may be important when determining the flux-flow resistivity near T_c, but their inclusion must await a more exact understanding of the interaction between the vortices and the fluctuations.

[23] See, e.g., A. L. Fetter and P. C. Hohenberg, Phys. Rev. 159, 330 (1967).

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[26] The concept of flow of isolated vortices must be questioned especially where the interaction between the vortices is strong enough to create a symmetric vortex lattice. It should be noted that the concept of flux bundles (i.e., a group of vortices that are so strongly interacting that it becomes more meaningful to talk of the group as a whole instead of its individual constituents) is needed to describe the pinning characteristics [see P. W. Anderson, Phys. Rev. Letters 9, 309 (1962)] seen in bulk samples (see Ref. 1). Possibly the concept of the flow of flux bundles instead of individual vortices will explain the power laws seen in Fig. 10.

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Sharpening of the Resistive Transition of a Superconductor with the Addition of Paramagnetic Impurities*

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We present evidence demonstrating that the addition of magnetic moments to a superconductor suppresses the Maki-Thompson contribution to the fluctuation conductivity. Measurements of the resistive transition of aluminum films with erbium impurities exhibit a sharpening of the transition with increasing impurity concentration which can be explained quantitatively using Thompson's scheme for regularizing the Maki-Thompson conductivity diagrams.

INTRODUCTION

The first systematic study of the resistive transition of moderately clean thin-film superconductors by Masker and Parks[1] revealed clear disagreement with predictions based on the mean-field theory using either a diagrammatic approach[2] or a simplified time-dependent form of the Ginzburg-Landau equations.[3–5]

Maki[6] reconsidered the Green's-function approach and pointed out for the case of bulk superconductors the importance of terms in the fluctuation conductivity which were ignored in the previous microscopic calculations. These terms correspond to an enhanced conductivity of the normal electrons due to their interaction with the ephemeral Cooper pairs. Thompson[7,8] discovered that these terms were divergent in the case of thin films and one-dimensional samples in the absence of pair-breaking perturbations; he proposed a heuristic procedure for regularizing the terms in the presence of pair-breaking perturbations (which are always present in real samples). Crow and co-workers[9] tested Thompson's model by reexamining the fluctuation conductivity in clean aluminum films in the presence of an applied pair breaker, viz., a parallel magnetic field. Later, Thomas and Parks[10] carried out similar experiments on one-dimensional microstrips, and both groups found strong evidence for both the existence of the Maki-Thompson contributions and their suppression in the presence of pair breaking. In the present paper we extend the investigation to a different source of pair breaking, namely, paramagnetic impurities, and find that with increasing concentration of localized moments the anomalous excess conductivity is suppressed and the resistive transition sharpens in the manner predicted by Thompson.

THEORY

Aslamazov and Larkin[2] (AL) considered the contribution to the excess conductivity from fluctuating Cooper pairs. They found that in a two-dimensional sample, where the thickness d is much less than the temperature-dependent coherence length $\xi(T) = \xi(0)\tau^{-1/2}$, the excess conductivity above that of the normal state, i.e.,

$$\sigma' = \sigma(T) - \sigma_N ,$$

is inversely proportional to the reduced temperature $\tau = (T - T_{C0})/T_{C0}$:

$$\sigma'_{\mathrm{AL}} = \left(\frac{e^2}{16\hbar}\right)\Big/\tau d . \qquad (1)$$

This can be rewritten as

$$\frac{\sigma'_{\mathrm{AL}}}{\sigma_N} = \left(\frac{e^2}{16\hbar}\right)\frac{R_\square^N}{\tau} \equiv \frac{\tau_0}{\tau} , \qquad (2)$$

where

$$\tau_0 = 1.52\times10^{-5}\, R_\square^N \tag{3}$$

and $R_\square^N$ is the normal-state resistance per square in Ohms.

