SUPERCONDUCTOR MICROSTRUCTURES

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The past few years have seen major strides in the development of high resolution microfabrication technology and in the successful application of this technology to superconductivity research. High quality Josephson tunnel junctions have been fabricated with cross-sectional areas approaching $10^{-10} \text{ cm}^2$ and with critical current densities as high as $10^6 \text{ amps/cm}^2$. Such junctions are almost ideally suited for use in quantum noise limited dc SQUID and SIS submillimeter wave applications. Experiments with such junctions have also yielded new insight into the fundamental origin of $1/f$ noise in tunnel junctions. Microlithography has also been used to fabricate a structure consisting of two tunnel junctions produced side by side on a superconductor micro-strip where the spatial separation between the two junctions is less than 1500 Å. This geometry has proven useful in extreme non-equilibrium superconductivity experiments and in three-terminal superconductor device research.

1. INTRODUCTION

The past decade, particularly the last few years, has seen very major strides made in the ability to fabricate high quality superconductor microstructures. This advance has been driven in large part, by the major effort (now somewhat diminished), that has been made to develop Josephson digital electronics as a viable technology for supercomputers and other very high speed digital applications. But it has also been driven by the desire of researchers to develop superconducting sensors to their quantum noise limit, and then to apply these sensors in various scientific investigations, and by the need to produce very small superconductor microstructures suitable for various microscience experiments, including non-equilibrium superconductivity, microscopic quantum tunneling and, most recently, studies of $1/f$ noise and localized states in Josephson junctions.

Along with numerous other research groups around the world, the superconductivity group at Cornell University has been part of this effort for a number of years. One of our major emphasis recently has been on pushing our microfabrication capability well into the sub-micrometer regime and on producing reliable, high quality, and high performance Josephson tunnel junctions and related microstructures in this size range for use in device research and in research intended to examine some of the limits of quantum superconductivity phenomena. In this paper I will review some of these recent activities. Obviously this paper is not intended as a summary of what is a very active field of low temperature research—space does not permit such a survey. Instead my intent is, by describing some of our work, to give an illustration of what may be accomplished in this area with the use of modern thin film materials and microfabrication technology.

2. THINNER IS BETTER—SMALLER IS BETTER

While thin film superconducting microbridges and similar structures are replete with intriguing phenomena, the vast majority of quantum superconductivity experiments and device applications are best addressed with the use of Josephson tunnel junctions. The basic requirements on the tunnel junction for these applications are first that the junction be stable and capable of withstanding thermal cycling, and second that the tunneling I-V characteristic of the junction approximate the ideal behavior. Generally this latter requirement is fulfilled if [a] the onset of quasi-particle current at $\epsilon V = \Delta_1 + \Delta_2$, where $\Delta_1$ and $\Delta_2$ are the energy gap of the two electrodes, is rather abrupt, with the onset occurring over $\delta V \approx 0.2 \text{ mV}$, preferably less; [b] the ratio of junction resistance $R_j$ for $\epsilon V < \Delta_1 + \Delta_2$ to the resistance $R_0$ for $\epsilon V \approx \Delta_1 + \Delta_2$ is high, preferably with $R_j/R_0 \geq 10$; and [c] the critical supercurrent of the junction approaches the ideal value $I_{c,j} = \pi(\Delta_1 + \Delta_2)/4\epsilon$.

Assuming these basic requirements are met, the parameter that most generally defines the performance limit of a tunnel junction is the critical current density $j_c$. While many applications of Josephson junctions can be fulfilled with junctions with relatively low critical current densities, $j_c = 10^2 - 10^3 \text{ A/cm}^2$, the best sensor results and the highest frequency response require a large $j_c$. This point is illustrated by considering the performance of DC SQUID magnetometers and SIS mixers.

2.1. DC SQUID

A DC SQUID consists of two resistively
shunted tunnel junctions connected together in a superconducting ring of inductance $L$. The purpose of the resistive shunts $R_S$ is to remove the hysteresis from the unshunted junction. This is accomplished when the McCumber parameter $B_c$ is reduced to less than unity

$$B_c \leq \frac{2\pi R_S i_c C}{\phi_0} \tag{1}$$

Here $C$ is the junction capacitance and $R_S$ is the net resistance of the shunted junction. (The shunting is assumed to be sufficiently strong to remove the non-linearities from the 1-V characteristic.) It has been well established (1) that the minimum intrinsic energy resolution of a SQUID, in the white noise regime, can be expressed as

$$\varepsilon_B = \gamma_1 \left( \frac{2\pi k_B T}{e i_c R_S} \right) + 0(\varepsilon) \tag{2}$$

