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13. ABSTRACT (Maximum 200 words)

Superconductor-normal-superconductor Josephson junctions are a prime candidate for the active devices in electronic circuits based on high-temperature superconductors. In this program, $CaRuO_3$ was used as a normal metal layer and yttrium barium copper oxide as the superconducting layers to produce Josephson junctions in edge-junction geometry. These superconductor-normal-superconductor junctions have been studied to determine their suitability for use in integrated circuits. The devices worked as Josephson junctions at temperatures up to at least 77 K with characteristic voltages in the range of 100-750 microvolts over most of their operating temperature range. The resistance of the junctions was dominated by the interface region rather than by the barrier layer itself. The properties of dc SQUIDs made from the junctions were excellent at 77 K. The variation in junction parameters over multiple devices was on the order of plus-or-minus thirty percent, which is encouraging but not yet sufficient for integrated circuit applications. Further process refinements may lead to more desirable device uniformity.

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PHASE I FINAL TECHNICAL REPORT

Advanced HTS S-N-S Devices

Contract No. F49620-92-C-0044
by
Conductus, Inc.

Period of Performance
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Report Date:
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Technical Summary:

Technical Problem:

Integrated circuits based on Josephson junctions and SQUIDs both offer unique levels of performance for a number of critical defense applications. In particular, SQUIDs have important uses in both magnetic anomaly detection in airborne environments and in non-destructive evaluation of aircraft structural features. More complex Josephson circuits can be used for very high performance signal processing circuits such as shift registers, analog-to-digital converters, high-speed counters, phase shifters, and other circuit building blocks. Junctions also can be used as sensors or mixers of high-frequency radiation. To date, significant demonstrations of any of these functions has required low-temperature superconducting circuit technology based on materials such as niobium and has required liquid helium cooling.

High-temperature superconductors provide the opportunity to implement Josephson electronics that operates at temperatures as high as liquid nitrogen temperature. The fundamental operation of Josephson junctions has already been amply demonstrated using high-temperature superconductors. In fact, reliable processes based on grain boundary effects have been developed for producing one or a few junctions for use in SQUID magnetometers and have already been used commercially. This SBIR program seeks the development of a process for fabricating large numbers of junctions with properties that are sufficiently uniform that they will permit HTS Josephson junctions to be used in complex integrated circuits. An important requirement is that such a junction process be compatible with the fabrication of multilayer circuits containing HTS films and compatible materials. In addition, the process must yield junctions whose properties are well-controlled and sufficiently uniform to meet the requirements of circuit designs. These vary depending upon specific architectures, but in most cases require uniformity of critical currents on the order of ±10%.

Task Objectives

The fundamental goals of this program as spelled out in the Phase I proposal were:

1. to evaluate candidate metallic oxide materials for barrier layers in superconductor–normal–superconductor (SNS) junctions,

2. to fabricate and test edge and/or trilayer junctions using the selected barrier materials, and

3. to evaluate the uniformity of critical current in the junctions.

These goals were all met during the course of the program as well as some preliminary work accomplished on investigating the properties of the crucial material interfaces that form the SNS junctions.

General Methodology:

The general approach in this six-month program was to fabricate and test SNS Josephson junctions made from YBCO superconducting films and $CaRuO_3$ barrier layers. These devices were made using our established laser deposition techniques for YBCO and compatible oxide films and our established circuit processing capabilities. Device performance was studied as a function of temperature, barrier thickness, and process conditions. The suitability of these junctions in dc SQUIDs was evaluated.

Summary of Phase I Results:

$CaRuO_3$ was used as a normal metal layer and YBCO as the superconducting layers to produce Josephson junctions in edge-junction geometry. These superconductor-normal-superconductor junctions have been studied to determine their suitability for use in integrated circuits. The devices worked as Josephson junctions at temperatures up to at least 77 K with characteristic voltages in the range of 100–750 μV over most of their operating temperature range. The resistance of the junctions was dominated by the interface region rather than by the barrier layer itself. The properties of dc SQUIDs made from the junctions were excellent at 77 K. The variation in junction parameters over multiple devices was on the order of plus-or-minus thirty percent, which is encouraging but not yet sufficient for integrated circuit applications. Further process refinements may lead to more desirable device uniformity.

Detailed Discusssion of Phase I Results

I. Barrier Materials

As elucidated in the Phase I proposal, several requirements were imposed on the selection of a barrier material for SNS junctions. First, the material needed to be electrically conducting – ideally, its conductivity not sensitive to doping, stoichiometry or oxygen concentration. Second, the material had to be lattice matched with YBCO in order to permit the epitaxial growth of all the layers in the junction (this implies a cubic structure for the barrier). Third, the material had to be chemically compatible with YBCO in order to minimize deleterious interactions at the crucial interface regions. Finally, the growth conditions of the material had to be compatible with those of YBCO.

