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PROPERTIES OF HIGH TEMPERATURE SQUIDS*

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ABSTRACT

We review the present status of weak links and dc and rf biased SQUIDS made with high temperature superconductors. A method for producing reliable, reproducible devices using Nb₃Sn is outlined and comments are made on directions future work should take.

INTRODUCTION

There are a wide variety of techniques available for producing weak links suitable for use as elements in both dc and rf biased superconducting quantum interference devices (SQUID's) operating at or below 4.2 K. However, there have been only a few reports of SQUID's operating above 10 K¹⁻⁵ where closed-cycle refrigeration systems are available. This is due both to the difficulty in producing high-T_c superconductors and to the difficulty in producing weak links in these materials--which may have critical-current densities as high as 10⁷ A/cm².

Recently, several groups have succeeded in fabricating weak links and SQUIDS operating in the temperature region 10-17 K. These development have important implications for their possible future use in conjunction with closed-cycle refrigeration systems. This paper reviews the fabrication and properties of present high temperature SQUIDS as well as outlines a reproducible, reliable method for producing rf SQUIDS using Nb₃Sn thin films. Also discussed are several directions future work should take in order to produce devices useable for various possible applications. Finally, we speculate on the future importance of high temperature SQUIDS.

DC SQUIDS

One of the major requirements of a weak link in a SQUID, either dc or rf, is that it carry a critical current $I_c \approx \Phi_0/L$ where Φ_0 is the magnetic flux quantum and L is the inductance of the device. SQUID's can be made to operate with a large I_c if they are fabricated in a low inductance geometry.

Palmer, Notarys, and Mercereau¹ noted that the T_c of NbN and Nb₃Sn showed appreciable thickness dependence below 1000 Å. By photoresist masking and argon ion beam etching, they were able to reduce the thickness and thereby locally introduce a reduction

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in the pair density in a well defined region. Using weak links made in this manner, they reported the operation of dc SQUIDS at temperatures up to 17 K.

Fig. 1. Voltage-field characteristics of dc SQUID at 13.96 K for different biasing currents (after Golovashkin et al.).

The area enclosed by these devices was $21 \times 54 \mu\text{m}$ indicating an inductance of approximately 10–100 pH and therefore a critical current of 20–200 μA . While these small area devices exhibit quantum interference effects, their small inductance makes it difficult to couple in external signals and consequently limits their usefulness for a number of applications.

By mechanically scribing 5000–7000 Å thick Nb_3Sn films, in order to form 1–5 μm wide by 1–2 μm long weak links, Golovashkin et al.^{3,4} were able to fabricate dc SQUIDS operating up to 16.5 K (see Fig. 1). The area enclosed by these interferometers, and hence the inductance, was a factor of 5–10 smaller than those of Palmer et al.¹ This enabled the devices to operate with correspondingly larger critical currents, and consequently quantum interference behavior was seen over a wide temperature range (more than 10 K). However, the low inductance limits the usefulness for practical applications.

RF SQUIDS

Fugita et al.² reported a technique for sputtering epitaxial single crystal NbN films with T_c 's over 15 K using cleaved single crystal MgO substrates. By subsequent photoresist masking and sputter etching, they were able to produce well defined weak links as is shown in Fig. 2. By incorporating these weak links in the 2-hole geometry shown in Fig. 3 of sensing area 2 mm^2 , they were

Fig. 2. A photograph of a planar SQUID. A close up view of the NbN bridge, where the scale indicates $3 \mu\text{m}/\text{div}$. (after Fugita et al.).

able to make a gradiometer with a flux resolution $10^{-3} \Phi_0 / \text{Hz}^{1/2}$. The highest operating temperature obtained was ~ 15 K with an operating range of approximately 0.5 K. The signal from one of their devices is shown in Fig. 4. They estimate that the intrinsic flux resolution was a factor of 10 better than that measured due to inadequate shielding and use of a measuring

Fig. 3. A schematic drawing of a NbN planar SQUID coupled to an rf coil, (after Fujita et. al.).

system that was not optimized. However, no attempt was made to determine to what extent the weak links contributed to the overall noise in the device.