Here $\gamma_1$ is a constant $\approx 2 - 5$ and the second term in Eq. (2) represents the quantum noise limit of the device. Since at $T = 4.2 K$, $2\pi k_B T/e = 2.3 mV$ one requires a quite high value of $i_c R_S$ to approach the assumed quantum limit of a few $\varepsilon$. But from Eq. (1) we have that

$$R_S i_c = \left( \frac{\beta_c i_c \phi_0}{2\pi C} \right)^{1/2} \tag{3}$$

where $c = \varepsilon_0 \varepsilon / d = C/A$ is the capacitance per unit area of the junction. Since it is required that $\beta_C \leq 1$, we see that once the barrier material and hence $c$ is chosen, the energy resolution of a dc SQUID varies nearly directly as $i_c^{-1/2}$.

A secondary consideration that can require $i_c$ to be even higher than the value suggested by Eq. (3) stems from the desire to shift any LC resonance in the SQUID ring to a frequency higher than the Josephson frequency $2\pi R_S / \phi_0$ of the SQUID. For an optimally designed SQUID with $L \phi_0 = \phi_0 / 2$ this requires that $\beta_C \leq 0.1 - 0.3$. However this last constraint on $\beta_C$ is not fundamental; SQUIDs can be operated with $\beta_C = 1$.

Niobium oxide tunnel junctions, which are the most widely used type, have a specific capacitance $c = 15 \mu F/cm^2$. Other barriers can offer values of $c$ which are $3$ times smaller. Thus to begin to approach the quantum limit it is necessary to produce tunnel junctions with $j_c = 1 - 3 \times 10^5 A/cm^2$, depending on $c$, while $j_c = 10^6 A/cm^2$ should be about the limit necessary for an optimally designed ($\beta_c < 0.3$), quantum noise limited SQUID $A = 4kT = 4k$. (We note in passing that $j_c = 10^6 A/cm^2$ is only one order of magnitude or so less than the Ginzburg-Landau critical current density of a bulk superconductor.)

2.2 SIS Mixer

An SIS (2) mixer operates on the basis of photon assisted tunneling with the non-linear quasiparticle I-V characteristic of a superconducting tunnel junction providing the mixing process. The undesired Josephson supercurrent is typically suppressed to zero by application of a magnetic field so as to avoid additional noise terms. While there may be some uncertainty (2) about the precise optimum value of the $R_N c$ time constant of the SIS junction it seems clear that $\omega R_N C$ of the junction should be of order unity. (The junction capacitance can be resonated out, at least in principle, but this could be difficult to do in the submillimeter region. The use of linear arrays may also allow larger $\omega R_N C$.) Thus for the 100 - 1000 GHz region where the radio astronomy application of SIS mixers is quite attractive we have the requirement that $\omega R_N \geq 10^3 GHz$. But for a tunnel junction $\omega R_N$ is given by

$$\omega R_N = e j_c / \pi^2 A c \tag{4}$$

Thus for a typical energy gap of $0.5 meV$ and specific capacitance $c = 15 \mu F/cm^2$ we again have the requirement of high $j_c$; $j_c = 2 \times 10^7 A/cm^2$ for $\omega R_N = 10^3 Hz$.

For digital applications of Josephson junctions it is of course again $\omega R_N$ that sets the limit on (unloaded) junction switching time. While sub-picosecond times may be nearly impossible to utilize in real circuits clearly maintaining the world record with high $j_c$ junctions seems desirable in view of the recent advances in GaAs switching times (now $\approx 10^9$).

2.2. Small Areas and Impedance Matching

The requirement for submicron dimensions for Josephson junctions follows simply from the need to impedance match a Josephson device to the world. For a SQUID it has been rather well established (1) that a SQUID inductance $L > 10^{-10} H$ is necessary for effective coupling to external signals. But an optimized SQUID has $L \phi_0 / 2$. Thus the junction area is given by

$$A = \frac{\phi_0}{2L j_c} \tag{5}$$

For $j_c = 10^4 - 10^5 A/cm^2$ the necessary junction area is then $A = 10^4 - 10^{-10} cm^2$, values that can be readily reached. We should note here that the requirement $L \phi_0 / 2$ is not rigid, larger values of $L \phi_0 / 2$ can be employed at moderate cost in SQUID performance. Thus the indicated restriction on $A$ can be relaxed perhaps by as much as a factor of ten. This is particularly useful if very large $j_c$ ($\approx 10^5 - 10^6 A/cm^2$) junctions are ever to be employed in a practical SQUID.

