNCTIONS: W.C. Danchi, J. Bindslev Hansen, M. Octavio, F. Habbal, and M. Tinkham, Phys. Rev. B30, 2503-2516 (1984).

4. RESPONSE OF Nb-aSi-Nb JUNCTIONS TO 604 GHz RADIATION: W.C. Danchi, F. Habbal, J.U. Free, M. Tinkham, and L.N. Smith, Proc. 1984 Appl. Supercon. Conf., San Diego; IEEE Trans. Mag. MAG-21. 219-222 (1985).

5. CHAOTIC BEHAVIOR OBSERVED IN A DC-BIASED JOSEPHSON JUNCTION DRIVEN AT FIR FREQUENCIES: Qing Hu, J.U. Free, M. Iansiti, O. Liengme, and M. Tinkham, Proc. 1984 Appl. Supercond. Conf., San Diego, IEEE Trans. Mag. MAG-21, 590-593 (1985).

6. NOISE AND CHAOS IN A FRACTAL BASIC BOUNDARY REGIME OF A JOSEPHSON JUNCTIONS: M. Iansiti, Qing Hu, R.M. Westervelt, and M. Tinkham, Phys. Rev. Lett. 55, 746-749 (1985).

7. REENTRANT TEMPERATURE DEPENDENCE OF CRITICAL CURRENT IN SMALL TUNNEL JUNCTIONS: H. Akoh, O. Liengme, M. Iansiti, M. Tinkham, and J.U. Free, Phys. Rev. B33, 2038-2041 (1986).

8. INTRODUCTION TO SPECIAL 75TH ANNIVERSARY ISSUE ON SUPERCONDUCTIVITY: M. Tinkham, Physics Today 39, 22-23 (1986).

9. RESPONSE OF JOSEPHSON JUNCTIONS TO FAR-INFRARED RADIATION NEAR THEIR PLASMA RESONANCE FREQUENCIES: Qing Hu, C.J. Lobb, and M. Tinkham, Phys. Rev. B35, 1687-1691 (1987).

10. NOISE AND CHAOS IN DRIVEN JOSEPHSON JUNCTIONS: M. Tinkham, Invited Paper in MIDIT Conference, Lyngby, Denmark, August, 1986; published in "Structure, Coherence and Chaos in Dynamical Systems", ed. by P.L. Christiansen and R.D. Parmentier, Manchester University Press, 1989, pp. 427-439.

11. CHARGING ENERGY AND PHASE DELOCALIZATION IN SINGLE VERY SMALL JOSEPHSON TUNNEL JUNCTIONS: M. Iansiti, A.T. Johnson, W.F. Smith, H. Rogalla, C.J. Lobb, and M. Tinkham, Phys. Rev. Lett. 59, 489-492 (1987)

12. POSSIBLE OSERVATION OF CHARGING ENERGY EFFECTS IN SINGLE ULTRA-SMALL JOSEPHSON TUNNEL JUNCTIONS: M. Iansiti, A.T. Johnson, W.F. Smith, C.J. Lobb, and M. Tinkham, LT-18 Conf., Kyoto, August, 1987; Jap. J. Appl. Phys. 26, Suppl. 26-3, 1557-8 (1987).

13. POSITIONAL DISORDER IN JOSEPHSON JUNCTION ARRAYS: EXPERIMENTS AND SIMULATIONS, M.G. Forrester, H.J. Lee, M. Tinkham, and C.J. Lobb, Phys. Rev. B37, 5966-69 (1988).

14. CROSSOVER FROM JOSEPHSON TUNNELING TO THE COULOMB BLOCKADE IN SMALL TUNNEL JUNCTIONS: M. Iansiti, A.T. Johnson, C.J. Lobb, and M. Tinkham, Phys. Rev. Letters 60, 2414-2417 (1988).

15. THE RESISTIVE TRANSITION OF HIGH TEMPERATURE SUPERCONDUCTORS: M. Tinkham, Phys. Rev. Lett. 62, 1658-1661 (1988).

16. PHYSICAL PROPERTIES OF THE NEW SUPERCONDUCTORS: M. Tinkham and C.J. Lobb, Chapter in Solid State Physics, Vol. 42, pp. 91-134, Academic Press, San Diego (1989).

17. RESPONSE TO COMMENT ON "CROSSOVER FROM JOSEPHSON TUNNELING TO THE COULOMB BLOCKADE IN SMALL TUNNEL JUNCTIONS", M. Iansiti, A.T. Johnson, C.J. Lobb, and M. Tinkham, Phys. Rev. Lett. 62, 484 (1989).

18. CHARGING EFFECTS AND QUANTUM PROPERTIES OF SMALL SUPERCONDUCTING JUNCTIONS: M. Iansiti, M. Tinkham, A.T. Johnson, W.F. Smith, and C.J. Lobb, Phys. Rev B39, 6465-6484 (1989).

19. POWER SPECTRA OF NOISE-INDUCED HOPPING BETWEEN TWO OVERLAPPING JOSEPHSON STEPS: Qing Hu and M. Tinkham, Phys. Rev. B39, 11358-63 (1989).

INVITED PRESENTATIONS AT CONFERENCES

1. SMALL-AREA JOSEPHSON DEVICES FOR SUBMILLIMETER WAVELENGTHS: M. Tinkham, Invited Paper at US-Japan Workshop on Josephson Junction Electronics, Kauai, Hawaii, June, 1985.

2. CHAOTIC PHENOMENA IN FAR-INFRARED IRRADIATED JOSEPHSON JUNCTIONS: M. Tinkham, Invited Paper, March Meeting of APS, Las Vegas, March 1986.

3. QUANTUM PROPERTIES OF VERY SMALL JOSEPHSON JUNCTIONS: M. Tinkham, Conf. on Quantum Coherence, Univ. of Minnesota, October, 1987.

4. OVERVIEW OF THE HIGH TEMPERATURE SUPERCONDUCTORS: M. Tinkham, RF EXPO East, Boston, November, 1987.

5. CHARGING ENERGY AND QUANTUM PHASE DELOCALIZATION IN SMALL JOSEPHSON JUNCTIONS and TWO DIMENSIONAL SUPERCONDUCTING ARRAYS AND GRANULAR SUPERCONDUCTORS: M. Tinkham, Latin-American Conference on High Temperature Superconductivity, Rio de Janeiro, May, 1988.

6. SUPERCONDUCTIVITY: PAST, PRESENT, AND FUTURE: M. Tinkham, IEEE meeting, Boston, MA, May, 1988.

7. THE RESISTIVE TRANSITION IN HIGH TEMPERATURE SUPERCONDUCTORS: M. Tinkham, Workshop on Superconducting Phenomenology, Los Alamos, September, 1988.

8. CONSIDERATIONS LIMITING CRITICAL CURRENTS IN HIGH TEMPERATURE SUPERCONDUCTORS: M. Tinkham, Invited paper at ISTEC Workshop on Critical Currents in High T_c SUPERCONDUCTORS, Oiso, Japan, Feb., 1989.