Prior to the start of this program, a set of candidate materials was identified. The following conducting oxides with a perovskite crystal structure comprise the list: CaMoO3, LaTiO3, SrRuO3, CaRuO3, SrCrO3, SrIrO3, SrCoO3, and related compounds. By the time the Phase I contract started, we had attempted to grow films of several of these materials based on the availability of powdered materials for sintered targets. While CaMoO3 did not readily grow under YBCO-like deposition conditions, SrRuO3 and CaRuO3 could both be grown in conducting thin film form. Because of this success, we were able to demonstrate working SNS junctions even before the current contract began. Also as a result of this success, we decided to concentrate entirely upon the other tasks in the program rather than continuing to search for new barrier materials.

The properties of the thin-film CaRuO3 can be summarized as follows. The material is a cubic perovskite with a lattice constant of slightly above 3.85Å, which puts it between the a and b lattice parameters of YBCO. The room temperature resistivity of the material is about 600 μΩ-cm. The material is clearly metallic as can be seen in Figure 1 below.

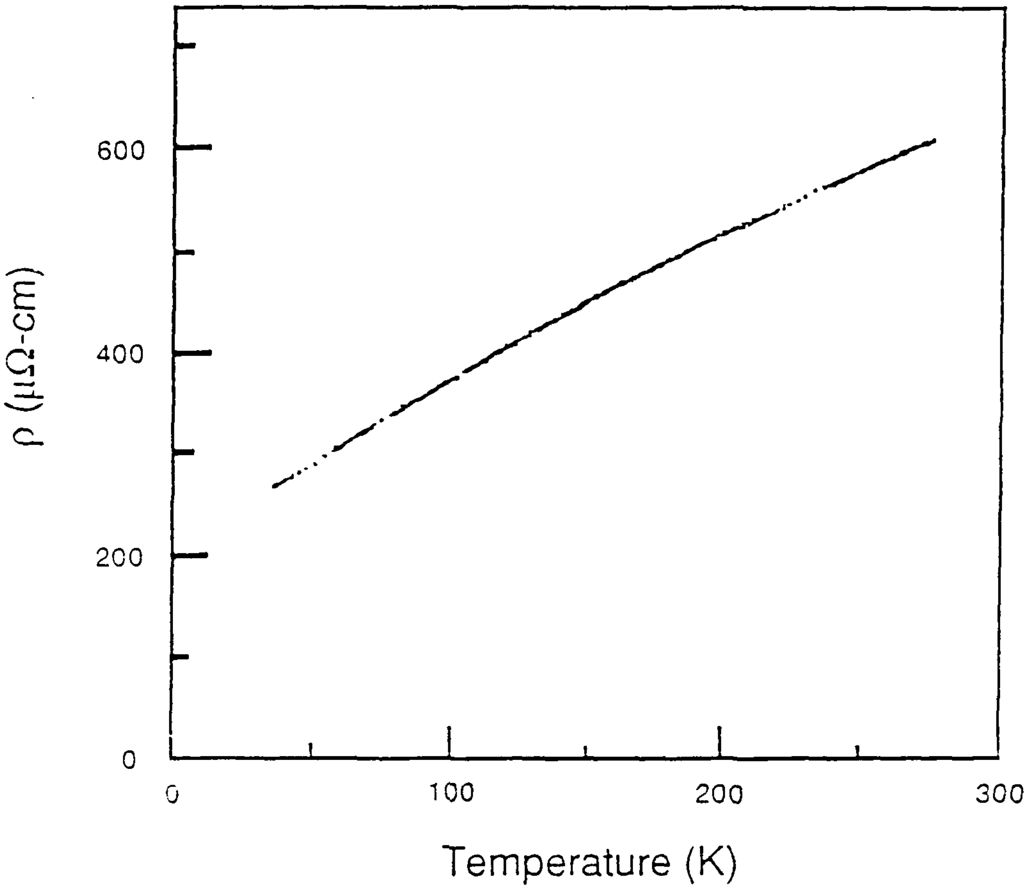


Figure 1 – Temperature dependence of resisitivity of CaRuO3.

The strontium version of the barrier material, SrRuO3 has comparable properties apart from the existence of a magnetic transition at about 150 K. This transition is seen in the resitivity of the material as shown in Figure 2 below and in the magnetization as measured in a SQUID magnetometer (Figure 3).

