The microwave power handling of a FIB generated weak link in a YBCO film

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Abstract. We have measured the power dependent microwave properties of a weak link in a YBa$_2$Cu$_3$O$_{7−δ}$ thin film formed by writing a line of damage using a focused ion beam. The measurement was made using a parallel plate resonator at 5.5 GHz with the weak link written across the width of one of the plates. The ion induced damage was characterized using a TRIM computer simulation and the dc properties of similar weak links was measured. Using a 200 eV Si ion dose of $2 \times 10^{13}$ cm$^{-2}$, the $T_c$ of the damaged region was reduced by 5.5 K and the normal resistivity was doubled. Surprisingly, the microwave measurements did not show any Josephson junction characteristics. Rather, the ion damaged region exhibited a greatly increased microwave resistivity that was constant as a function of microwave power up to rf fields of 20 mT at 21 K.

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1. Introduction

The presence of weak-links in granular material can give rise to diverse dependence of surface resistance upon microwave magnetic field. In this context, weak links are usually modeled in terms of the resistively shunted junction (RSJ) model \([1, 2, 3, 4, 5, 6]\). Oates et al performed a control experiment using a stripline resonator geometry with an edge junction and found that the weak link followed an RSJ type behaviour \([7]\). In the present study we used a parallel plate resonator geometry with a macroscopic weak link formed by focused ion beam (FIB) irradiation across one of the films. There are significant differences between edge junctions and FIB weak links and it is interesting to test whether an FIB weak link will also follow RSJ behaviour.

Xie et al \([8]\) developed an RSJ based model to describe nonlinear absorption of microwaves in a weak-link Josephson junction. This predicts that for an ideal Josephson junction, the microwave power absorbed (power absorbed is proportional to the surface resistance) will remain independent of the microwave screening current up to a threshold value dictated by the critical current density of the junction, \(J_c\). Further sharp steps in microwave absorption occur periodically with increasing microwave current as a result of dynamic flux quantization where one or more fluxons pass through the junction during each microwave cycle.

We expect to observe a significant deterioration in surface resistance for microwave currents exceeding \(J_c\) and further increase in the surface impedance as microwave currents grow larger. (At 77 K, \(J_c \sim 3 \times 10^4\) A·cm\(^{-2}\), which for our films would give a microwave field of \(B_{rf} \sim 0.08\) m·T.) The long FIB pattern would act as a parallel network of sub-junctions rather than a single junction, so that the detail of flux penetration steps would be averaged out in a network of such sub-junctions \([9]\).

2. Experimental Method

Three \(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}\) thin films on \(\text{CeO}_2\) buffered, sapphire substrates, grown by pulsed laser deposition, were supplied by the Institute for Microstructural Sciences of the National Research Council of Canada. The growth method of these films is described in Ref. \([10]\). The films were 150 nm thick at the edges and 190 nm thick at the center. Two virgin films, \(V_1\) and \(V_2\) were used as a reference set for the parallel plate resonator. The third film \(J_1\), had a bisecting 50 nm line of ion damage written across its full width by FIB. \(V\) vs \(I\) dc measurements on similar weak links have been reported previously \([11]\). A pair of \(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}\) films on \(\text{LaAlO}_3\) substrates from DuPont, \(V_3\) and \(V_4\), were also measured for further reference.

Microwave measurements were made using a parallel plate resonator consisting of two 10 mm by 5 mm HTS films, separated by a 0.15 mm thick, high purity sapphire spacer. This structure has a fundamental resonance frequency at 5.5 GHz. The losses are associated with the effective surface resistance \(R_s\) (not corrected for finite sample thickness), dielectric and
Figure 1. Calculated non-ionizing energy loss for 200 keV Si ions incident on YBa$_2$Cu$_3$O$_{7-\delta}$. The $T_c$ values are our estimate for a dose of $2 \times 10^{13}$ cm$^{-2}$, starting with a $T_c$ for the undamaged YBa$_2$Cu$_3$O$_{7-\delta}$ of 85 K.

radiation losses. This can be expressed as [12]

\[ Q^{-1} = \tan \delta + \alpha_s + \beta \left( \frac{R_s}{s} \right). \]

The first two terms are due to loss in the dielectric and radiation loss, $\tan \delta$ represents the dielectric loss in the spacer between the two superconducting films, $\alpha_s$ gives the radiation loss. These are small for the geometry and materials used here and will be neglected [13]. The term $\beta(R_s/s)$ is the loss due to the surface resistance of the two superconducting films. Using $\beta = 1/(\pi \mu_0 f)$, the surface resistance can then be calculated directly from the measured $Q$.

