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Resistive Voltage in Superconducting Lead Films

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The dc electrical resistivity has been measured for evaporated Pb films at 4.2 K under a perpendicular magnetic field, and partly with an application of a small oscillatory field. The thickness dependence of the perpendicular critical field H_c^p was compared with the theoretical predictions which involve the presence of a stable vortex state for thinner films with thickness smaller than a critical thickness d_c. The depinning current density was also studied for our grown films. All these results show that our films have a number of crystalline imperfections.

1. Introduction

From the flux-flow measurements on superconductors, it has been established that the influence of flux pinning on the flux-flow phenomena in superconducting films or foils can be reduced by an application of a small oscillatory magnetic field, causing an enhancement of the resistive voltage.[1] We have also been interested in these phenomena in various superconductors such as tantalum foil and lead-indium alloy film.[2-6] As part of continuing studies, we shall present here the experimental results of the resistive voltage for lead films, mostly on the perpendicular critical field at which the superconducting-to-normal state transition occurs. The variation of the critical field with varying the film thickness has so far been studied for different materials by many workers and now well established, as reviewed shortly below.

2. Perpendicular critical field of Type I superconductor

It has been pointed out that for a sufficiently thin plate the transition to the normal state is a microscopic second-order transition with the order parameter at the transition rising continuously from zero:[7] From Tinkham's calculation and from the GLAG theory, the transition field is written by

$$H_c^p(T, d)=\sqrt{2}\,K(T, d)H_c(T), \qquad \cdots\cdots\cdots(1)$$

where

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$$K(T,\ d)=[2\sqrt{2}\pi\lambda^2(T,\ d)H_c(T)]/\psi_0 \qquad \cdots\cdots\cdots(2)$$

In these expressions $H_c(T)$ is the thermodynamic critical field, ψ_0 the flux quantum ($\psi_0=ch/2e=2\times10^{-7}$ G cm^2), and $\lambda(T,\ d)$ the weak-field penetration depth which depends on the temperature and on the film thickness. The quantity $K(T,\ d)$ is the Ginzburg-Landau parameter which in that theory is defined only near T_c, but, in the Tinkham's theory is used over the entire temperature range. A modified expression for eq. (1) is given in a form applicable to a thin film with thickness d,

$$H_c{}^P(T,\ d)=\sqrt{2}K(T,\ \infty)H_c(T)\ (1+b/d), \qquad \cdots\cdots\cdots(3)$$

where

$$K(T,\ \infty)=2\sqrt{2}\pi H_c(T)\lambda^2{}_\infty(T)/\psi_0 \qquad \cdots\cdots\cdots(4)$$

and

$$b=[3\lambda^2{}_L(T)\xi_0/8\lambda^2{}_\infty(T)].$$

Here ξ_0 is the Pippard coherence distance, $\lambda_\infty(T)$ the bulk weak-field penetration depth, λ_L the London penetration depth. The Tinkham model means that a superconducting film of Type I with thickness less than a critical value d_c has a stable vortex state instead of an intermediate state under a perpendicular magnetic field; the intermediate state has a higher free energy than the vortex state.

On the contrary, as the film thickness increases, the surface energy plays a less important role, and the intermediate state becomes the stable state, proior to the transition to the normal state. Guyon *et al.*[8] have calculated that the effect of the positive surface energy is to depress the transition below $H_c(T)$ to a field $H_c{}^D$ given by

$$H_c{}^D=H_c(T)[1-(C\Delta/d)^{1/2}], \qquad \cdots\cdots\cdots(5)$$

where Δ is the suface-energy parameter and C is a constant which, depending on the particular geometrical model chosen to describe the intermediate state may have values, 0.8–2. The critical thickness d_c is obtained by equating eqs. (1) and (5) to

$$d_c\approx(C\Delta)/(1-\sqrt{2}K)^2. \qquad \cdots\cdots\cdots(6)$$

The validity of these predictions is already reported for lead films;[9] measurements of transverse magnetization and ac susceptibility.

