Observation of superconductivity of the twinning plane by using the eddy-current method

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The resistance of a Sn bicrystal containing a (301) twinning plane has been measured by using the eddy-current excitation method in the frequency range of 20 Hz to 2 MHz at temperatures close to the critical temperature. The existence of a superconducting layer with a thickness of $(1–2)\times 10^{-3}$ cm has been established near the twinning plane in the temperature interval $T_c < T < T_c + 0.02$ K.

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Superconductivity of the twinning plane (TP) of a tin crystal was reported in Ref. 1. The superconductivity was revealed by the diamagnetic moment, which was recorded by a sensitive magnetometer that included a quantum interferometer. In this paper we shall discuss the results of an observation of superconductivity of the TP of tin bicrystals by the eddy-current method[2] at frequencies of 20 Hz to 2 MHz.

The test samples in the shape of cubes with edges of 1 and 4 mm or 10-mm-long rectangular parallelepipeds with 1 × 1-mm, 4 × 4-mm, and 4 × 1-mm cross-sectional areas with a TP in the central cross section were cut from bicrystals by using an electric-spark method. A 2-mm-long measuring coil, mounted on the sample with a small gap, could be moved along the sample in order to examine its different parts. The

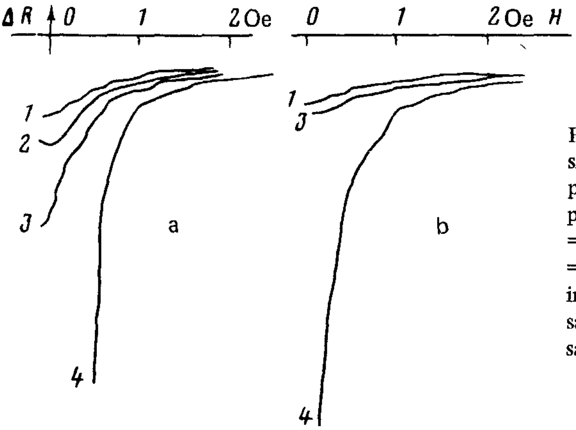

FIG. 1. Traces of the variation of the resistance of the coil introduced by the sample vs the magnetic field at different temperatures. 1, T-T_c = 0.02 K; 2, T-T_c = 0.01 K; 3, T-T_c = 0.005 K; 4, T-T_c = 0.001 K. The frequency of the measuring field is F = 56 kHz. (a) A section of sample contains a TP, (b) a section of the sample that contains a single crystal.

coils were wound with a thin wire and had 200–2000 turns, depending on the frequency range of the measuring current. The coil with a sample was connected into a bridge circuit or into the circuit of a self-excited oscillator. The relative sensitivity of the circuit to a change in the sample impedance was $\sim 10^{-4}$. The temperature in the vicinity of the critical temperature $T_c = 3.722$ K of the superconducting transition of tin was measured with a carbon thermometer and from the pressure of helium vapor; its instability during one measurement was 10^{-4} K. The earth's magnetic field was compensated for by Helmholtz coils with an accuracy of 0.01 Oe.

During the experiment we have recorded the signal ΔR, which is proportional to small changes of the resistance or inductive reactance introduced into the coil by the sample. Figure 1 shows traces of ΔR vs the magnetic field H applied to the sample. The part of the sample with the TP is characterized by a signal that appears at $T = T_c + 0.02$ K (Fig. 1a); this signal increases with decreasing temperature and is masked by the superconductivity of the sample at $T = T_c$. For a comparison, Fig. 1b shows the $\Delta R(H)$ dependences of the adjacent single-crystal portion of the sample without the TP. In this case the $\Delta R(H)$ dependence has the typical shape of a superconducting transition with the preceding fluctuations of the superconducting phase in the bulk of the sample.

