Nanometer scale masked ion damage barriers in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$

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Abstract—Irradiation of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ with H_2^+ ions with an energy of 100 keV can be used to fully suppress superconductivity. Simulations indicated that such an irradiation process in combination with a high-aspect ratio mask can be used to create highly localized damage regions in thin films. Results from focused electron beam irradiation studies suggest that a barrier region consisting of disordered material needs to be less than 15 nm long in the transport direction, in order to give good quality Josephson junctions. The main challenge for the masked ion damage technique is therefore to create a mask with a feature size on the scale of 10 nm and sufficient ion stopping power. Using an experimental set-up that allows electrical characterization of the barrier region during ion irradiation, we have studied a variety of masking materials and focused ion beam patterning techniques.

Index Terms—Superconducting devices, nanotechnology YBCO, SNS devices

I. INTRODUCTION

A reliable high temperature superconductor (HTS) junction fabrication technology for large-scale integration has been a long-standing requirement. One of the candidate technologies, at least in terms of junction quality and reproducibility, is the focused electron beam irradiation technique (FEBI) developed in Cambridge and elsewhere [1, 2] in which the superconducting transition temperature (T_c) is locally suppressed by irradiation-induced damage. It was realized early on that much of the electron-induced damage is unstable at room temperature, and so the properties of early junctions changed rapidly with time. In order to address this problem a protocol was developed in which excess damage was created to the barrier, followed by an anneal at a temperature above 100°C; the effect of this anneal is to remove the damage with a low recovery activation energy and leave stable high energy defects. Junctions fabricated in this fashion are stable for many months at room temperature [3].

The FEBI process has been applied, both for SQUID fabrication and also in a demonstrator rapid single flux quantum (RSFQ) logic circuit [3]. However the FEBI technique is realistically limited to circuits consisting of fewer than 100 junctions and so alternative techniques will be required for large-scale circuit fabrication. Several groups

have recently demonstrated junction formation by masked ion damage (MID) in which ions from a broad beam ion source locally damage regions of superconductor to form the junction barriers, while the remainder of the circuit is protected by a mask which absorbs the implanted ions [4-6]. Although MID has the advantage that junction barriers are formed by a parallel, rather than a serial technique (as is the case for FEBI), the difficulties of preparing successful mask structures have meant the progress to date has been relatively slow.

Work elsewhere has largely focused on heavy-ion irradiation through organic masks to induce damage in the superconductor. In our work we have chosen to work with metal masks; high electron density metals such as Au have a much greater stopping power than organic resists and so reduce the depth of the slot which has to be milled in the mask. We also work with protons as the irradiating species, largely because they offer the closest similarity to electron irradiation [7]. Initial junction fabrication using this technique was limited both by the width of the slot in the mask structure, and by the spreading of the damaged area under the mask due to collisions with the side-walls of the mask structure [6]. This paper presents the latest results on MID junction fabrication with metal masks, including preliminary data on the effects of annealing on the junction properties.

II. JUNCTION FABRICATION

100nm thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) films were grown by laser ablation on SrTiO_3 substrates. These films were then coated with 450 nm of Au and patterned by conventional photolithography and Ar ion milling to create 2.5 μm wide superconducting tracks. The T_c of these tracks prior to further processing was at least 90 K. The thickness of the Au

Fig. 1. Secondary electron image from the FIB system of a metal mask showing the milled aperture for ion implantation.

^{*} Manuscript received September 18, 2000. This work was supported by the U.K. Engineering and Physical Sciences Research Council under grant No. GR/M84756.

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Fig. 2. Schematic diagram of the implantation process. The proton beam is aligned with the milled slot in the gold masking layer and inclined at an angle θ to the substrate normal.

masking layer was chosen to be sufficient to absorb the implanted protons, whilst ensuring that the slot which defines the junction barrier could be cut with sufficient accuracy. Simulations have shown us that scattering in the vicinity of the mask aperture leads to an effective ion range in the sidewall of the aperture which is considerably larger than for the mask in the absence of the aperture. For this reason, and because its processing is considerably simpler, we have switched to using a single Au-layer mask rather than the Nb/Au bilayer used previously [6].