The use of a small area junction also allows a higher shunted junction resistance for better, perhaps direct, matching to room temperature.
amplifiers. Since we have
\[
R_g = \left( \frac{\beta_c Q_0}{2\pi c} \right)^{1/2} \frac{1}{Jc^{1/2} A}
\]
we have the result that a nearly quantum noise limited SQUID with \( Jc = 10^7 \text{ A/cm}^2 \) and \( A = 10^{-10} \text{ cm}^2 \) would have \( R_g = 80 \Omega \) and could be directly coupled to a state-of-the-art, wide-band, room-temperature amplifier. In a similar manner a small area, high \( Jc \) SIS junction provides better matching both to the mixer antenna and the IF preamplifier. In Josephson junctions, smaller is better.

3. MICROFABRICATION

3.1. Materials

Extensive experience has established that in order to obtain stable tunnel junctions at least one of the junction electrodes must be a refractory metal, e.g., Nb. In recent years improvements in vacuum technology have fully solved earlier difficulties in producing Nb films with superconducting properties equivalent to the bulk. Today excellent Nb films with bulk \( T_c \) and residual resistivity ratios ranging from 3 to greater than 10 can be readily produced by rf sputtering, magnetron sputtering or electron beam evaporation.

More recently, thin films of Nb compounds have been produced for Josephson junction application. Perhaps the most notable examples are NbN thin films which can be produced by reactive sputtering (3). When deposited on room temperature substrates such films can have \( T_c \)'s of the order of 12 - 13 K; when deposited on heated substrates \( T_c \) as high as 17 K can result.

For the second or counter electrode the superconducting material can either be a soft metal, typically a lead alloy, or a refractory metal. Both types of junctions have demonstrated excellent stability, but the all refractory junction is clearly to be preferred. However it has generally been the case that an all refractory junction requires the use of a barrier material other than Nb2O5. It appears that Nb2O5 deteriorates during the deposition of a refractory metal overcoat, yielding less satisfactory I-V characteristics. Apparently, all high quality refractory junctions require either the use of non-Nb2O5 barriers or the deposition of a very thin, \( \sim 1 \text{ nm} \), normal metal protective overcoat of the Nb2O5 barrier before deposition of the counter-electrode. For artificial barriers excellent results have been obtained with deposited aSi(1) (4) and oxidized Al (5) layers. It has yet to be demonstrated that such results can be extended to the very high \( Jc \), submicron area junctions of interest here, although no fundamental problems are apparent. All of the work reported in this paper utilized Nb-Pb alloy counter-electrodes.

3.2. Barrier Formation

Early efforts with Nb tunnel junctions suffered from difficulties in forming good quality tunnel barriers on the patterned Nb base electrode. This problem was solved (6,7) several years ago through development of successful ion processes for first cleaning the Nb film with inert ion bombardment and then growing the oxide layer with oxygen ion bombardment. This can be achieved with either an rf plasma or a dc ion beam. The essential point is that the cleaning process be effective and be carried out at the appropriate ion energy to properly prepare the Nb surface for the subsequent oxide growth (7). One advantage of the reactive ion beam oxidation process (6) is that it is carried out at a chamber pressure of the order of \( 10^{-10} \text{ Torr} \), far below the pressure range used in the rf plasma process. Consequently problems of impurities backscattering into the Nb from the plasma are greatly reduced with the use of the ion beam process.

Reactive ion beam oxidation has proven to be very successful in producing very high quality Nb-Pb alloy junctions. Critical current densities ranging from less than 1 A/cm to greater than \( 10^6 \text{ A/cm}^2 \) can be produced with quite good control. Examples of I-V characteristics of such junctions are shown in Fig. 1. Recent experiments with large area ion beams (8) have shown that this process can also produce large arrays of junctions with excellent uniformity.

3.3. Microlithography

Recent advances in microlithography have brought this technology to the point where commercial Si chips are being produced by photolithography with 1 \( \mu \text{m} \) minimum feature size. Producing single devices with 1 \( \mu \text{m} \) dimensions has been possible in the laboratory for quite some time. Now with deep UV contact lithography replication of \( .25 \mu \text{m} \) features can be achieved, provided a contact mask with equivalent dimensions is obtained.

The most important recent advance in microlithography has been the development of electron beam lithography. This process can be performed with either a microprocessor controlled emittance SEM for research work or by a specially designed computer controlled electron beam writer. E-beam lithography is now the method of choice for generating photolithography masks and for direct writing of submicron features. Direct e-beam writing is particularly useful in the research environment where the ability to customize each sample is invaluable. The minimum resolution of the most widely available beam writer is about 0.15 \( \mu \text{m} \); for a customized SEM the minimum features can be as small as 25 nm.