3. Experimental

The film specimens were prepared by evaporating Pb onto a glass substrate at room temperature in a pressure of about 5×10^{-7} Torr. The glass substrates were cleaned by soaking them in dichromate solution followed by washing in distilled water. The specimen had the width of 1.6 mm and the distance between the two voltage probes was 4.3 mm. The film thickness was determined by a weight method and was estimated by the electrical resistance at room temperature. The electrical measurements were carried out at 4.2 K by the same method as used previously; the static and oscillatory magnetic fields were applied perpendicularly to the plane of the film. The characteristic features of each sample are summerized in Table I.

Table I. Sample characteristics; d film thickness (the upper figure was determined by a weight method and the lower one estimated by the resistance), R_{300} and ρ_{300} resistivity at 300 K, $R_{300}/R_{4.2}$ resistance ratio between 300 and 4.2 K, r evaporation rate, $H_c{}^p$ perpendicular critical field at 4.2 K and l mean free path.

Sample No.	d (Å)	R_{300} (Ω)	ρ_{300} ($\times 10^{-5}$Ω-cm)	$\frac{R_{300}}{R_{4.2}}$	$\frac{R_{300}}{R_{77}}$	r (Å/sec)	$H_c{}^p$ (G)	l ($\times 10^4$Å)
UKL—0	12000	0.435				27.3		
UKL—1	8000 7180	0.786	2.34 2.10	218.3	4.160	41.0 36.8	450	1.55
UKL—2	3200 3830	1.485	1.77 2.10	148.5	4.034	37.6 45.1	475	1.05
UKL—3	1600 1820	3.100	1.85 2.10	89.86	3.899	35.6 40.4	537	0.635
UKL—5	1600 1760	0.321	1.91 2.10	356.7	4.147	82.1 90.3	487	2.54
UKL—7	800 920	6.140	1.82 2.10	36.33	3.586	26.7 30.7	875	0.252
UKL*)—bulk		2.790	2.14		4.478			

*) Dimensions : 0.21cm×0.22cm×0.60cm.

In this table the mean free path l of the samples was calculated by the relation $\rho_R l = 1.5\times10^{-11}$ $\Omega-\mathrm{cm}^2$ found by Cody and Miller,[9] where ρ_R is the residual resistivity at 4.2 K and is related with the following Matthiessen's rule ($\rho_0 = 2.1\times10^{-5}$ Ω-cm at room temperature);

$$(\rho_0+\rho_R)/\rho_R = R_{300}/R_{4.2}. \qquad \cdots\cdots\cdots(7)$$

4. Results and discussion

A typical $V_s - I_s$ characteristic for a sample UKL-3 at various static fields is shown in Fig. 1. The initial nonlinear portion arises from a flux-pinning and final linear portion indicates the flux-flow state; these behaviors are in good agreement with those observed in Type II superconductors. The sample becomes the normal state for the magnetic field beyond 500 G. In the $V_s - I_s$ curve we define the critical current as the one at which the resistive voltages begin to appear appreciably in our dc potentiometer

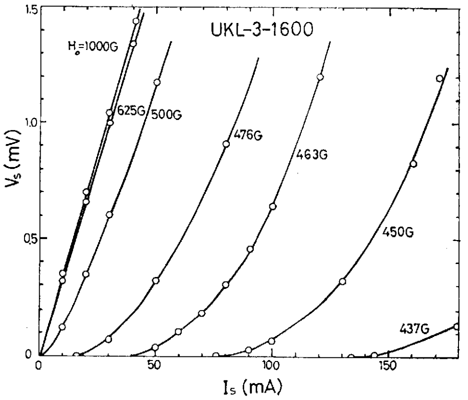

Fig. 1. Resistive voltage vs. sample current for a sample UKL-3 at various static magnetic fields H_0.

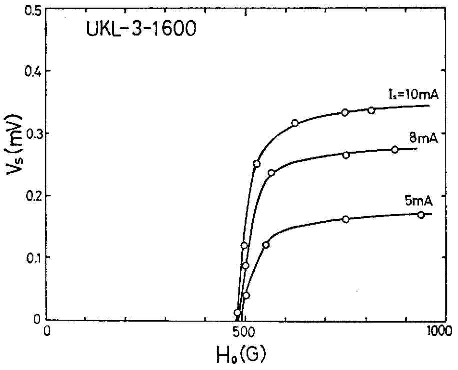

Fig. 2. Resistive voltage vs. static magnetic field at different sample currents (UKL-3).

