CRITICAL CURRENTS IN SUBMICRON $YBa_2Cu_3O_7$ LINES

H. Assink, A.J.M. v.d. Harg, C.M. Schep, N.Y. Chen, D. v.d. Marel, P. Hadley, E.W.J.M. v.d. Drift, and J.E. Mooij
Delft University of Technology, Faculty of Applied Physics, Lorentzweg 1, 2628 CJ Delft, The Netherlands

Abstract-- Lines in $YBa_2Cu_3O_7$ with widths down to 200 nanometers and properties comparable with the original film, have been defined using electron beam lithography and plasma etching. One predicted property of lines smaller than the magnetic penetration depth is an increase in the critical current density due to pinning of the vortices at the edge of the sample. There have been several reports of experimental observation of edge pinning in narrow $YBa_2Cu_3O_7$ lines. We present systematic measurements of narrow lines that should be far into the edge pinning regime. Nevertheless no increase of critical current density is observed in the smallest lines.

I. INTRODUCTION

The critical current that is typically observed in thin film samples is the depinning critical current. In other words a voltage appears when pinned vortices start to move across the sample. When lines are patterned narrower than the penetration depth, a different mechanism starts to determine the limiting critical current. This mechanism, called edge pinning, is caused by the pinning of vortices at the edges of the sample [1,2]. In this paper we present a systematic study of the critical current as a function of the width of $YBa_2Cu_3O_7$ lines. In contrast to previous experiments, [3,4] no increase in critical current density as a function of linewidth was observed.

II. SAMPLE PREPARATION

Thin films (50 nm) of $YBa_2Cu_3O_7$ were grown on $SrTiO_3$ [100] substrates by pulsed laser ablation. During deposition the substrate temperature was maintained at 750 °C and the oxygen pressure was 750 mTorr. The laser power density at the target was 3 mJ cm^{-2}. The films thus produced are predominantly c-axis oriented. The critical temperature of the films is typically 91 K with a transition width of 2 K. The resistivity is typically 300 $\mu\Omega$cm at 100 K.

Silver contact pads were defined on the film using a lift-off process. Lines in the $YBa_2Cu_3O_7$ were patterned by electron beam lithography and sputter etched using argon in an electron cyclotron resonance plasma etcher. During etching the sample was RF-biased at a voltage of -250 V. This resulted in an etch rate of about 30 nm/min.

III. RESULTS

One hundred twenty eight lines, with eight different widths in the range 200 nm to 2 μm, were patterned on a single substrate. To test the uniformity of the lines, the resistivity of all the lines were measured at room temperature. The average value of the resistance and its standard deviation are shown in Fig. 1. All the lines were defined to be twenty times longer than wide. Therefore the lines should have the same resistance. However, there is a slight increase in the resistance for the narrowest lines. This can be a result of damage that occurs to the edges of the lines during processing. We fit the resistivity to the data by assuming that, due to processing, all of the lines were smaller than their patterned widths by an amount, Δd. The resulting room temperature resistivity is 890 $\mu\Omega$-cm with a relative accuracy of 2.5%. The damaged portion, Δd, is found to be 36 nm with a 95% certainty interval of 0 to 44 nm. This width of the damaged portion is four times smaller the resolution for ion milling of $YBa_2Cu_3O_7$ reported by Fong *et al.*[5].

Figure 2 shows the resistivity as a function of temperature for several of the lines. It shows that the narrow lines have approximately the same critical temperature and resistivity as the wider lines. The critical temperature of the widest lines is 88 K, the 300 and 200 nm wide lines have a T_c of 87.5 and 87 K respectively. The narrowest lines however, tend to have a longer resistive tail; the 200 nm line did not become completely superconducting until 72 K.

