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Submicron Superconducting Lines Fabricated from Sputtered Y-Ba-Cu-O Films

H. Tsuge, S. Matsui*, N. Matsukura, Y. Kojima* and Y. Wada

Microelectronics Res. Labs., Fundamental Res. Labs.*, NEC Corporation

4-1-1 Miyazaki, Miyamae-ku, Kawasaki 213, Japan

High-Tc superconducting lines, as narrow as 0.8 μm, have been fabricated from Y-Ba-Cu-O films. The films were prepared on MgO (100) substrates heated at 690°C by rf magnetron sputtering. The lines were patterned using ion-beam etching and focused ion-beam lithography. The resulting superconducting lines, 0.8 μm wide and 2 mm long, showed a zero resistance temperature of 61 K and a critical current density of 4.1×10^3 A/cm^2 at 50 K with smooth surfaces.

1. INTRODUCTION

Since the discovery of compound oxide[1,2] with high superconducting transition temperature,Tc,, tremendous efforts have been made to produce thin films with Tc near bulk values. To date, high-Tc films have been fabricated using various methods involving magnetron sputtering[3-5] and e-beam evaporation[6-9]. This result suggests the possibility of electronic applications of these thin films. For realizing such applications, it is also necessary to develop appropriate microfabrication techniques. These films have been patterned mainly by wet etching[10,11] and laser etching[12], which are not easy to use for making fine patterns. In a previous report[13], the authors proposed a reactive ion-beam etching using Cl_2 as an useful patterning technique for Y-Ba-Cu-O films. Though an enhancement in sputtering yield was observed, the etching selectivity to a resist mask seemed to be insufficient for microfabrication in this stage.

This paper reports a microfabrication process for high Tc films, using ion-beam etching and focused ion-beam (FIB) lithography. In addition, this process has been used to fabricate submicron Y-Ba-Cu-O superconducting lines with millimeter order length. Well-defined high-Tc lines with a smooth surface have been achieved by low temperature annealing of as-deposited crystalline films after patterning.

2. FILM PREPARATION

Thin films were deposited on MgO (100) substrates by rf magnetron sputtering using a sintered Y-Ba-Cu-O target. The film composition was controlled by putting Y and/or CuO pellets on the target in order to produce stoichiometric $YBa_2Cu_3O_{7-y}$. The sputtering was carried out at a substrate temperature of 690°C in a total sputtering pressure of 2.7 Pa using an Ar - 60% O_2 mixture. The deposition rate was kept to 9.7 nm/min and typical film thickness was 0.8 μm. These deposition conditions were determined to obtain as-deposited high-Tc films with smooth surfaces, which were particularly important for fabricating fine superconducting lines. The resulting films had a zero resistance temperature,Tc(R=0), of 72 K with the grain size of several hundred nm diameter. X-ray diffraction analysis showed that an a-axis was dominantly oriented, normal to the film plane. When the film were annealed in flowing O_2 at 800°C for 3 hours, followed by furnace cooling to room temperature, the Tc(R=0) was improved up to 82 K, without any marked change in grain size and preferred orientation.

3. ION-BEAM ETCHING

Figure 1 shows the etch rate versus ion-beam incident angle in ion-beam etching for Y-Ba-Cu-O. The etching conditions were 2.7×10^{-2} Pa Ar pressure, 1 mA/cm^2 current density and 500 V acceleration voltage. The dependence providing the maximum etch rate at 40-50° is similar to that for many other oxides. A 20° incident angle was selected due to the ability of highly accurate patterning. The pattern width gain, caused by redeposition effects, was about 40 % of the etched film thickness. The etch rate for Y-Ba-Cu-O,

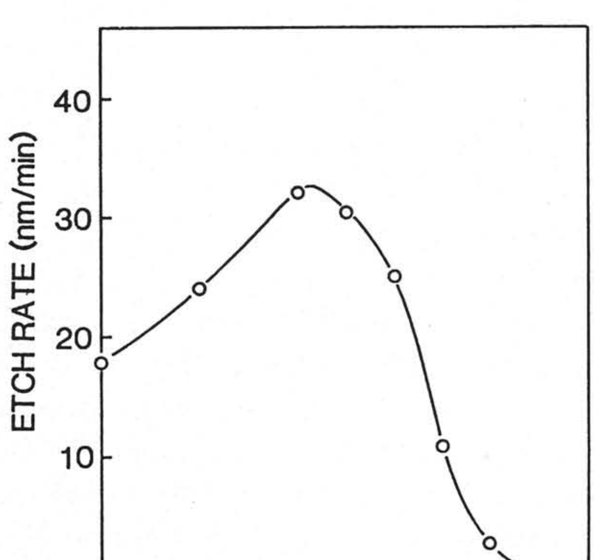

Fig. 1. Etch rate dependence on ion-beam incident angle in ion-beam etching for Y-Ba-Cu-O.

