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Imaging the Current Density in Superconducting Thin Films

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Abstract. In this paper we describe an imaging technique in which heat pulses are used to probe the current distribution in superconducting thin films. We have used the technique to study tin films having a thickness comparable to the penetration depth and have found evidence for an enhanced current density at the film edges. We observe that the width of the edge current tracks is $\propto 1/d$, where d is the film thickness.

Introduction

The discovery of high T_C superconductivity has stimulated renewed interest in the properties of superconducting thin films and 2-D superconductivity. One question, still to be fully answered, concerns the distribution of current in such systems. Consider a homogeneous film having thickness d, width w and penetration depth λ. It is expected that if $d \leq \lambda$ and $wd \gg \lambda^2$, the current is confined to strips of width approximately equal to the in-plane magnetic screening length at each edge of the film [1]. According to Pearl, who described the superconducting properties of thin films in terms of vortex motion, the appropriate screening length L_S is given by $L_S = 2\lambda^2/d$ [2]. Experimental evidence for an enhanced current density at the edges was obtained by probing the magnetic field close to a current carrying film [3]. However, the spatial resolution of this technique was not very high and so it was not possible to determine the width of the current tracks. We have developed an imaging technique for probing the large scale inhomogeneities in the superconducting properties in high T_C superconducting films. In the case of a homogeneous film the technique is able to give information regarding the current distribution in the film. We have used it to probe the current density in tin films having a thickness comparable to the zero temperature London penetration depth.

Imaging Technique

Figure 1 shows the imaging system. The tin films, thicknesses 50, 100 and 200nm, were vacuum evaporated onto 380μm thick polished silicon substrates. Contacts were formed at each end of the film defining a 5mm x 5mm active area. A layer of constantan was evaporated onto the opposite side of the silicon wafer. The sample was mounted in a helium cryostat with optical access and maintained at a temperature close to the film's superconducting transition, 3.6K. Laser pulses, duration 100ns and peak energy 0.5mJ, produced by a Q-switched Nd-YAG laser were focused onto the constantan film in which they are thermalised raising the temperature to about 10K in a region about 50μm across. This generates a burst of nonequilibrium acoustic phonons which traverse the substrate and are incident on a small area of the tin film ($\approx$200μm across) raising its temperature by about 6mK. The resulting change in resistance of the film is detected by passing a constant bias current through the film and monitoring the voltage transient across it. The signal is averaged and its intensity measured using a boxcar integrator. To obtain maximum resolution, the timing of the boxcar gate was set to select only that part of the signal due to ballistic phonon modes propagating directly across the substrate. A full 2-D image is made by raster scanning the laser over the sample by means of a pair of computer-controlled galvanometer mirrors and recording the signal intensity as a function of beam position. The advantage this phonon probe technique has over other scanning methods in which a laser is used to probe the superconducting film directly [4] is that optically induced pair breaking is avoided.

