Thermal–electrical domains in metals

G. I. Abramov, A. Vl. Gurevich, V. M. Dzugutov, R. G. Mints, and L. M. Fisher
All-Union Electrical Engineering Institute; Institute of High Temperatures, Academy of Sciences of the USSR

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A report is made of the experimental and theoretical detection and study of thermal-electrical domains in current-carrying metals under conditions of free convection of the cooling gas. It is shown that two types of domains exist—low-temperature and high-temperature.

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At large current densities j in normal metals certain spatially inhomogeneous states—thermal–electrical domains—can arise (see, for example, Ref. 1). Domains of this sort have been observed experimentally under conditions where a boiling liquid was used as a coolant.[2,3] The domain formation in that case is due to features in the heat-transfer power $W = W(T)$ as a function of the temperature T (the presence of a critical boiling region in which $dW/dT < 0$). In the present study we have detected and investigated the thermal–electrical domains arising as a result of the typical metallic temperature dependence $\rho(T)$ of the resistivity. In the measurements the sample was placed in a gaseous medium with heat transfer by free convection, in which case $W(T)$ is a monotonic function.

The experiments were carried out on cylindrical samples of aluminum with $\rho(300\ \mathrm{K})/\rho(4.2\ \mathrm{K}) \cong 10^4$. The diameter d of the conductors was 0.1–1.0 mm, and the length L varied from 60 to 300 mm. The samples were placed in a metal or glass cryostat immersed in a bath of liquid helium or nitrogen. Heat exchange between the bath and the sample was provided by gaseous helium at a temperature T_0 which was monitored by a thermocouple; T_0 was 4.5 K or lower in the helium experiment and 78 K or lower in the nitrogen experiment. Experiments in which the sample was cooled by the ambient air ($T_0 \cong 300$ K) were also carried out.

The conductor under study was connected to a stabilized (to within 10^{-4}) voltage source which delivered a voltage to the sample that was linearly increasing in time. Potential contacts were joined to the samples for measurements of the voltage drop over the entire conductor (U) and over separate parts of it (U_i). The voltage drops U and U_i and the current I in the sample were recorded simultaneously.

Let us consider the main experimental results obtained at the liquid-helium temperature. Figure 1 shows $I = I(U)$ for a sample with dimensions $d = 0.1$ mm and $L = 156$ mm. There is initially a linear growth in $I(U)$, but as the voltage increases the rate of growth slows markedly, and at $U > U^*$ the current drops sharply. With further increase in U the current continues to decrease, asymptotically approaching a constant value I_p. As U is brought back down, one sees a hysteresis which depends on the value of L.

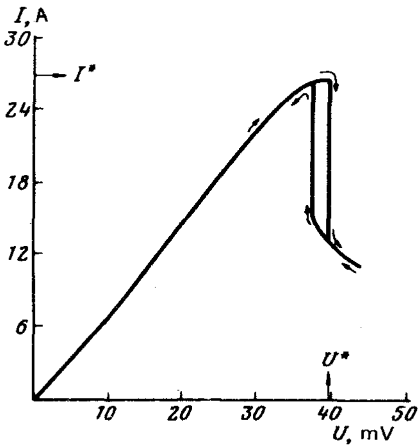

FIG. 1. The function $I(U)$ in an aluminum sample with $d = 0.1$ mm and $L = 156$ mm for $T_0 = 4.5$ K; $\rightarrow$ - - increasing voltage; $\leftarrow$ - - decreasing voltage.

For $U < U^*$ the voltage drops across the segments of the sample are proportional to their length. For $U > U^*$, on the other hand, one of the U_i increases sharply, while the remaining U_i fall off; this is evidence of the formation of an electrical domain (for $d = 0.1$ mm and $L = 156$ mm the electric field in the domain is at least 25 times as large as in the rest of the sample). The average temperature $T = T^*$ of the conductor without the domain at $I = I^*$ and $U = U^*$ can be estimated from the known dependence $\rho = \rho(T)$ for aluminum; such an estimate yields $T^* = 30$ K.

In the experiments at $T_0 = 78$ and 300 K we observed domains of a different type. The domain formation here could be detected visually from the incandescence of a segment of the wire (for $T_0 = 300$ K, $d = 1$ mm, $L = 237$ mm, and $I = 33.7$ A the length of this segment was around 50 mm). The corresponding behavior of $I(U)$ and $U_i(U)$ is qualitatively similar to that described above.

Experiments in which the sample was cooled by ambient air showed that a part of the domain was found in the liquid state (it was easily penetrated, for example, by a copper probe). The melted section of the wire, which was in a horizontal position, was held intact by a "skin" of oxide film. We also measured the electric field inside and outside the domain. For a sample with $d = 1$ mm, $L = 237$ mm, and $I = 33.7$ A the field was 111 mV/cm inside the domain and 34 mV/cm outside.

