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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 properties of an SIS mixer using a slightly nonideal junction, with finite LO power, were determined by analytic expansion of the equations of the quantum theory of mixing. The resulting equations have a particularly simple form. The minimum noise temperature is controlled by the leakage current of the junction. Even the most nearly ideal junctions made today require a considerable LO for best sensitivity; nevertheless, even a comparatively large leakage current allows mixer noise to be only a small factor above the quantum limit. The saturation properties of SIS mixers subjected to broad-band thermal noise obey the equations derived for monochromatic saturating signals. The Josephson junction tuning inductor was

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19. Abstract (continued)

analyzed with the conclusion that such a device is not feasible with present fabrication techniques. Computer calculations using synthetic SIS junction I-V characteristics predicted the performance of an optimized receiver over its entire operating frequency range. Many aspects of the operation of SIS mixers were clarified and unexpected new phenomena were predicted. A "photon picture" interpretation of the quantum theory of mixing is in the early stages of development. Niobium nitride edge junctions with excellent current-voltage characteristics were fabricated using novel barrier formation processes. The role of surface damage in the quality of NbN edge junction electrical characteristics was investigated and unexpected results were obtained.

A Final Technical Report
Grant No. AFOSR 89-0233

February 1, 1989 - May 31, 1990

SIS MIXER RESEARCH

Submitted to:

Air Force Office of Scientific Research
Building 410
Bolling Air Force Base
Washington, DC 20332

Attention:

Dr. Harold Weinstock
Superconductivity Electronics Program

Submitted by:

Arthur W. Lichtenberger
Research Assistant Professor

Marc J. Feldman
Research Associate Professor

Report No. UVA/525704/EE91/101
November 1990

DEPARTMENT OF ELECTRICAL ENGINEERING

SCHOOL OF
ENGINEERING
& APPLIED SCIENCE

University of Virginia
Thornton Hall
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UNIVERSITY OF VIRGINIA
School of Engineering and Applied Science

The University of Virginia's School of Engineering and Applied Science has an undergraduate enrollment of approximately 1,500 students with a graduate enrollment of approximately 600. There are 160 faculty members, a majority of whom conduct research in addition to teaching.

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FINAL TECHNICAL REPORT

AFOSR Grant #89-0233

SIS Mixer Research

Report period: February 1, 1989 - May 31, 1990
Report prepared: November 1990

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 properties of an SIS mixer using a slightly nonideal junction, with finite LO power, were determined by analytic expansion of the equations of the quantum theory of mixing. The resulting equations have a particularly simple form. The minimum noise temperature is controlled by the leakage current of the junction. Even the most nearly ideal junctions made today require a considerable LO for best sensitivity; nevertheless, even a comparatively large leakage current allows mixer noise to be only a small factor above the quantum limit. The saturation properties of SIS mixers subjected to broad-band thermal noise obey the equations derived for monochromatic saturating signals. The Josephson junction tuning inductor was analyzed with the conclusion that such a device is not feasible with present fabrication techniques. Computer calculations using synthetic SIS junction I-V characteristics predicted the performance of an optimized receiver over its entire operating frequency range. Many aspects of the operation of SIS mixers were clarified and unexpected new phenomena were predicted. A "photon picture" interpretation of the quantum theory of mixing is in the early stages of development. Niobium nitride edge junctions with excellent current-voltage characteristics were fabricated using novel barrier formation processes. The role of surface damage in the quality of NbN edge junction electrical characteristics was investigated and unexpected results were obtained.

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, and of its predictions of superconductor-insulator-superconductor (SIS) mixer behavior.
2. The second objective of this research is to understand the properties of SIS mixers having very broad input bandwidth.
3. The third objective of this research is the delineation of the noise predictions of the quantum theory of mixing and a careful study of SIS mixer noise.
4. The fourth objective of this research is to analyze the excess noise of arrays of SIS junctions.
5. The fifth 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.
6. The sixth objective of this research is to fabricate and evaluate NbN edge junctions and to study the mechanisms of oxide growth on a shaped NbN surface.
7. The seventh objective of this research is to begin research towards the realization of a large array of planar-antenna-coupled SIS direct detectors on a single chip.