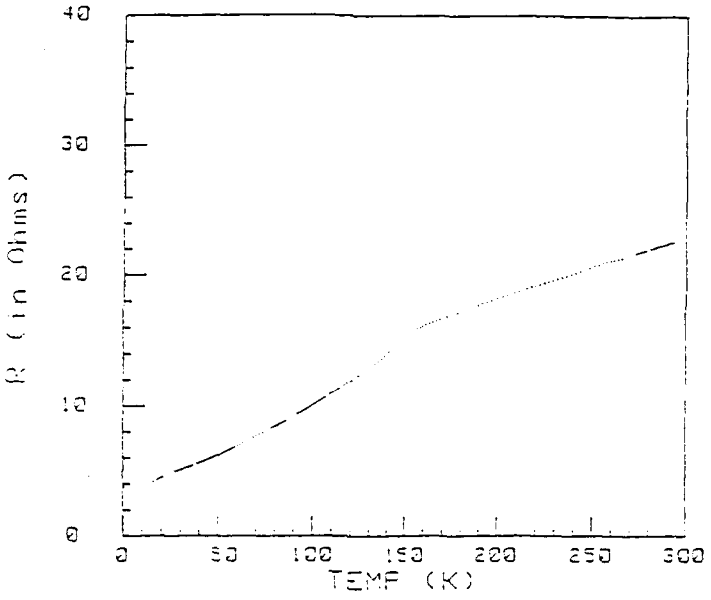


Figure 2 – Resistance of thin-film SrRuO3.

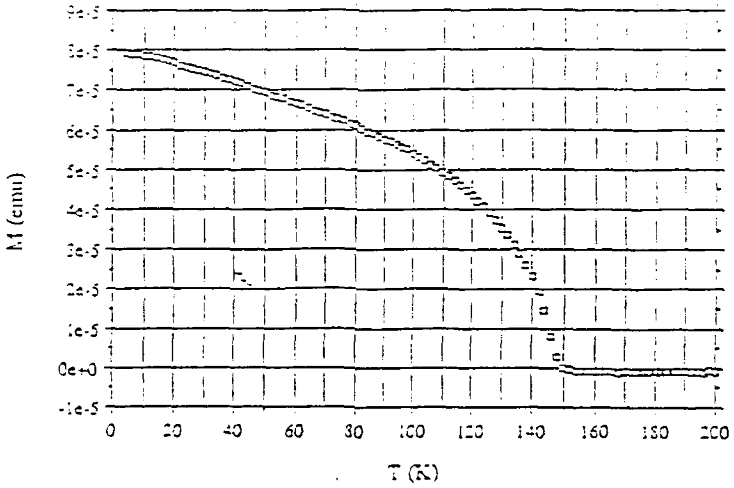
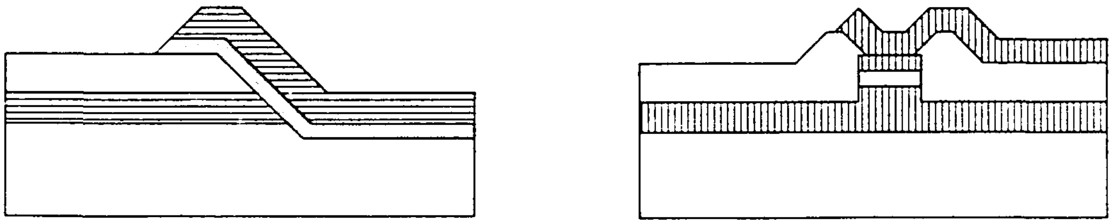


Figure 3 – Magnetization of thin-film SrRuO3
(measurement courtesy of L. Lombardo, Stanford University)

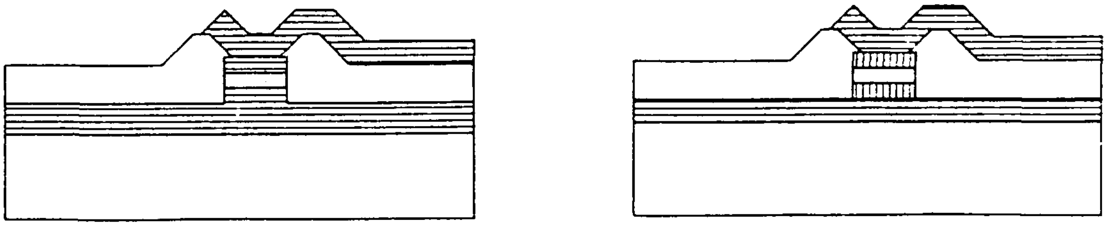
II. Fabrication and Testing of SNS Junctions

There are a number of geometries for fabricating epitaxial SNS junctions. Four candidate structures are depicted in Figure 4 below. For ease of fabrication and facility of wiring, the first two structures are preferred. Given the resistivity of the selected barrier materials, it is difficult to achieve desirable junction resistances using a trilayer geometry without requiring sub-micron lithography to define the junctions. Even one or two micron etched moats and dielectric windows will require significant process development in order to be realized with these oxide materials (such structures are not even commonplace in niobium junction technology). Because of this difficulty, we concentrated on the edge junction geometry. By its nature, this geometry yield small-area junctions by virtue of the fact that one dimension is set by film thicknesses that are far smaller than lithographically-defined dimensions.



