

Measurement of the domain drift velocity of superconductors in the intermediate state

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The voltage produced when direct current flows through a cylindrical sample in the intermediate state was measured. A perturbation of a constant uniform magnetic field, periodic along the cylinder axis, was produced on the sample surface. An additional voltage, due to the motion of the intermediate state in the inhomogeneous field, then appeared on the ends of the sample. In the case of a perturbation moving uniformly along the cylinder axis, the additional voltage was determined by the difference between the perturbation velocity and the drift velocity of the local structure distortions. The additional voltage vanished when these velocities were equal. This has made it possible to measure the dependence of the drift velocity on the current through the sample. The drift velocity, in agreement with the theory, turned out to be proportional to the current density and independent of the configuration of the normal and superconducting layers.

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In a type-I superconductor in the intermediate state, the volume of the metal breaks up into regions of superconducting (s) and normal (n) phases. In the case of thermodynamic equilibrium in a plate or a cylinder in a uniform magnetic field, this domain structure constitutes regularly alternating n and s layers. Within the framework of macroscopic electrodynamics, in which the electromagnetic fields are averaged over a large number of domains, different arrangements of the layers are possible at the same values of the averaged fields.^[1] When dc current J flows through the samples, the layers can go into motion. In the case of a pure uncompensated metal at $\Omega\tau \gg 1$ (Ω is the cyclotron frequency in the critical field H_c and τ is the carrier relaxation time) the layers inclined at the Hall angle to the current directions will move with maximum velocity, the layer velocity component along the current direction being $v_{\text{layer}} = j/Ne$ (j is the current density, N is the difference between the electron and hole densities, and e is the electron charge). At any other layer orientation, as shown by Andreev and Sharvin,^[1] their velocity will be less. In^[1] they considered also the propagation of local perturbations in the layer configuration without a change of the averaged electromagnetic fields. It turned out that such layer-configuration distortions drift perpendicular to the direction of \mathbf{E} , i.e., at an angle $\approx 1/\Omega\tau$ to the current direction, with the drift-velocity component along the current equal to $v_D = j/Ne$ independently of the initial arrangement of the layer. In some sense this is analogous to fluid flow, where the role of the fluid velocity is played by the drift velocity v_D .

It is known from experiments^[2] on the layer motion that the motion of the layers slows down when the current J is increased even several percent above the critical value J_c , so that $v_{\text{layer}} < j/Ne$. The simplest explanation of this phenomenon is obtained by assuming that as their velocities increase, the n-s boundaries are slowed down more effectively by the inhomogeneities of the sample. The layers, which were initially almost perpendicular to the current direction, then rotate and their velocity decreases.^[2] In this situation, it is of certain interest to investigate the effect of the factors that slow the layers down on the drift velocity v_D of the

local distortions of the n-s boundaries. We can use for this purpose the method of measuring the current-voltage characteristics of the sample in an inhomogeneous magnetic field.

It was observed earlier that when a current J flows through a cylindrical intermediate-state indium sample located in a uniform field \mathbf{H} , an additional potential difference \tilde{U} is produced at the ends of the cylinder, on top of the usual "ohmic" voltage, if a weak static inhomogeneous magnetic field H_1 is produced on the surface of the sample. This magnetic-field perturbation, periodic along the cylinder axis, was produced in the experiments of^[3,4] with the aid of a coil bifilarly wound around the sample. The static perturbation H_1 was immobile in the laboratory frame, and the additional voltage \tilde{U} was determined, according to the theory of this effect, by the drift velocity v_D . In particular, \tilde{U} reversed sign when the direction of the current J was changed. In the more general case of an alternating perturbation moving along the sample surface with velocity \mathbf{v} , the value of \tilde{U} should be determined by the velocity difference $v_D - \mathbf{v}$. To verify this assumption, we have performed experiments in which the perturbation H_1 was a peculiar traveling wave propagating along the sample axis with specified velocity.

The results confirm the mechanism proposed in^[4] to explain the onset of the additional voltage \tilde{U} . In turn, this circumstance suggests that the drift velocity is $v_D = j/Ne$ up to values $J/J_c \approx 0.2$.

1. The equations describing the propagation of macroscopic perturbations of electromagnetic fields in the intermediate state were derived by Andreev^[5] under the assumptions $\Omega\tau \gg 1$ and $J \ll J_c$. For perturbations proportional to $\exp(i\mathbf{k} \cdot \mathbf{r} - i\omega t)$, where \mathbf{k} is the wave vector parallel to the sample surface, the frequency of the perturbation ω and the density of the direct current j enter in the equations that describe the distribution of the magnetic fields in the sample as the combination $\tilde{\omega} = \omega - \mathbf{k} \cdot \mathbf{j}/Ne$. The additional dc voltage \tilde{U} , which is produced at the ends of the sample in the presence of the perturbation on top of the usual ohmic voltage, is determined by an electric-field increment E_2 , which is inde-

pendent of the coordinates and is quadratic in the perturbation. This increment E_2 depends also on the frequency of the perturbation and on the current J only via the quantity $\tilde{\omega}$. It is therefore clear that the dependence of \tilde{U} on J , obtained in [3, 4] for a static perturbation with $\omega = 0$, can be extended to the case of a perturbation moving along the sample axis with velocity $v = \omega/k$, by simply substituting $J \rightarrow J - J_0$, where the current J_0 corresponds to the condition $\tilde{\omega} = 0$, i.e., $v = v_D$.

