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SIS MIXER RESEARCH

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13. ABSTRACT (Maximum 200 words)

Theoretical and experimental research has been conducted to elucidate the basic physics behind the properties of superconductor-insulator-superconductor (SIS) tunnel junction receiving devices. The saturation behavior of the SIS mixer and the SIS direct detector was calculated. The direct detector was found to saturate at far higher powers than previously believed, allowing the possibility of practical application. SIS mixer saturation was measured using both monochromatic and thermal signals, and these experiments dramatically verified the theoretical expression. Quantum noise in the quantum theory of mixing was identified as the residual remaining when the usual noise sources are minimized. The quantum noise limit was shown to be reached in only two special cases. Computer calculations determined that the behavior of SIS receivers divides into two frequencies regimes, the cross-over frequency depending upon junction quality. The properties of these two regimes were delineated. A study of the role of the image termination of SIS mixers found that the nonlinear quantum reactance results in an effective time delay at the input port. Many aspects of the operation of SIS mixers at submillimeter wavelengths were clarified. Niobium nitride edge junctions with excellent current-voltage characteristics were fabricated using a novel barrier formation process.

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FINAL TECHNICAL REPORT

AFOSR Grant #86-0056

SIS Mixer Research

Report period: November 1985 - November 1988
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I. Summary

Theoretical and experimental research has been conducted to elucidate the basic physics behind the properties of superconductor-insulator-superconductor (SIS) tunnel junction receiving devices. The saturation behavior of the SIS mixer and the SIS direct detector was calculated. The direct detector was found to saturate at far higher powers than previously believed, allowing the possibility of practical application. SIS mixer saturation was measured using both monochromatic and thermal signals, and these experiments dramatically verified the theoretical expression. Quantum noise in the quantum theory of mixing was identified as the residual remaining when the usual noise sources are minimized. The quantum noise limit was shown to be reached in only two special cases. Computer calculations determined that the behavior of SIS receivers divides into two frequencies regimes, the cross-over frequency depending upon junction quality. The properties of these two regimes were delineated. A study of the role of the image termination of SIS mixers found that the nonlinear quantum reactance results in an effective time delay at the input port. Many aspects of the operation of SIS mixers at submillimeter wavelengths were clarified. Niobium nitride edge junctions with excellent current-voltage characteristics were fabricated using a novel barrier formation process.

II. Research Objectives

The research objectives set forth in the proposal leading to this grant are the following:

1. The first objective of this research is to conduct a careful and exhaustive analytical examination of the quantum theory of mixing, in order to derive new general results from the theory and to clarify the behavior of superconductor-insulator-superconductor (SIS) mixers.
2. The second objective of this research is to analyze the behavior of arrays of SIS junctions.
3. The third objective of this research is to study the limitations of SIS mixers at higher frequencies, close to and exceeding the energy gap frequency of the superconductors used.
4. The fourth objective of this research is to fabricate and evaluate plasma-etched NbN edge junctions to study the mechanisms of oxide growth on a shaped NbN surface.

III. Research Accomplishments

Significant progress was made towards achieving each of these research objectives. In the following description of research accomplishments, the numbers in square brackets refer to the publications listed below in Sec. IV.

1. Quantum Theory: Several projects which use the quantum theory of mixing to illuminate the behavior of SIS receiving devices have been completed under this grant support.

a. Saturation of the SIS direct detector: We employed the quantum theory of mixing to calculate the saturation properties of the SIS direct detector [2]. Although early papers on SIS direct detection reported the highest sensitivities ever achieved for a direct microwave detector, this device has been largely ignored in the literature since 1981. One reason for this neglect has been the understanding that were the SIS direct detector to saturate as severely as the SIS mixer, it would not be usable. This is because the direct detector cannot resort to either of the techniques employed to avoid SIS mixer saturation; in particular, it must have a broad bandwidth to be useful. However, our calculation shows that the SIS direct detector begins to saturate only at powers far larger than for a comparable SIS mixer. This result has warranted a reconsideration of SIS junctions for high sensitivity direct detection of millimeter wavelength radiation, in competition with the helium-three-cooled bolometers now used.

