Twinning-induced increase in the superconducting transition temperature of tin

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(Submitted 15 July 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 4, 191–194 (25 August 1983)

The superconductivity of specimens of pure tin, containing a large number of microscopic twins, is investigated. It is established that the critical temperature of a large number of sections of twinning planes increases considerably due to a weakening of the proximity effect as a result of close positioning of twins. Specimens in which the superconductivity appears at a temperature twice as high as the usual critical temperature of tin are obtained.

PACS numbers: 74.70.Dg, 74.70.Gj, 61.70.Ng

1. Twinning plane (TP) superconductivity of Sn, whose critical temperature T_c is $\Delta T_c \simeq 0.04$ K higher than T_c of the surrounding bicrystal, was discovered in Ref. 1. Taking into account the suppression of the TP superconductivity by the effect of proximity of the normal metal, such a ΔT_c must be viewed as significant. Weakening of the proximity effect by the adjacency of two (or many) TP, located at a distance $d \sim \xi_0$ ($\xi_0 = 3.5 \times 10^{-5}$ cm is the coherence length), was observed in Ref. 2; in this manner, it was possible to increase ΔT_c to 0.08 K. The obvious way of avoiding the proximity effect is to remove the normal metal; to do this, the specimen must consist of a pair of thin ($d \ll \xi_0$) twin crystals with a TP situated in the middle. A very attractive structure is one consisting of many thin plane-parallel crystals with mutual orientation of twins.[2] A calculation of ΔT_c of such a periodic structure[3] demonstrated the effectiveness of this method. However, a method does not yet exist for preparing such a specimen.

Another way of increasing ΔT_c is to create a specimen consisting of microscopic twin-crystals, in which the dimensions of these crystals and the average distance between sections of the spatial lattice of TP is less than ξ_0. This method was successfully tested in Refs. 2 and 4. The purpose of the present work was to investigate specimens with a much denser spatial lattice of TP.

To measure ΔT_c, we constructed an apparatus in which the temperature of the specimen can vary from 2 to 200 K while maintaining the temperature of the measuring instrument, a differential quantum magnetometer, at a constant level of 2 K.[5]

2. In the first experiments, a fine grid of TP was created in the surface layer of a Sn specimen by electric-spark cutting of the specimen (Mo wire or W ∅ 50 μm; the voltage $\sim$100 V, capacitance $\sim$5 μF, and the medium consisted of decane $C_{10}H_{22}$). The electron-microscope photograph of this surface is shown in Fig. 1a.

Figure 2 shows the traces of the magnetic moment M of the specimen as a function of the slowly (over the course of 1–10 min) varying magnetic fields. At $T \simeq 20$ K, the specimen is in the normal state and the hysteresis loop (Fig. 2a), caused by eddy

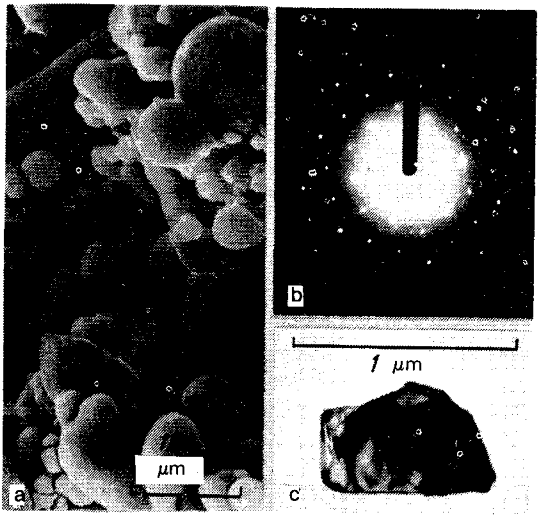

FIG. 1 a) Electron microscope photograph of a section of a Sn specimen; b) Sn particle; c) diffraction picture of the Sn particle.