III. Research Accomplishments

The research objectives listed above and in the proposal anticipated a grant period of three years. In actuality the grant period was sixteen months, and this included a partial hiatus of research activity during the months of September, 1989, through January, 1990, when no grant money was spent due to the change of principal investigator. Nevertheless, significant progress was made towards achieving many of the research objectives. In the following description of research accomplishments, the numbers in square brackets refer to the publications listed below.

A. Theoretical Research

1. Near-ideal SIS mixer: We have previously shown that the quantum noise limit for an SIS mixer can be reached only in the special case of a perfectly ideal SIS junction in the limit of small local oscillator power. During the period of this grant we studied a more physically realistic situation. The properties of an SIS mixer using a slightly nonideal junction, with finite LO power, were determined by analytic expansion of the equations of the quantum theory of mixing. We found that the minimum noise temperature of a slightly nonideal SIS mixer is controlled by the leakage current of the junction. The resulting equations have a particularly simple form: The increase in the minimum added-noise temperature over the quantum limit $T_Q = \hbar\omega/2k$ is given by $\delta T_Q = (\hbar\omega/k)\sqrt{I_0 I_2/I_1}$; this minimum requires that the reduced LO voltage across the junction, $\alpha = eV_{LO}/\hbar\omega$, be given by $\alpha^2 = 8\sqrt{I_0/I_2}$. ($I_n$ is the current measured on the unpumped I-V curve of the junction at voltage $V_0 + n\hbar\omega/e$.)

Thus the leakage current at the bias point, I_0, is the crucial parameter in determining the minimum mixer noise: even an infinitesimal I_0 forces the reduced LO voltage α to be of order unity. Therefore, although an SIS mixer using an ideal junction can reach the quantum noise limit only in the limit of zero LO power, even the most nearly ideal junctions made today require a considerable LO for best sensitivity. This is the reason why all SIS mixer experiments operate with an $\alpha \approx 1$. Nevertheless, even a comparatively large I_0 allows mixer noise to be only a small factor above the quantum limit. Thus the noise temperature using any reasonably good quality SIS junction is essentially equal to that using a perfect junction.

As in the case of the ideal SIS mixer, the minimum noise requires one particular value of source impedance, but is obtained regardless of the value of the image termination impedance. It is remarkable that the image termination impedance has no effect on these results because it does have a very marked effect on both the shot noise and on the quantum noise coupled into the mixer through the image port. Thus this result raises the question of the origin of the noise in realistic SIS mixers.

This research has been considerably expanded after the grant period and submitted for publication [5]. The calculations performed in this work are unique in that they employ 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. Note that this research delineates the limitations of the small LO power approximation which is employed in many other publications.

2. Saturation: We had previously determined an explicit expression for the gain saturation of the SIS mixer. This theory considered only monochromatic saturating signals, whereas in practice an SIS mixer is usually both calibrated by and is used to detect broad-band thermal signals. We have now analyzed a series of experiments which measured the saturation properties of SIS mixers subjected to broad-band thermal noise [8], and shown that the theory applies to this situation as well.

3. Josephson tuning inductor: The idea of using the inductance of a zero-voltage-biased Josephson junction to resonate the geometrical capacitance of SIS junctions in an SIS mixer has arisen many times, and appears in the published work of at least three groups working on SIS mixers. This concept is extremely appealing, because it would provide current-controlled variable tuning and thus allow broad tunable bandwidth submillimeter mixers using rather large SIS junctions, which are much less susceptible to Josephson effect interference.

We analyzed the Josephson tuning inductor and showed that such a device is not feasible with present fabrication techniques. The reason is that a series array of at least twenty Josephson junctions are needed to resonate each mixer junction, in order that the inductor behave linearly and not as a parametric amplifier. These twenty junctions must be spaced very close, less than a micron apart, to limit their geometrical inductance, and must have good homogeneity. They should be insulator-barrier tunnel junctions because other types of Josephson junctions made today are either too unreliable or have too small a value of shunt resistance. The geometrical capacitance of these junctions must be small, which in practice means that their critical current density must be much larger than that of the SIS mixer junctions. Thus the Josephson junction tuning inductor, while not impossible, must await the development of techniques capable of fabricating series arrays of many closely-spaced homogeneous insulator-barrier Josephson junctions with very high current density. This work has not been published, but has been distributed to several colleagues for comment.