C-axis edge geometry

A-axis tri-layer geometry



C-axis tri-layer geometry

A-axis and C-axis combined
tri-layer geometry

Figure 4 – Geometries for epitaxial SNS junctions.

In fact, the junctions tested prior to the start of this program were edge junctions of the type shown above. Figure 5 shows the current-voltage characteristics of SNS edge junctions using the $CaRuO_3$ barrier material. Particularly at higher temperatures, the characteristics are typical of resistively-shunted junctions. However, such characteristics can be observed from a variety of device structures. Thus, once the program began, the first tests to be performed were to determine whether the barrier material was really playing a role in the behavior of the junctions. One first had to see whether the weak link was simply due to the contact between two YBCO layers without regard to the presence of the barrier. Then it was necessary to rule out the possibility that the junctions were really pinholes or other shorts rather than true SNS devices. For these tests, it is important to understand that the SNS junctions produced had typical critical currents on the order of a few hundred microamps corresponding to current densities of 10^4-10^5 amps/cm^2. The first tests were to produce edge junctions with no barrier layer. As seen in Figure 6, such devices had critical currents

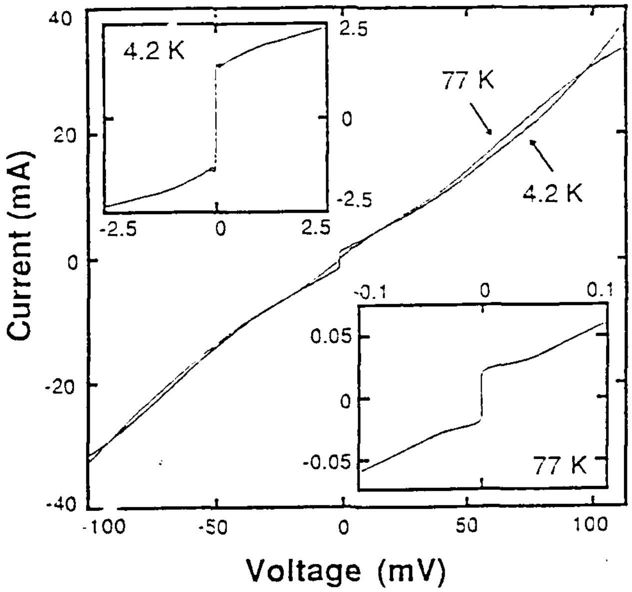


Figure 5 – Current-voltage characteristics of an SNS edge junction.

on the order of 10-20 milliamps corresponding to over 10^6 amps/cm^2. This result rules out the possibility that the multilayer structure and attendant processing alone produced the reduced critical currents.

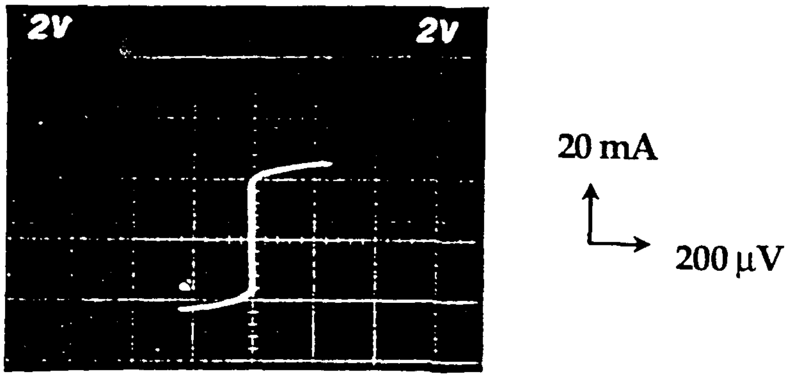


Figure 6 – Edge junction structure with no barrier layer.

The second test was to use an insulating layer instead of the conducting oxide for the barrier. In this case, 100 Å of SrTiO3 was used. As seen in Figure 7 below, there was no critical current in the device and its resistance was on the order of 100 kΩ. This result demonstrates that the edge structure does not contain shorts through the dielectric layer that is supposed to isolate the two YBCO layers except for the edge contact.