The above result, Eq. (2), must be generalized to include the Maki-Thompson contribution σ'_{MT} to the fluctuation conductivity, which was ignored in the AL calculation; i.e., $\sigma'_{\mathrm{total}} = \sigma'_{\mathrm{AL}} + \sigma'_{\mathrm{MT}}$. Thompson's procedure[8] for calculating σ'_{MT} in the presence of pair breaking consists of introducing a low-momentum cutoff $q_C = \xi^{-1}\tau_C^{1/2}$, where

$$\tau_C \equiv (T_{C0} - T_C)/T_{C0} \tag{4}$$

is the reduced shift in transition temperature in the presence of pair breaking, T_{C0} and T_C being the mean-field transition temperatures in the absence of and presence of pair breaking, respectively. The result for a two-dimensional film is given by

$$\sigma'_{\mathrm{MT}} = \left(\frac{e^2}{16\hbar}\right)\frac{2}{\tau d}\ln\left(\frac{\tau+\tau_C}{\tau_C}\right) , \tag{5}$$

which is valid for $\sigma'_{\mathrm{MT}}/\sigma_N \ll \tau_C$. We have then for the total fluctuation conductivity

$$\frac{\sigma'}{\sigma_N} = \frac{\tau_0}{\tau+\tau_C} + \frac{2\tau_0}{\tau}\ln\left(\frac{\tau+\tau_C}{\tau_C}\right) , \tag{6}$$

where the AL term has been recalculated using the Thompson cutoff q_C. According to Thompson,[8] the present form of the theory, Eq. (6), is valid only for small shifts in T_C so that $\tau_C \lesssim 0.1$.

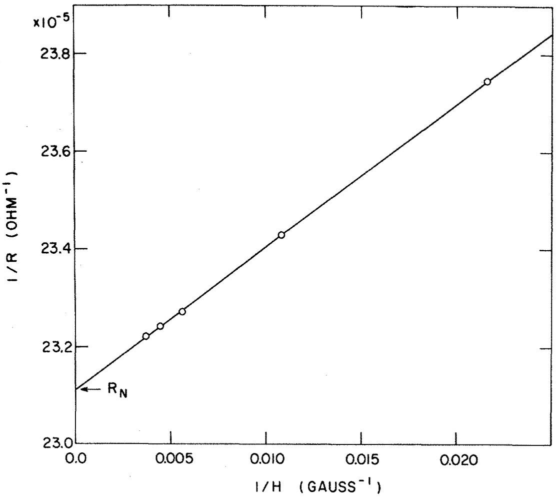

FIG. 1. Demonstration of the method used to determine the normal-state resistance R_N (data shown are for sample 8, taken at a temperature near T_c). The linear behavior observed is that expected from the mean-field theory.

EXPERIMENTAL PROCEDURE

To illustrate the effect of magnetic impurities on the superconducting transition in thin films we chose the $\mathrm{Al}_{1-x}\mathrm{Er}_x$ system. Aluminum was used as the host system because of the small size of its intrinsic pair breaking which leads to a large ratio of $\sigma'_{\mathrm{MT}}/\sigma'_{\mathrm{AL}}$. To escape the problem of ill-defined localized moments, a rare-earth dopant rather than a transition-metal dopant was used.

The alloy charges from which the samples were evaporated were prepared by first evaporating erbium onto aluminum strips of known thickness (~0.05 mm) in a vacuum of 10^{-6} Torr. The thickness of the erbium layer was monitored by measuring

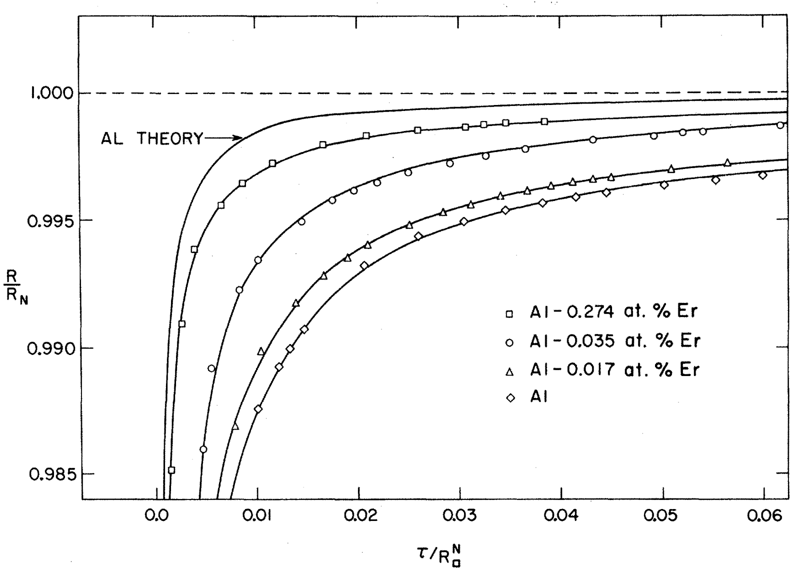

FIG. 2. Sharpening of the resistive transition of a series of aluminum samples with the addition of erbium. The resistance axis is highly expanded to give a sensitive display of the data and the solid lines through the data are plots of Eq. (6).