When the wire was held in a vertical position, the domain moved upward at a velocity $v = 0.43$ mm/sec; when the polarity of the current was reversed, v increased to 0.63 mm/sec. The dependence of v on the direction of the current is apparently due to the thermoelectric effect.[4]

Let us consider the physical causes for the appearance of a stationary thermal domain. Such a domain can exist in an infinite sample if for the homogeneous states the heat-balance condition $Q(T) = W(T)$ holds at two or more values of the temperature $[Q = \rho(T)j^2]$. For free convection $W(T) \sim (T - T_0)^a$ is a monotonic function of

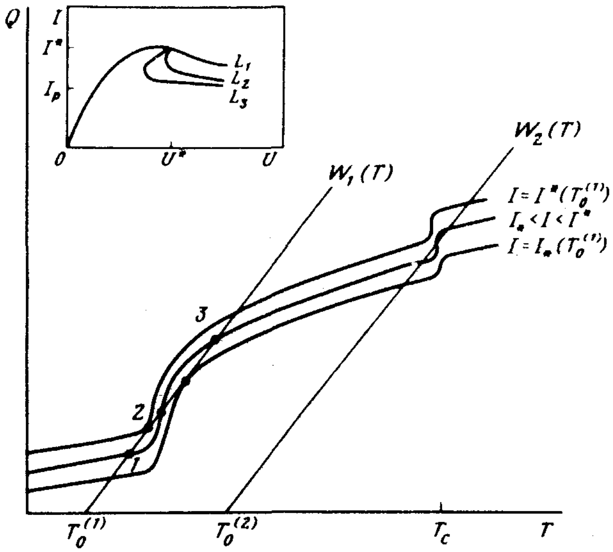

FIG. 2. The functions $Q(T)$ and $W(T)$ for various values of T_0 and j; the inset shows the typical shape of the voltage–current characteristic of a sample with a thermal–electrical domain ($L_1 < L_2 < L_3$).

$T(a \sim 1)$, so a domain arises only if there are rather abrupt changes in $\rho(T)$. Such a situation is characteristic of metals: It arises in pure metals in going from helium to nitrogen temperatures, and also in metals and alloys at various phase transitions, including melting. This situation is illustrated in Fig. 2, which shows the functions $Q(T)$ and $W(T)$ for progressively varying T_0 and j (T_c is melting temperature).

Let us consider in more detail the low-temperature region in Fig. 2. In the interval $I_*(T_0^{(1)}) < I < I^*(T_0^{(1)})$, two stable states can arise: $T = T_1$ and $T = T_3$, corresponding to points 1 and 3. If, on the other hand, $I > I^*$, then the state $T = T_1$ vanishes, and at fixed I the system should undergo a transition to state $T = T_3$. In the fixed-voltage regime such a transition cannot occur, since it would lead to a strong increase in I and to a decrease in the current below I_*. As a result, only a part of the sample goes into the high-temperature state, i.e., a domain is formed.

The current I^* at which the domain arises is found from the equation

$$j^{*2} \frac{\partial \rho}{\partial T}\bigg|_{T_1} = \frac{\partial W}{\partial T}\bigg|_{T_1} \tag{1}$$

We note that relation (1) in this case is not a condition of thermal instability, i.e., is not the condition for the loss of stability of the homogeneous state $T = T_1$. For the high-temperature domain we have

$$j^* = \sqrt{\frac{W(T_c)}{\rho_s(T_c)}}\,, \tag{2}$$

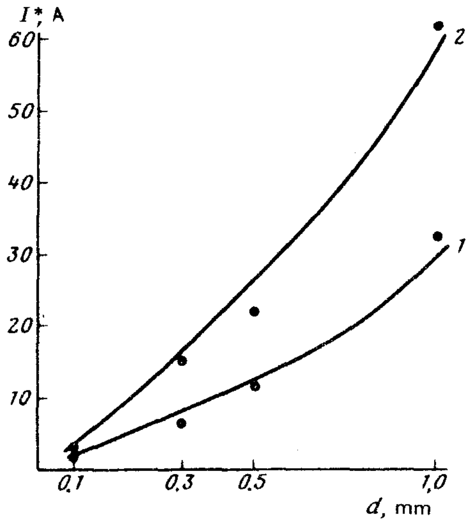

FIG. 3. The function $I^*(d)$ for various cooling conditions: 1) cooling by ambient air ($T_0 = 300$ K); 2) cooling by gaseous helium ($T_0 = 78$ K). The points are experimental data; the curves show the calculated results.

where ρ_s is the resistivity of the solid phase. For free convection we have $W(T) \sim d^{3\eta-2}(T-T_0)^{1+\eta}$, where $\eta = 0.125$–0.133 (Ref. 5),. and so the current I^* is related to d and T_0 by the relation

$$I^* \sim d^{1+1,5\eta}(T_c - T_0)^{\frac{1}{2}(1+\eta)}$$

Figure 3 shows I^* as a function of d for various values of T_0. If the functions $\kappa = \kappa(T)$, $\rho = \rho(T)$, and $W = W(T)$, are known (κ is the thermal conductivity), one can easily calculate the voltage–current characteristic of a sample with a thermal–electrical domain by proceeding from the heat-conduction equation. The results of such a calculation are in good agreement with the experimental data, both qualitatively (see the inset in Fig. 2) and quantitatively.

We also note that in the semimetal series (bismuth, antimony, etc.) the resistivity $\rho(T)$ decreases upon melting. In this case for samples with a large enough value of d, current filamentation arises in the high-temperature region, and domain formation occurs at low temperatures.

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