We have determined the complete expression for the responsivity of the SIS direct detector, including the lowest order terms dependent upon the incident signal power which cause the saturation. Assuming typical parameter values, we found that a thermal signal of temperature T and bandwidth $\Delta\nu$ around frequency ν will suppress the responsivity by less than 1% so long as $T\Delta\nu/\nu \leq 600$. This is roughly 200 times larger than the saturation power of a comparable SIS mixer. Experiments performed in conjunction with L.R. D'Addario of the National Radio Astronomy Observatory (NRAO) using N = 2 and 4 SIS junctions in series, qualitatively verified the saturation theory [4]. However, the measured detector responsivity was greater than the quantum limit $e/N\hbar\omega$. This is not understood. A careful analytical treatment of two non-identical series junctions showed that this discrepancy is much too large to be caused by differences between the junctions.

In part because of this work there is now a renewed interest in the possibility of employing SIS junctions for direct detection of millimeter wavelength radiation, eventually as elements of a focal-plane array detector.

b. Saturation of the SIS mixer: Saturation can be a serious problem for SIS mixers. Single-junction SIS receivers are likely to operate with some degree of saturation, and, in fact, thermal noise far below room temperature will in some cases produce severe saturation.

We have determined an explicit expression for the gain saturation of the SIS mixer [4]. Previous work had given only the approximate power at which saturation would occur. Our expression, assuming typical parameter values, implies that a thermal signal must obey $T\Delta\nu/\nu \leq \nu/40$ GHz to avoid 1% gain suppression of a unity-gain single-junction SIS mixer. Thus room temperature radiation in a 1% bandwidth will saturate such a mixer at frequencies as high as 120 GHz. Our explicit expression has proven useful to designers of practical SIS receivers; to avoid saturation the mixer can either be narrow-banded or employ a series array of junctions. Note that our results cast doubt upon recent reports of low-noise single-junction SIS receivers which have extremely wide bandwidths.

We performed painstaking mixer experiments, in conjunction with A.R. Kerr and S.-K. Pan of NRAO, which unambiguously verify the saturation expression both in magnitude and parameter dependence [10]. The experimental gain versus monochromatic input signal power agrees with the theoretical prediction to within 0.2 dB in gain over more than 25 dB in signal power. This precision is especially remarkable in that there are no adjustable fitting parameters. Such perfect agreement is surprising for many reasons, which are discussed at length in the publication.

In an additional series of experiments we measured the saturation properties of SIS mixers subjected to broad-band thermal noise [19]. Both this theory and the experiments discussed above consider only monochromatic saturating signals, whereas in practice an SIS mixer is usually both calibrated by and is used to detect broad-band thermal signals. It has been argued that out-of-band thermal noise will cause an SIS receiver to saturate at levels well below the theory would predict. Nevertheless, the thermal saturation experiments found essentially perfect agreement with the theory over the entire range of data. In this case there were two fitting parameters for each mixer -- the unsaturated gain and the effective bandwidth of the thermal noise -- whose values were only approximately known, and so the precision of the agreement with theory is not as surprising, but it gives confidence that the theory describes saturation by thermal as well as by monochromatic signals.

c. Frequency scaling: In conjunction with Kerr and Pan we used the mixer saturation expression to formulate a set of frequency scaling relations for SIS mixers which maintain either the saturation power or temperature [7]. Given an SIS element optimized for one frequency band, these relations completly determine the optimum SIS element for a scaled mixer block at any other frequency, between 50 and 350 GHz. This work assumed an optimum source impedance independent of frequency for the SIS mixers, consistent with our earlier calculations, but this assumption may be false. We now believe that the optimum source impedance increases with frequency for a given SIS mixer [20]. This result, if valid, works against the performance of SIS mixers at higher frequencies. To scale an SIS mixer up in frequency would require the junction critical current density to increase as the square of the frequency, rather than simply proportional to frequency as is generally believed.

d. Quantum noise: We have investigated the origin and characteristics of quantum noise in the quantum theory of mixing [3]. The proposal underlying this grant stated that "This noise is <u>not</u> contained in (the) quantum theory . . ." We now know that this statement is false. We have shown that the lowest possible equivalent input noise power of *any* device obeying the quantum theory of mixing in the three-port, low IF model, allowing *arbitrary* terminations at each frequency, is $\hbar\omega/2$ per unit bandwidth. This means that no extraneous noise source need be postulated to produce the quantum noise, contrary to many papers written on the quantum theory of mixing. Instead, the quantum noise is the residual remaining when both of the obvious noise sources, thermal noise in the termination impedances and shot noise, are minimized, and it is generated by the combination of these two minimized noise sources. Other phase-preserving, high-photon-gain, linear amplifiers, such as the maser and the parametric amplifier, have the same minimum noise, and this is ultimately a consequence of the Heisenberg uncertainty principle.

