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PHOTOLITHOGRAPHICALLY PATTERNED THIN-FILM MULTILAYER DEVICES OF $YBa_2Cu_3O_{7-x}$

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Abstract

We have fabricated thin-film $YBa_2Cu_3O_{7-x}$-$SrTiO_3$-$YBa_2Cu_3O_{7-x}$ multilayer interconnect structures in which each *in situ* laser-deposited film is independently patterned by photolithography. In particular, we have constructed the two key components necessary for a superconducting multilayer interconnect technology, crossovers and window contacts. As a further demonstration of the technology, we have fabricated a thin-film flux transformer, suitable for use with a Superconducting QUantum Interference Device (SQUID), that includes a ten-turn input coil with 6μm linewidth. Transport measurements showed that the critical temperature was 87K and the critical current was 135 μA at 82K.

Introduction

The vast majority of electronic circuits require a thin-film multilayer technology to provide interconnects between devices. In the context of superconducting devices,[1] there are two structures needed for a complete interconnect technology: (i) "crossovers" (two superconducting thin-film wires separated by an electrically insulating layer), and (ii) contacts (superconducting connections between different superconducting layers). In a previous publication,[2] we described crossovers in which two films of $YBa_2Cu_3O_{7-x}$ (YBCO) were isolated from each other by an intervening film of $SrTiO_3$ while retaining a high transition temperature (T_c). Subsequently, we fabricated multiturn coils[3] and flux transformers[4] suitable for coupling magnetic flux to thin-film high-T_c SQUIDs.[5] The success of the fabrication processes is due to the high degree of epitaxial growth exhibited by each layer.[6] In the original crossover process,[2] however, all three layers were deposited through shadow masks, and, in the coils,[3,4] only the last layer was patterned photolithographically. However, for most practical applications it is highly desirable to define each layer with photolithography so that one can "step and repeat" patterns with small or complicated features and achieve precise alignment of different layers. In this paper, we describe processes in which all three films are patterned independently by photolithography; as an example of this technology, we describe the fabrication of a flux transformer with $T_c \approx 87K$.

Photolithograpically Patterned Crossovers

There are two distinct problems that arise when one tries to use photolithography rather than shadow masks to pattern the lower layer of YBCO. First, while a shadow mask produces a line with rounded edges, photolithography followed by an etch tends to produce sharp edges that are more difficult to insulate. Second, we have found that exposure of the surface of YBCO to photoresist leaves a layer of contamination that often prevents the epitaxial growth of subsequent layers. We have found that both problems can be ameliorated by etching the surface in a 2% solution of Br in methanol.[7] This process removes the surface contamination and thins the film, thereby making insulation easier.

We now describe the process used to fabricate the crossover shown in Fig. 1, in which only the first YBCO film is patterned photolithographically. The films are deposited using *in situ* laser deposition onto cleaved and polished (100) MgO substrates.[2-4] After depositing approximately 300nm of YBCO with the substrate at 740°C, we remove the sample from the vacuum chamber and pattern it into a 100μm wide strip using standard photolithography and either a 0.1% nitric acid solution or an Ar ion mill (450 V, 1.5 mA/cm²) to etch the film. We strip the resist with acetone, immerse the substrate in the Br solution for up to 30s, rinse the substrate with methanol to stop the etch and blow it dry with N_2 before remounting it in the vacuum chamber. After evacuating the chamber with the substrate at 200°C, we rapidly raise its temperature to 690°C and deposit 600nm of $SrTiO_3$ through a shadow mask. We break vacuum to exchange targets and shadow masks, and, after a similar evacuation procedure, deposit approximately 400nm of YBCO. As we see in Fig. 2, the transition temperature of the lower YBCO film was 85K, the insulation between the lower and upper YBCO films at 77K was greater than 100MΩ at 77K, and the critical current of the lower film at the same temperature was 170mA, corresponding to a critical current density of 7×10^5 A cm^{-2}. The transition temperature of the upper YBCO film (not shown) was 87K. Thus, this process produces satisfactory crossovers on photolithographically patterned YBCO films.

