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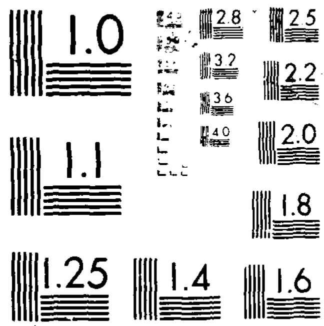
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An Annual Technical Report
November 1986 - November 1987
Grant No. AFOSR-86-0056

SIS MIXER RESEARCH

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Submitted to:

Air Force Office of Scientific Research
Building 410
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Washington, D.C. 20332

Submitted by:

M. J. Feldman
Research Associate Professor

Report No. UVA/525658/EE88/102

February 1988

SCHOOL OF ENGINEERING AND APPLIED SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22901

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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 of the gain of the SIS mixer was measured using both monochromatic and thermal signals, and these experiments dramatically verified the theoretical expression derived in the previous report period. A study of the role of the image termination for SIS mixer behavior found that the nonlinear quantum reactance results in an effective time delay at the input port of the mixer. Many aspects of the operation of SIS mixers at submillimeter wavelengths were clarified, including a discussion of the potential of the new oxide superconductors for this field. The goal of the realization of high quality niobium nitride edge junctions was advanced by optimizing the edge profile and by improving the insulating barrier.

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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. Status of the Research

Several projects which were completed in the previous report period have now appeared in publication. One is an investigation of the origin and characteristics of quantum noise in the quantum theory of mixing [1; numbers in square brackets refer to the publications listed below in Sec. IV]. The calculation performed in that 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. Several researchers are known to be studying that report in an attempt to use the same techniques for their own work. The other completed project is the calculation of the saturation properties of the SIS direct detector, which was shown to saturate at powers far larger than had been expected [2]. 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.

1. Quantum theory: 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. In the previous research period we determined an explicit expression for the gain saturation of the SIS mixer [2]. We have now performed painstaking mixer experiments, in conjunction with A.R. Kerr and S.-K. Pan of the National Radio Astronomy Observatory, which unambiguously verify this expression both in magnitude and parameter dependence [7]. 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 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 a more recent series of experiments we measured the saturation properties of SIS mixers subjected to broad-band thermal noise [12]. 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. These results have 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. In addition, these results cast doubt upon recent reports of low-noise single-junction SIS receivers which have extremely wide bandwidths.

In conjunction with Kerr and Pan, we previously used the mixer saturation expression to formulate a set of frequency scaling relations for SIS mixers which maintain either the saturation power or temperature [5]. Given an SIS element optimized for one frequency band, these relations completely 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 [15]. 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.

We used the quantum theory of mixing to examine the role of the image termination for SIS mixer operation [8]. (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.

2. Arrays: Work on this topic is still in its early stages. Our calculations to date have strengthened our belief that the large excess noise in arrays of SIS junctions, which has been seen in experiments, is caused by a nonlinear interaction driven by the standard noise sources in the various junctions. We have not yet been able to formulate this nonlinear problem in order to find a tractable solution, although we are optimistic that this can be done. If our interpretation is correct, then this work will have significant and widespread implications for any active arrayed device which has a very low driving power.

3. High frequency: The third objective of this research grant is to study the limitations of SIS mixers at high frequencies. This was precisely the theme of a recent publication [9], 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 includes a stringent limitation on the use of inductive-loop tuning structures, the most obvious choice for integrated circuit tuning. We show 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 of the parasitic series inductance along the leads of the SIS junction or array which lies inside the resonant loop. Inductive-loop tuning can be effective only at frequencies far below the self-resonant frequency of the SIS element.

This work also includes the first indication that saturation, by a small signal or noise input, is an important concern for submillimeter SIS mixers. It is 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 [9]. Thus high frequency SIS mixer design must consider the possibility of saturation.

This work also includes the first discussion of the possible impact of the new oxide superconductors upon submillimeter SIS mixing [9]. 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.

In the previous report period we developed a new computer program to predict the potential performance of SIS mixers over the entire frequency range of interest [3]. Some of the results of this work have appeared in print [9], but many aspects warrant further research and a final publication is still in preparation [14].

4. Plasma-etched NbN edge junctions: In the previous period we reported NbN/PbBi edge junctions [16, 17] of extremely high quality. These junctions were formed by using a CF_4/O_2 reactive ion etching (RIE) process to both cut an edge on an NbN film and to form an insulating barrier on that edge. In this early work the SiO_2 passivation layer required for practical devices was omitted, and also the yield of good junctions was unacceptably low. Subsequent work has been 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 have 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. However, we suceeded 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 [18]. Unfortunately, trace residues of these gasses are incompatible with other RIE processes performed in our laboratory. We are presently equipping a CF_4 plasma etcher for the CHF_3 process.

