

Nonlinear conductivity of thin films in a mixed state

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The existence of nonequilibrium effects in a dynamic mixed state of superconducting films, which was predicted in the theory of Larkin and Ovchinnikov, is proved experimentally.

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The nonequilibrium states arising in superconductors are the cause of a number of interesting effects in thin superconducting films. Thus, the electrons under isothermal conditions in narrow films are super-heated relative to the lattice, which produces a hysteresis in the I - V characteristics that is not associated with Joule heating.^{1,2} Because of a large energy relaxation time of electrons τ_e , the nonequilibrium states in the mixed dynamic state of a superconductor appear in the normal nuclei of the moving vortices, as was shown for the first time by Larkin and Ovchinnikov.³ An associated decrease of the viscosity coefficient $\eta(u)$ with increasing velocity of the vortices u leads to the fact that the frictional viscosity force $F_\eta = \eta(u)u \sim J(V)$ and the I - V characteristics go through a maximum and acquire an N -shape. A recording of such I - V characteristics in a circuit with a current source has a cutoff for characteristic values of the electric field E^* and current J^* , which was reported earlier.⁴

In this communication we give facts confirming the existence of nonequilibrium effects in a dynamic mixed state of superconductors, which were predicted in Ref. 3.

We investigated Sn, Al, and Sn-6% In alloy films with a width $w > \lambda_1$. The films were prepared by thermal evaporation in a vacuum using a single crystal quartz substrate. The parameters of some samples are given in Table I (w, L , and d are the width, length, and thickness of the films, respectively). For all the investigated materials the variation of the I - V characteristics with decreasing temperature and increasing external magnetic field H_1 perpendicular to the films occurs in qualitatively equal fashion (Fig. 1).

In the external magnetic field upon establishment of the pinning current the film goes over to the mixed dynamic state resulting from the motion of vortices, which corresponds to a broad, essentially nonlinear resistive region in the I - V characteristics.

TABLE I.

N ^o Sample	Material	w , cm	L , cm	d , Å	l , Å	κ
1	Sn	$21 \cdot 10^{-4}$	$1.25 \cdot 10^{-2}$	500	800	0.7
2	Sn - 6% In	$87 \cdot 10^{-4}$	$3.4 \cdot 10^{-2}$	400	100	2.2
3	Al	$1.14 \cdot 10^{-1}$	$4.7 \cdot 10^{-1}$	300	40	5.6

A sharp bend or cutoff in the I - V characteristics occurs when the values of the current J^* and voltage V^* characteristics for the given magnetic field are attained. As the magnetic field increases, the I - V characteristics are smoothed out gradually, and at $h = H/H_{c1} \gtrsim 0.3 - 0.4$ the bends and cutoffs disappear in them. As Larkin and Ovchinnikov showed,³ because of a large energy relaxation time in a mixed dynamic state of superconductors, an increase of the energy of normal excitations inside a vortex with increasing velocity of its motion may drastically change the energy distribution function of the excitations. Thus, the number of normal excitations inside a vortex decreases with increasing velocity, i.e., its size $\xi(u)$ decreases, which decreases the velocity coefficient η with increasing u , and the viscous frictional force has a maximum at $u = u^*$. The theory³ gives the following expressions for E^* and u^* at the maximum point of the I - V characteristics:

$$E^* = \frac{BD^{1/2} [14 \zeta(3)]^{1/4} (1-t)^{1/4}}{(\pi \tau_c)^{1/2}}, \quad (1)$$

$$u^* = \frac{D^{1/2} [14 \zeta(3)]^{1/4} (1-t)^{1/4}}{(\pi \tau_c)^{1/2}}, \quad (2)$$

where $D = v_F l / 3$, l is the length of the free path, $t = T/T_c$, and B is the induction in the sample.

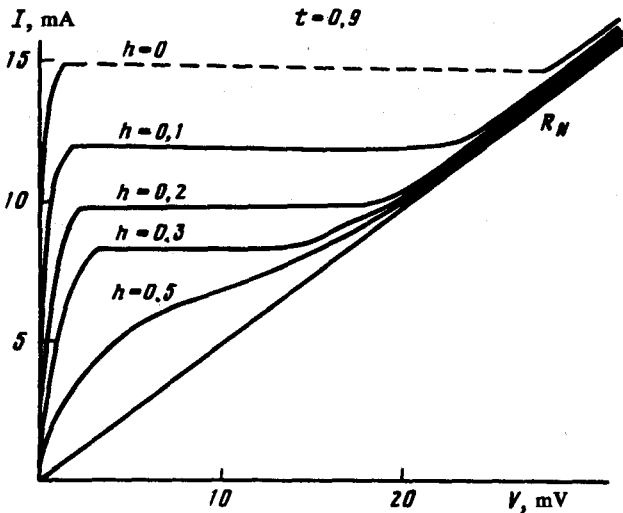


FIG. 1. I - V characteristics of Al film for different values of the magnetic field.

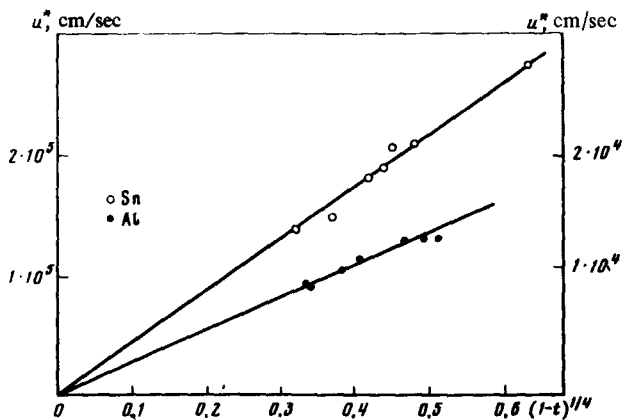


FIG. 2. Temperature dependence u^* of No. 1 (Sn) and No. 3 (Al) samples; solid lines represent a calculation.

In all the films analyzed by us, irrespective of the material, the values of E^* and u^* are dependent on the temperature and on the magnetic field, consistent with Eqs. (1) and (2). It should be noted that the dependence of E^* and u^* on the energy relaxation time τ_ϵ is especially clearly manifested in the comparison of these values for Sn and Al in which τ_ϵ differ by two orders of magnitude.^{5,6} Figure 2 shows the temperature dependence of u^* for samples No. 1 and No. 3 (see Table I). It can be seen that in the investigated temperature range the experimental data are in good agreement with the theoretical calculation for $\tau_\epsilon(\text{Sn}) = 6.6 \times 10^{-10}$ sec and $\tau_\epsilon(\text{Al}) = 4 - 7 \times 10^{-8}$ sec. The obtained agreement between the experiment and the theory³ allows us to say that the observed peculiarities in the I - V characteristics in the external magnetic field $0.05 < h \leq 0.4$ are due to the nonlinear dependence of the viscosity coefficient on the velocity of the vortices.

We focus attention on the fact that the experimental I - V characteristics contain peculiarities that are not described by the theory in its existing form. Thus, beyond the cutoff point (E^* , J^*) we can see a broad, resistive region and the approach of the I - V characteristic to R_N is preceded by a region of constant excess current characteristic for narrow ($w < \lambda_1$) films in the absence of an external field H . Unfortunately, the theory does not investigate the I - V characteristics beyond the maximum. On the basis of the existing experimental data, we cannot answer unambiguously the question whether a vortex state remains in the film after the cutoff point or whether it goes over to some new state with different dependences of the order parameter on the coordinates and on time.

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