Overall, the microwave measurement has a precision of 5 $\mu$\Omega and the signal sensitivity is lost for $R_s$ values greater than 20 m\Omega. The microwave measurements were performed in a continuous flow cryostat with a temperature stability within 0.2 K. The TE10 mode was used. This mode has maximum screening current in the central band of the film coincident with the FIB line.

3. Fabrication of a Focused Ion Beam Junction

One method of producing a weak link is to locally damage the superconducting material using a focused ion beam (FIB). In our case, we used a 200 keV Si ion beam focused to a spot size of 50 nm. It has been reported that the $T_c$ reduction due to ion irradiation is proportional to the non-ionizing energy loss [14, 15]. TRIM [16] simulation showed that the damage due to the 200 keV Si ions incident on a YBa$_2$Cu$_3$O$_{7-\delta}$ thin film varies with distance into the film, shown in Fig. [1]. The reduction of $T_c$ will depend on depth and will be scaled by the ion dose.
Figure 2. Model of the cross-section of an ion damaged YBa$_2$Cu$_3$O$_{7-\delta}$ film, showing lines of constant $T_c$. At 77 K only the bottom (dark) layer of YBa$_2$Cu$_3$O$_{7-\delta}$ would be superconducting.

The TRIM simulation also shows that the beam spreads laterally and that the total width of the damaged region will be about 200 nm.

Since a typical YBa$_2$Cu$_3$O$_{7-\delta}$ film is not smooth, the reduction of $T_c$ will tend to follow the surface profile. Figure 2 shows a model of a cross-section with lines of constant $T_c$. At a temperature of 77 K only the bottom layer of YBa$_2$Cu$_3$O$_{7-\delta}$ will be superconducting. The various valleys in the YBa$_2$Cu$_3$O$_{7-\delta}$ film (which occur at grain boundaries) would give rise to a variety of types of weak links. A large valley would yield an SNS structure and could give rise to a Josephson junction based on the proximity effect. A shallow valley would have a thin superconducting region next to the substrate and would be a flux flow type of weak link. In any case, the bulk of the YBa$_2$Cu$_3$O$_{7-\delta}$ of the top portions of the film will act as a normal shunt of the weak links. At temperatures below 71 K, the entire thickness of the YBa$_2$Cu$_3$O$_{7-\delta}$ film will be superconducting.

4. dc characterization

A YBa$_2$Cu$_3$O$_{7-\delta}$ film similar to the one we used to make microwave measurements, was patterned into four point probe structures to allow dc measurements. The results for a 10 $\mu$m wide channel with a single FIB line written across it at a dose of $2 \times 10^{13}$ cm$^{-2}$ are given in Figure 3. The main transition shows that the undamaged YBa$_2$Cu$_3$O$_{7-\delta}$ has a $T_c$ of 86 K. A detailed view of the small resistance part of the data, reveals a small transition due to the ion damaged line with a $T_c$ of 80.5 K for very small currents. This is the temperature where the first continuous superconducting path forms. The critical current of the weak link, at 77 K, was 0.6 mA, which is 25 to 50 times less than it would be for an undamaged film. From the small transition, we find that the normal resistance of the damaged line is 0.34 $\Omega$ at 85 K.

In order to further investigate the properties of the ion damaged material, a 20 $\mu$m by
Figure 3. Resistance vs temperature data for a 10 µm wide channel of a YBa$_2$Cu$_3$O$_{7-\delta}$ film written with a single FIB line. The measuring currents were: full - $10^{-6}$ A, dashed - $10^{-4}$ A, and dotted $10^{-2}$ A. The inset is a blow-up of the foot of the transition.