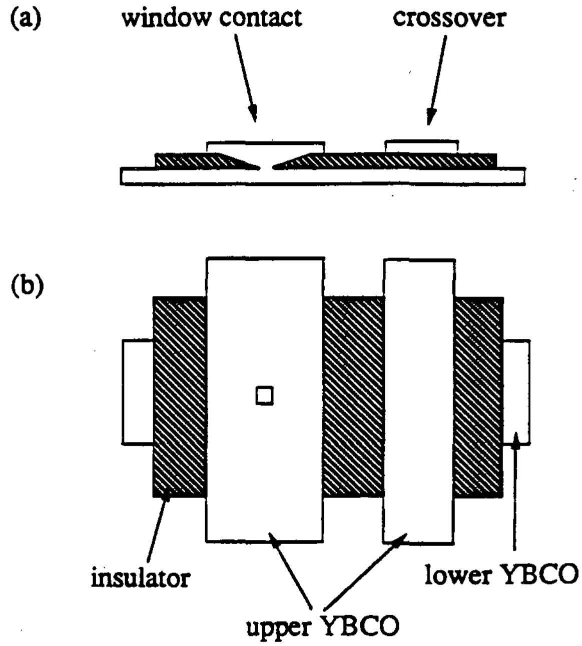

Figure 1. (a) Cross-sectional view and (b) top view of window contact (left) and crossover (right).

Window Contacts

The second structure needed for a complete interconnect technology is a superconducting contact. We have fabricated superconducting window contacts, that is, a superconducting connection between two YBCO films made via a window patterned in an intervening $SrTiO_3$ film (Fig. 1). Initially we had success fabricating window contacts using relatively thin insulating layers, 100nm or less. However, our first attempts to use thicker $SrTiO_3$ films were unsuccessful, presumably because the upper YBCO film was discontinuous at the edges of the window. Unfortunately, to make window contacts compatible with crossovers, the $SrTiO_3$ film has to be about 400nm thick. To remedy this problem, we have developed a technique for producing beveled walls in the windows in the $SrTiO_3$ layer, thereby obtaining a gently sloping surface that supports the subsequent growth of the upper YBCO film.

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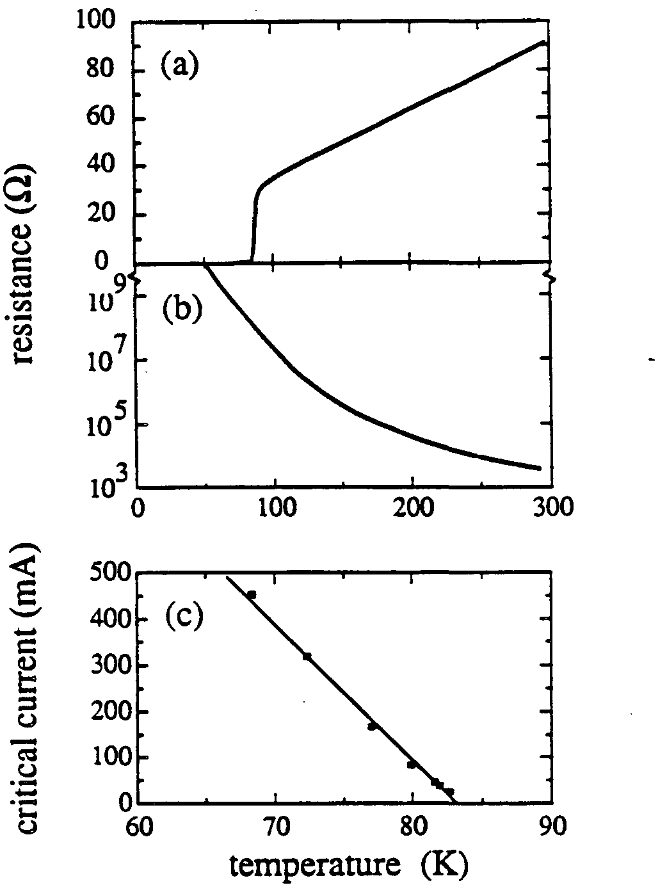

Figure 2. Crossover: (a) resistance vs. temperature of lower YBCO line, (b) resistance between $4 \times 10^4 \mu m^2$ of line and upper YBCO film, and (c) critical current of lower line 100μm wide and 0.3 μm thick.

