# Dynamic properties of thin films near the superconducting transition temperature

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An oscillatory structure has been detected experimentally in the conductivity of aluminum thin films near $T_c$. This structure is interpreted as a consequence of a Berezinskiĭ–Kosterlitz–Thouless phase transition in a two-dimensional system of weak links formed in microscopically inhomogeneous, granular films.

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In this letter we are reporting a study of the resistive state near the superconducting transition of aluminum films on glass substrates in oxygen at a pressure of $5\times 10^{-5}$ Torr. The films had a surface resistivity $R^n_\square \approx 10\Omega$, a thickness $d\sim 250$–300 Å, and other dimensions of $1\times 10$ m. To study the transition $R(T)$ in more detail we measured $dR/dT$ by modulating the film temperature below the $\lambda$-transition in HeII. Second sound was excited by a bismuth film and received by the test film. The distance between the source and the receiver was $\sim 2$ cm. The second-sound signal was observed clearly at a source power $\sim 200\ \mu$W, at a constant transport current $\sim 100\ \mu$A through the sample, and at a frequency $\sim 10$ kHz. Figure 1 shows the temperature dependence of $R$ and $dR/dT$. The step structure on the $R(T)$ curve, which was observed for a large number of samples, is not a consequence of edge effects or inhomogeneities of the films over distances $r \gtrsim \lambda_{GL} \sim 10^4$ Å.

The current-voltage ($I$-$V$) characteristics of the samples are very nonlinear in the interval 1.45 K $< T <$ 1.9 K and exhibit the "excess" current which increases with decreasing $T$ and which is characteristic of weak-link systems. The second derivatives of the current with respect to the voltage, $d^2I/dV^2$, found by a modulation method, exhibit an oscillation with strictly periodic peaks, whose relative height is on the order of 10% in terms of the conductivity (Fig. 2). The derivatives show an irregular behavior as the temperature is raised or lowered from an optimum value.

The complex $R(T)$ behavior, the oscillatory behavior of the conductivity, and the response of the film to a microwave signal can be attributed to vortex structures in a two-dimensional system of weak links which arise in granular samples. A phase transition in a two-dimensional superfluid may occur at $T = T_{KT}$, in which thermally excited pairs of vortices of opposite polarity ("vortices" and "antivortices") dissociate.[1,2] One of the systems in which such a phase transition may occur is an array of weak links. Pettit and Silcox[3] have shown that films synthesized by a technique similar to that of the present experiments consist of grains of nonuniform size, with transverse dimensions ranging from 40 to 400 Å. The critical temperature of such films has been found to be very sensitive to the average grain size, so that systems of various weak links (SIS, SINIS, SININIS, etc.; $S$ and $N$ are superconducting and normal regions, and $I$ is a grain boundary) form over a broad temperature range (1.4–2.1 K). The

  

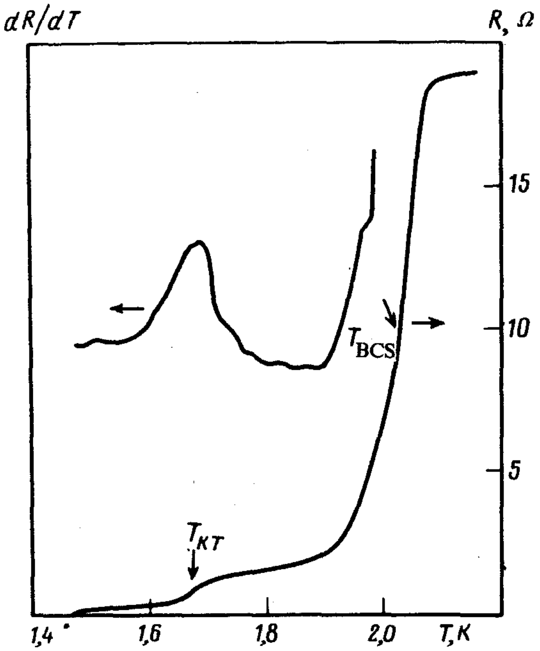


FIG. 1. Temperature dependence of the resistance, $R(T)$, and of the derivative of the resistance, $dR(T(/dT)$, of the aluminum films.

