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Title: MEASUREMENT OF PENETRATION DEPTH λ(T) in $YBa_2Cu_3O_{7\text{-DELTA}}$ THIN FILMS

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Measurement of penetration depth $\lambda(T)$ in $YBa_2Cu_3O_{7-\delta}$ thin film

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We present the magnetic penetration depth $\lambda(T)$ in two laser ablated $YBa_2Cu_3O_{7-\delta}$ thin films, determined by the two-coil method. The slope of $1/\lambda^2(T)$ near T_c, the only exactly measurable quantity, extrapolates to 930Å at $T=0$, which compares well with 830Å in the high quality single crystal recently reported by Hardy *et al.*, and which exhibited a linear T dependence at low T. For $T < 30K$, we find $\lambda(T)/\lambda(0)-1 = a(T/T_c)^2$ where $a = 0.5$.

1. INTRODUCTION

$\Delta\lambda(T) = \lambda(T)-\lambda(0)$ at low T measures the number of thermally excited quasiparticle and therefore can show the minimum in the gap function $\Delta(k)$. In BCS superconductors, $\Delta\lambda(T)$ is almost constant below $0.2T_c$. In high-T_c superconductors, $\Delta\lambda \propto T^p$ at low T has been observed by several groups,[1-4] and a linear dependence in single crystal $YBa_2Cu_3O_{7-\delta}$ has also been recently reported.[5] There is a current trend to interpret these results as the existence of an unconventional (non s-wave) order parameter in the high-T_c cuprate superconductor.[5,6] In this paper, we examine the similarities and differences between film and crystal data in an effort to resolve the discrepancies currently in the literature.

2. EXPERIMENT

Our two laser ablated $YBa_2Cu_3O_{7-\delta}$ thin films are circular, with diameters of 2cm and 2.2cm and thicknesses of 330Å. Sample A has J_c $10^7A/cm^2$ at 4.2K, T_c 88.5K, and transition width 0.2K; sample B has J_c $10^6A/cm^2$ at 4.2K, $T_c =$ 88.0K, and transition width 1K.

We determine λ from the mutual inductance of two coils on opposite sides of the film.[7] The maximum induced supercurrent in the film is $4x10^4A/cm^2$. To obtain λ, we model numerically the induced voltage in the pickup coil, $V_p(\lambda)$, as a function of λ. The measured voltage at a given temperature is mainly from the pickup coil but it has small contribution from other parts of the circuit. So it is denoted as $V_p(T) + C$. C is independent of T and is known to be about as big as $V_p(0)$. We extract $\lambda(T)$ by choosing C, then comparing the numerical $V_p(\lambda)$ with the measured $V_p(T)$. While physically reasonable choices for C are restricted, different choices of C influence the deduced T dependence of λ. Hardy et al. measured $\Delta\lambda(T)$ directly and had to choose $\lambda(0)$ to get $\lambda(T)$, which has an analogous effect on the deduced T dependence of λ.

3. DATA

When C is chosen so that our two films have the same $\lambda(0)$ 1800Å, then the $\lambda(T)$'s are essentially identical, demonstrating good reproducibilty. This is somewhat surprising since sample A had a J_c 10 times larger than sample B and there were no visible scratches in sample B. Apparently, some sort of flaw limits J_c without influencing λ. Thus, we believe that our $\lambda(T)$ is intrinsic to $YBa_2Cu_3O_{7-\delta}$ grains.

We chose C so that our $\lambda(0)^2/\lambda(T)^2$ would be similar to what Hardy *et al.*[5] obtained with the choice $\lambda(0)$ 1500Å. Figure 1 shows our data for A and B, which overlap almost completely with each other. The open circles are from Hardy et al. Note the similar flat portion between 30K and 50K in

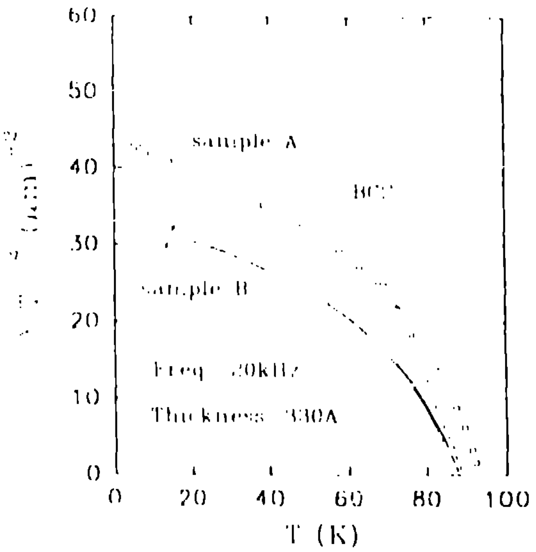

Figure 1. $1/\lambda(T)^2$ vs. T for the two $YBa_2Cu_3O_{7-\delta}$ films A and B. Circles indicate single crystal data from Hardy *et al.*. BCS is drawn in dashed line as a reference.

both sets of data. When the crystal and film data are both plotted as $\lambda(0)^2/\lambda(T)^2$, there are essentially identical except below 30K, where the film data curve and the crystal data maintain their linearity. The other difference between the two results is that the slope of $1/\lambda^2$ near T_c for the crystal is 20% larger than for the films, consistent with the differences in λ(0)'s. This is a real difference, which is not affected by the choice of fitting parameters C or λ(0) in the respective analyses.

$\Delta\lambda(T)$ has T^2 dependence for $T < 30K$ in our films. This might be the crossover temperature expected in a disordered *d*-wave superconductor.[8-10] The exponent of 2 in "T^2" is independent of the fitting parameter, C, because any change in voltage in the pickup coil comes entirely from the change in λ, so they are proportional to each other.[1] The raw data also show T^2 dependence. Quantitatively, with C chosen so that $\lambda(0)$ 1800Å, the size of the T^2 term is $\Delta\lambda \quad 0.5\lambda(0)T^2/T_c^2$.

Finally, we note that the slightly larger λ in films relative to crystals could be caused by a very small amount of disorder. In Ni-doped films, λ increases by a factor of 3 to 10 at only a few percent Ni.[11]

4. CONCLUSIONS

$\lambda(0)^2/\lambda(T)^2$ in two $YBa_2Cu_3O_{7-\delta}$ thin films and clean crystals are very close, except below 30K where films exhibit T^2 and crystals show T. Both differ clearly from the simple function $\lambda(0)^2/\lambda(T)^2$ ~ $(1 - T^2/T_c^2)$, which is reported often for films. Thus, the differences between films and crystals are smaller than is commonly believed, and there is good reason to believe that data on films represent the intrinsic behavior of the superconductor.

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