20 µm square was damaged using the focused ion beam with the same dose of $2 \times 10^{13}$ cm$^{-2}$. As can be seen in Figure 4, the transition of the damaged area is now a large feature. $T_c$ is 80.5 K, the same as for the single FIB line, which implies that the ion damage is the same for a single line and a large area. Since the size of the damaged region is well defined, the measured resistance of 15 Ω gives a value of the resistivity of 230 µΩ·cm at 85 K. This is about double

Figure 4. Resistance vs temperature data for a 20 µm wide channel of a YBa$_2$Cu$_3$O$_{7-\delta}$ film written with a 20 µm by 20 µm FIB area. The measuring currents were: full - $10^{-6}$ A and dashed - $10^{-4}$ A.
the measured resistivity of the undamaged YBa$_2$Cu$_3$O$_{7-\delta}$ which, extrapolated down to 85 K, was 114 $\mu\Omega$-cm. Using this resistivity measurement and the resistance measurement of the single FIB written line, the effective width of the ion damaged region can be found. It is 200 nm, which is in agreement with the value predicted by TRIM.

5. Microwave results

Various pairs of the YBa$_2$Cu$_3$O$_{7-\delta}$ films were measured with the parallel plate resonator. A summary of the films used in this study is given in Table 1. $V_1$, $V_2$ and $J_1$ were supplied by the National Research Council of Canada while $V_3$ and $V_4$ are YBa$_2$Cu$_3$O$_{7-\delta}$ films from DuPont.

Figure 5 shows the effective surface resistance behaviour for a number of combinations of films at 21 K. The combination of $V_2V_4$ has the lowest residual value of $R_s$ and shows catastrophic failure at 50 mT, but is nonlinear with an increase in $R_s$ of 35 $\mu\Omega$ from 2–50 mT. The $V_3V_4$ combination is independent of power up to 8 mT, shows a region of increasing nonlinearity and fails catastrophically at 20 mT. $V_4$ is clearly a “cleaner” film than $V_3$. From the nature of the failure of $V_3V_4$ and the absolute value of $R_s$ it is probable that there is one defective region close to the edge of the film $V_3$.

The $V_2J_1$ combination also displays extremely good power handling at 21 K. The absolute value of $R_s$ is higher in $J_1$ than in $V_2$, $V_3$, or $V_4$ but there is no evidence of nonlinear behaviour up to 20 mT. While the $V_1V_2$ combination shows that $V_1$ is the worst film of the batch. Quasi logarithmic power dependence is observed at all powers and this parallel plate film combination fails catastrophically at 20 mT. At 21 K the $V_1J_1$ combination principally reflects the granular behaviour of $V_1$, although the data is much noisier for this set, the average value given by the dashed line has a lower overall $R_s$ value than for the virgin film combination. The noise in the data arose from poor temperature stability ($\pm$ 0.2 K) during this particular run.

These results indicate that $V_1$ is a virgin film with some other microstructural features which provide a mechanism for power dependence. $J_1$ has been damaged by FIB but this does not seem to have changed it’s power dependence however, its residual surface resistance has clearly been increased by this process.

Figure 6 shows the effective surface resistance at 75 K. The $V_3V_4$ and $V_2V_4$ film combinations are almost indistinguishable. They display similar power dependence up until

| Film | $T_c$   | Treatment | $R_s$, 21 K | $R_s$, 75 K |
|------|---------|-----------|-------------|-------------|
| $V_1$| 87 K    | as-grown  | 100 $\mu\Omega$ | 390 $\mu\Omega$ |
| $V_2$| 87 K    | as-grown  | 40 $\mu\Omega$  | 160 $\mu\Omega$ |
| $V_3$| 90 K    | as-grown  | 50 $\mu\Omega$  | 140 $\mu\Omega$ |
| $V_4$| 90 K    | as-grown  | 40 $\mu\Omega$  | 140 $\mu\Omega$ |
| $J_1$| 84.5 K  | FIB track | 60 $\mu\Omega$  | 350 $\mu\Omega$ |
10 mT where $V_3 V_4$ fails. Their residual surface resistances are also very similar. The $V_2 J_1$ combination shows that $J_1$ does not change the power dependence of this combination overall but does increase the residual surface resistance.