2. The samples employed and the experimental procedure are described in detail in [4]. A distinguishing feature of the experiment is the special circuit for feeding the bifilar coil. This coil, of superconducting wire of 0.34 mm diameter, consisted of two sections. The winding was turn to turn, so that the wavelength of the fundamental harmonic of the perturbation constituted four wire diameters, i.e., $\lambda = 1.36$ mm. The gap between the turns and the sample surface was about 0.3 mm. The two sections of the bifilar coils were fed from two ac generators supplying currents J_m of equal frequency and amplitude. The currents through the sections were shifted in phase by $\varphi = \pm\pi/2$. The generator frequency ν could be decreased to $\nu = 0$.

Each section of the coil produced a standing wave on the sample surface. These waves were shifted in the sample axis direction by $\lambda/4$. It is easily shown that the superposition of two fundamental-harmonic standing waves of length λ , shifted in phase by $\varphi = \pm\pi/2$, and shifted along the axis by $\lambda/4$, produce a traveling wave of the same length and frequency, propagating along the sample axis with velocity $v = \lambda\nu$. The propagation direction is determined by the sign of φ .

3. Measurements of the sample voltage as a function of a given direct current $J \lesssim 100$ A were performed on a cylindrical single crystal of ≈ 4 mm diameter, made of high-purity indium (sample 2 of [4]). When alternating current was passed through the bifilar coil, the registered voltage had an appreciable ac component. This component resulted both from the electromagnetic induction in the potential leads to the nanovoltmeter, and from the alternating voltage on the sample. The latter had a noticeable dependence on J , and in particular it decreased in amplitude on passing through the value $J = J_0$. We are interested here, however, only in the dc component of the voltage U , which can be easily separated by constructing the envelopes of the total-voltage oscillating curves, obtained with an x-y recorder. Unfortunately, this operation, in conjunction with the null drift of the nanovoltmeter, leads to a rather large error in the value of U , as high as 10 nV. Nonetheless, the expected shift of the current-voltage characteristics with increasing perturbation frequency was observed quite distinctly. Figure 2 shows typical current-voltage characteristics obtained by averaging the oscillating voltage on the sample. The voltage U is determined as the difference between the two characteristics, $\tilde{U} = U(J_m \neq 0) - U(J_m = 0)$.

In accord with the theory, when the frequency ν is increased the $\tilde{U}(J)$ curves shift along the abscissa axis. For the curves shown in Fig. 2, a positive direction of the abscissa axis corresponded to coinciding directions of j and to equal values of the perturbation velocity v . When the phase-shift φ between the generators of the current J_m reverses sign, the current-voltage characteristics shift in the opposite direction of the abscissa axis.

The current $J = J_0$ was determined from the intersec-

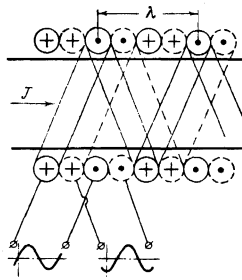


FIG. 1

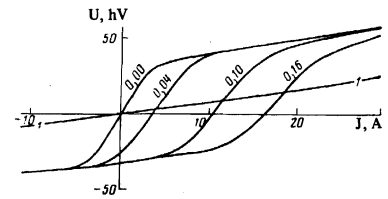


FIG. 2

FIG. 1. Excitation of the traveling perturbation.

FIG. 2. Current-voltage characteristics of intermediate-state indium at $T = 1.35^\circ\text{K}$ ($J_c = 240$ A), $C_n = 0.2$. Curve 1—at $J_m = 0$. The remaining curves were obtained at $J_m = 12$ A. The perturbation frequencies in hertz are marked on the curves.

tion of the characteristics $U(J_m \neq 0)$ and $U(J_m = 0)$. Within the limits of experimental error, the values of \tilde{U} are symmetrical about the point $J = J_0$. We define $J = J_1$ as that value of the current through the sample at which the derivative $\partial\tilde{U}/\partial J$ decreases to half its maximum value. In these experiments it was observed that $|J_1 - J_0|$ increases noticeably with increasing frequency ν . The causes of this phenomenon remain unclear. It must also be noted that in experiment practically no decrease of \tilde{U} was observed with increasing difference $|J - J_0| \gg |J_1 - J_0|$, as would follow from the formulas of [4]. This discrepancy may be due to the complicated spectral composition of the perturbation, which differs from a simple traveling wave of the type $\exp(i\mathbf{k} \cdot \mathbf{r} - i\omega t)$, and to the conditions of macroscopic electrodynamics in the case of the higher harmonics. At the same time, the order of magnitude of $|J_1 - J_0|$ agrees with the value $\Omega\tau \approx 2.5$, which determines the width of the maximum of $\partial\tilde{U}/\partial J$.