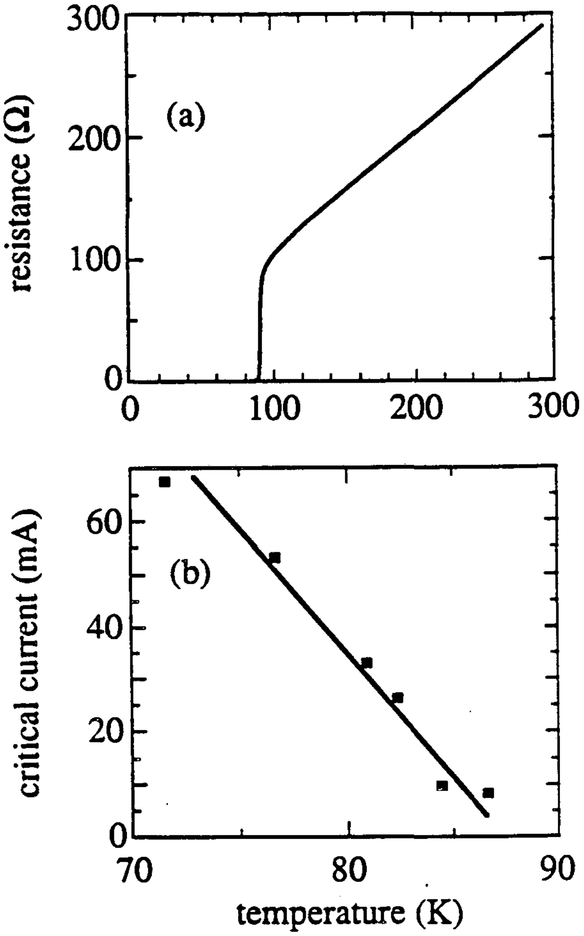

Figure 3. Window contact: (a) resistance vs. temperature and (b) critical current vs. temperature measured between upper and lower YBCO films through window in $SrTiO_3$.

Our procedure for constructing a window contact is as follows. We first deposit 300nm of YBCO and pattern it with either shadow masks or photolithography and a nitric acid etch, and clean the surface with the Br etch after stripping the resist. We then typically deposit 400nm of $SrTiO_3$ (less if the bottom layer has been patterned with a shadow mask) and spin on a relatively thick (2μm) layer of photoresist which is subsequently baked at 70°C. We expose the window pattern moderately out-of-focus and develop as usual. This produces a window in the resist with gently sloping walls. We then etch using an ion mill at 600V for up to 40 min, thereby cutting through the $SrTiO_3$ in the window to expose the lower layer of YBCO. We determine when to end the mill by careful examination of the window under a microscope: too little etching leaves an insulating layer, while too much can degrade the quality of the contact. We then finish by milling at 450V for a few minutes to reduce damage to the exposed YBCO. This process leaves beveled walls in the window in the $SrTiO_3$, the steepness of the slope being determined by the relative etching rates of the photoresist and the $SrTiO_3$ and the initial slope in the resist walls. Finally, we deposit 400nm of YBCO for the upper layer, and pattern with the ion mill or chemical etch.

We note that we do not use the Br etch after cutting the $SrTiO_3$ window because it tends to remove YBCO under the $SrTiO_3$ layer. We believe that this undercutting prevents the growth of a good superconducting connection between the upper and lower YBCO films. Despite the fact that the exposed surface of the lower layer of YBCO must be damaged by the mill, we have found it is possible to achieve good contacts, presumably because the surface damage is annealed out during the deposition of the last YBCO layer.