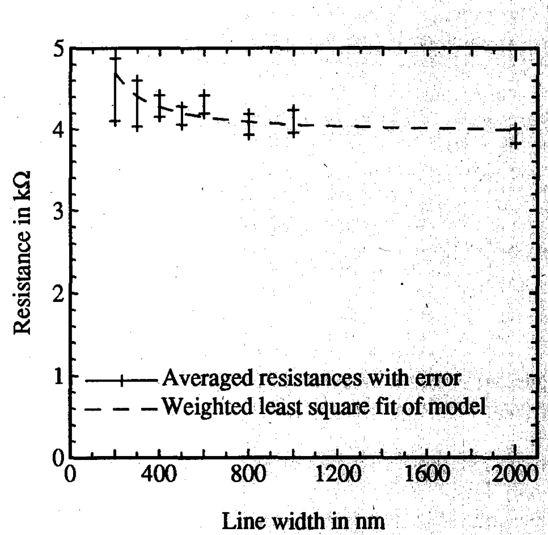

Fig. 1 The resistance of lines of several widths, averaged over sixteen measurements each. Each line is twenty times longer than it is wide. The 95% certainty intervals are shown as well as a weighted fit through these points according to the model of process induced narrowing (see text).

Manuscript received August 24, 1992.

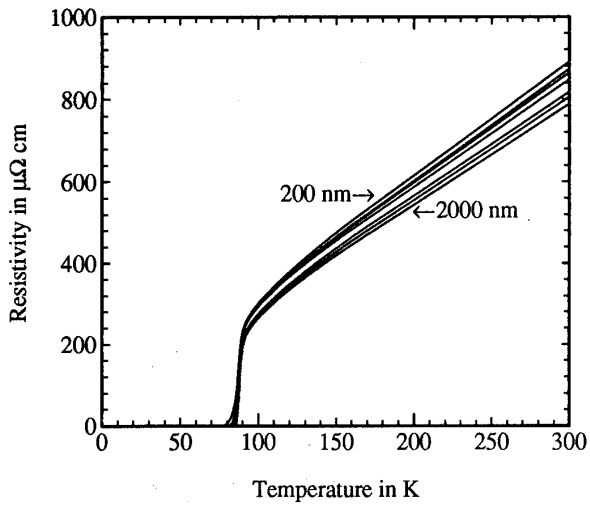

Fig. 2 A typical plot of resistivity as a function of temperature for eight lines of different widths. In this case the line with the highest resistivity was the 200 nm line and the line with the lowest resistance was the 2 μm line. As is shown in Fig. 1, on average the narrower lines tend to have a slightly higher resistance.

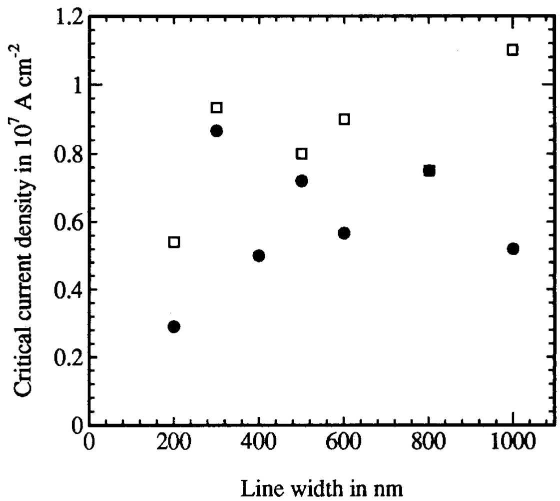

Fig. 3 The critical currents of the lines of two sets of lines. Each set consists of lines of 200 nm, 300 nm, 400 nm, 500 nm, 600 nm, 800 nm, 1000 nm, and 2000 nm. The filled circles are the Jc measurements for one set of lines and the open squares are another set of lines on the same substrate. No systematic increase of J_c is observed as the linewidth decreases.

Between the measurements the samples were stored in air. We wanted to investigate how the lines degraded and if narrower lines degraded faster. In order to do this, we measured the temperature dependence of the resistance of a set of lines every week. There was no change in critical temperature but the resistance of the lines increased approximately 5% per week. The slope of the curves, $d\rho/dT$ (between 130 and 300 K) showed even less change (10% increase in five weeks). The narrower lines did not significantly degrade faster than the broader lines.