4. Receiver sensitivity prediction: It is a straightforward computation to predict the behavior of an SIS mixer using quantum mixer theory once the relevant parameters have been chosen, and several researchers have made such calculations. But choosing appropriate values for the many parameters requires considerable judgement, and these calculations have generally made restrictive assumptions and have been of little use to other workers in this field. Under AFOSR support, we have remedied this situation to some extent, using synthetic SIS I-V characteristics to simulate a wide range of realistic SIS junctions, and calculating receiver sensitivity as the figure of merit in order to predict the performance of optimized SIS mixers over their entire operating frequency range.

During the grant period we extensively rewrote the computer program used in these calculations, making it more accurate and a much faster and more versatile instrument. We added the criterion that the signal reflection gain and the signal to image conversion gain should both be small in an optimized receiver. This consideration is essentially always ignored in theoretical calculations as well as in laboratory experiments, but is important for practical working receivers to avoid unwanted reflections in the rf system. The importance of such a criterion for the SIS mixer is appreciated by remembering that when the IF conversion gain is large the signal reflection gain and the signal to image conversion gain will also be large and can in principle be infinite.

The results of the new computer program agree with the old one in general outline, but much new insight into the behavior of SIS mixers has been gained. Selected results are: The frequency dependence of the receiver sensitivity shows very distinct effects of quantized photon energy. If extremely high values of IF conversion gain are not allowed, an optimized SIS receiver has very little signal reflection and image gain for both low and high frequencies, but these gains are quite large over the rather narrow frequency range of transition between semi-classical and fully quantum response. For most operating frequencies the sensitivity of any double-sideband SIS receiver can be roughly optimized by minimizing the reflected power at the local oscillator frequency. This work is still in progress.

5. Photon picture: We have begun the development of a "photon picture" interpretation of the quantum theory of mixing, in which there is no reference to the rf current or voltage. The input radiation consists of a stream of photons, and the SIS junction, characterized by its dc I-V curve, can absorb or emit these photons. So far we have succeeded in deriving the standard results for SIS direct detection of weak signals using this model, and the model gives a clear intuitive interpretation for each term in the equations. This research project is far from complete.

B. Experimental Research

1. NbCN/PbBi Edge Junctions: It is generally expected that SIS heterodyne receivers will eventually provide the highest sensitivities at submillimeter wavelengths. The requirements for submillimeter SIS mixer elements are submicron junction areas and high current densities. The edge junction geometry is well suited to meet these requirements. Our previous research indicated that NbCN/PbBi submicron junction areas with high quality electrical characteristics can be obtained.

Using our previous techniques NbCN/oxide/PbBi edge junctions were fabricated with an ion gun in three steps to: (1) cut the bilayer edge, (2) clean the edge after defining the photoresist liftoff stencil, and (3) grow the tunnel barrier on the NbCN edge with reactive ion beam oxidation. The quality parameter $V_m(V)$ (we define $V_m(V)$ as the product of the critical current, taken to be equal to 0.7 times the quasiparticle current rise, and the subgap resistance measured at the voltage V) was examined as a function of the ion beam voltage used in all three steps. The dependence of $V_m(3mV)$ on this ion beam voltage was dramatic: higher ion beam voltages yielded strikingly poor quality junctions. One explanation for these results was that the process of ion milling at higher beam voltages causes mechanical damage to the NbCN surface, resulting in degraded electrical characteristics.

We expected that some other method of cleaning and oxidation for these three steps, which avoided the mechanical disturbance of the NbCN film, would result in higher quality devices. The use of CF_4 based plasma etching in our process was investigated since fluorine radicals can etch NbCN in a nonphysical dry chemical process. The new fabrication sequences that were therefore investigated for the NbCN/oxide/PbBi edge junctions are briefly outlined below:

(A) An SiO_2/NbCN bilayer film was initially formed.

(B) The bilayer film was patterned with photoresist and an edge was formed with either a CF_4 and O_2 plasma etch technique utilizing a separate plasma etcher or an Ar ion beam .

(C) An opening in the SiO_2 film was formed to permit electrical contact of the NbCN base electrode.