In using e-beam lithography it is necessary that a resist scheme be developed that both can minimize some of the limitations of e-beam lithography and is compatible with the processing requirements of the particular structure being produced. Hunt has recently developed
such a system (9) suitable for the case of submicron Josephson junction fabrication with ion processing. This four level resist system has been demonstrated down to 0.1 μm level and could easily be extended further if desired. Other resist variations are possible. The conclusion is that the lithographic capability now exists to produce research device structures down to and past the 0.1 μm range.

4. EDGE JUNCTIONS

In order to produce tunnel junctions with areas \( \approx 10^{-10} \text{ cm}^2 \) while retaining good process and dimensional control Kleinsasser and Buhrman (6) developed a successful procedure for forming tunnel junctions on the exposed faceted edge of an otherwise insulated Nb film. A rather similar procedure was developed by Broom, et al., (10) and was employed recently in the IBM digital electronics effort. Figure 2a-d illustrates the Kleinsasser edge junction process and Fig. 2e shows a completed junction. Since one dimension of the junction is very well defined by the film thickness to 1 μm, photolithography can easily yield junctions with \( A \approx 10^{-9} \text{ cm}^2 \).

The I-V characteristics of edge junctions are quite good—in our experience essentially the same as for the more conventional sandwich or overlap junction, assuming the same care is taken in cleaning the Nb and growing the oxide layer.

Hunt (9,11) has used e-beam lithography to extend this edge technique into the \( 10^{-10} \text{ cm}^2 \) region. Figure 3 shows such e-beam junctions with area \( A \approx 2.5 \times 10^{-10} \text{ cm}^2 \). The I-V characteristics of Fig. 1 are all taken from e-beam junctions. There seems to be no deterioration of junction quality with decreasing size. Since edge junctions have been fabricated on Nb films as thin as 500 Å, junction areas at least as small as \( 5 \times 10^{-11} \text{ cm}^2 \) could be readily produced if desired.

While the Nb edge junction process is very successful it could prove useful in some applications to use the higher Tc, higher energy gap NbN material. The question is whether NbN films can successfully withstand the edge junction fabrication process. Hallen (13) has begun investigating this point and in some preliminary work with room temperature deposited NbN (Tc = 12.5K) has been able to produce \( 10^{-2} \text{ cm}^2 \) edge junctions with a very credible I-V characteristic as shown in Fig. 4a. Work on higher Tc NbN is now proceeding.

Due to the difficulty in suppressing the supercurrent with a magnetic field in a very small area SIS device there is considerable interest in investigating the performance of small area SIN junction in high frequency mixer applications. Not too surprisingly, the Nb edge junction process is very satisfactory for producing such junctions. Fig. 4b shows the I-V characteristic of such a Nb-Al SIN junction with area \( \approx 5 \times 10^{-10} \text{ cm}^2 \).
Figure 2. Edge-junction fabrication. (a) An Al₂O₃ film deposited on the Nb base film using argon-oxygen ion beam deposition and lift-off. (b) Ion milling through the Nb film leaves a tapered edge protected by Al₂O₃. (c) The counterelectrode completes the junction; one dimension is limited by the Nb film thickness. (d) The other dimension is determined by the width of the overlap region. (e) Electron micrograph of 10⁻⁷ cm⁻² edge junction formed by photolithography.

5. THE HIGH \( j_c \) LIMIT

As I have discussed, the reactive ion beam oxidation process can produce tunnel junctions with quite high critical current densities, \( j_c \sim 10^6 \text{ A/cm}^2 \). However, as can be seen to some extent in Fig. 1, the properties of such junctions can be less than ideal. In particular, high \( j_c \) junctions exhibit a reduced energy gap and, in some cases, a transition of some portion of the electrode material to the normal state for \( i > 2A/eR_N \). These effects are caused by the very high density of quasiparti-
6. MICROSCIENCE WITH MICROSTRUCTURES

The ability to fabricate superconductor microstructures on a submicrometer scale is also proving very useful in various other research efforts. Two such efforts have been the study of extreme non-equilibrium efforts in superconducting thin films and the study of the microscopical origin of 1/f noise in tunnel junctions.

6.1. Three Terminal Nonequilibrium Experiments

In the past several years a new type of three-terminal superconducting device has been proposed based on the suppression of the energy gap by quasiparticle injection (15,16). A typical device in this category has a three-layer sandwich geometry consisting of two stacked Josephson junctions with a shared middle electrode. One junction is used to inject quasiparticles into the common electrode, the I-V characteristic of the second junction is then affected as ∆ of the shared electrode is reduced. Such a geometry has been extensively used in non-equilibrium superconductivity experiments. As a three-terminal device this system can yield power gain, although the speed of the device is marginal due to heating effects in the top and bottom electrodes (17). The most serious defect is that this device, as is the case for all three-terminal gap suppression devices, suffers from the lack of isolation between input and output making it of little use for digital circuit applications.