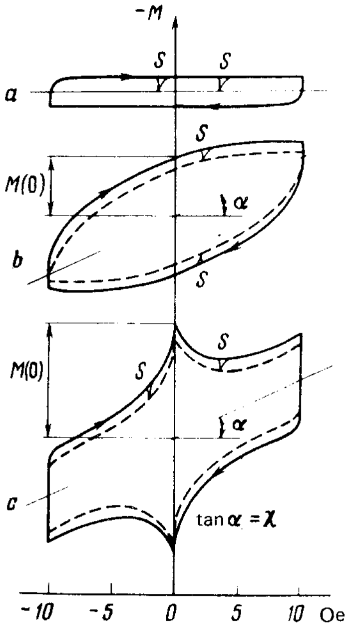

FIG. 2. Traces of the magnetic moment of Sn specimens as a function of the slowly varying magnetic field H; a) normal state, $T = 20$ K; b) section with $7 < T < 12$ K; tablet with $3.72 < T < 7$ K; the peak at $H = 0$ is due to the current flowing along the perimeter of the section,[4] differing from the tablet by the high demagnetizing factor; S indicates a disruption of the magnetic field.

currents, forms a rectangle. As T is decreased, the following situation occurs (Fig. 2): 1) The trace of $M(H)$ inclines by an angle α, which is due to the appearance of the diamagnetic susceptibility of the specimen $\chi_D \propto \mathrm{tg}\alpha$;2) nonlinear hysteresis of superconducting currents which are destroyed by the field H (an undamped superconducting current is observed by interruptions S in the variation of H). Figure 3 shows the results of the measurements. We note that the sensitivity in observing χ_D is much lower than M.

3. In subsequent experiments, we investigated microscopic particles of Sn. To maintain chemical purity of the particles (with different dimensions, ~ 1 μm on the average), two specimens of *Sn* were obtained by mutual electric spark working. An electron photograph of a particle is shown in Fig. 1b; its single crystalline nature is indicated by the diffraction pattern in Fig. 1c (the cross section of the electron beam

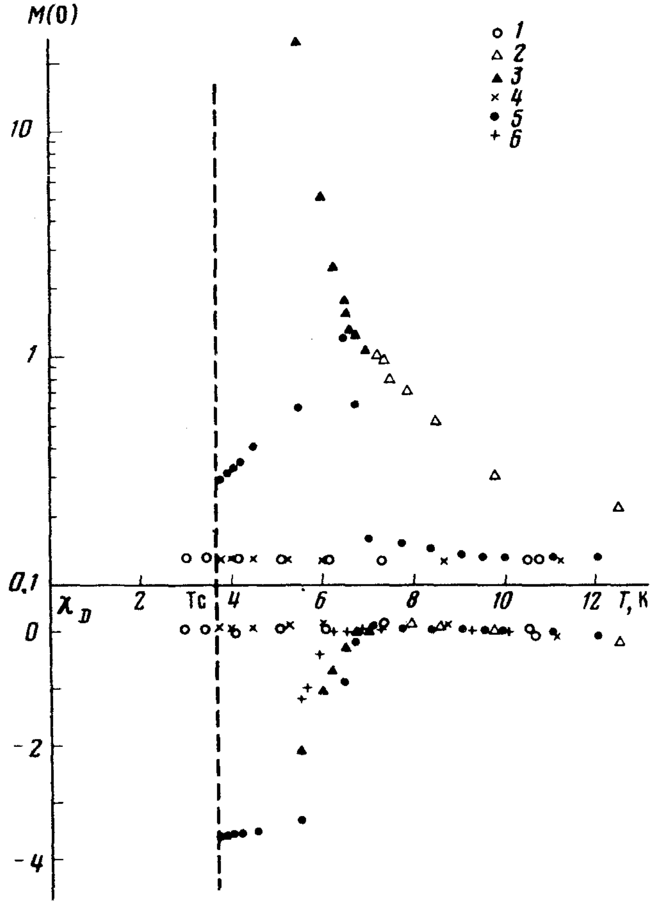

FIG. 3. Magnetic moment M at $H = 0$ and diamagnetic susceptibility χ_D of Sn specimens as a function of temperature T ($T_c = 3.72$ K is the critical temperature of Sn). 1) The readings of the apparatus without the specimens (control); 2) section, trace as in Fig. 2b; 3) section, trace as in Fig. 2c; 4) crystalline particles; 5) tablet pressed out of particles; 6) same after annealing.

extends over the size of the particle). The results of investigations of ~1 mm^3 powder of such particles are shown in Fig. 3 by the symbols 4: there are no changes in M and χ_D up to $T_c = 3.72$ K, when bulk superconductivity of Sn appears. The Sn particles were then subjected to mechanical twinning by deformation them at $T \simeq 80$ K, when the probability of twinning is high[6]: the particles were pressed into a tablet (~1 mm^3) with a density of 6 g/cm^3. The surface layer of the tablet was removed to avoid contamination; holding at room temperature removed residual stress from the tablet.