To prepare these mask apertures, the patterned chip was mounted to a carrier to which electrical connection was made by Al wire bonds. This carrier was transferred to the focused ion beam system (FEI FIB 200). Using 30 keV Ga ions, 50nm-wide slots were milled in the Au (Fig. 1). Accurate control of the milling depth is achieved by the in-situ measurement of the track resistance during milling [8]; since the room-temperature conductance of the YBCO is negligible compared with that of the Au, the resistance increase during the milling is easily measured. Earlier experiments have shown that it is vital to avoid Ga-implantation of the YBCO which very strongly suppresses the superconducting properties; for this reason the milling depth was chosen so as to leave 30-40nm of Au at the base of the trench which is sufficient to absorb the implanted Ga.

Chips with their completed mask structures were transferred on their sample mounts to an ion implanter which has been equipped with a custom cryogenic stage. Through careful shielding and filtering of the signal lines we can accurately measure Josephson characteristics *in-situ*. By cooling the sample below T_c we can probe the electrical characteristics of the YBCO region, exposed by the slit, during implantation. Dosing can be controlled accurately by monitoring the resistance of the region at a given temperature and using the resistive transition as an endpoint. Proton irradiation was performed at an energy of 50 keV (in practice H_2^+ ions with an energy of 100 keV) with an angle (θ) of 15° between the incident beam and the sample normal to

Fig. 3. Junction properties as a function of ion dose measured in the implanter. (a) Dynamic resistance (dV/dI) versus temperature for four different implantation doses: $\times$ 1.7×10^{15} , $+$ 1.9×10^{15} , $\blacktriangle$ 2.5×10^{15} , $\circ$ 5×10^{15} cm $^{-2}$. (b) Critical current versus temperature for the same four implantation doses. (Inset) Critical temperature vs implantation dose for unmasked YBCO track (triangles) and junctions (circles).

eliminate ion channeling effects (Fig. 2). The following procedure was adopted to monitor and control the implantation process: the chips were cooled through the superconducting transition to ensure no change in the original T_c ; the samples were then held at a constant temperature of just above the desired T_c of the barrier; implantation was then performed while the junction resistance was monitored; tracking the resistance as a function of dose provides a qualitative check that the sample alignment was correct and that ions were reaching the YBCO track. Since detailed measurements could be taken in the implanter, implantation was periodically halted to allow current voltage characteristics to be recorded at different temperatures.

III. JUNCTION MEASUREMENT

Measurements in the implanter enable the junction properties to be determined without the complicating effects of subsequent annealing at room temperature or higher. Fig 3 shows how the resistance and critical current of a particular junction vary with temperature and successively increased implantation dose. It is evident that, as expected, the critical temperature of the junction is increasingly suppressed by ion irradiation and that the resistance of the barrier rises correspondingly. Like the FEBI junctions, MID devices show a rapid variation of critical current (I_c) with temperature. This

Fig. 4. Critical current (circles) and resistance (diamonds) versus temperature for two different junctions (open and closed symbols respectively). Data is plotted for the first measurement following removal from the implanter.

behavior is consistent with existing models of superconductor normal superconductor (SNS) junctions with soft boundary conditions [6, 9].

After removal from the implanter the current vs voltage characteristics of the junctions were measured over a range of temperatures in a test probe in He gas. Microwaves could be applied to assess the Shapiro step strength and modulation.

Fig. 4 shows the dependence of the critical current on temperature ($I_c(T)$) for two representative junctions on the same chip. The junction with the higher critical temperature (open symbols) shows a behavior which is very similar to that previously reported for devices made using a composite Nb/Au mask [6], in that the critical current rises very rapidly with decreasing temperature. The junction with the lower critical temperature (filled symbols) shows a more progressive increase in critical current and a resistance which is much more constant over the temperature range of the measurement. This device also shows RSJ-like behavior over a wider temperature range.

The steep $R(T)$ curve exhibited by the higher T_c junction is

Fig. 5. Current versus voltage for a junction at 55K under different intensities of microwave radiation.

Fig. 6. Critical current versus temperature for two different junctions (open and closed symbols respectively). Data is plotted for the first measurement following removal from the implanter (circles), after a three hour anneal at 100°C (squares), and following a further three hour anneal at the same temperature (diamonds).

typical for a barrier whose effective resistive length changes rapidly as a function of temperature: scattering of ions causes the barrier to have a graded distribution of T_c s both along the length and thickness of the track [1, 5]. Since they were on the same chip, both these devices received an identical implantation dose. The most likely reason for the difference in their behavior is that the degree of focus of the Ga-ion beam used to mill the mask varied from point to point on the substrate surface. The effect of a greater degree of defocus will be to broaden the milled trench and to reduce its depth; this in turn will reduce the ion dose experienced by the YBCO film beneath and increase the effective barrier width due both to the increased trench width and the increased ion scattering from the greater residual Au thickness at the base of the trench.