Table I. Etch rate and etch rate ratios for Y-Ba-Cu-O to the other materials in 20° incident angle.

Material	Y-Ba-Cu-O	CMS	MgO
Etch rate (nm/min)	24	16	13
Etch rate ratio Y-Ba-Ca-O/M	-	1.5	1.8

CMS(chloromethylated polystyrene) and MgO, and the etch rate ratios for Y-Ba-Cu-O to the other materials are listed in Table I, wherein CMS is a masking material and MgO is an underlayer material during Y-Ba-Cu-O etching. The etch rate for Y-Ba-Cu-O is reasonably high for practical use. The etch rate ratios indicate that CMS and MgO can act as a masking material and stopper, respectively, for Y-Ba-Cu-O etching.

4. SUPERCONDUCTING LINE

Superconducting lines were fabricated in the following process. A 1.0-µm-thick CMS resist, spun on a 0.8-µm-thick as-deposited film, was exposed at 1×10^{13}/cm^2 by 260 keV Be^{++} FIB. Developing and rinsing of the resist were carried out with an organic solvent instead of a water based substance, which would have damaged reactive Y-Ba-Cu-O supercoductors[14]. The film was patterned by ion-beam etching with the CMS mask, followed by O_2 plasma etching to remove the mask. The superconducting lines were completed with annealing in flowing O_2 at 800°C for 3 hours. The line width for evaluated superconducting lines was in the range of 0.5-20 µm in resist mask size. Line length was 2 mm. Electrical properties were measured using a usual four-probe method.

Figure 2 shows micrographs of a Y-Ba-Cu-O superconducting line. Line width is 0.8 µm

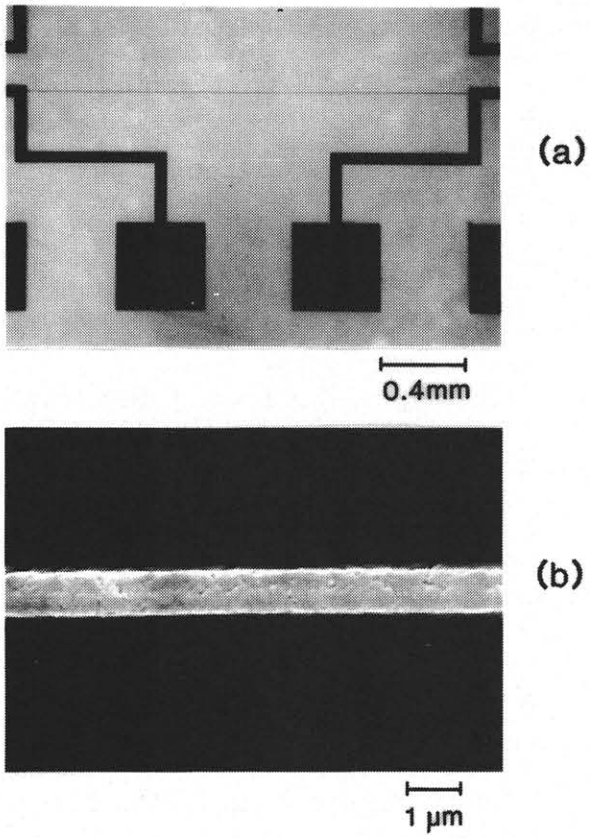

Fig. 2. Micrographs of a superconducting line, 0.8 μm wide and 2 mm long.
(a): Overall view of the line, (b): Line details.