The quantity $\Delta R(H = 0)$ measured for the part of the sample with the TP is strongly temperature dependent. The $\Delta R(T\text{-}T_c)$ dependence is shown in Fig. 2. The points, which were obtained for different samples at different frequencies of the measuring field and which are collected on the graph within the measurement error limits, lie on a straight line which is described in logarithmic coordinates by the dependence $\Delta R = \Delta R_0 \exp[-(T\text{-}T_c)/\tau]$, where $\tau \sim 0.8 \times 10^{-3}$ K. This agrees well with the dependence obtained for the magnetic moment.[1]

Therefore, we have a sufficient reason to assume that the signal $\Delta R(H)$ observed at $T > T_c$ is caused by the superconductivity of tin near the TP. This is confirmed by the dependence of the signal ΔR on the relative orientation of the measuring currents in the sample with respect to the TP. At low frequencies (20–90 Hz) of the measuring field the signal peaks at $T > T_c$ when the TP is oriented parallel to the plane of

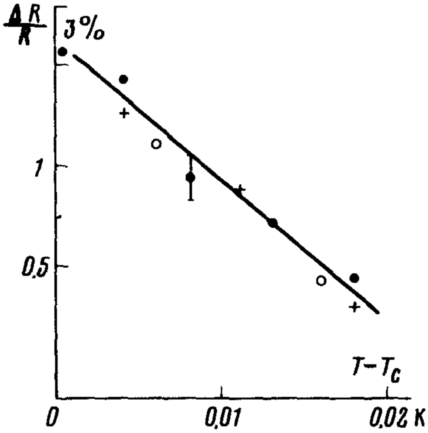

FIG. 2. Dependence of $\Delta R(H=0)$ (see Fig. 1), corresponding to the change in the sample resistance R introduced into the coil as a result of its transition to the superconducting state, on the temperature $T_c = 3.722$ K for different samples and measuring-field frequencies. (●) $4 \times 4 \times 10$-mm sample, $F = 56$ kHz; (○) $4 \times 1 \times 10$-mm sample, $F = 430$ Hz; (+) $4 \times 4 \times 4$-mm sample, $F = 2$ MHz.

the coil, i.e., when the inductive coupling of the TP with the coil is maximum. There is no signal when the TP is at right angles to the plane of the coil.

The low- and high-frequency regions of the measuring field are separated by a frequency which is characteristic for each sample; at this frequency the depth of the skin layer is approximately equal to the transverse dimensions of the sample and the best matching of the sample to the coil is achieved. Therefore, the transition to measuring-field frequencies $F > 400$ Hz is characterized by a decrease of the relative signal by a factor of ~5 at $T > T_c$, which remains almost constant at 400 Hz $< F <$ 2 MHz.

The effective thickness δ of the superconducting layer near the TP can be estimated from the relative magnitude of the signal $\Delta R/R$ determined by it, where R is the change in the resistance of the coil introduced by the sample as a result of its transition to the superconducting state. In a measuring field of sufficiently high frequency, when the skin effect is pronounced, we have $\Delta R/R \approx \delta/d$, where $d \approx 2$ mm is the range of sensitivity of the coil on the sample surface. From this we obtain $\delta \approx (1\text{-}2) \times 10^{-3}$ cm.

In Ref. 1 the layer thickness was determined to be close to $\xi_0 \approx 3.5 \times 10^{-5}$ cm–the coherence length in a superconductor. Such a large difference is explained by the fact that the value of δ measured by us is determined by the characteristic dimensions of the superconducting regions, into which the TP is divided. In fact, when the superconducting part of the TP is oriented parallel to the eddy currents, its effect on the sample impedance is equal in order of magnitude to that of a spherical superconducting region whose diameter is approximately equal to the characteristic size of the TP region. The structure of superconducting regions with dimensions of the order of ξ_0 cannot be determined from the measurements at frequencies for which the skin-layer depth is $\gg \xi_0$. However, it is difficult to determine this structure by changing the direction of the field H, because the superconducting sections of the TP in each region are not parallel. Further evidence for this conclusion comes from the fact that there is not noticeable dependence of the signal observed at $T > T_c$ on the direction of the field H. An electrodynamic calculation from the results of measurements at $F < 90$ Hz is consistent, within the error limits, with the model in which the

TP is divided into superconducting and normal regions whose size ratio is (2–3): 1.

In summary, as a result of measurements in varying magnetic fields at frequencies up to 2 MHz, we have established the existence of a thin layer of a superconducting phase near the TP at $T > T_c$, which had previously been detected in a static magnetic moment. Although the induction method used by us is less sensitive than the quantum-interferometer method, its sensitivity was adequate to observe the effect detected in Ref. 1. There is no doubt that the TP superconductivity has other important characteristics.

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