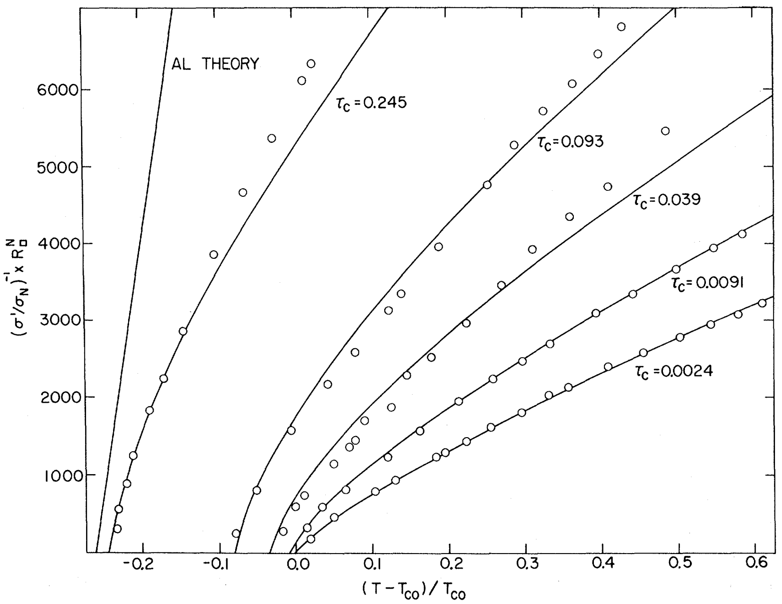

FIG. 3. Sensitive comparison of the data and Eq. (6), with values of τ_c as labeled. All samples showing AL behavior would fall on the given straight line when plotted with these variables.

the change in resonant frequency of a quartz crystal as the film was deposited on its surface. Immediately after the erbium evaporation, the aluminum-erbium sandwich was coated with 100 Å of aluminum to prevent oxidation of the erbium when exposed to air. When brought to atmospheric pressure these strips were folded and rerolled repeatedly to achieve thorough mechanical mixing, then immediately placed in the film evaporation chamber. Weighing of the aluminum strip coupled with the erbium thickness measurements gave us a relative accuracy in the impurity concentration of about 5%.

The $Al_{1-x}Er_x$ alloy films were prepared by flash evaporation at a rate greater than 100 Å/sec of the mechanically mixed alloy charge from a wetted tungsten filament. At the pressure of the evaporation ($\sim 10^{-5}$ Torr) the boiling points of aluminum and erbium are nearly equal. The films, which were deposited onto room-temperature glass substrates, were hermetically sealed with a layer of SiO immediately after evaporation to inhibit oxidation of the erbium impurities.

Within a few hours after the samples were removed from the evaporator, a zig-zag pattern[1] was scribed onto the surface within a restricted area of the film. The samples were then placed into the evacuated Dewar. Voltage measurements were taken using a standard dc four-probe method with current densities kept low enough to eliminate non-Ohmic electric field effects.[11] The sample temperature was monitored by a resistance thermometer calibrated against the vapor pressure of liquid helium during each run.