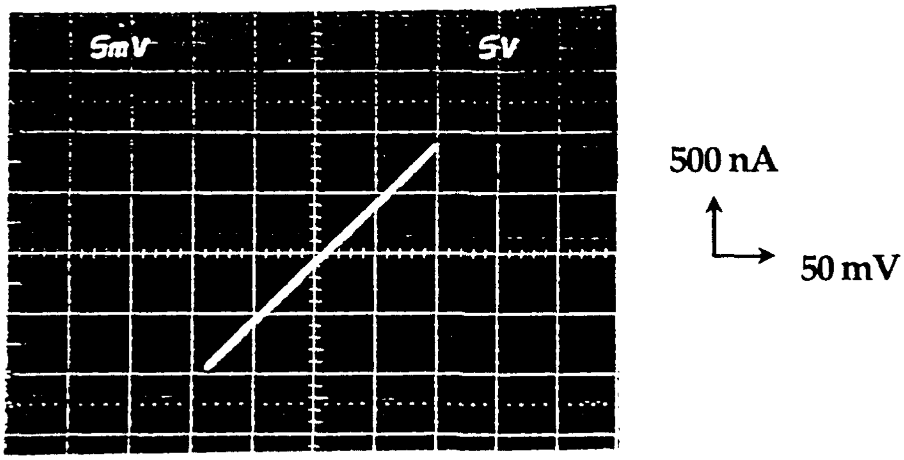


Figure 7 – Edge junction with SrTiO3 barrier layer.

From these results, we concluded that the junctions were functioning as designed in that the current flow is through the three-layer structure intended to act as a junction. The next set of experiments sought to understand the properties of the junctions in terms of the barrier thicknesses and expected resistances.

The temperature dependence of the critical current and resistance in these junctions is shown in Figure 8 below. The resistance varies only weakly while the critical current falls off rapidly. This essentially linear dependence is typical of YBCO junctions of all types. The particular junction shown here had a

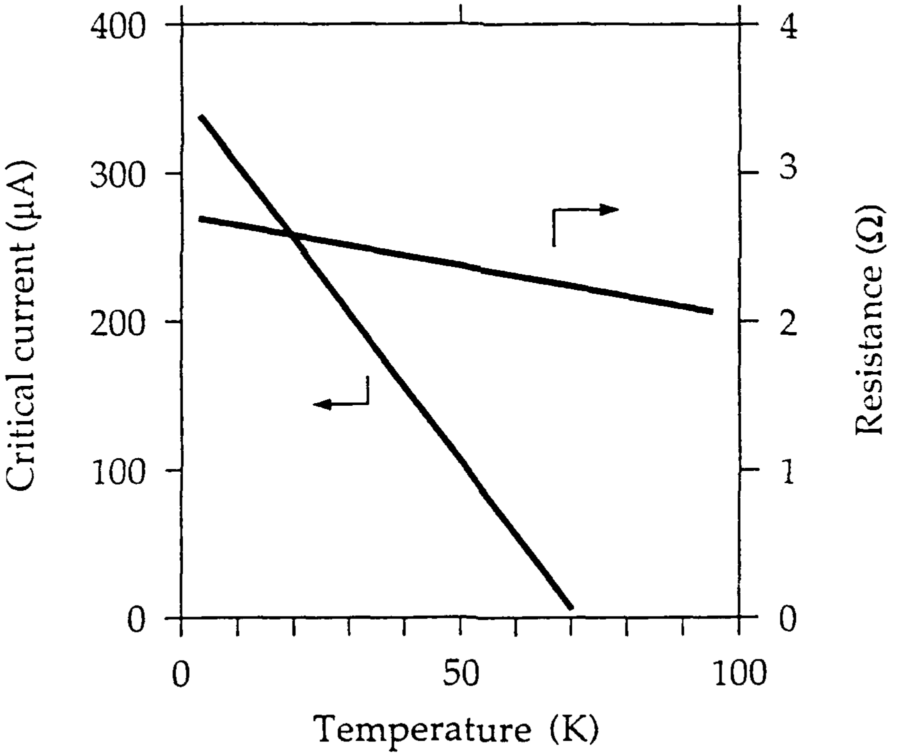


Figure 8 – Temperature dependence of I_c and R_n.

somewhat reduced critical temperature and did not superconduct at 77 K. Many other devices worked at considerably higher temperature, but nonetheless had comparable temperature dependences.