The results of investigations of the superconductivity of the tablet are shown in Fig. 3 by the symbols 5; the rapid growth of M and the growth of χ_D begin at 7 K The observed drop in M and the termination of growth of χ_D at $T \lesssim 6$ K occur for a methodological reason: the scanning amplitude of the field, ± 10 Oe, is not sufficient to destroy superconductivity in the tablet and only particular hysteresis cycles are observed. After annealing up to 200 °C for 2 h, the temperature of the increase in χ_D decreased (6 in Fig. 3); however, annealing in the air could lead to oxidation and to a change in the structure of the tablet.

4. We shall begin the discussion with the experiments involving the particles. We emphasize their chemical purity: while preparing the particles, the tin was never in contact with other metals; compounds that could have formed do not conduct electricity; the exact value of T_c of the particles serves as a means for gauging their purity. The amount of tin, which is superconducting at ~6 K, can be estimated from χ_D in a tablet under the assumption that $\chi_D = -1/4\pi$, for particles, we estimate their volume to be $\sim 10^{-4}$ that of the tablet. This fact, however, does not suggest that superconducting particles are rare, since Meissner's effect for them is not complete.

We call attention to a very graphic result of the experiment: The appearance of superconductivity of Sn at the higher temperature, ~7 K, was achieved by deforming the particles while maintaining their chemical purity and keeping them free of stress. In many studies of Sn (as of other metals), T_c was found to increase as a result of structural factors (in the absence of stress) by more than ~15% (for example, Ref. 7), while in our experiments an increase of ~100% in T_c was achieved. The observed TP superconductivity apparently arises under conditions when its suppression by the proximity effect is weakened by the close proximity of the sections of TP, created by deformation of Sn particles. Here we must explain why the density of twins in microparticles is higher than, for example, in a ground crystal. In the case of mechanical twinning, twins grow with the narrow faces from the surface into the bulk of the crystal, until they reach the boundaries of the crystal; their further growth becomes more difficult or impossible.[8] The twin layers therefore become thinner with decreasing size of the crystal and with strong deformation which caused the appearance of many twins in a particle, so that the TP grid in the crystal must be especially dense.

The experiment with a section of a Sn specimen showed that the same $T_c \simeq 7$ K as the experiment with a tablet (Fig. 3). The reason for this coincidence is as follows. Separation of TP into sections with dimensions R decreases[3] ΔT_c and the decrease is steep for $R \lesssim \xi_0$. On the other hand, convergence of sections of TP increases ΔT_c due to the weakening of the proximity effect.[2,3] A consequence of these two circumstances is the existence of an optimal density of the spatial grid of sections of TP for which ΔT_c is maximum. This value of ΔT_c is measured in experiments with real specimens because of the difference in the values of R. A theoretical analysis performed by A. I. Buzdin on a model of bicrystalline spheres with diametral TP led to an estimate of the maximum value of ΔT_c of the order of several T_c for $R \sim \xi_0$, in agreement with results of the experiments.

Measurements of M on a section (Fig. 3, symbols 2), as well as on a tablet (symbols 5) indicate the appearance of superconductivity at $T > 7$ K as well. This superconductivity could be due to random formation of thin, parallel layers of twins, characterized by the conditions $d \ll \xi_0$, $R \gg \xi_0$, for which $\Delta T_c \gg T_c$.[3]

Thus the experiments described above have confirmed that a higher superconducting transition temperature, which was discussed in Refs. 2 and 3, of many closely spaced twinning planes is attributable to a weakening of the proximity effect, which suppresses superconductivity of a single twinning plane.

We thank P. L. Kapitsa for his interest in this work, V. I. Ozhogin for assistance, A. I. Buzdin for many discussions, E. G. Knizhnik for making the electron diffraction pictures, and G. S. Chernyshev for technical assistance.

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Translated by M. E. Alferieff
Edited by S. J. Amoretty