(D) A liftoff stencil was formed with open fingers overlapping the SiO_2 /NbCN edge. The wafer was then "lightly" cleaned by plasma etching followed by an ε-PbBi counter electrode deposition and counter electrode definition by liftoff.

Our first approach was to form the edge with a $CF_4 + O_2$ plasma. The CF_4 plasma-defined edges were initially cleaned (step D) in an Ar plasma at -450V self bias with the intention of forming NbCN/PbBi electrical shorts. The resulting electrical characteristics, however, were very good, with $V_m(3mV) > 100mV$. The barrier of these junctions was actually grown during the $CF_4 + O_2$ edge formation step and was only thinned instead of removed by the subsequent Ar etch. Repeatability of the process was poor, probably due to the extremely sharp edge angle that is typically obtained with plasma defined NbN edges. The potential for obtaining excellent electrical characteristics by means of a CF_4 based edge treatment was, however, established.

Our second approach was to return to an ion milling step for the bilayer formation and to etch the well defined SiO_2/NbCN edge with a CF_4 based plasma immediately prior to oxidation and counter electrode deposition. As an early test, we first utilized an 5 µm Ar plasma clean at -200V, omitting any oxidation step. The electrical characteristics were quite good, with V_m(3mV) > 150mV. Further tests found the process to be repeatable and the critical current density dependent on the etch duration. In our prior work, the V_m(3mV) for junctions with edge formation, cleaning, and oxidation ion beam voltage of 600V was only 4mV. The barrier of the plasma-cleaned junctions was formed by thermal oxidation of the 600V ion-milled NbCN surface. It is quite surprising that this surface yields good electrical characteristics with thermal oxidation but poor characteristics with ion beam oxidation.

The next experiment was to replace the Ar with CF_4 10% + Ar 90% for the plasma clean at -200V, again omitting any subsequent oxidation step. It was found that the existing barrier was again thinned but also beneficially modified by the etch, resulting in excellent electrical characteristics, with V_m(3mV) > 250 mV. An Auger analysis indicated the presence of fluorine and carbon in the NbCN barrier for these junctions. One explanation for these results is that fluorine from the CF_4 etch reacted chemically with the remaining barrier to form a superior fluorinated NbCN oxide. A second possibility is that the etch left a fluorinated or carbon layer on the oxide surface which formed an improved oxide/PbBi interface.

The NbCN edge junctions made in this research are of extremely high quality with V_m(3mV) figures much larger than any reports of NbN edge *or planar* junctions of which we are aware. Surprisingly, the junction quality is not dependent on the ion beam voltage used to cut the bilayer edges for these thermally oxidized barriers. Such a dependence was found in our earlier work for the ion beam voltage used to define the base electrode edge, to clean the edge prior to oxidation, and to perform the reactive beam oxidation. It appears that the junction quality is much more strongly dependent on the barrier growth technique: thermal oxidation proving superior to reactive ion beam oxidation for NbCN. The highest quality devices (V_m(3mV) > 250mV) have been obtained by modifying the existing thermally grown oxide with a CF_4 + Ar plasma.

2. NbCN/Si:H/NbCN Edge Junctions: We have initiated research on a different edge junction material system, NbCN/Si:H/NbCN, in conjunction with the Naval Research Laboratories in Washington D.C. The main advantage of this material system is the Si barrier which has a specific capacitance of at least a factor of three smaller than MgO, which is the typical barrier used with NbN structures. This will permit the use of larger junction areas at a given frequency. The Si barriers are also almost an order of magnitude thicker than MgO for a given current density. This may permit the use of higher current densities with Si, which is very important for SIS junction use at terahertz frequencies.

The basic fabrication process for sub-micron NbCN/Si:H/NbCN junctions has been initially investigated, yielding fair quality ($V_m \approx$ 10mV) electrical characteristics. A thorough examination of the barrier chemistry and formation process on the NbCN edge will be required to improve the electrical characteristics. This research is now presently unfunded.

IV. Publications

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

1. 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).

2. 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).

3. 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).

4. A.W. Lichtenberger, C.P. McClay, R.J. Mattauch, M.J. Feldman, S.-K. Pan, and A.R. Kerr, "Fabrication of Nb/Al-Al2O3/Nb Junctions with Extremely Low Leakage Currents," IEEE Trans. Magnetics MAG-25, 1247 (1989).