In addition, we showed that the mixer quantum noise limit can be reached in only two special cases, approximated by the super-Schottky mixer in the limit of *large* local oscillator power, and by the SIS mixer in the limit of *small* power. For the ideal SIS mixer, the minimum noise is found for one particular value of source impedance, regardless of the value of the image termination impedance. This appears to violate the assumptions of the most widely quoted theory [C.M. Caves, Phys. Rev. D26, 1817 (1982)] of quantum noise in linear amplifiers.

The calculation performed in this work was unique in that it employed the complete equations of the quantum theory of mixing in the three-frequency, low-intermediate-frequency model, making no simplifying approximations. The success of this work has prompted several researchers to attempt to use the same techniques in their own research.

e. Image termination: We used the quantum theory of mixing to examine the role of the image termination for SIS mixer operation [11]. (Most previous work has assumed a double-sideband mixer, merely one important case.) First, we showed analytically that a smaller image conductance always increases the range of parameter values which produce infinite available gain. This is the reason for the relatively poor performance of shorted-image SIS mixers. Second, we plotted conversion loss for specific SIS mixers on a Smith chart of image termination admittance, for various values of mixer parameters. All of the plots are symmetric about an axis rotated counterclockwise from the real axis. The angle of rotation appears to be a general property of a specific mixer. We related the rotation to the nonlinear quantum reactance: a rotation on a Smith chart is equivalent to a time delay at the input port of the mixer; the calculated time delay is numerically equal to the time retardation of the sharp spike which occurs in the quasiparticle response function and which is the principal effect of the nonlinear quantum reactance. This result appears to have broad implications for understanding the quantum theory of mixing, and is still under study. It explains why the nonlinear quantum reactance is experimentally inconspicuous, as we have maintained in previous publications.

2. Arrays: Experiments show that an SIS mixer using a series-connected array of SIS junctions as its active element can generate considerably more noise than an equivalent single-junction mixer, in spite of a simple proof that there should be no extra noise. No explanation for this effect has been suggested. We believe that the excess noise is caused by a nonlinear interaction among the junctions in the array, that the conventional noise generated in one junction can in certain circumstances actively affect the behavior of the others. If indeed there is excess noise from a nonlinear interaction among the elements in an array, this has significant widespread implications. *Any* device which is extremely small in physical size will require very little power. If the power requirement is small enough, even thermal or shot noise may cause nonlinear interactions, and the standard theories must fail. Whether or not this occurs in SIS array mixers, it is certain that as the technology of micro-miniaturization proceeds a variety of other devices will exhibit noise-driven nonlinearities.

This nonlinear problem is difficult to analyze. It is not possible to make the linear "small-signal" approximation, the universal analysis tool, a kind of perturbation theory, which is used in essentially every theoretical discussion of noise in signal-processing devices. Therefore we chose to study an unrealistic model system with I-V relation $I = I_0 [1 - \exp(-V/V_0)]$ biassed at $I = V = 0$, rather than addressing the complicated equations of the SIS junction. We believe that this is the simplest equation which is still a plausible approximation for the differential I-V relation for an SIS junction in the vicinity of its optimum bias point.

We succeeded in formulating the series junction problem for this simple model system, and found a tractable solution. The noise generated in one model junction does indeed drive the others nonlinearly, increasing the total noise. The system noise increases strongly with the number of junctions employed, very much like in the experimental SIS mixer results.

This work, however, is incomplete and has not been published because the applicability to SIS mixers has not been demonstrated. It remains to be determined whether the ratio of the shot noise current in a biassed and pumped SIS junction compared to I_0 is large enough to generate the excess noise seen in the experiments. If this is the case, we can make a strong argument that the excess noise in SIS array mixers is caused by this mechanism.

3. High Frequency: The third objective of this research grant was to study the limitations of SIS mixers at high frequencies. This was precisely the theme of an invited publication [6] in which we discussed current knowledge about the behavior of submillimeter SIS mixers. We identified many of the problems to be encountered in the design and realization of THz mixers.