The poor microstructure of $V_1$ dominates the power dependence of the $V_1 V_2$ and $V_1 J_1$ combinations showing logarithmic power dependence in both cases. Again, the influence of the FIB line upon the behaviour of $J_1$ is to raise it’s residual surface resistance. At 75 K the difference in $R_s$ between $V_2$ and $J_1$ is about $100 \mu\Omega$.

Measurement became difficult above 75 K when the microwave response is limited by background noise. Neither at 21 K or at 75 K is there any evidence for junction-type behaviour.
Microwave properties of FIB weak link in parallel plate combinations using the FIB film J₁.

6. Analysis

In this section, we will concentrate on the effect of the FIB line. The measurements on the pair V₂J₁ yield a combined "apparent" surface resistance of 60 $\mu\Omega$ (at 21 K), which is independent of microwave power. Measurements on the films V₂, V₃, and V₄ show that the surface resistance of V₂ is about 40 $\mu\Omega$. The extra loss seen by the measurement must be due to film J₁. There are two possible sources of the loss; 1) the surface resistance of the area of the film and 2) the FIB damaged line.

The microwave properties of J₁ were not measured before the FIB line was written, so we cannot be sure of the source of the extra loss. However, if the loss is due to a poor quality YBa₂Cu₃O₇−δ film, we would expect to see a strong power dependence as was shown by sample V₁. Our dc measurements on other FIB damaged samples showed that $T_c$ and $J_c$ were reduced and that the normal dc resistivity was doubled. From this we expect that the FIB damage should also have an effect on the microwave properties. We conclude that it is likely that, at least some of, the extra microwave loss is due to the FIB damaged line.

In order to be more quantitative in the analysis of the data, a term representing the FIB line can be added to the parallel plate resonator model [11]. We will assume that the $R_s$ values of the two films are the same and that there is a line resistor across only one of the films. The extended model can be written,

$$Q^{-1} = \tan \delta + \alpha s + \beta \left( \frac{R_s}{s} \right) + \gamma \left( \frac{R_l}{sL} \right).$$

The first three terms on the right hand side are the usual ones. The last term represents the FIB resistor. The FIB line is represented by a linear resistivity which has units of $R_l = [\Omega \cdot \text{m}]$. $L$ is the length of the plate in the direction of the microwave current. The FIB line was written across the width of the substrate and its length is $W$. For a uniform current flowing in the $L$ direction, the total resistance is $R = R_l/W$. $\gamma$ is the geometric factor, which can be found by solving the electromagnetic problem for the geometry of the parallel plate resonator. For the specific microwave mode used in this experiment, the calculation gives $\gamma = 1/\pi\mu_0f$.

If we assume that the difference between the microwave losses for the pair of films V₂V₄ and the pair V₂J₁ is only due to the FIB damaged line, then a value of $R_l$ can be found. Due to this assumption, the deduced resistances should be considered as maximum values. We find that at 21 K $R_l = 2 \times 10^{-7} \Omega \cdot \text{m}$ and at 75 K $R_l = 2 \times 10^{-6} \Omega \cdot \text{m}$. The lumped element resistance value can be found by dividing by the length of the FIB line. This gives $4 \times 10^{-5} \Omega$ at 21 K and $4 \times 10^{-4} \Omega$ at 75 K. In order to compare these results with more familiar materials, these values can be converted to equivalent volume resistivity in the standard way by multiplying by the cross-sectional area and dividing by the length of the current path. This gives effective resistivities, at 5.5 GHz, of $\rho_{eff} = 1.7 \times 10^{-7} \Omega \cdot \text{m}$ at 21 K and $\rho_{eff} = 1.7 \times 10^{-6} \Omega \cdot \text{m}$ at 75 K.

