Electric-field domains in a metal at low temperatures

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Domains with a strong electric field in copper at low temperatures when the specimen is heated with a current are observed experimentally for the first time.

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The possibility of the appearance of electric domains in a metal was predicted theoretically in Ref. 1. Their existence stems from the instability of the homogeneous distribution of the electric field on the section of the I–V curve with negative differential conductivity $j' \equiv \partial j/\partial E$, an N-shaped I–V curve (j is the current density, and E is the electric field intensity). Such an I–V curve can occur for metals under conditions of Joule heating when the inequality $d/dT[\sigma(T)q(T)] < 0$ is satisfied [$\sigma(T)$ is the conductivity and $q(T)$ is the heat flux out of the specimen under fixed conditions of heat removal].[1] It is easily realized in pure metals at low temperatures, when $\sigma(T) \sim T^{-3} - T^{-5}$. In the case of weak dependence $q(T)$, for example, $q(T) \sim (T - T_0)$ (T_0 is the temperature of the surrounding medium), and high Debye temperature of the metal, this inequality can be satisfied for relatively dirty specimens as well ($\sigma_{4.2\ \mathrm{K}}/\sigma_{300\ \mathrm{K}} \cong 10 - 50$). According to estimates, current densities for which $j' < 0$ are of the order of 10^9 A/m^2. This value is experimentally easily attainable in thin specimens.

In order to prepare the specimens, in the present work, we used a copper wire with a cross section of 2×10^{-9} m^2 (ϕ 0.05 mm) and ratio $\sigma_{4.2\ \mathrm{K}}/\sigma_{300\ \mathrm{K}} = 75$. The measurements were performed at constant current in liquid helium for two types of specimens. One of these consisted of an impregnated multiturn coil with a dense winding (wire length ~ 1 m) and the other was an uninsulated copper wire which was stretched on stainless-steel hooks ϕ 0.1 mm and placed on a spring-loaded frame. Such hooks maintained the heat transfer conditions and the current distribution essentially constant and allowed measuring the electric field intensity, averaged over the sections, $\overline{E}_i = V_i/l_i$, using the standard potentiometric method V_i is the voltage drop on a section of length l_i.

The I–V curves of the specimens studied, which represent the dependence $j(\overline{E})$, are shown in Fig. 1 ($\overline{E} = V/L$, V is the voltage drop across the specimen, and L is the length of the specimen). Curve a corresponds to specimens stretched on the hooks ($L = 1.01$ m for 1; $L = 0.73$ m for 2; and $L = 0.34$ m for 3). As is evident from the figure, the I–V curve is essentially linear up to values of $\overline{E}_c = 0.7$ V/m. For times shorter than 0.1 s, a spontaneous transition occurs out of the points $j_c(\overline{E}_c)$ to the branch of the I–V curve characterized by a current density that does not depend on $\overline{E}$. The length of the specimen only affects the magnitude of the increment $\overline{E} - \overline{E}_c$ at the time of the transition, which is explained by the different ratio of the resistance of the external circuit and the specimen (deviation from the fixed voltage regime). As $\overline{E}$ is decreased, hysteresis is observed. The forward and reverse passages are marked on the figure by arrows.

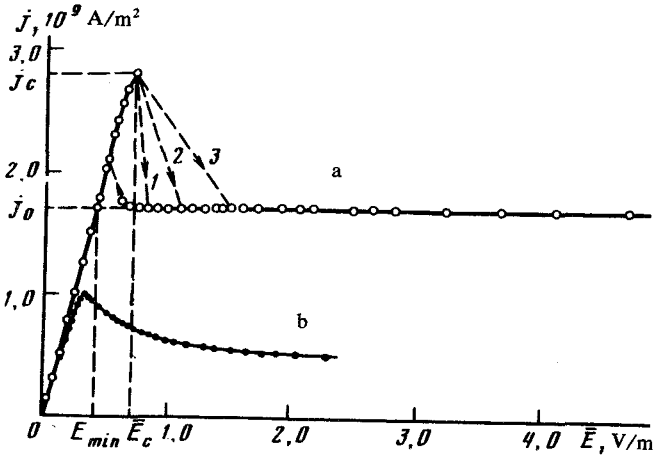

FIG. 1.