The normal-state resistivity was determined by application of an external field aligned perpendicular to the sample in the transition region. This alignment was obtained by locating the peak in excess conductivity when the magnetic field was parallel to the plane of the sample. Having obtained the parallel direction to an accuracy of 0.1 deg the magnet was rotated by 90°. A plot of the conductivity versus the inverse of the applied perpendicular field (Fig. 1) was then made and the extrapolated intercept corresponding to infinite field determined the normal-state conductivity. This

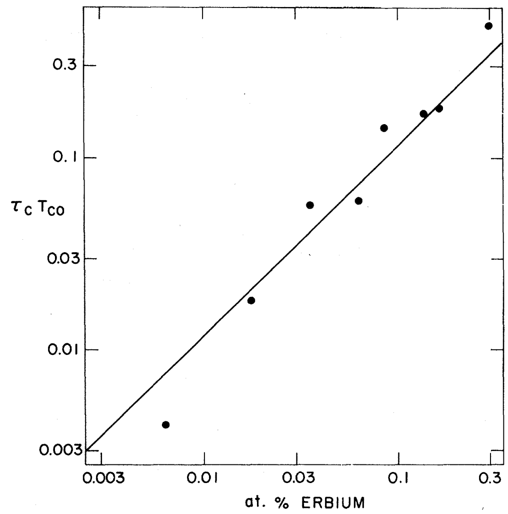

FIG. 4. Plot of the shift in transition temperature $\Delta T_C \equiv \tau_C T_{C0} = \tau_C T_C/(1-\tau_C)$ versus at.% erbium, where T_C is the measured transition temperature and τ_C is determined from the observed quenching of σ'_{MT} via Eq. (6).

TABLE I. Sample parameters.

Sample No.	at.% Er	$R_\square^N$ ($\Omega/\square$)	T_c (°K)	τ_c	T_{c0} (°K)	ΔT_c (°K)
1	0.274	8.13	1.575	0.237	2.062	0.487
2	0.165	9.50	1.679	0.092	1.851	0.172
3	0.137	6.11	1.590	0.094	1.755	0.165
4	0.083	2.28	1.430	0.091	1.573	0.143
5	0.064	4.87	1.615	0.034	1.674	0.059
6	0.034	19.4	1.950	0.028	2.007	0.057
7	0.017	16.2	1.872	0.0091	1.890	0.018
8	0.006	7.34	1.649	0.0024	1.653	0.004

plot was linear in the high-field limit in accordance with the theory of Abrahams, Prange, and Stephen.[12] The normal-state resistance measured in this way was found to be independent of temperature within the temperature range of the experiment.

EXPERIMENTAL RESULTS

A straightforward way of illustrating the effect of the magnetic impurities on the superconducting transition is to plot the ratio of the sample resistance R to the normal resistance as a function of $\tau/R_\square^N$ with the resistance axis highly expanded. All samples showing Aslamazov-Larkin behavior should then lie on a single curve which is designated by "AL theory" in Fig. 2. We see, however, that the samples have noticeably broader transitions, and that the sharpness of the transition depends upon the impurity concentration. The broadest curve is for a clean aluminum film prepared in the same manner as our previous samples: 99.999% aluminum was evaporated from a tungsten wire and hermetically sealed with SiO before exposure to atmospheric pressure. As expected from Thompson's theory, the transitions become sharper with the addition of magnetic impurities. The lines drawn through the data are theoretical curves from Eq. (6).

A more revealing plot for comparison with the theory is shown in Fig. 3. In this figure the data for all samples exhibiting AL behavior, regardless of the value of $R_\square^N$, should fall on a straight line of slope 6.58×10^4. The experimental curves deviate from this, however, exhibiting the expected behavior. The theoretical lines were obtained by comparing our data to Eq. (6). The quantities T_c and τ_c were treated as arbitrary parameters to give the best fit to the data. Note that a change in T_c merely shifts the curves to the left or right, whereas a change in τ_c alters the shape of the curves. The values of τ_c so determined allow one to calculate T_{c0} for each sample according to Eq. (4). Table I gives a summary of the sample parameters.

In Fig. 4 we have plotted the shift in transition temperature $T_{c0}-T_c=\tau_c T_{c0}$ as a function of at. % of erbium. As discussed previously, the relative concentration of magnetic impurities is known only to roughly 5% accuracy; this may account for some of the experimental scatter. The important result, however, is that the shift in T_c implied by the quenching of σ'_{MT} scales with the concentration of magnetic impurities c over roughly two decades. The nearly strict proportionality between $\tau_c T_{c0}$ and c is expected for the range of τ_c values used in the present study, according to the well-known Abrikosov-Gorkov theory.[13] We also note that the shift in T_c due to intrinsic pair-breaking effects in clean aluminum films[14] is only 2% of the shift in T_c exhibited by the sample with the highest impurity concentration.