In order to more reproducibly fabricate these junctions, we have installed a variable oriface valve and a capacitance manometer, purchased with laboratory funds, on the high-vacuum diffusion pump system now used to clean the edge and to deposit the PbBi counter-electrode. All attempts to obtain high-quality, insulating barriers on NbN in this system have failed. We have 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. We are presently installing a second RF planar electrode in this single-electrode system in order to solve this problem.

Thus all of the ingredients required to fabricate high quality NbN edge junctions appear to be at hand. We have learned how to obtain a satisfactory edge profile on SiO_2/NbN films. We should soon regain our ability to form a superior insulating barrier on these edges. Further improvements to the edge-junction vacuum system are planned for the near future, including 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. These improvements should add to the speed, the cleanliness, and the reproducibility of our NbN edge junction process.

5. Related research: We are involved in several other projects which may lead to significant advances in the grant research. Our Nb/Al_2O_3/Nb trilayer SIS junctions [19, 20] have extremely low leakage currents. We have designed and tested a variety of novel integrated tuning structures suitable for high frequency SIS mixers [6, 10]. Mixer tests revealed and illuminated many interesting aspects of SIS junction behavior [4]. We have successfully realized an SIS receiver [11, 13] with double sideband mixer noise temperature of 10 K and conversion gain of 0.1 dB 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. M.J. Feldman, "Quantum Noise in the Quantum Theory of Mixing," IEEE Trans. Magnetics MAG-23, 1054 (1987).
2. 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).
3. C.K. Huang and M.J. Feldman, "High-Frequency Performance of the Superconductor Quasiparticle Mixer," Bull. Am. Phys. Soc. 32, 713 (1987).
4. S.-K. Pan, A.R. Kerr, J.W. Lamb, and M.J. Feldman, "SIS Mixers at 115 GHz using Nb/Al–Al_2O_3/Nb Junctions," National Radio Astronomy Observatory, Electronics Division Internal Report No. 268 (NRAO, Charlottesville, 1987).
5. 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).
6. 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.
7. 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.
8. M.J. Feldman and D.W. Face, "Image Frequency Termination of the Superconducting Quasiparticle Mixer," Jpn. J. Appl. Phys. 26, 1633 (1987).
9. M.J. Feldman, "Theoretical Considerations for THz SIS Mixers," Int. J. Infrared Millimeter Waves 8, 1287 (1987).

10. A.R. Kerr, S.-K. Pan, and M.J. Feldman, "Integrated Tuning Elements for SIS Mixers," to appear in Int. J. Infrared Millimeter Waves.

11. S.-K. Pan, A.R. Kerr, M.J. Feldman, A. Kleinsasser, J. Stasiak, R.L. Sandstrom, and W.J. Gallagher, "An SIS Mixer for 85-116 GHz Using Inductively Shunted Edge Junctions," to appear in the 1988 IEEE MTT-S International Microwave Symposium Digest.

12. 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.

13. 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," in preparation, to be submitted to IEEE Trans. Microwave Theory Tech.

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

15. A.R. Kerr, M.J. Feldman, and S.-K. Pan, "SIS Mixer Design by Frequency Scaling," in preparation.

16. A.W. Lichtenberger and R.J. Mattauch, "Effects of Ion Beam Energy on the Characteristics of NbN/PbBi Edge Junctions," in preparation.

17. 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.

18. X.-F. Meng and M.J. Feldman, "Edge Profiles on SiO_2/NbN Films by Reactive Ion Etching," in preparation.

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

20. A.W. Lichtenberger, C.P. McClay, S.-K. Pan, A.R. Kerr, M.J. Feldman, and R.J. Mattauch, "Ultra-low Leakage Current Nb/Al_2O_3/Nb Superconducting Junctions," 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
Chung-Ken Huang, graduate student
Ricky S. Amos, graduate student
Dallas M. Lea, Jr., undergraduate student

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

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. 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."
2. Presented the invited lecture "Theoretical Considerations for SIS Mixers" at the Submillimeter (Terahertz) Receiver Conference, April 7-8, 1987, at Lake Arrowhead, California.
3. Attended the Superconductivity Symposium, April 30, 1987, in Crystal City, Virginia.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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.
9. Presented the invited lecture "SIS Mixers -- Theory and Practice" at the National Radio Astronomy Observatory, Charlottesville, Virginia, November 10, 1987.
10. 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.

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