We have devised a reliable method for producing weak links in Nb_3Sn .⁵ Using these weak links, we have produced gradiometers of sensing area 2 mm^2 operating at over 14.5 K.

Since the technique should be applicable to other high T_c superconductors we will describe it in some detail (see also Ref. 6).

Fig. 4. An oscilloscope display of a periodic signal vertically as a function of magnetic flux in a NbN planar SQUID (after Fujita et al.).

RADIATION DAMAGE PRODUCED Nb_3Sn WEAK LINKS

High- T_c Nb_3Sn thin films were prepared by sputtering from a stoichiometric-reacted pressed-powder target onto sapphire substrates using a Varian high-rate magnetron sputtering system. For the work reported here, typical film thicknesses were $\sim 500 \text{ \AA}$, and typical transition temperatures were ~ 17.5 K. The T_c seems to be slightly thickness dependent,

since the transition temperatures for our thicker films ($\sim 1 \mu\text{m}$) are typically ~ 17.8 K. Typical room-temperature resistivity ratio

$\rho_{300}/\rho_{17.5} = 2.4$ is smaller than the values we have obtained with thicker films (3.5-5.4). The preferred orientation and lattice parameter determined by x-ray diffraction analysis were $\langle 210 \rangle$ and $5.291 \text{ \AA}$, respectively, for our thin Nb_3Sn films.

The six steps we use for the fabrication of Nb_3Sn thin-film weak links are as follows: (1) $500 \text{ \AA}$ Nb_3Sn is deposited on a polished sapphire substrate; (2) a bridge of width $5\text{-}30 \text{ }\mu\text{m}$ and

Figure 5. Resistance measurement as a function of temperature for a weak link.

Figure 6. Critical-current variation as a function of temperature for the weak link of Figure 5.

length $200 \text{ }\mu\text{m}$ including four pads for the four-point probe measurement is etched using acid (see inset to Fig. 5); (3) a Cu film $\sim 4000 \text{ \AA}$ thick is deposited over the entire substrate (4) a sharp razor blade is used to cut an opening of $0.5\text{-}5 \text{ }\mu\text{m}$ in the Cu over the bridge; (5) the entire system is irradiated with a controlled dosage of α particles of energy 50 keV ; (6) the Cu is etched away. Figure 5 shows the resistance-vs-temperature measurements of one of our weak links.

The major portion of the film still has the same T_c after radiation damage, indicating that the Cu film was sufficiently thick to protect the underlying Nb_3Sn from damage.

Figure 6 shows the critical-current variation of this weak link as a function of temperature ($I_c^{2/3}$ versus T).

It is clear that over quite a large temperature range, there is a linear relation between $I_c^{2/3}$ and temperature.

If we define the intrinsic transition

Figure 7. Critical-current variation as a function of temperature for the weak link of Fig. 2.

TABLE I. Transition temperature of Nb₃Sn films at various dosages.

Dosage (ions/cm ²)	Transition temperature T' _c (°K)
1.2 × 10 ¹⁴	16.5
2.4 × 10 ¹⁴	15.8
7 × 10 ¹⁴	14
1 × 10 ¹⁵	13
1.5 × 10 ¹⁵	9.5
5 × 10 ¹⁵	2.5 ~ 3.0

effective-noise temperatures. It has been shown⁸ at lower temperatures with samples immersed directly in liquid He that a measuring system such as ours allows effective-noise temperatures equal to the substrate temperature to be obtained. If this is

temperature of the irradiated region T'_c as the intersection of the extrapolation to the temperature axis, then T'_c is 14.1 K for this weak link. In addition, if we plot ln I_c as a function of temperature as shown in Fig. 7, it can be easily observed that for T > T'_c there is a linear relation between ln I_c and T. Hence, the critical current of this weak link is

$$I_c \propto (T'_c - T)^{3/2}$$

for T < T'_c and

$$I_c \propto \exp(-\gamma T)$$

for T > T'_c. T'_c defined in this way depends on dosage as shown in Table I. These results agree well with our T_c measurements on large-area films directly irradiated without Cu protection.

Measurements of the differential resistance dV/dI is more sensitive than a direct measurement of current-voltage characteristic. We have obtained dV/dI-vs-I

characteristics for several weak links. Figure 8 shows the results for one weak link as compared to the theoretical prediction⁷ assuming two different

Figure 8. Differential resistance dV/dI as a function of I . Theoretical points are calculated from the theory of Ref. 7 assuming two different noise temperatures T^* .