The shape of the I–V curve (curve a in Fig. 1) and the presence of hysteresis indicate the onset of an inhomogeneous distribution of the field in the specimen: creation of an electric domain.[2] Indeed, while studying the distribution of the electric field over the specimen, illustrated in the insert in Fig. 2 (1 is the copper wire, 2 are the current leads, 3 are the voltage leads, 4 is the spring-loaded frame, and 5 are the stainless-steel hooks), it was found that at the time the current density dropped sharply in one of the sections of the copper wire, the intensity increased sharply, while it decreased in the rest of the wire. The process of domain creation ceased when a current density $j = j_0$. was attained. The section in which an electric-field domain appears is not localized in space: The domain could arise at any point of the specimen and move randomly along the wire, retaining its width with $\overline{E} = \text{const}$. This fact was established as a result of an analysis of the experimental data obtained by simultaneous automatic recording of the voltage drop both across the section with the domain and

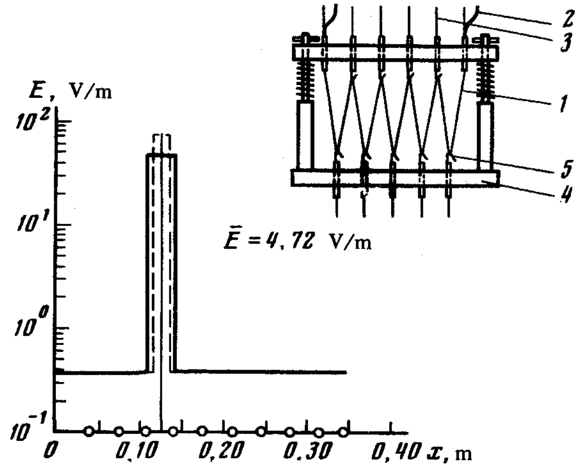

FIG. 2.

across sections of the wire next to it. Five-channel N-327-5 automatic plotter was used to record the voltage.

The field intensity outside a domain was always close to the value $E_{\min}$, which corresponds to the linear section of the I–V curve with $j = j_0$.

As the average field intensity was increased, the domain was stable over the entire region of $\overline{E}$ investigated. With the decrease of $\overline{E}$, it existed for $\overline{E} < \overline{E}_c$, which gave rise to hysteresis. The transition to a homogeneous field distribution occurred at the time of the jumplike increase in j to a value corresponding to the linear branch of the I–V curve.

In Fig. 2, the solid line shows the distribution of the electric field intensity $\overline{E}_i$ along the copper wire with $\overline{E} = 4.72$ V/m at the time the nucleating domain was located between two neighboring potential contacts, separated by a distance $l_i = 3.3$ cm. The positioning of the potential contacts is indicated along the abscissa axis in Fig. 2 by points. The dashed line in this figure illustrates the distribution of the field intensity in the domain assuming that its form is nearly rectangular, while its width is ~2 cm. In estimating the width, we started from the results of the automatic plot of the change in voltage with time in sections of the wire next to the domain, as well as from the fact that its width at $\overline{E} = 4.72$ V/m cannot be less than 1 cm, since in this case the temperature in the domain would be close to the melting temperature of copper.

As is evident from the figure, the electric-field intensity in the domain is almost 200 times greater than the field intensity outside of it.

The effect of the heat transfer on the nature of the distribution of $\overline{E}$ and, therefore, on the shape of the I–V curve is illustrated by curve b in Fig. 1, which corresponds to a specimen shaped like a coil. Such a structure yielded good heat transfer not along the current, but between the neighboring coils of the specimen, which appreciably decreased its effective length, retaining at the same time the fixed voltage regime. For specimens with length $L < 2\pi[j_c \kappa T d / (\overline{E}_c q(T) \mathrm{Max}|j'|)]^{1/2}$, the field distribution should be stable and uniform[1] (κ is the thermal conductivity of the metal, and d is the thickness of the specimen). The I–V curve obtained for an effectively short specimen (curve b in Fig. 1) corresponds to a static characteristic with negative differential conductivity and does not exhibit hysteresis while the field distribution is uniform over the entire interval of $\overline{E}$. The values of j_c and $\overline{E}_c$, which are lower compared to the curve a, are explained by lower $q(T)$ in this experiment, as a result of the better insulation of the specimen from the surrounding medium.

In conclusion, we would like to note that the phenomenon discovered in this work could be interesting not only from the point of view of solid state physics, but, because of the nonlinear nature of the I–V curve, it could find application in technology as well.

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[2] A. F. Volkov and Sh. M. Kogan, Usp. Fiz. Nauk **96**, 633 (1968) [Sov. Phys. Usp. **11**, 881 (1969)].

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