IV. DISCUSSION

In an anisotropic material such as $YBa_2Cu_3O_7$ the penetration depth depends on the orientation of the crystal with respect to the magnetic field. For bulk samples the penetration depth has been measured to be λ_{ab}=140 nm and λ_c=700 nm [6]. In thin films the effective penetration depth can be longer than is measured in the bulk. The effective penetration depth for films thinner than the bulk penetration depth is,

$$\lambda_{\perp}=\frac{\lambda_{Bulk}^2}{d} \tag{1}$$

where d is the thickness of the film [7]. For c-axis oriented films such as the ones that were used in this study the relevant bulk penetration depth is λ_{ab}. In our case the effective penetration depth is about 400 nm and the narrowest lines are well into the region where edge pinning should be observed. The measurements, however, do not agree with the predictions of the edge pinning model. The critical current densities of thirteen lines measured at 4.2 K are shown in Fig. 3. The current densities were calculated using the patterned widths of the lines. There are measurements on two different lines for each of the seven line widths. Although there is considerable scatter in the data there is no systematic increase of J_c as the line width decreases. The spread in J_c is greater than the spread in resistance because resistance averages over the whole line while the J_c is sensitive to the weakest point. The averaged critical current density of one pattern is higher than the other. This could be due to a different composition or a different film thickness at the location of the two patterns. The lines of one pattern are very close to each other (within 0.1 mm) while the two patterns themselves are about 2 mm from each other.

The edge pinning model assumes a homogeneous superconductor, with no loss of quality near the edges. It is possible that damage at the edges of the lines that is caused by processing changes the boundary condition at the edge and this suppresses the edge barrier. Another possibility is that the lines are not homogeneous and that the vortices are crossing at some weak points in the lines. This later possibility is supported by the current-voltage characteristics of the lines.

The current-voltage curve for a 200 nm line is shown in Fig. 4. All of the lines showed similar behaviour. At large

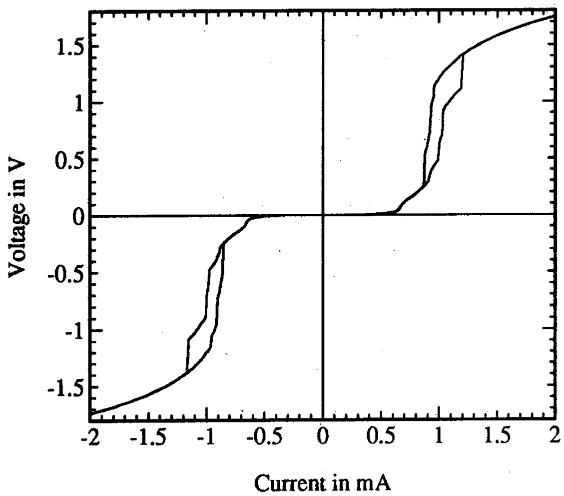

Fig. 4 The voltage as function of current for a 200 nm wide line. This I-V curve is typical for all the lines, showing hysteresis and steps at higher voltages.

bias the voltage increases in several steps indicating that the voltage appears at discrete points along the lines. The hysteresis observed in these lines has also been observed in grain boundary junctions and in low T_c microbridges but the cause of the hysteresis in either case remains unclear. If they are grain boundaries then they must be low angle grain boundaries due to the magnitude of the critical current densities observed here [8]. However, the critical currents of grain boundary junctions are strongly affected by weak magnetic fields [9]. The critical currents of the lines measured here were about two thirds of their zero field values at a field of 0.6 T. At low voltages there is a nonhysteretic region of the curve. This suggests that flux flow is the mechanism producing the voltage in this region.

V. CONCLUSIONS

We have patterned lines down to 200 nm which have approximately the same superconducting properties as the original film. These lines are much narrower than the effective penetration depth and edge pinning models predict that there should be an increase in the critical current density for the narrowest lines. No such systematic increase of the critical current density has been observed.

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