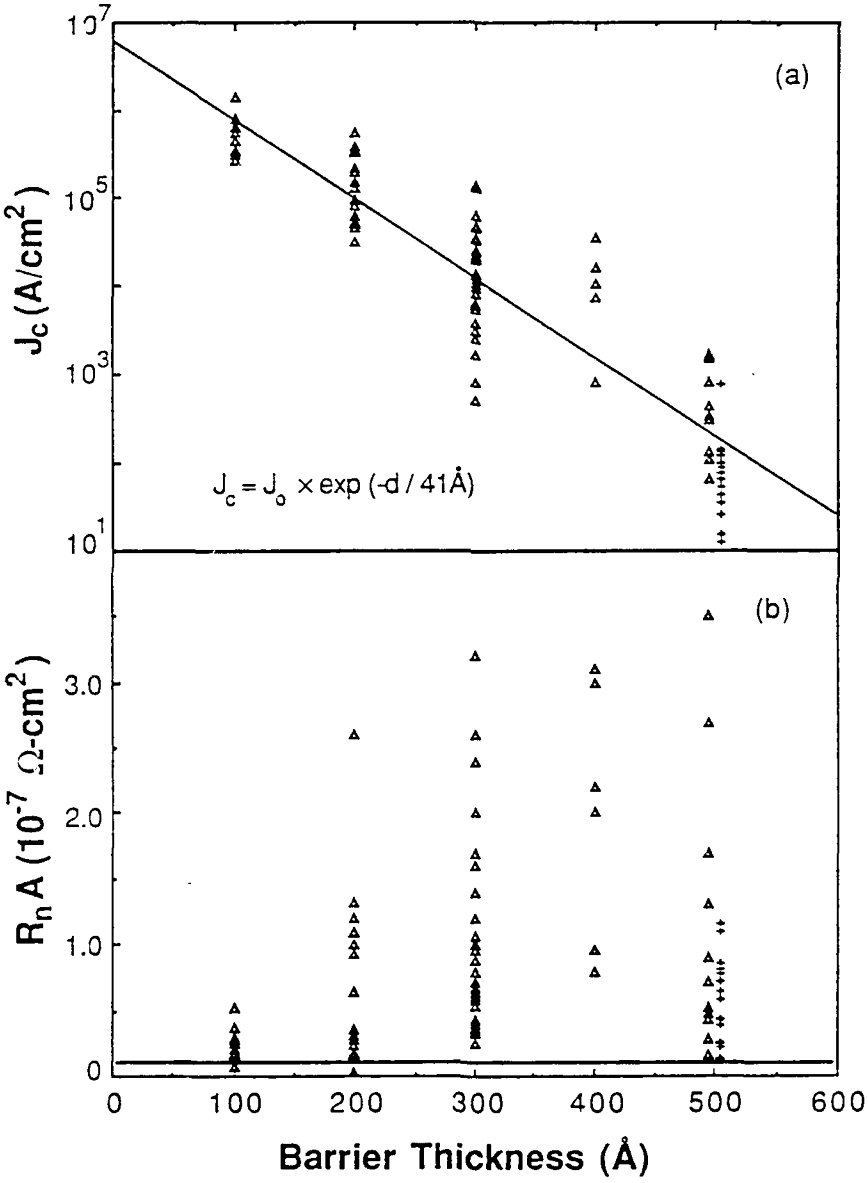


Figure 9 – Barrier thickness dependencies of junction parameters.

By varying the barrier thickness in the junctions, we were able to investigate the dependence of the current density in the junctions and their specific resistance upon this parameter. As seen in Figure 9 on the previous page, one observes an exponential dependence upon barrier thickness and there appears to be only scatter in resistance. Desirable current densities are obtained for thicknesses on the order of 200Å, which is a reasonable thickness to reproduce in the laser deposition process. Furthermore, the observed exponential dependence is what one would expect in an SNS junction.

The resistance data, on the other hand, does not agree with this conclusion in that the resistances observed are roughly two orders of magnitude greater than what one would predict from the resistivity of the barrier material. This suggests that interface resistance is the dominant contribution to the device resistance, despite the fact that the critical current appears to be determined by the barrier thickness. The most recent results strengthen these conclusions. Improved processing conditions for the junctions have lowered the resistance by about an order of magnitude and reduced the scatter. The straight line at the bottom of Figure 9 corresponding to 10^{-8} Ω-cm^2 represents the recent data.