Figure 3(a) shows resistance vs. temperature for a contact, measured between the upper and lower YBCO films; the transition temperature was 87K. This contact was 9 x 15 μm^2, and the lower YBCO layer was patterned using a shadow mask while the 70nm thick $SrTiO_3$ layer and the upper YBCO layers were patterned photolithographically. Figure 3(b) shows the critical current of the contact vs. temperature, measured with a 10μV criterion; the value at 77K is 53mA. The corresponding critical current density of the $135 \mu m^2$ contact would be $4 \times 10^4 Acm^{-2}$; however, it is almost certain that the critical current was limited by the 9μm wide YBCO film leading to the upper part of the contact, since there the current density corresponds to $1.6 \times 10^6 Acm^{-2}$.

Photolithograpically Patterned Flux Transformer

In general, one would like to be able to incorporate both photolithographically patterned crossovers and window contacts in the same circuit. To demonstrate that this is possible, we fabricated thin-film flux transformers with small 10-turn input coils (see Fig. 4). The first layer of YBCO, 300nm thick, is patterned as shown in Fig. 4(a) to form a strip or "crossunder" that eventually will contact the innermost turn of the input coil. We pattern the 400nm thick $SrTiO_3$ film to produce two windows, one on each end of the crossunder, using the procedures described above. Finally, we deposit and pattern the top YBCO layer, which is also 400nm thick, to form the spiral input coil and the pickup loop shown in Fig. 4(b). The inner end of the spiral coil and the end of the pickup loop are aligned to contact the lower YBCO layer through the windows. A photograph of a completed input coil is shown in Fig. 5; the linewidth of the turns is 2-3μm. The smaller linewidth was due to undercutting during the acid etching of the upper layer; the same photomask yields a 6μm linewidth with ion milling.

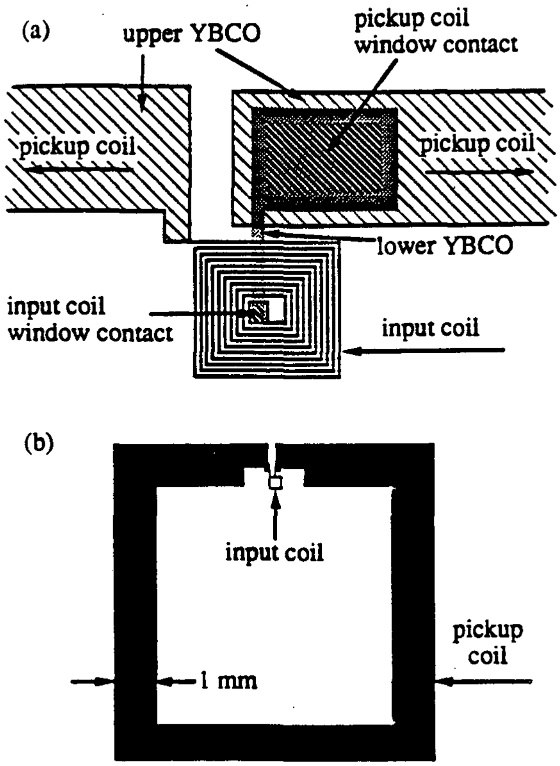

Figure 4. Flux transformer: configurations of (a) input coil and connections to pickup loop, and (b) pickup loop (not to scale).

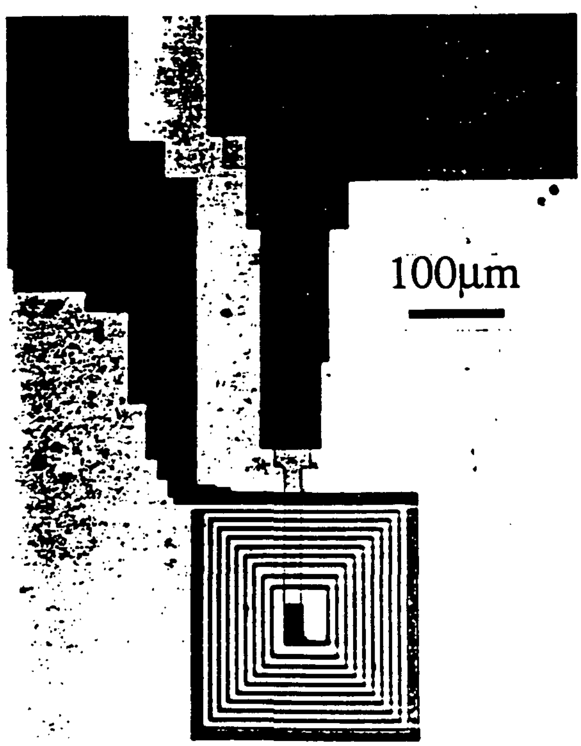

Figure 5. Photograph of 10-turn input coil patterned as in Fig. 4(a).

