Influence of an alternating field on the superconducting transition in tin

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An alternating electromagnetic field of large amplitude gives rise to a shift, not connected with the change of the sample temperature, of the field of the superconducting transition.

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Observation of the current states in tin has revealed that the hysteresis phenomena that vanish when the sample goes over into the superconducting state can be restored by increasing the amplitude of the radio-frequency field.[1] According to[2], observation of the current state calls for the presence of a nonsuperconducting layer of metals, the thickness of which greatly exceeds the depth of the skin layer. An impression is gained that when an alternating field is introduced, the superconducting is destroyed in the entire volume of the metal in a weaker magnetic field than without radio-frequency irradiation. The present paper is devoted to a check on this assumption.

The first experiment was performed on single-crystal disks of 0.6 and 0.4 mm diameter and 17.8 mm thickness. Subsequently we used for measurements a tin cylinder 3 cm long and of 0.93 cm diameter. The resistance ratio $\rho_{300\mathrm{K}}/$

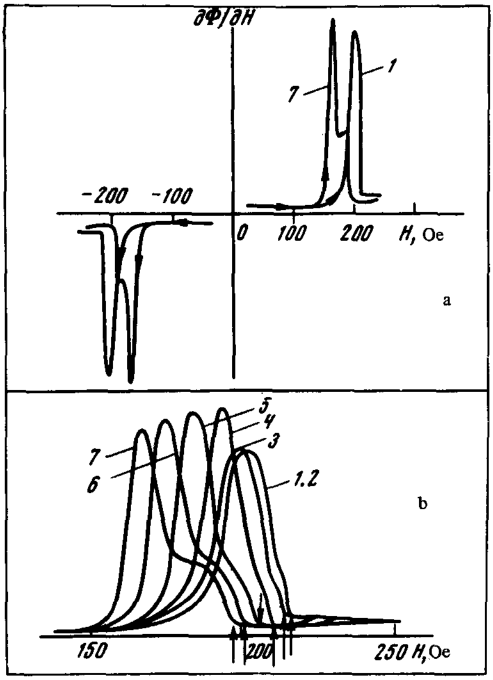

FIG. 1. Shift of superconducting transition in an alternating field, $T=2.06\,^\circ\mathrm{K}$, $\omega/2\pi=4000$ Hz. On curve 1—$H=0$, 2—34, 3—43, 4—50.5, 5—67, 6—84, 7—97 Oe. The arrows mark the directions of the plotting.

$\rho_{4.2\mathrm{K}}$ for the cylinder amounted to 10^5. In the measurements on the disks, the vector of the constant magnetic field was in the plane of the disk, and when working with the cylinder and with the disk were analogous. All the results presented below pertain to the tin cylinder.

The sample was placed in a cylindrical inductance coil that produced the alternating field. The coil length exceeding somewhat the sample length. The diameter was 1 millimeter larger than the diameter of the tin cylinder. The sample was placed inside the inductance coil on two paper strips, so that a gap existed between the cylinder and the coil. A second inductance coil was wound around the first and served as the receiving coil. The coils were also separated by a gap of approximately 1 mm. The presence of the gap was essential in order to improve the heat dissipation, especially at temperatures above the λ point.

The signals from the second coil passed through an *RC* filter with time constant 0.1 sec and was applied to the *Y* coordinate of a high-sensitivity (5 mV/cm) x-y recording potentiometer. The superconducting transition was revealed by the emf induced in the second coil when the magnetic field was pushed out at the instant of the transition from the normal state to the superconducting state, or when the field penetrated into the sample during the reverse transition. The constant magnetic field was rotated slowly and uniformly $(\partial H/\partial t$

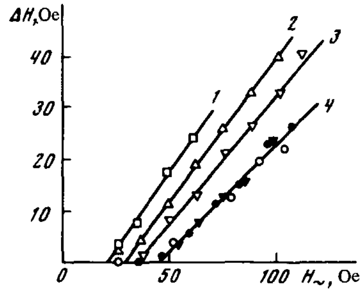

FIG. 2. Dependence of the shift on the amplitude of the alternating field: 1—$T = 3.25$ K, 2—$T = 2.97$ K, 3—$T = 2.74$ K, 4—$T = 2.02$ K. The different symbols on curve 4 mark results obtained at the three frequencies $\omega/2\pi = 10^3$ Hz, $\omega/2\pi = 1.5 \cdot 10^4$ Hz, $\omega/2\pi = 2.27 \cdot 10^5$ Hz.