An effective resistivity can be found from the measured $R_s$ of our undamaged YBa₂Cu₃O₇−δ, which is $4 \times 10^{-5} \Omega$ at 21 K. Multiplying this by the film thickness gives
Table 2. Equivalent lumped element resistance for a line resistor in units of Ω. The values for superconducting YBa$_2$Cu$_3$O$_{7−δ}$ are for microwave frequency 5.5 GHz and the values for normal materials are for dc.

|           | 21 K     | 75 K     | 85 K     |
|-----------|----------|----------|----------|
| FIB-YBCO  | $1.7 \times 10^{-8}$ | $1.7 \times 10^{-7}$ | $2.3 \times 10^{-6}$ |
| YBCO      | $7.2 \times 10^{-12}$ | $2.55 \times 10^{-11}$ | $1.1 \times 10^{-6}$ |
| Copper    | $1 \times 10^{-10}$ | $2 \times 10^{-9}$  | $2 \times 10^{-9}$  |

ρ$_{eff}$ = $7.2 \times 10^{-12}$ Ω·m. Similarly, at 75 K, ρ$_{eff}$ = $2.5 \times 10^{-11}$ Ω·m. The dc resistivity of pure copper is ρ = $2 \times 10^{-8}$ Ω·m at 300 K, about ρ = $2 \times 10^{-9}$ Ω·m at 77 K, and about ρ = $1 \times 10^{-10}$ Ω·m at 21 K. For comparison, the surface resistances calculated from these resistivities are, $R_s$ = $2.1 \times 10^{-2}$ Ω at 300 K, $R_s$ = $6.6 \times 10^{-3}$ Ω at 77 K, and $R_s$ = $1.5 \times 10^{-3}$ Ω at 21 K. In the case of our line resistor (area = $(5 \times 10^{-3}$ m$)^2 \times (1.8 \times 10^{-7}$ m) and current path length = $2 \times 10^{-7}$ m), lumped element resistances can be calculated. These values are summarized in table 2.

It is remarkable that the resistivity (i.e., the losses per unit volume) of the damaged YBa$_2$Cu$_3$O$_{7−δ}$ is much larger than the undamaged YBa$_2$Cu$_3$O$_{7−δ}$ and even larger than for copper. At 21 K, the damaged YBa$_2$Cu$_3$O$_{7−δ}$ is still superconducting, but exhibits quite large microwave losses. The resistivity at 75 K of the FIB-YBa$_2$Cu$_3$O$_{7−δ}$ approaches the normal value at 85 K. Consistent with much of the damaged material being normal at 75 K and with the assumption that the extra microwave loss is due to the microwave damage.

The physical damage caused by the FIB writing can be compared to the electrical damage. Doping due to Si ion implantation is about 1 part in $10^5$ which is very small and we wouldn’t expect this to have a large effect. The resulting number of vacancies (about 1500 vacancies per Si ion from the TRIM calculation) is about 2% of the total YBa$_2$Cu$_3$O$_{7−δ}$ atoms. This damage results in the doubling of the normal resistivity and the lowering of $T_c$ by 5 K or about 6%. The effects on the microwave loss are more dramatic. The microwave loss in the FIB damaged material at 21 K, was increased by a factor of 6000 over the loss in the undamaged YBa$_2$Cu$_3$O$_{7−δ}$. The increase in the loss at 75 K was by a factor of 16,000. A small amount of physical damage has a large effect on normal resistivity and $T_c$ and a huge effect on microwave losses.

7. Conclusions

We measured the microwave loss of a resonator constructed with a film which had a 50 nm line written across it by FIB irradiation. We did not observe evidence for Josephson effects in this film. The microwave surface impedance measurements highlight the variance of the power dependence seen in individual films. Massive damage may be inflicted upon the film without altering the power dependence even though the TE10 mode requires a high screening current density in this region. However, mass creation of defects is observed to increase the residual surface resistance of the film. These microwave power independent losses are not due
to Josephson effects or the granular nature of the thin film, but due to microscopic defects.

The as grown YBa$_2$Cu$_3$O$_{7-\delta}$ films start with a large concentration of defects. We have seen that adding more defects leads to a large increase in $R_s$. On the other hand, adding defects to the best quality single crystals lowers $R_s$ (by decreasing the quasiparticle scattering time). Perhaps there is an optimum concentration of defects at a level between these two extremes. Noting the low value of $R_s$ for good single crystals ($R_s \sim 10^{-5}$ $\Omega$ at about 5 GHz [17]), there is still room for improvement of YBa$_2$Cu$_3$O$_{7-\delta}$ thin films, if they can be grown with fewer defects.

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