The central issue in evaluating these junctions then remains to understand their behavior in terms of the source of the observed resistance and the potential uniformity of the junctions. The Josephson behavior of the junctions is evident from measurements of the devices in applied microwave and dc magnetic fields. Figure 10 shows current-voltage characteristics under microwave irradiation and the voltage modulation of a single junction by an applied magnetic field. The magnetic field was applied normal to the substrate, which is not precisely the appropriate geometry with respect to the junction. Nevertheless, the behavior

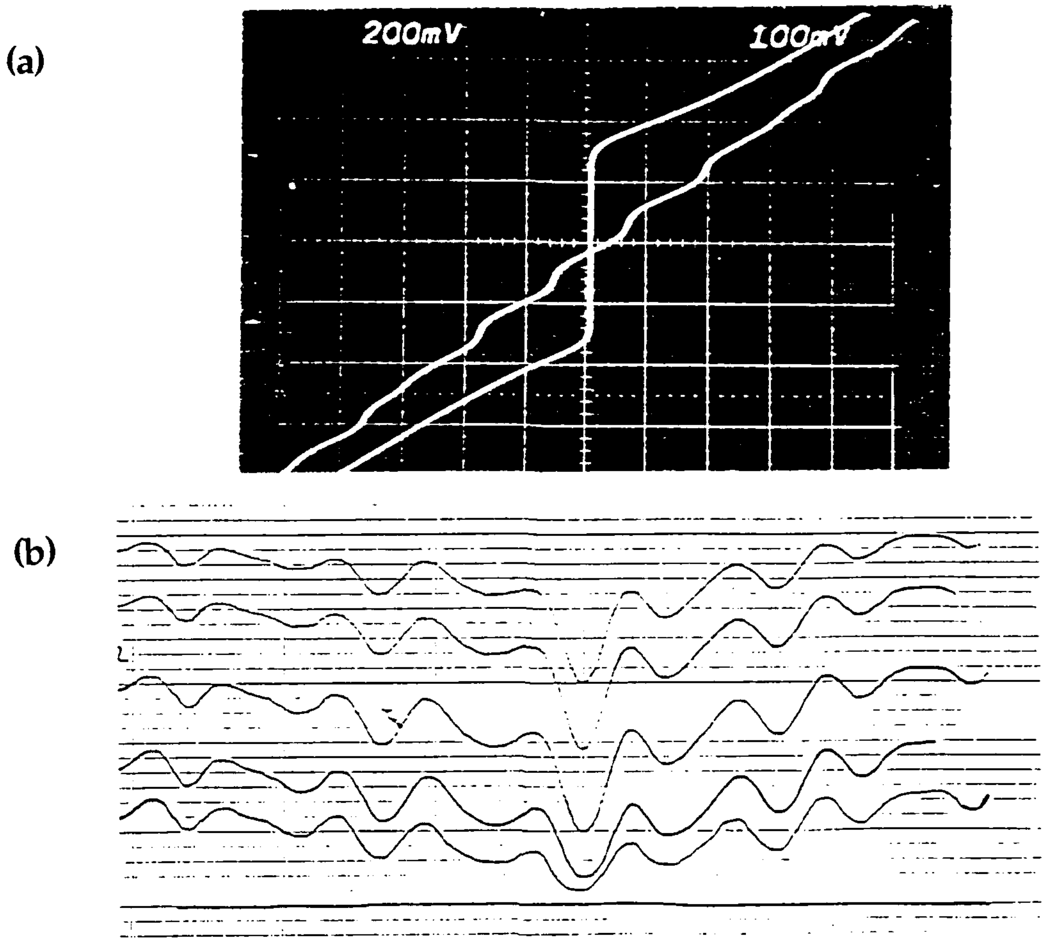


Figure 10 – (a) Microwave steps in I-V characteristics and (b) Voltage modulation of single junction under different bias conditions.

observed is what one would expect for a single junction. We will return to the issue of the interface effects in the junctions in the next section.

III. Junction Uniformity Tests

Initial tests of junction uniformity yielded results that were encouraging but not good enough for use in complex circuits. Several sets of 13 identical junctions were measured on 0.5 cm square chips. For the best chip, the spreads in critical currents and normal-state resistances were on the order of ±30%. In combination, the spread in the I_cR_n product was on the order of ±20%. This is nearly good enough for a number of applications. The key question is to what extent can it be improved?

Improved process conditions and control of critical dimensions will certainly help. However, the main issue is that of the interface resistance between the barrier material and the YBCO. Even with the latest improved devices, this resistance constitutes about 90% of the observed resistance in the device. One can easily imagine three explanations for this phenomenon.

(i) Damage caused by processing: the data shown in Figure 6 suggests that the processing does not induce any additional resistance, at least in the YBCO layer.

(ii) Oxygen deficiency in the YBCO at the interface: if the observed resistance of 10^{-8} Ω-cm^2 is due to oxygen-deficient YBCO with a resistivity of 10 mΩ--cm, then a 100Å oxygen-deficient region must exist. To test this idea, we looked at S-N junctions containing only one interface and observed the differential conductance of the devices. The results looked like all the previous tunneling results in YBCO with a strong linear background conductivity and weak features at about 20 mV. This seems to indicate that the interface is looking directly at ordinary YBCO (at least to the extent that any experiment has in the past).