5. M.J. Feldman, "An Analytic Investigation of the Superconducting Quasiparticle Mixer in the Low Power Limit," submitted to IEEE Trans. Magnetics MAG-27.

6. A.W. Lichtenberger, D.M. Lea, C. Li, F.L. Lloyd, M.J. Feldman, R.J. Mattauch, S.-K. Pan, and A.R. Kerr, "Fabrication of Micron Size Nb/Al-Al2O3/Nb Junctions with a Trilevel Resist Liftoff Process," submitted to IEEE Trans. Magnetics MAG-27.

7. R.S. Amos, A.W. Lichtenberger, M.J. Feldman, R.J. Mattauch, and E.J. Cukauskas, "Fabrication of NbCN/PbBi Edge Junctions with Extremely Low Leakage Currents," submitted to IEEE Trans. Magnetics MAG-27.

8. 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.

V. Professional Personnel under Research Grant

Marc J. Feldman, Research Associate Professor
Robert J. Mattauch, Professor
Arthur W. Lichtenberger, Research Assistant Professor
A. Christopher Hicks, graduate student

All personnel were members of the Department of Electrical Engineering of the University of Virginia during this employment. During the period of this research grant Marc J. Feldman joined the Department of Electrical Engineering of the University of Rochester as Senior Scientist and Associate Professor, and was awarded a subcontract under this grant to pay part of his salary.

A Masters of Science degree was awarded to Ricky S. Amos, who completed his research while employed under a precedent to this research grant, on August 1990. His thesis was entitled "Fabrication and Characterization of Submicron Area Superconductor Devices."

A Masters of Science degree was awarded to A. Christopher Hicks on August 1990. His thesis was entitled Development of an Edge Geometry and a New Trilayer Insulation by Planarization Process for Small-area SIS Junctions."

VI. Interactions

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

1. Sat on the Program Committee of the 1989 Workshop on SuperConductive Electronics: Devices, Circuits, and Systems, and chose and invited the speakers for the session on "Low Tc Devices and

Circuits." This involved extensive discussions with other Program Committee members Nancy Welker, William Gallagher, Fernand Bedard, Michael Gurvitch, Martin Nisenoff, Richard Ralston, and Richard Harris at the following locations:

1a. Attended a Program Committee meeting, January 27, 1989, at IBM Corp., Yorktown Heights, NY.

1b. Attended a Program Committee meeting, March 6, 1989, at the Microelectronics Research Laboratory, Columbia, MD.

1c. Attended the 1989 Workshop on SuperConductive Electronics: Devices, Circuits, and Systems, and chaired the session on "Low Tc Devices and Circuits," October 1-5, 1989, St. Michaels, MD.

2. Presented the invited lecture "Superconducting Receivers for Submillimeter Astronomy," at the Steward Observatory, University of Arizona, Tucson, Arizona, May 23, 1989, and discussed mixer operation with Peter Strittmatter, Robert Martin, and John Payne.

3. Attended the First International Symposium on Space Terahertz Technology, March 5 - 6, 1990, at the University of Michigan, Ann Arbor, Michigan.

4. Presented the invited lecture "Heterodyne Detection with Superconductors," at the Symposium on High Temperature Superconductors in High Frequency Fields, March 28-30, 1990, at the College of William and Mary, Williamsburg, Virginia.

Arthur W. Lichtenberger participated in the following major interactions during the grant period:

1. Presented the invited lecture "Self Aligned Submicron SIS Junction Insulation Techniques", October 16, 1980, at NITS, Boulder, Colorado.

2. Presented the invited lecture "Fixed Tuned SIS Mixers for Millimeter Wavelengths", October 18, 1989, at the Jet Propulsion Laboratory, Pasadena, California.

3. Presented the invited lecture "NbCN Junctions for Submillimeter Wavelengths", October 19, 1989, at the TRW Space and Technology Group, Redondo Beach, California.

4. Presented the invited lecture "A Trilevel Resist Process for Micron Size SIS Junction Insulation", January 9, 1990, at the University of Illinois, Urbana, Illinois.

DISTRIBUTION LIST

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