and line length is 2 mm. The SEM micrograph shown in Fig.2(b) indicates that the line is well defined with a smooth surface and a sharp edge along the line. The Tc(R=0) for the line was 61 K. Almost the same values were reproducibly obtained for the same dimensions. The Jc values were 2.7×10^4A/cm^2 at 4.2K and 4.1×10^3A/cm^2 at 50 K. These superconducting characteristics were found to be affected by the line dimensions. Figure 3 shows the resistive-to-superconducting transition for lines with various line widths. The resistive transition shifts toward lower temperatures by using a patterning process and with decreasing line width. In particular, the "tail" observed near Tc(R=0) becomes marked with narrow lines. The Tc versus line width is indicated in Fig.4. The Tc starts to decrease from 10 μm with

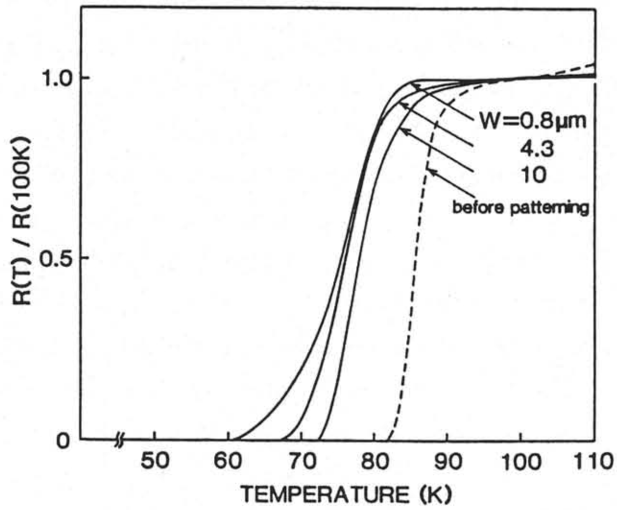

Fig. 3. Resistive transition for individual lines with different widths. The dashed line curve shows data for film prior to patterning.

decreasing line width, resulting in 61 K for 0.8 μm, which is the minimum width used in this experiment. The degradation from the patterning process is mainly caused by contamination from the lithography process. Moreover, it was found that the degree of the degradation was strongly dependent on original film quality. Such apparent reduction in Tc by patterning process, as seen in Fig.3, was not

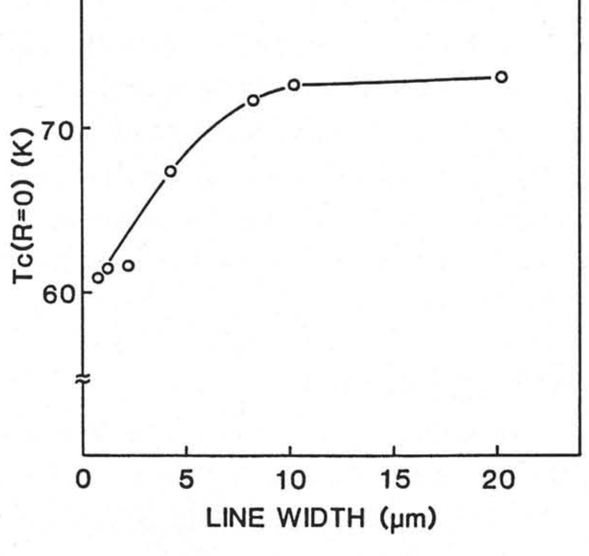

Fig. 4. Zero resistance temperature, Tc(R=0), vs line width.

observed for single-crystal-like Y-Ba-Cu-O films developed recently in our laboratory. Superconducting lines prepared from these films hardly showed any significant Tc change depending on the line width in the range of 1.2 - 20 μm. These results suggest that grain boundaries are selectively damaged during lithography process, resulting in the Tc reduction. Tc dependence on line width shown in Fig.4 can be also explained by considering lateral contamination through grain boundaries, which takes place during developing and rinsing. This fact shows that properties for submicron order superconducting lines are expected to be greatly improved by using single-crystal-like films with few grain boundaries in stead of polycrystalline films.

5. CONCLUSIONS

A microfabrication process, using ion-beam etching and FIB lithography for high-Tc films, has been developed. This process has been applied to fabricating submicron Y-Ba-Cu-O superconducting lines with millimeter order length. Superconductivity for the line was improved, without any marked change in film structure, by low temperature annealing of as-deposited crystalline films after patterning. The superconducting lines, 0.8 μm wide and 2 mm long, showed a zero resistance temperature of 61 K and a critical current density of 4.1×10^3 A/cm^2 at 50 K. In addition, it was found that the degradation in superconducting properties by patterning was primarily due to damages in grain boundaries, caused by the lithography process.

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