This work included a stringent limitation on the use of inductive-loop tuning structures, the most obvious choice for integrated circuit tuning. We showed that such a tuning structure cannot be used for SIS arrays above about 100 GHz, and can be used for single junctions at high frequency only with difficulty. This is because the parasitic series inductance along the leads of the SIS junction or array which lies inside the resonant loop has a surprizingly large impact. Inductive-loop tuning can be effective only at frequencies far below the resonant frequency of the SIS junction capacitance and this inductance.

This work also included the first indication that saturation, by a small signal or noise input, is an important concern for submillimeter SIS mixers. It was generally believed that saturation would not be a problem at high frequency, because the standard derivation states that the saturation power increases as the square of the operating frequency. However, interference from Josephson drop-back noise and from the ac Josephson steps greatly reduces the range of acceptable dc bias for all published high frequency SIS mixer experiments, and this decreases the saturation power by the square of the reduction of the dc bias range [6]. Thus high frequency SIS mixer design must consider the possibility of saturation.

This work also included the first discussion of the possible impact of the new oxide superconductors upon submillimeter SIS mixing [6]. It is a surprising conclusion that a high quality 77 K SIS junction could *in principle* give quantum-noise-limited sensitivity mixing even in a 77 K environment. In addition, a THz SIS mixer using high-T_C junctions would be unconstrained by Josephson interference, a major obstacle for THz mixers using conventional superconductors.

We developed a new computer program, based on the quantum theory of mixing, which is capable of predicting the performance of SIS mixers both at low frequency, where the behavior is relatively familiar, and at high frequency, up to a few times the superconducting energy gap frequency. The program uses synthetic SIS junction I-V characteristics with variable parameters so that the behavior of a wide range of realistic SIS junctions can be simulated and their performance charted as a function of junction quality. We found [5, 6] that for a given SIS junction in an optimized (at each frequency) mixer mount, the receiver sensitivity should *improve* to higher frequency after leaving the classical limit until reaching some "best" frequency. Above that, the receiver noise should linearly increase with frequency staying at roughly 2-5 times the quantum limited noise temperature $\hbar\omega/2k$ until nearly twice the energy gap frequency (about 3 THz for high quality NbN SIS junctions under development).

We distinguished between the "low" and "high" frequency regimes, as being respectively below and above that best frequency. The most important effect of junction quality is that the transition frequency is proportional to the voltage width δV of the energy gap current rise in the junction I-V curve, closely equal to $\delta V(e/2\hbar)$. Therefore, of course, junction quality is crucial in the low frequency regime. But contrary to general belief, junction quality is important even in the high frequency regime, in that a moderately good junction may give twice the receiver noise temperature as an excellent junction.

We found that SIS receiver behavior is qualitatively different in the two frequency regimes. For instance, at low frequency the noise temperature of an optimized receiver is strongly dominated by IF amplifier noise. Therefore the receiver can be effectively tuned for optimum performance by using a monochromatic signal and searching for maximum IF output. But at high frequency the mixer noise is of comparable importance, and so the receiver must be tuned by the more tedious procedure of searching for the minimum noise temperature. Since most previous SIS receivers have operated in the low frequency regime, receiver design criteria are derived from experience in this region. But at present, with higher quality junctions and/or higher signal frequencies, many SIS receivers are beginning to operate in the unfamiliar high frequency regime. Some of the results of this work have appeared in print [6], but many aspects warrant further research and a final publication is still in preparation [21].

4. Plasma-Etched NbN Edge Junctions: We have fabricated NbN/oxide/PbBi edge junctions of extremely high quality [16, 22]. The best junctions obtained have $V_m(4\text{ mV}) \approx 75$ mV, a figure which is unequaled by any junction made of any superconductor in any laboratory. [$V_m(v)$ is defined as 0.7 times the quasiparticle current rise times the subgap resistance measured at voltage v.] Also, the quasiparticle current rise at the energy gap is sharper than for almost any NbN-based SIS junction. Thus our novel barrier formation process yields NbN/PbBi *edge* junctions that have I-V curves of higher quality than similar *planar* junctions made elsewhere.