Figure 9. Steps for the fabrication of Nb_3Sn SQUID's.

the case here, it indicates a much higher intrinsic noise in these weak links than in those made in low- T_c materials. However, it will be necessary to study Nb_3Sn weak links made to operate with low critical currents at 4.2 K in order to determine whether the large noise temperature is caused by the absence of direct contact with liquid helium or by large intrinsic noise in these weak links.

Nb_3Sn SQUIDS

There are six steps in the fabrication of Nb_3Sn SQUID's as shown in Fig. 9. (1) Approximately 500 Å Nb_3Sn is deposited on a sapphire substrate; (2) the film is coated with photoresist, and (3) a two-hole pattern is etched using standard photolithographic techniques. (4) A protective Cu layer is deposited and (5) a narrow line is cut through the Cu layer over the bridge region. (6) The whole film is subjected to a controlled dose of α particles at 50 keV. (7) The Cu layer is then etched away after the irradiation. The detailed dimensions of the final SQUID are shown in Fig. 10. In order to couple external signals into the SQUID more effectively, a large block

Figure 10. Detailed dimensions of the Nb_3Sn SQUID's.

relation $I_c \sim \Phi_0/L$ for optimum SQUID performance, the effective inductance of the SQUID is found to be approximately 0.3 nH. This indicates that the Nb_3Al block is effective in reducing the self-inductance of the planar geometry by a factor of 10. From the slowly varying behavior of the critical current as a function of temperature (Fig. 10), one would expect that the rf signal of the SQUID would vary smoothly over a wider temperature range rather than the sharp-peak behavior shown in Fig. 10. However, as mentioned before, only a single-layer μ -metal can was used for the magnetic shielding of the SQUID so that the operating temperature range may have been limited by external electromagnetic noise in our laboratory.

FUTURE WORK

The ease of operation afforded by a high temperature SQUID in conjunction with a closed cycle refrigerator makes further work in this area especially valuable. All work to date has produced

of Nb_3Al with $T_c \sim 18.2$ K prepared by arc melting was clamped onto the SQUID (Fig. 11). In addition to allowing better coupling, this Nb_3Al actually reduces the self-inductance of the SQUID to allow it to operate at higher critical currents. This block was polished with fine emery paper, however, no attempt was made to polish it optically flat. The self-inductance of these thin-film SQUID's without the Nb_3Al block is calculated to be approximately 2 nH. However, from the curves of the measured signal level of the SQUID and the critical current of its weak link as a function of temperature measured separately (Fig. 12) and using the criterion that the critical current of the weak link I_c obeys a

Figure 11. Schematic drawing of the planar SQUID coupled to an rf tank coil shielded with a Nb_3Al block.

Figure 12. Measured signal level of a SQUID and the corresponding critical current as a function of temperature of its weak link.

devices which are either limited in sensing area or in operating temperature range. In addition, it is likely that the present weak links exhibit non-sinusoidal current-phase relations, leading to excess noise and a reduction in overall sensitivity.

For many applications, a reduced SQUID sensitivity can be tolerated or is even desirable. Here, effort should be made to find techniques for producing weak links operating over a wide temperature range; even if they exhibit non-ideal Josephson behavior. In the opposite extreme, it is also necessary to have high temperature SQUIDS with maximum achievable sensitivity within the limits that operation at high temperatures impose. Here, ideal Josephson weak links are required even if they only operate over a narrow temperature range. For convenience in temperature regulation, operation at the hydrogen triple-point temperature 13.96 K would be desirable.

Applications for SQUIDS reported to date in such orders as biomedicine, geophysics, rock magnetism, and communication systems have been almost exclusively initiated or developed by low temperature physicists. It seems clear that in order for there to be widespread use of these developments, or for there to be additional applications in areas, it will be necessary to provide complete

stand-alone systems that do not require the use of liquid helium. Consequently, further developments of high temperature SQUIDS, in conjunction with developments in closed-cycle refrigeration systems, will certainly be important to a more widespread exploitation of SQUID technology.

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