Structure of layer produced on a surface of aluminum when a magnetic field $H > H_c$ is turned on

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A microscopic study is made of the structure of the layer. It is observed that the layer is close in its structure to a two-dimensional mixed state of a type-I superconductor [L. D. Landau, private communication to D. Shoenberg (see D. Shoenberg, Superconductivity, Cambridge Univ. Press, 1938, p. 50); L. P. Gor'kov and O. N. Dorokhov, Sov. Phys. JETP **40**, 956 (1975); A. F. Andreev and Yu. K. Dzhikaev, JETP Lett. **26**, 590, (1977)].

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The two-dimensional mixed (TDM) state of type-I superconductors, the possible existence of which was pointed out way back by L.D. Landau[1] was experimentally observed by I.L. Landau and Sharvin[4] in a study of the current-voltage characteristics of hollow superconducting cylinders. A characteristic feature of the TDM state is the presence in it of an electric field and of a current that ensures a magnetic-field discontinuity $\Delta H \leqslant 2H_c$ on the layer. The TDM state can be regarded as the limiting case of the intermediate states when the period of the structure of this state is decreased to dimensions on the order of the coherence length.[1,3]

One can hope that a layer of such a state is produced on the surface of a type-I superconductor when the external magnetic field $H > H_c$ decreases jumpwise to zero. From the continuity of the tangential component of the magnetic field it follows that the field in the surface layer also decreases to zero, whereas the field in the interior of the sample remains equal to the initial value because of the eddy currents. The region near the surface in which $H < H_c$ should become superconducting. The produced layer cannot trap in the sample the magnetic flux, which at that time exceeds the critical value. This means that a vortical electric field should exist in the layer, and the structure of the layer corresponds to the intermediate or to the TDM state.

In the present paper we attempt a microscopic study of the resultant structure. We present below preliminary results of such a study.

The measurements were performed on a parallelepiped cut from single crystal aluminum with $R_{300\,\mathrm{K}}/R_{4.2\,\mathrm{K}} = 2\times 10^4$ and having dimensions $1\times 1\times 2$ cm (Fig. 1). The roughness on the sample surface were removed by polishing, after which the case-hardened layer was etched. Electrolytic polishing produced a mirror-bright surface.

We studied that state of the surface layer of one of the faces of the sample, parallel to the (110) plane of the crystal. The measurements were made with the aid of microcontacts produced by electric breakdown of Al-Al_2O_3-Ag tunnel structures. The thicknesses of the Al_2O_3 and Ag films were respectively of the order of 30 and 1000 Å. The

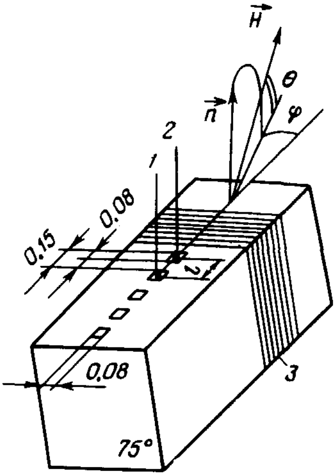
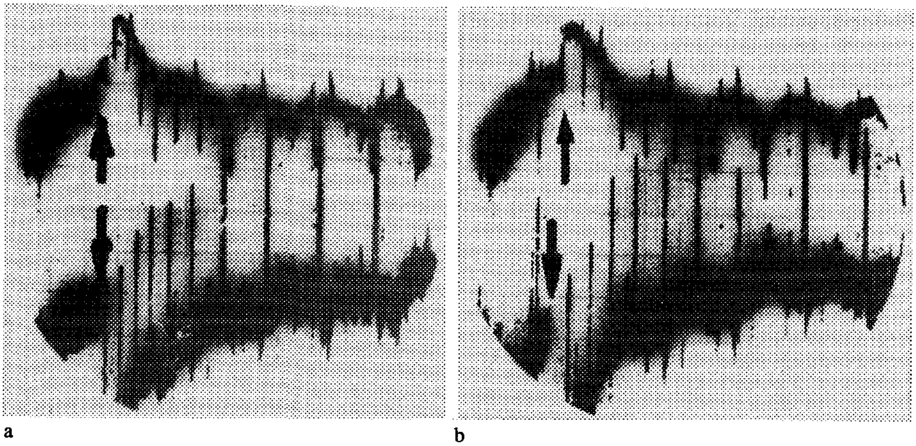


FIG. 1. Experimental setup: **H**—magnetic field intensity vector; **n**||[110]—vector normal to the surface; 1,2—breakdown tunnel junctions, the points denote the locations of the microcontacts; 3—coil of 100 turns; *l*—distance between contacts. The dimensions are in centimeters.

breakdown was produced at helium temperature in the manner described by Bogatina and Yanson.[5] It is seen from the results that each tunnel contact contained only one short-circuit. The resistances of the microcontacts ranged from 10^{-2} to 1 Ohm. An estimate of the short-circuit dimensions from the formula proposed by Sharvin[8] $R \approx p_F/ne^2d^2$ (p_F is the Fermi momentum, n is the electron density, d is the contact dimension) yields values $d \sim 3\times10^{-6}$–3×10^{-5} cm. Since the coherence length for aluminum is $\zeta_0=1.36\times10^{-4}$ cm,[7] in our case $d \ll \zeta_0$.