We have attempted to cut the required edge on NbN films using two different techniques, by ion beam milling [16] and by reactive ion etching (RIE) [15]. Ion milling creates a clearly defined edge, but the high voltage (500 V) ion beam required for a sufficient milling rate leaves the surface of the newly exposed edge damaged to a depth greater than the small coherence length of NbN. Very poor junctions result. A lower voltage ion beam cleaning step was used to remove the damaged surface layer: the junction quality increased dramatically as the cleaning beam voltage was reduced. This technique produced very good but not excellent NbN/PbBi edge junctions with $V_m(3\text{ mV}) = 55$ mV at a beam voltage of 125 V, below which our ion gun did not function.

RIE with CF_4/O_2 was the method used to cut the edge and to form the insulating oxide for the highest quality junctions mentioned above. The fabrication procedure for these junctions was, in brief, to passivate the NbN film with sputtered SiO_2, to define by photolithography and then to cut an edge on the NbN in a parallel-plate plasma etcher using CF_4 and O_2, to define by photolithography the counterelectrode area, to clean the NbN edge with an Ar plasma in a high vacuum system and then to reactively oxidize it by admitting O_2 into the plasma, and finally to evaporate a PbBi counterelectrode, using photoresist liftoff to remove the excess. We found that we could make extremely high quality junctions, having very low leakage current and sharp current onset at the gap voltage, with no SiO_2 passivation layer, if the plasma oxidation step was omitted altogether. The insulating barrier is apparently formed during the CF_4/O_2 plasma edge cutting step; Auger Electron Spectroscopy determined that the barrier contains Nb, C, O_2, and F. Others have noted that the inclusion of F in Nb_2O_5 yields a barrier almost free of deleterious suboxides.

To optimize the shape of the NbN edge we investigated using 1) a two-step wet chemical etch, 2) a two-step wet chemical etch followed by a plasma etch, and 3) a single-step CF_4/O_2 plasma etch. The third technique is clearly superior, yielding a far more desirable edge profile and surface morphology under a scanning electron microscope. We modified our high vacuum plasma system to handle CF_4 so that the NbN edge could be oxidized in a $CF_4/Ar/O_2$ plasma.

In this work the SiO_2 passivation layer required for practical devices was omitted, and also the yield of good junctions was unacceptably low. Subsequent work was directed towards remedying these two deficiencies.

To form a suitable, gently sloping, edge profile on an SiO_2 on NbN film it is necessary that SiO_2 be etched more rapidly than NbN. We extensively investigated the influence of etching gas composition and other parameters on etching rates and edge profiles, using 1) CF_4, 2) CF_4/O_2, 3) CF_4/CH_4, 4) CF_4/CHF_3, and 5) CHF_3. It was found that CF_4 and CF_4/O_2 plasma etching generally yields poor edge profiles on the SiO_2/NbN bilayer films, although these gasses are standard for etching Nb and many other materials. RIE with these gasses etches NbN more rapidly than SiO_2, with the result that the edge of an SiO_2 on NbN bilayer film is undercut and unsuitable for junction fabrication. However, we succeeded in obtaining satisfactory edge profiles using the other three gas combinations, and the angle of the edge can be controlled by changing the proportions of the gasses [15]. Since trace residues of these gasses are incompatible with other RIE processes performed in our laboratory, we equipped the CF_4 plasma etcher for the CHF_3 process.

In order to more reproducibly fabricate these junctions, we installed a variable oriface valve and a capacitance manometer on the high-vacuum diffusion pump system used to clean the edge and to deposit the PbBi counter-electrode. Although many interesting aspects of plasma dynamics were revealed, all attempts to obtain high-quality, insulating barriers on NbN in this system failed. We conducted an extensive Auger analysis of NbN surfaces subjected to various cleaning and oxidation processes. It appears that PbBi from the chamber walls contaminates the surface of these films during any plasma process, and this seriously degrades the quality of the barriers. The installation of a second RF planar electrode in this single-electrode system should solve this problem. Also, the replacement of the diffusion pump with a cryopump, the addition of three mass flow controllers for CF_4, O_2, and Ar, and the addition of a viewport and a residual gas analyzer should add to the speed, the cleanliness, and the reproducibility of our NbN edge junction process.