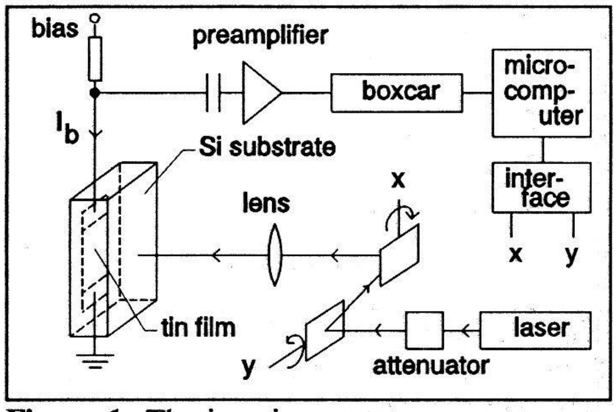

Figure 1 The imaging system

Results and discussion

Figure 2 shows a full image of the d=200nm film at a temperature near the bottom of the superconducting transition and at a bias current, I_b=0.5mA (this is below the critical current density measured in [1]). Assuming that the film is homogeneous with regard to its superconducting properties (the film edges were trimmed to remove any tapering), the voltage signal is given by $\delta V(x,y)=J(x,y)(dR/dT)\delta T$. Where J(x,y) is the current density in the film and dR/dT its temperature sensitivity. Therefore, the strong response from the edges of the film in figure 2 indicates that the current density is higher in those areas. Similar results were obtained with the 50 and 100nm films as shown in the linescans, figure 3. In each case $T \approx T_C$ and I_b=0.5mA. It is clear, however, that as d is reduced the current tracks widen. Allowing for the finite size of the probe beam, the current density falls to 1/e of its maximum value, at the edge, at approximately 150/d mm in from the edges, where d is in nm. This result implies a bulk penetration depth $\lambda \approx 7\mu m$ which is considerably larger than might reasonably be expected. Using the normal expression for the temperature dependence of λ, that is $\lambda(T)= \lambda_0(1-t^4)^{-1/2}$, where λ_0 is the zero temperature London penetration depth and $t=T/T_C$, we find that T must be within < 1mK of T_C to give $\lambda(T)=7\mu m$. This is much smaller than the range of temperature over which the edge effects can be observed. The edge tracks were observed to widen as the temperature is increased, eventually becoming smeared out near the top of the transition curve. The wide edges are consistent with the results of [4] in which no edge effects were seen in 50μm wide films. One possible explanation is that the current tracks take up a sufficient width of the sample to keep the current density below its critical value, J_c. This is consistent with our observation that the current tracks widened as I_b was increased. However, it also suggests that J_c is about 2.5×10^6 Am^{-2}, some four orders of magnitude less than measured in [1] (although it should be remembered that in [1] it was *assumed* that the current flowed in edge tracks of width $\approx \lambda$). Such a low value of J_c may be a result of working at temperatures close to T_C, or it could be due to the microscopic properties of the film: Electron microscope pictures show the films to be composed of small grains, approximately 5μm across, joined by weak links.

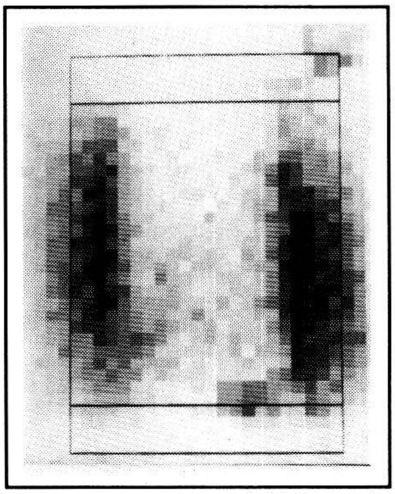

Figure 2 Image of 200nm tin film at a temperature close to the bottom of the superconducting transition. Film current, I=0.5mA.

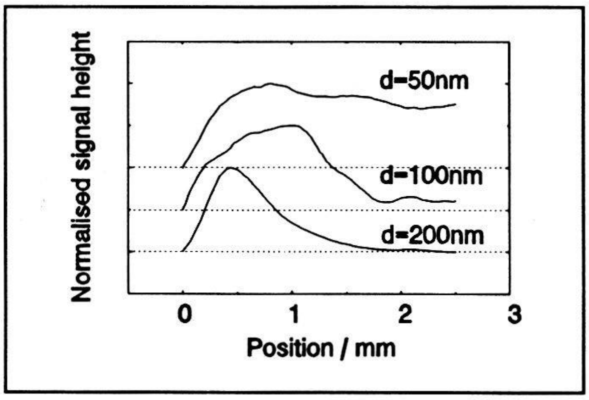

Figure 3 Linescans of 50, 100 and 200nm films. The scans were taken horizontally half way through the centre of the films, starting at the left hand edge. In each case $T \approx T_C$ and I_b=0.5mA.

Acknowledgements

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