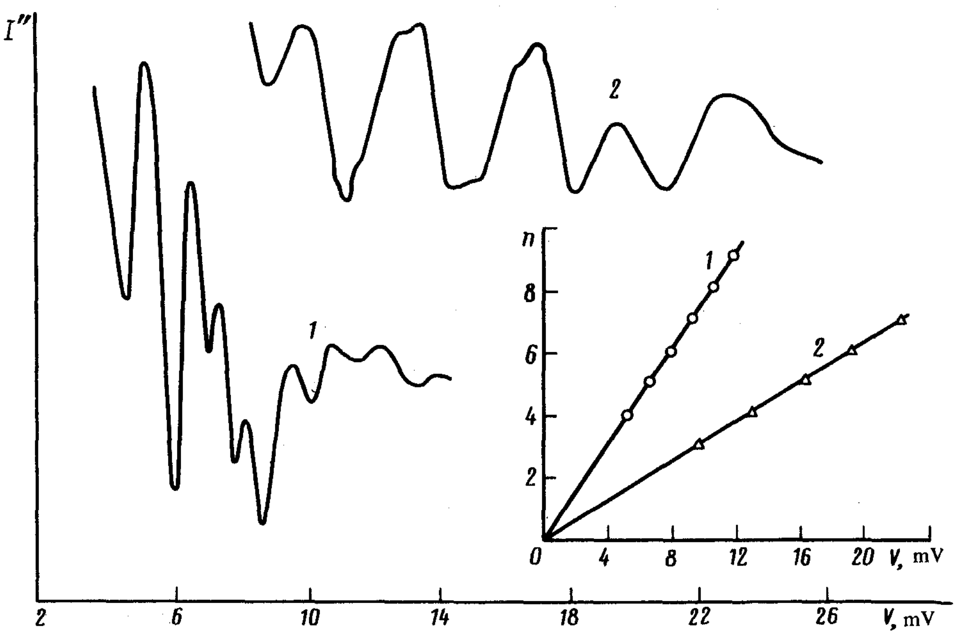


FIG. 2. Effect of the voltage applied to the film, $V$, on the derivative $d^2I/dV^2$ and on the oscillation-period index $n$. 1) Film 10 mm long; 2) 5 mm.

average distance between such links, $b$, is estimated to be $\sim 10^3$ Å. The array of weak links in a film with a thickness $d \ll \lambda_{GL}$ is two-dimensional. The temperature fluctuations in such films are known to become very large near $T_c$; in general, these fluctuations completely disrupt the phase coherence over distances greater than $\chi_{GL}$. At $T > T_{KT}$, however, free vortices are likely to form and lead to a local minimum of the thermodynamic potential. In the absence of a magnetic field, and at low measurement currents, the conditions are most favorable for the formation of Josephson vortices, i.e., vortices that have no cores, since their energies are several orders of magnitude smaller than the energy of Abrikosov vortices. Because of the symmetry of the system, Josephson vortices are cylindrical in a rather thick film ($W \gg \lambda_{GL}$) and interact with each other over large distances with a force

$$F = \pm \left(\frac{\phi_0}{\Lambda_\pi}\right)^2 \frac{2d}{2}\,; \qquad b << r << \frac{2\lambda_J^2}{d}.$$

At $r \gtrsim \lambda_J \gg b$ the phase varies only slightly over a distance equal to the size of a single link; equating the supercurrent density at the boundary of the vortex to the current density from the London equation, we find $\lambda_J^2 = dc^2\hbar/8\pi e I_c$. We assume that the temperature dependence of the critical current $I_c$ is linear as $T \to T_c$:

$$I_c = \frac{2\pi^3 k_B(T_c - T)}{r\,\zeta(3)\,eR^*}\,.$$

Here $R^*$ is the effective resistance of the weak link, which is a measure of $dI_c/dT$ in the limit $T \to T_c$. For SINIS, SININIS, etc., weak links the value of $R^*$ is much higher than the normal resistance of the weak link, provided that the grain boundaries are relatively impermeable. From the expression for the temperature of a topological phase transition[2] we fine $T_c/T_{KT} = 1 + R^*/20.6\ \mathrm{k}\Omega$. The value of $R^*$ can be estimated from the fluctuational broadening of the $R(T)$ curve for the transition:

$$T_c/T_{K\text{-}T} = 1 + (5 + 11)/aT_c\,; \qquad a = \left. d\ln R(T)/dT \right|_{T \to T_c}. \tag{1}$$

Estimate (1) agrees with the feature observed on the $R(T)$ curve (Fig. 1).

At $T < T_{KT}$ vortices of opposite polarity combine into pairs, which do not contribute to energy dissipation at low measurement currents. The result is a sharp decrease in the film resistance at $T_{KT}$ (Fig. 1). This behavior of the Berezinskiĭ—Kosterlitz—Thouless transition in an array of random weak links in a film is explained on the basis that the value of $\lambda_J$, which determines $T_{KT}$, is itself determined by the average characteristics of the weak links over an area much larger than the characterstic dimensions of the microscopic inhomogeneities of the film, by virtue of the conditions $\lambda_J \gg \lambda_{GL} \gg b$.

The existence of Josephson vortices in a film tells us why an extremely complicated system of weak links exhibits coherent behavior. Below the melting point, $T_m < T_{KT}$, $T_m = 1.5$–$1.7$ K, the liquid of paired vortices "crystallizes" into a lattice consisting of vortices of opposite polarity. The transport current causes the sublattices of vortices of opposite signs to begin to move in opposite directions; this motion generates an electromagnetic field with the Josephson frequency $\omega = 2\mathrm{eVD}/hL$, where

$D$ is the lattice constant, $L$ is the length of the sample, and $V$ is the voltage applied to the sample. Radiation self-detection effects similar to those which are seen in a resonant system of ordinary Josephson contacts lead to features in the conductivity of the film at voltages $V = V_{nm} = n\phi_0 c/m2D(\sqrt{\epsilon^i})$, where $n$ and $m$ are integers, $c$ is the speed of light, and $\epsilon^i$ is the dielectric constant of the insulator of the half-wave reosonator, which consists of a substrate, a shielding copper plane, and the test aluminum film. The period of the conductivity oscillation should vary in inverse proportion to the length of the sample in this case, in agreement with experiment (Fig. 2). The lattice constant estimated from the expression for $V_{nm}$ with $\epsilon = 4$ is $D = 10^{-2}$ cm.

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