We now believe that it is advantageous to form the NbN edge using ion milling, and then to remove the damaged surface layer using a CF_4/O_2 RIE. This procedure should combine the virtues of both methods of edge formation, and avoid their disadvantages. Others have noted the likelihood that fluorine contributed by a CF_4/O_2 RIE is instrumental in the formation of the highest quality native oxide on the surface of Nb and Nb-based A15 compounds. Our results indicate that the same is true for NbN.

The NbN/PbBi edge junctions made in this research are arguably the best candidates for submillimeter wavelength applications. Their energy gap voltage is ~ 4.6 mV, only marginally less than presently achieved using all-NbN junctions. Their quality is superior to current all-NbN junctions, and the edge geometry is a natural way to make very small area SIS junctions. Stability and robustness should not be a problem for these junctions, because the bottom electrode is refractory; witness the reliability of the Nb/Pb-alloy junctions in the NIST voltage standard, for which the junctions cover as much as 10% of the area of a chip and a single flaw is disastrous.

5. Related Research: We are involved in several other projects which have made significant advances in areas closely related to the research supported by this grant. Our $Nb/Al_2O_3/Nb$ trilayer junctions [17], specifically designed for SIS mixer applications, have extremely low leakage currents. They have quality parameters $V_m(2\text{ mV}) > 1.5$ Volts at 2 K, an astounding result. We have designed and tested a variety of novel integrated tuning structures suitable for high frequency SIS mixers [9, 14]. Mixer tests revealed and illuminated many interesting aspects of SIS junction behavior [8]. We have successfully realized an SIS receiver [12, 13, 18] with double sideband mixer noise temperature of less than 6 K and unity conversion gain which is tunable from 85 - 116 GHz, setting a new standard for judging millimeter wavelength receivers.

IV. Publications

The following publications relevant to the grant research appeared in print or were in preparation during the grant period:

1. R.G. Hicks, M.J. Feldman, and A.R. Kerr, "A General Numerical Analysis Program for the Superconducting Quasiparticle Mixer," NASA Technical Memorandum TM-86145 (National Aeronautics and Space Administration, Washington, D.C., July 1986).
2. M.J. Feldman, "Saturation of the Superconductor Quasiparticle Direct Radiation Detector," J. Appl. Phys. 60, 2580 (1986).
3. M.J. Feldman, "Quantum Noise in the Quantum Theory of Mixing," IEEE Trans. Magnetics MAG-23, 1054 (1987).
4. M.J. Feldman and L.R. D'Addario, "Saturation of the SIS Direct Detector and the SIS Mixer," IEEE Trans. Magnetics MAG-23, 1254 (1987).
5. C.K. Huang and M.J. Feldman, "High-Frequency Performance of the Superconductor Quasiparticle Mixer," Bull. Am. Phys. Soc. 32, 713 (1987).
6. M.J. Feldman, "Theoretical Considerations for THz SIS Mixers," Int. J. Infrared Millimeter Waves 8, 1287 (1987).
7. A.R. Kerr, M.J. Feldman, and S.-K. Pan, "SIS Mixer Design by Frequency Scaling," National Radio Astronomy Observatory, Electronics Division Internal Report No. 267 (NRAO, Charlottesville, 1987).
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9. A.R. Kerr, S.-K. Pan, and M.J. Feldman, "Integrated Tuning Elements for SIS Mixers," 1987 International Superconductivity Electronics Conference, Tokyo, Digest of Technical Papers, pp. 372-375, August, 1987.
10. M.J. Feldman, S.-K. Pan, and A.R. Kerr, "Saturation of the SIS Mixer," 1987 International Superconductivity Electronics Conference, Tokyo, Digest of Technical Papers, pp. 290-292, August, 1987.
11. M.J. Feldman and D.W. Face, "Image Frequency Termination of the Superconducting Quasiparticle Mixer," Jpn. J. Appl. Phys. 26, 1633 (1987).
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13. S.-K. Pan, A.R. Kerr, M.J. Feldman, and A. Kleinsasser, "SIS Technology Boosts Sensitivity of mm-Wave Receivers," Microwaves & RF 27, no. 9, pp. 139-146, September 1988.
14. A.R. Kerr, S.-K. Pan, and M.J. Feldman, "Integrated Tuning Elements for SIS Mixers," Int. J. Infrared Millimeter Waves 9, 203 (1988).
15. X.-F. Meng, R.S. Amos, A.W. Lichtenberger, R.J. Mattauch, and M.J. Feldman, "NbN Edge Junction Fabrication: Edge Profile Control by Reactive Ion Etching," IEEE Trans. Magnetics MAG-25, 1239 (1989).
16. A.W. Lichtenberger, M.J. Feldman, R.J. Mattauch, and E.J. Cukauskas, "The Effects of Ion Gun Beam Voltage on the Electrical Characteristics of NbCN/PbBi Edge Junctions," IEEE Trans. Magnetics MAG-25, 1243 (1989).