(iii) Intrinsic effects: these might be such things as mismatches in carrier density and Fermi velocity in the material, or perhaps spin fluctuations.

If the excess resistance is due to intrinsic effects, then it will not represent an impediment to making reproducible junctions. In fact, the excess resistance is desirable from the standpoint of device parameters. If the effects are contingent upon deposition and/or processing conditions, then they must be controlled in order to yield a useful device process.

A final observation on the quality of these junctions is that when they are used to produce dc SQUIDs, the modulation depth and noise properties are both excellent. Figure 11 shows the modulation of an SNS SQUID at 77 K, showing about 15 μV of voltage modulation with applied flux.

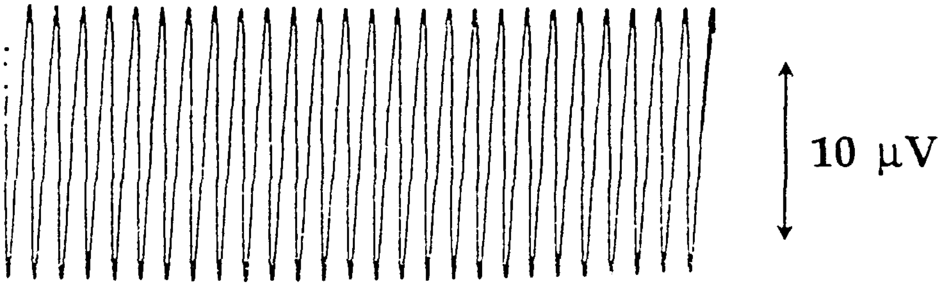


Figure 11 – Voltage modulation of SNS dc SQUID.

The flux-noise in these SQUIDs is excellent with Figure 12 showing the noise characteristics for SQUIDs of two different geometries. The smaller device exhibits a white noise of about 6 $\mu\Phi_O$, which is extremely low for a YBCO device.

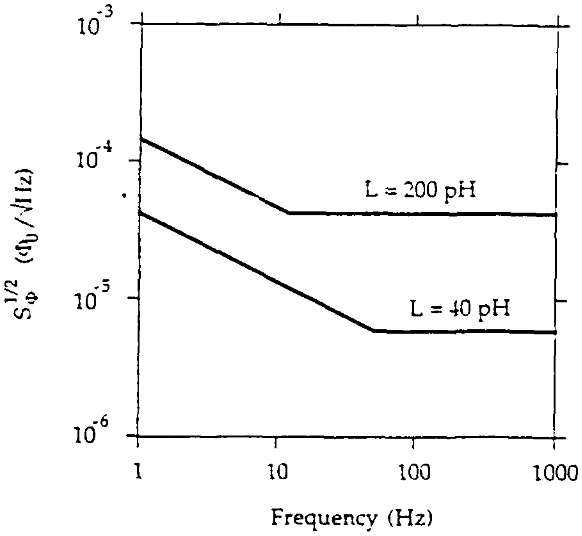


Figure 12 – Noise spectra for SNS dc SQUIDs.

Important Findings and Conclusions

In this Phase I SBIR program, we have achieved the following results:

- Demonstrated the use of $CaRuO_3$ as an epitaxial barrier layer for HTS SNS Josephson junctions with reasonable device uniformity and good characteristics.
- Demonstrated that the junctions are true multilayer devices containing a conducting oxide layer and not pinhole or short circuit devices, nor are they mere artifacts of multilayer structures..
- Demonstrated that interface resistance plays a dominant role in determining the characteristics of the junctions; understanding and controlling this resistance will be the key to establishing a useful device process.

More generally, the SNS junctions studied here appear to be superior to grain boundary devices from several key perspectives. In their present state of development, they can be produced with greater uniformity than can grain boundary devices, and key parameters such as I_cR_n product, SQUID modulation depth, and SQUID noise levels are all superior to the grain boundary junctions. For these reasons, it is clear that these devices warrant further development for use in all applications of HTS junctions.

Implications for Future Work

Phase II of this program would be to design, fabricate and test a number of basic Josephson integrated circuits of increasing complexity using the junctions studied under this Phase I program. Of particular interest would be building-block circuits for more complex systems such as shift registers as well as functional circuits that could be incorporated into future products such as sampler circuits. A forthcoming Phase II proposal will detail a series of circuits that would be developed in that program. Conductus is continuing to extend the capabilities of HTS-based SQUIDs and circuits in both its government-funded programs and in commercial product development so that we are confident that superconducting components of significant interest can be considered for this project.