The current-voltage characteristics $U(J)$ were plotted at a fixed frequency $\nu = 0.10$ Hz and at different orientations of the uniform constant magnetic field \mathbf{H} in a plane perpendicular to the cylinder axis. Within the limits of experimental error, the $U(J)$ curves were independent of the direction of \mathbf{H} . The value $H \leq H_c$ determined the concentration of the normal phase, $C_n = 2H/H_c - 1$. The current-voltage characteristics plotted at different values of C_n have shown that \tilde{U} and $|J_1 - J_0|$ depend on the concentration C_n in accord with the data of [4]. In particular, $\tilde{U} = 0$ in the normal and in the purely superconducting states. At the same time, J_0 in the intermediate state does not depend on the concentration of the normal phase.

As already noted in [4], the characteristics $\tilde{U}(J)$ depend strongly on the temperature T . With increasing temperature there is not only a decrease in the maximum value of $|\tilde{U}|$, but also an increase in the width of the maximum of $\partial\tilde{U}/\partial J$. However, the value of J_0 is independent of temperature in the investigated range $T = 1.3$ to 2.2°K .

4. At $J = J_0$ the drift velocity v_D is equal to the velocity of propagation of the perturbation $v = \lambda\nu$. The experimental data indicate that v_D is independent of the direction of \mathbf{H} in a plane perpendicular to the current, of the concentration of the normal phase, and of the temperature, and is determined entirely by the current through the sample. Figure 3 shows the results of the measurements of J_0 at various frequencies ν , in the

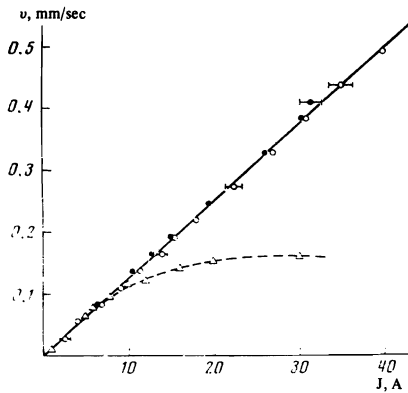


FIG. 3. Measured velocity vs. the current J : \circ and \bullet —for v_D (different circles denote data of different experiments); Δ —for v_{layer} .

form of plots of $v_D(J)$. The quantity subject to the largest error is J_0 , and therefore horizontal error bars are marked on Fig. 3 for certain characteristic points. It is clear from these data that within the limits of experimental error the value of v_D increases in proportion to the current. The sign of J_0 corresponds to a positive value of the carrier charge. This agrees with the data on the Hall effect.^[6] Assuming a uniform distribution of the current over the sample cross section, we can calculate the current density and determine the carrier density $N = j/ev_D$. The straight line drawn through the experimental points on Fig. 3 corresponds to $v_D = (1.45 \pm 0.1) \times 10^{-4}$ cm/sec at $j = 1$ A/cm². The carrier density calculated from these data is close to the value obtained from Hall-effect data^[6] and to the theoretical value $N = 3.93 \times 10^{22}$ cm⁻³ calculated from the known lattice constant of indium at a carrier number 1 hole/atom.

As described earlier, in addition to plotting the current-voltage characteristics, we used the same sample to measure the velocity v_{layer} of the n-s layers at the oscillation frequency ν_c of the microcontact resistance as a function of the current through the sample at $J_m = 0$. The layer velocity was determined from the known period of the structure^[2] $d \approx 0.3$ mm at $T \lesssim 2^\circ\text{K}$ and

$C_n \approx 0.5$ in accord with the relation $v_{\text{layer}} = \nu_c d$. In view of the condition $J \ll J_c$ it can be assumed that d is independent of the current. Data on the dependence of v_{layer} on J are also shown in Fig. 3 and are represented by the dashed line. At $J \lesssim 8$ A we have $v_{\text{layer}} \approx v_D$, with increasing current the layer velocity increases more slowly than v_D , and at $J \approx 30$ A it becomes practically independent of the current. At the same time, $v_D \propto J$ up to currents $J/J_c \approx 0.20$.

Thus, the various factors that cause the rotation of the entire regular system of layers and thereby decrease v_{layer} have no noticeable effect on the "hydrodynamic" velocity v_D , which we assume can be measured by observing the vanishing of the voltage \tilde{U} . The shift of the maximum of $\partial\tilde{U}/\partial J$ with changing velocity of the traveling perturbation is by itself an illustrative manifestation of the "hydrodynamic" properties of the motion of the intermediate-state structure, by virtue of which all perturbations are "carried away" by the electric current.

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113