Figure 4. (a) I-V characteristic of A = 10⁻⁹ cm² NbN-PbBi edge junction. Horizontal scale 2 mV/div., vertical scale 10 µA/div. i₃ has been suppressed to zero. (b) I-V characteristic of Nb-AI SIN junction with A = 5 x 10⁻¹⁰ cm². Horizontal scale 1 mV/div., vertical scale 20 µA/div.

Figure 5. Measured reduction of energy gap ∆ as a function of J_c for various Nb-PbBi junction geometries.
Recently, Hunt (12) has designed a different three-terminal structure in an effort to enhance the speed of the gap suppression device while minimizing electrode heating, and, from the physics point of view, in an effort to clearly observe non-equilibrium efforts in the very strong gap suppression regime. This structure consists of a Nb–very thin insulator–Nb thin film stack with two junctions formed on the exposed edges of the Nb films. As shown in Fig. 7a the counter electrode is shared by the top and bottom junctions, either one of which can be used for quasiparticle injection while the other is used to monitor the response of the injected film. A SEM micrograph of a completed double edge junction sample is shown in Fig. 7b. The center-to-center spacing of the two junctions is $\approx 1200 \, \text{Å}$. Some samples of this type have also been fabricated with an $\text{Al}_2\text{O}_3$ film replacing one of the Nb layers thereby allowing normal electrode injection experiments.

The design of this structure is such that heating of the two Nb electrodes is minimal, while changes in the fanout dimensions of the shared electrode can be used to modify electron and phonon trapping effects. With this structure indirect measurements of device switching under heavy injection indicate a response time of $\approx 50 \, \text{ps}$ with a PbBi counter electrode. This was obtained with only nominal gain. Some reasonable improvement in power gain appears possible with better design; but power gain $> 1$ can be purchased only at the cost of decreased
speed.

This structure has proven very useful for the study of the strong gap suppression regime. In general we are finding that the behavior as \( \Delta \to 0 \) is not in accord with existing non-equilibrium models. Details of this work will be published elsewhere (12).


The study of the low frequency excess noise properties of small area tunnel junctions has been of interest over the last few years due to the effect such noise may have on SQUID performance as well as to the more general question of the origin of flicker on \( 1/f \) noise in interfacial systems. In experiments with small area Nb-PbBi tunnel junctions, Rogers and Buhrman recently demonstrated (18) that the \( 1/f \) noise in such junctions result from tunnel barrier conductance fluctuations. These conductance fluctuations were assumed to be due to the slow filling and emptying of localized states in the barrier. This process locally modulates the barrier height and hence causes the overall conductance to fluctuate. Consistent with this result, it was determined (19) that the \( 1/f \) noise scaled inversely with area and increased as junction quality decreased. (The scaling with \( A^{-n} \) obviously has significant implications for the use of very small junctions in dc SQUID applications.) By extending the work on submicron tunnel junctions, and by increasing the precision and scope of the noise measurements it has now proven possible to determine that in general the \( 1/f \) noise spectrum of a \( 10^{-9} \) cm\(^2\) junction is, over the observed spectral range of 1 Hz to 25 KHz, composed of a very limited number (\( \approx 3 \)) of Lorentzian noise spectra. By making measurements as a function of bias and temperature it has been possible to observe that each Lorentzian noise oscillator has its own voltage and temperature dependence, corresponding to the particular microscopic dynamics of each fluctuation localized state. Thus we have found that the submicron scale can be effectively used to cut apart the ensemble averaged \( 1/f \) noise seen in large tunnel junctions, allowing us for the first time to examine the microscopic physics that underlies this phenomena.

7. SUMMARY

The major advances in superconducting materials and microlithography of the past few years can be very successfully used to produce useful structures for both low temperature device and microphysics research. The effective use of this technology can be expected to yield better device results and new scientific surprises in the years to come.

ACKNOWLEDGEMENTS

The work described here was carried out by the past and present members of the Cornell superconductivity research group, particularly A. Kleinsasser, A. Callegari, B. Hunt, J. Brown, C. Rogers, R. Robertazzi and H. Hallen. This research was supported by ONR. Additional support received from NSF through the National Research and Resource Facility for Submicron structures and the Cornell Materials Science Center.

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