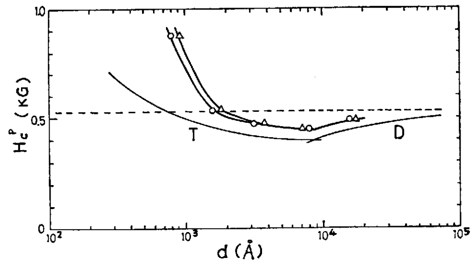

Fig. 3. Perpendicular critical field $H_c{}^p$ plotted as a function of thickness at 4.2 K; the open circles show the thickness determined by the weight method and the open triangles correspond to the estimated values from the electrical resistivity (see text and Table I).

(~0.001 mV). In Fig. 2 is illustrated the dependence of the voltage V_s on the static field H_0 at different sample currents I_s. The resistive voltage appears at about 500 G and it reaches to a constant value near 600 G, indicating the normal state. One can see that the transition to the normal state is not abrupt, but rather gradual, as frequently found in thin film superconductors. Although the perpendicular critical field $H_c{}^p$ could be determined by a magnetization measurement, we define it as the field at which the extrapolated line from the saturated region crosses with that from the initial maxium slope in the $V_s - H_0$ curve.

In Fig. 3 is plotted the perpendicular critical field $H_c{}^p$ vs. film thickness. $H_c{}^p$ is minimum at the thickness d_c=8000~10000 Å. For thicker films with $d > d_c$, $H_c{}^p$ increases gradually as d increases, while for thinner films with $d < d_c$ it increases rapidly as the thickness is decreased. The dotted horizontal line shows the thermodynamic critical field H_c of bulk Pb at 4.2 K. The curves labeled T and D are the theoretical ones calculated by eqs. (3) and (5), respectively. The several parameters are cited from those found by Cody and Miller;⁹⁾ $K(4.2, \infty)=0.5$, $H_c(4.2)=528$ G, $b=260$ Å, and $C\Delta=630$ Å. The observed values of $H_c{}^p$ are larger than the theoretical values, and particularly a large discrepancy is seen for thinner films, which may be ascribed to the purity of the starting material and to the formation of a number of islands or crystalline defects in the grown films. However, the critical thickness d_c is in good agreement with that found by Cody and Miller.

The critical currents or depinning currents J_p are determined from the $I_s - V_s$ characteristics shown in Fig. 1 and are plotted in Fig. 4 as a function of the static field for different Pb films. It can be seen that the thinner films have larger depinning current densities or stronger pinning forces, which is in qualitative agreement with the behavior of $H_c{}^p$ (Fig. 3) and with the existence of the stable vortex state in the thinner films with $d < d_c$.

Finally, we have attempted to measure the voltage enhancement by an application of a small oscillatory magnetic field over the frequency range 10 Hz~50 kHz. As a result, the present samples did not show any maximum in the frequency dependence of the induced voltage arising from a relaxation process of magnetic-flux penetration. This is due to our experimental sensitivity of the potentiometer used and the frequency ranges covered as discussed previously.[6]

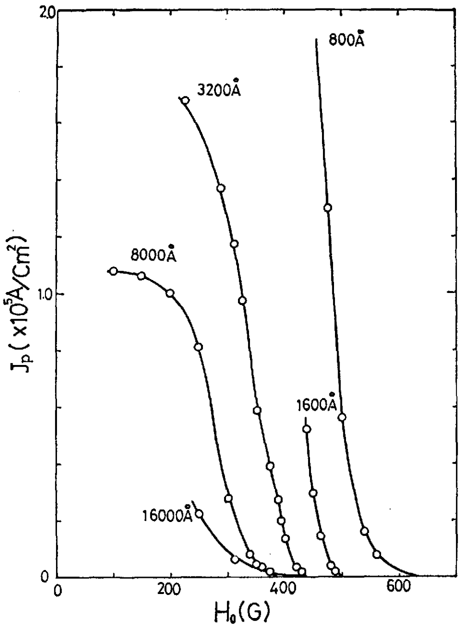

Fig. 4. Critical current density J_p vs. magnetic field H_0 for various films.

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