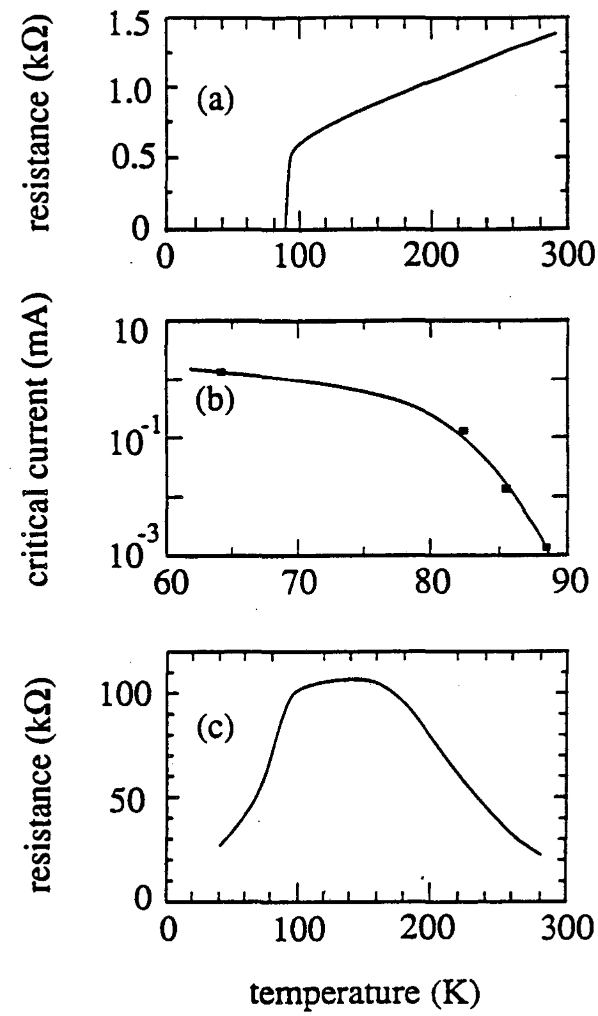

Figure 6. Input coil: (a) resistance and (b) critical current of input coil vs. temperature; (c) resistance between turns of input coil and crossunder vs. temperature.

Figures 6(a) and 6(b) show resistance and critical current vs. temperature for a transformer in which we had cut open the pickup loop. The transition temperature was 87K, and the critical current was 135μA at 82K (5μV criterion); the corresponding critical current of the 6μm-wide turns of the input coil was about 3 x $10^4 Acm^{-2}$. We subsequently opened the innermost turn of the coil as well and measured the insulation between the lower and upper YBCO films. The resistance decreased as the temperature was lowered below T_c [Fig. 6(c)], possibly because of poor coverage of one or more edges of the lower YBCO layer by the $SrTiO_3$. Nonetheless, the resistance of about 60kΩ at 77K is more than adequate for this application.

Concluding Remarks

In summary, we have demonstrated the fabrication of superconducting multilayer crossovers and window contacts using photolithographic patterning of each layer. Although the procedures have proved adequate, some improvements could undoubtedly be made: for example, the degree of thinning and any edge-smoothing produced by the Br etch is not very easily controlled. In addition, we should emphasize that most of the parameters such as layer thicknesses and etching times have not been optimized. Furthermore, the relatively low resistance of the insulation shown in Fig. 6(b) is probably due to poor edge coverage, indicating that our process needs refining. Nonetheless, our results demonstrate that it is now possible to fabricate relatively complicated superconducting interconnect structures from YBCO.

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