17. A.W. Lichtenberger, C.P. McClay, R.J. Mattauch, M.J. Feldman, S.-K. Pan, and A.R. Kerr, "Fabrication of Nb/Al–Al_2O_3/Nb Junctions with Extremely Low Leakage Currents," IEEE Trans. Magnetics MAG-25, 1247 (1989).

18. S.-K. Pan, A.R. Kerr, M.J. Feldman, A. Kleinsasser, J. Stasiak, R.L. Sandstrom, and W.J. Gallagher, "An 85-116 GHz SIS Receiver using Inductively Shunted Edge Junctions," IEEE Trans. Microwave Theory Tech. MTT-37, 580 (1989).

19. M.J. Feldman, S.-K. Pan, and A.R. Kerr, "Saturation of the SIS Mixer by Monochromatic and Thermal Signals," in preparation, to be submitted to IEEE Trans. Microwave Theory Tech.

20. A.R. Kerr, M.J. Feldman, and S.-K. Pan, "SIS Mixer Design by Frequency Scaling," in preparation, probably for IEEE Trans. Microwave Theory Tech.

21. M.J. Feldman and C.K. Huang, "Frequency Regimes of the Superconductor Quasiparticle Mixer," in preparation.

22. A.W. Lichtenberger, R.S. Amos, A.S. Lewis, R.J. Mattauch, and M.J. Feldman, "CF_4 Cleaning Process for High Quality NbN/PbBi Edge Junctions," in preparation.

23. C.P. McClay and A.W. Lichtenberger, "Overhang Technology Using Image Reversal Photoresist," in preparation.

24. C.P. McClay, A.W. Lichtenberger, R.J. Mattauch, and M.J. Feldman, "Versatile Current Source and Measurement Circuitry for Well Controlled Anodic Oxidation of Thin Films," in preparation.

V. Professional Personnel under Research Grant

Marc J. Feldman, Research Associate Professor
Robert J. Mattauch, Professor
Xiao-Fan Meng, Visiting Associate Professor
Arthur W. Lichtenberger, Research Assistant Professor
Niu-Niu Chen, Post-doctoral Research Associate
Alan S. Lewis, graduate student
Chung-Ken Huang, graduate student
Steven W. Yates, graduate student, 2 months
Ricky S. Amos, graduate student
Dallas M. Lea, Jr., undergraduate student

All personnel were members of the Department of Electrical Engineering of the University of Virginia during this employment. X.-F. Meng is Associate Professor in the Physics Department of Peking University, Beijing, PRC.

A Masters of Science degree was awarded to Alan S. Lewis on November 21, 1986. His thesis was entitled "The Effect of Composition on the Superconducting Properties of Niobium Nitride and Niobium."

A Masters of Science degree was awarded to Chung-Ken Huang on August 5, 1987. His thesis was entitled "Frequency Regimes of Superconducting Quasiparticle Mixer."

VI. Interactions

Marc J. Feldman participated in the following major interactions during the grant period:

1. Presented the invited lecture "Quantum Detection of Millimeter Wavelengths" at Yale University, New Haven, Connecticut, November 15, 1985, followed by extensive discussions with Yale personnel on the fabrication and properties of SIS junctions.
2. Attended the March Meeting of the American Physical Society, March 31 - April 4, 1986, in Las Vegas, Nevada.
3. Presented two papers, "Quantum Noise in the Quantum Theory of Mixing," and "Saturation of the SIS Direct Detector and the SIS Mixer," at the 1986 Applied Superconductivity Conference, September 29 - October 3, in Baltimore, MD.
4. Presented the invited lecture "Mixers, Local Oscillators, and Amplifiers" at the 1986 US-Japan Workshop on Josephson Junction Electronics, October 3-4, at the National Academy of Sciences, Washington, D.C.
5. Toured the laboratories of P.L. Richards and W.C. Danchi and extensively discusssed the properties of SIS mixers, at the University of California, Berkeley, California, in conjunction with attendance at an unrelated research conference, October 24-25, 1986.
6. Attended the March Meeting of the American Physical Society, March 16-20, 1987, in New York City, New York, along with Chung-Ken Huang. Huang presented the talk "Low- and High-Frequency Performance of the Superconductor Quasiparticle Mixer."
7. Presented the invited lecture "Theoretical Considerations for SIS Mixers" at the Submillimeter (Terahertz) Receiver Conference, April 7-8, 1987, at Lake Arrowhead, California.
8. Attended the Superconductivity Symposium, April 30, 1987, in Crystal City, Virginia.
9. Served on the Solid-State and Microstructures Engineering panel for the National Science Foundation Research Equipment Grant Program, June 4, 1987, in Washington, D.C.
10. Presented the paper "Image Frequency Termination of the Superconducting Quasiparticle Mixer" at the XVIII International Conference on Low Temperature Physics, August 20-26, 1987, in Kyoto, Japan.
11. Presented two papers, "Integrated Tuning Elements for SIS Mixers" and "Saturation of the SIS Mixer," at the 1987 International Superconductivity Electronics Conference, August 28-29, 1987, in Tokyo, Japan.
12. Presented the invited lecture "SIS Mixers: Theory and Practice" at the Nobeyama Radio Observatory, Nobeyama, Japan; toured the superconductive electronics laboratory at NRO with extensive discussions with J. Inatani, T. Kasuga, M. Tsuboi, and others on the fabrication and properties of SIS junctions and receivers, August 30 - September 3, 1987.
13. Presented the invited lecture "SIS Mixers" at the Department of Astrophysics, Nagoya University, Nagoya, Japan; toured the superconductive electronics laboratory at Nagoya with extensive discussions with H. Ogawa, Y. Fukui, and K. Kawabata on the fabrication and properties of SIS receivers, September 3-4, 1987.
14. Presented the invited lecture "SIS Mixers -- Theory and Practice" at the National Radio Astronomy Observatory, Charlottesville, Virginia, November 10, 1987.
15. Presented the invited lecture "Superconducting Tunnel Junctions for Millimeter-Wave Mixers" at the University of Rochester, Rochester, New York; toured the superconductive electronics laboratory at Rochester with extensive discussions with M.F. Bocko, A.M. Kadin,

and S. Shapiro on the properties of SIS junctions, November 20, 1987.

16. Attended the symposium "Superconductivity in Virginia," May 19, 1988, in Richmond, Virginia.

17. Attended the workshop "Superconductivity and Microwaves" at the 1988 IEEE/MTT-S International Microwave Symposium, May 23, 1988, in New York City, New York.

18. Consulted with personnel at Sperry Marine Corp., Charlottesville, Virginia, July 19 and 26, August 2 and 9, and September 13 and 20, 1988; presented three introductory lectures on superconductive electronics.

19. Attended the Solid State Terahertz Sources Workshop, August 16, 1988, in Pasadena, California.

20. Toured the SIS mixer fabrication and testing laboratories of T.G. Phillips at the California Institute of Technology, Pasadena, California, August 17, 1988.

21. Presented the invited lecture "SIS Mixer Research" at the Jet Propulsion Laboratory, Pasadena, California; toured the laboratories of W.R. McGrath and P.H. Siegel, August 18, 1988.

22. Toured the superconductive electronics laboratories of the TRW Space and Technology Group, Redondo Beach, California, August 19, 1988.

23. Attended the 1988 Applied Superconductivity Conference, August 21-25, 1988, in San Francisco, California, along with Arthur W. Lichtenberger and Xiao-Fan Meng. Together we presented three papers, "NbN Edge Junction Fabrication: Edge Profile Control by Reactive Ion Etching," "The Effects of Ion Gun Beam Voltage on the Electrical Characteristics of NbCN/PbBi Edge Junctions," and "Fabrication of Nb/Al–Al_2O_3/Nb Junctions with Extremely Low Leakage Currents."

24. Attended the US-Japan Workshop on Josephson Junction Electronics, August 25-26, 1988, in Berkeley, California.

DISTRIBUTION LIST

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7 - 8	M. J. Feldman, EE
9 - 10	E. H. Pancake, Clark Hall
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