= const) in time. The received signal, proportional to $\partial\Phi/\partial t$ (Φ is the magnetic-induction flux through the sample) was proportional to $\partial\Phi/\partial H$.

We used in the experiments alternating fields with frequencies ranging from 10^6 to 10^3 Hz. In this frequency range, the skin effect was anomalous. Indeed, at 10^3 Hz the skin layer depth in tin is $\delta_a \approx 4 \times 10^{-3}$ cm,[3] whereas the electron mean free path in our samples at helium temperatures was $l \approx 3 \times 10^{-2}$ cm.

A typical experimental curve is shown in Fig. 1. It was recorded in a magnetic field that increased at a rate low enough to make the shape of the transition curve independent of this rate. It is seen from Fig. 1(b) that the alternating field produced not only a shift but also a deformation of the transition curves. For a quantitative description of the shifts, it is convenient to use those points of the curves [marked by arrows in Fig. 1(b)], in which the entire volume of the sample can already be regarded as being in the normal state.

The dependence of the shift ΔH on the alternating-field amplitude is shown in Fig. 2. The shift of the superconducting transition begins not with zero, but with a certain finite value $H_\sim$. When the direction of the constant magnetic field deviates from the cylinder axis, the value of ΔH decreases sharply.

The form of the function $\Delta H(H_\sim)$ remains unchanged in the range from 10^3 to 2×10^5 Hz (curve 4 of Fig. 2). Further increase of the frequency leads to the appearance of a noticeable shift of the superconducting transition at smaller $H_\sim$ than those corresponding to the point where the $\Delta H(H_\sim)$ curve has a kink. The absence of a frequency dependence in a wide range of frequencies indicates definitely that the shift of the superconducting transition is not due to a rise of the sample temperature above that of the helium bath. It appears that the heat rise becomes appreciable only at frequencies near 1 MHz and it is precisely the heat rise which accounts for the change in the shape of the $\Delta H(H_\sim)$ curve at these frequencies. Indeed, the power released in the normal state per square centimeter of sample surface at $\omega = 2\pi \cdot 10^6$ and $H_\sim = 50$ Oe amounts to $W = \omega\delta(H^2/4\pi) = 5 \cdot 10^{-2}$ W. In our case the sample was in the normal state only during a fraction of the period and the released power was somewhat lower. Therefore the figure obtained above provides the upper bound of the heat rise for further estimates. Owing to the Kapitza jump, the released power overheats the sample by $\Delta T \approx (40/T^3)W \approx 0.25$ K at $T = 2$ °K and shifts the transition by an amount $\Delta H \approx 2H_0 T/T_c^2 \Delta T \approx 20$ Oe. the experimentally observed shift under these conditions was approximately 10 Oe. Lowering the frequency decreases the thermal shift of the superconducting transition, which is proportional to $\omega^{2/3}$, and at frequencies 1 kHz the thermal shift is negligibly small in comparison with the experimentally observed one.

At temperatures below the λ point, the general form of the $\Delta H(H_\sim)$ curves remains the same (Fig. 2), and the field amplitude $H_\sim$ at which the shift of the superconducting transition begins decreases monotonically with increasing temperature. It should be noted, to be sure, that the results obtained in this temperature region must be approached with caution, since an uncontrollable overheating of the sample could take place.

The shift of the superconducting transition in an alternating field may be connected with the appearance of direct current on the sample surface. The reason for the appearance of the direct current is the nonequivalence of the two half-cycles of the alternating field: in one of the half cycles the total field $H + H_\sim \cos\omega t_1$ may exceed the critical field H_c of the superconductor, while in the second half-cycle $H + H_\sim \cos\omega t_2 < H_c$ (under similar conditions, when direct and alternating currents were passed simultaneously through the conductor, an emf was produced at the terminals of a superconducting wire[4,5]). The absence of a shift of the transition at small values of $H_\sim$ might be due to magnetic "superheating." However, display of the superconducting transition on an oscilloscope screen, similar to that in[6], has revealed that the transition is observed already at amplitudes $H_\sim$ half as large as the fields corresponding to the kink of the $\Delta H(H_\sim)$ curve. In addition, the cause of the deformation of the transition curves when the alternating field is introduced remains unclear.

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