Fig. 5 shows a the current versus voltage characteristic of the junction with the lower T_c measured at 55K. The shape of the curve is consistent with the resistively-shunted junction (RSJ) model, with some excess current. The figure also shows the effect of applying microwaves: three Shapiro steps are clearly visible. Sensitivity to microwave radiation persists over a temperature range of approximately 10K below the junction T_c .

IV. THERMAL STABILITY

A potential problem of any device technology based on the damaging of a crystal lattice, is the thermal stability of the fabricated device. We have already shown that annealing takes place in the implanter at cryogenic temperatures [6], and there is a substantial difference in the junction properties measured in the implanter and when subsequently measured in a test probe have been stored at room temperature.

Following our previous work on FEBI junctions [1], we annealed our devices at 100°C for three hours and then re-measured them. Fig. 6 shows the effect on the $I_c(T)$ of the two junctions of Fig. 4 of two successive anneals of this type. In both cases, the effect of the first anneal is to substantially increase the T_c of the junctions. This is the effect expected,

Fig. 7. Current versus voltage for a junction following successive three hour anneals at 100°C. Left to right: no anneal (58K), after three hour anneal (64K), after a total of six hours (58K). The curves are displaced by 20 μ V for clarity.

since the higher temperature will anneal out a proportion of the damage caused by the implantation.

It is evident from Fig. 6 that the effect of a further anneal is not a simple continuation of this trend; the T_c does not increase further, but instead the slope of $I_c(T)$ changes so that a lower temperature is required to achieve the same I_c .

Examination of the junction current voltage characteristics shows that substantial changes occur between each of these anneals. Fig. 7 shows data for the lower critical current density junction before and following each of the two anneals. The temperatures have been chosen so that approximately the device show approximately the same I_c in each case. The device shows a systematic decrease in resistance and quality (as assessed by the degree of curvature at the critical current transition); following the second anneal the device no longer RSJ-like and shows no Shapiro steps. This effect is again evident following the second anneal for the higher T_c junction, but after the first anneal the junction quality (in terms of $I(V)$ and Shapiro step modulation) improved. There is thus a qualitative difference in the behavior of these two devices.

V. DISCUSSION

In our preliminary report of MID junctions fabricated with meal masks we showed that the damaged barrier was considerably longer than the physical mask width [6]. The detailed measurements of electrical properties as a function of dose presented in Fig. 3 enable us to provide a similar estimate for these new junctions. The inset to Fig. 3(a) shows that there is good agreement in the rate of T_c suppression with ion dose between long unmasked tracks and the junction. This allows us to use the accurately measured track resistivity to provide an estimate of the barrier resistivity for each dose. Relating the junction resistance to this resistivity allows a calculation of the electrical length (L) of the barrier for each device. For the low T_c junction shown in Fig. 4 L is approximately 70nm, rising to 100nm for the higher T_c device. The difference in L supports the suggestion given in section III that the difference between the devices is due to different focus accuracy. The value of L for these devices is

therefor shorter than the value reported for the previous masking technique of 110 nm. The results reported in this paper therefore represent an improvement in the MID fabrication process since our last report.

The similarity of the damage induced by proton and electron irradiation has already been commented on [7]. However, the annealing effects in these devices are more complex than observed with FEBI devices. We believe that the progressive deterioration in the properties of the lower T_c junctions is a consequence of the diffusion of Ga implanted into the residual Au layer. This is supported by the fact that those junctions most affected are those in which this Au layer is thinnest and hence in which the Ga has the shortest distance to diffuse.

VI. CONCLUSIONS

The greater stopping power of the Au is clearly one of the factors which has led to an improvement in device properties. The results of the experiments shown here imply that with a correctly focused beam and further refinement of the masking process, results comparable to the FEBI junctions are likely to be attainable.

ACKNOWLEDGMENTS

R.S. is grateful to the U.S. National Science Foundation for support.

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