In summary, we have demonstrated that the anomalous excess conductivity in aluminum films is quenched by the addition of paramagnetic impurities in the manner predicted by Thompson. These results, taken together with the results in Refs. 9 and 10, provide definitive evidence for the existence of the Maki-Thompson terms in the fluctuation conductivity and the suppression of these terms by pair-breaking perturbations.

Note added in proof. In a recent note Testardi[15] speculated that the anomalous paraconductivity observed in Al films arises from sample inhomogeneity resulting from internal stresses. While it would be difficult to dismiss such a possibility on the basis of the earliest work[1] on Al films, there exists now sufficient and varied data to form a strong case against it. It would be necessary to bolster the Testardi conjecture with bizarre assumptions in order to reconcile the present results with the following previous results which have been explained quantitatively by the fluctuation theory: the functional dependence of the anomalous paraconductivity on (i) parallel magnetic field in two-dimensional Al films,[9] (ii) parallel magnetic field in one-dimensional Al films[10] [where the functional dependence is different than in (i)], and (iii) electric field in two-dimensional Al films.[16]

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Destruction of Superconductivity by Laser Light

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Superconductivity is destroyed by laser light in Pb films of thickness comparable to the optical penetration depth δ and less than the superconducting coherence length ξ. Thermal effects, which have been independently determined, cannot account for this. For films of thickness greater than δ and ξ, only the thermal effect is observed. In a proposed explanation it is shown that the electron gas may be heated from 3 to 18 °K above the lattice temperature by the light absorption in these experiments.

I. INTRODUCTION

Several experimental[1] and theoretical[2] studies of the behavior of superconductors in high-frequency electromagnetic fields have been reported recently.

The destruction of superconductivity by laser light in thin Pb films is reported in this paper. This paper deals mainly with the description of the anomalous effect and the experiments to establish the magnitude of the heating caused by the laser pulse.

II. EXPERIMENTAL

To determine unambiguously the heating of the film produced by the laser illumination, the film resistance was used to measure the film temperature. This requires a temperature coefficient of resistance $d\ln R/dT$ of at least several parts per thousand at temperatures just above T_c for films of thickness comparable to the optical penetration depth (~ several hundred Å). Only a few metals will satisfy this requirement. One of the most satisfactory is lead.

Films were obtained by argon getter sputtering of high-purity Pb at 4–6 Å/sec onto polished single-crystal sapphire substrates.[3] Sample shapes suitable for standard four-terminal resistance measurements were obtained by scribing away thin lines of the Pb films on the substrate face. Sample dimensions were usually 2–4 (between potential probes)$\times$0.5 mm.

For most of the experiments, film thicknesses of about 275 Å were used. Several films 1500–2000 Å were also studied. In all cases the films had an electrical resistivity at 300 °K ($\sim 25\times10^{-6}$ Ωcm) roughly equal to that of bulk Pb. Resistivity ratios $\rho(300\,°\mathrm{K})/\rho(8\,°\mathrm{K})$ were ~ 3 to 4 for the thinner films.

The sapphire substrates were plates approximately 1 cm$\times$0.5 cm$\times$0.7 mm (thick). These plates were ultrasonically soldered with gallium to a block of oxygen-free high-conductivity (OFHC) copper roughly 1$\times$2 cm. The arrangement is shown in Fig. 1.

Two lasers were used. Both were argon multicolor multimode lasers. About half the power from the laser was multimode at 5145 Å, one-third the power was single-mode multicolor, and the remainder was single mode at 5145 Å. The outputs were a 40-μsec pulse at 2 W and a 6-μsec pulse at 5 W. The light was focused to circular spots at the sample of ~ 4 and $2\frac{1}{2}$ mm diameters for the two lasers, respectively. Estimating an optical loss of 50%, for the lens, mirror, and window, a sample reflectivity of 60%, and a (measured) transmittance[4] of ~ 0 to 10% gives the energy fluxes shown in Table I.

Note that even for the 275-Å films (~ 10% transmittance[4]) the optical penetration depth was com-