In the experiments we determined the time dependence of the voltage on the contact with the magnetic field turned off. The current through the contact was fixed. Since the current-voltage characteristic of the short circuit changes significantly when the aluminum goes from the normal to the superconducting state, it is easy to deter-


a

b

FIG. 2. Photograph of oscilloscope screen $\theta=-1.2^\circ$: 2a) $\phi=0^\circ$: 2b) $\phi=+2^\circ$. Upper curve—signal from contact 2 (Fig. 1), lower—from contact 1. The arrows mark the instant of the onset of superconductivity. Horizontal scale 10 msec/div.

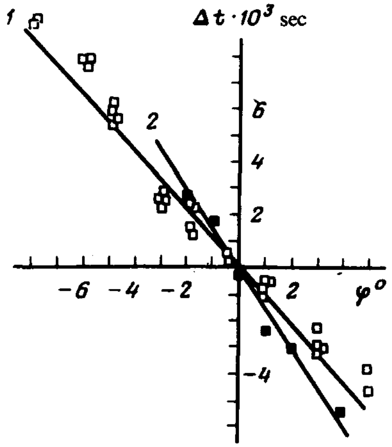


FIG. 3. Plots of $\Delta t(\phi)$; 1 and 2 differ in the sign of the magnetic field.

mine the state of the sample region under the contact from the value of the voltage. The measurements were performed at a temperature 0.4 K. The magnetic flux in the sample remained above the critical value $\Phi_c = H_c S$ (S is the cross-section area of the sample) for a time of approximately 1 second after turning off the external magnetic field $H = 2H_c \approx 176$ Oe. The state of the surface layer of the samples was investigated during the first 20 msec after the formation of the superconducting regions on the surface. The voltage from the contact was fed to an amplifier having a bandwidth 20 Hz–1 MHz, from which the signal was fed to one of the channels of a two-beam S8-11 oscilloscope with memory. The triggering of the oscilloscope time sweep was synchronized with the instant when the field was turned off.

Typical signals from two contacts are shown in Fig. 2. The arrows mark the instant when superconductivity of the surface layer sets in. The narrow pulses correspond to the normal state of the region under the contact. By rotating the magnetic field in the plane of the surface it is possible to find a position ($\phi = 0$) such that the pulses on the two contacts are in synchronism [Fig. 2(a)]. Variation of the angle ϕ causes the pulses to go out of synchronism [Fig. 2(b)]. The time shift Δt between the corresponding process from the two contacts is a linear function (see Fig. 3) of the angle ϕ at small values of this angle.

These results can be easily understood if it is assumed that the normal regions constitute bands of length $> l = 0.08$–0.23 cm, extended along the magnetic field and moving over the surface perpendicular to H. Their velocity, according to Figs. 1 and 3, is $V = l \sin\phi / \Delta t \approx l\phi / \Delta t \approx (1.3$–$3.7)$ cm/sec. The uncertainty in the velocity measurement is due to the uncertainty in the distance between the point contacts. Figure 3 shows also that when the magnetic field is reversed the direction of the motion does not change, but the velocity does. From pulse duration τ and from the velocity we can determine the transverse directions of the normal regions. At $\theta = 1.2^\circ (\tau = 0.4 \times 10^{-3}$ sec) they amount to $(5$–$15) \times 10^{-4}$ cm $\approx (4$–$12)\zeta_0$. The dimensions of the superconducting regions are approximately 20 times larger, $(1$–$3) \times 10^{-2}$ cm. A correlation between the pulses from the two contacts could be observed only in an oblique magnetic field ($\theta \geqslant 0.6°$). The duration of the pulses of the normal phase depended very strongly on the angle θ. It ranged from 2×10^{-3} sec at $\theta=2.4°$ to 2×10^{-5} sec at $\theta=0°$.

The time dependence of the voltage picked off the coil 3 (Fig. 1) has a spike that is synchronized with the instant of the onset of the superconducting layer. At this instant, a magnetic flux $\Delta\Phi\approx0.5H_cP\xi_0$ (P is the perimeter of the sample cross section perpendicular to the magnetic field) is forced out of the sample. Assuming that when the layer is produced the magnetic flux is forced out of it to the outside and is not trapped in the sample, the layer thickness turns out to be of the order of ξ_0.

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