Twinning plane of a metallic crystal—a two-dimensional superconductor

M. S. Khaĭkin and I. N. Khlyustikov
Institute of Physical Problems, USSR Academy of Sciences

(Submitted 8 January 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 3, 167–170 (5 February 1981)

Superconductivity of the (301) twinning plane of a tin crystal was observed at temperature $T_c < T < T_c + 0.15$ K. A new concept of a "two-dimensional metal," which is formed by the crystal lattice of the twinning plane, by a two-dimensional group of electrons moving parallel to the twinning plane, and by two-dimensional phonons of the twinning plane, is introduced to explain this effect.

PACS numbers: 74.10. + v, 74.70.Gj, 61.70.Ng

The superconductivity of strained tin crystals, which occurs at temperatures $T_c < T < T_c + 0.15K$ in the region of magnetic fields $H < 5$ 0e(T_c is the critical temperature of bulk metal), was reported and investigated in Ref. 1. The superconductivity was detected from the appearance of a diamagnetic moment M_D and from the increase in electrical conductivity of the sample. The measurements were made by means of a **SQUID**; the method and the instrumentation used in the experiment were described in Refs. 1 and 2. It was assumed that the effect is attributable to the superconductivity along the dislocations.

It was found, however, that the superconductivity[1] is associated with the twinning plane (TP) rather than with the dislocations. In fact, the tin crystals, which are strained in order to eliminate twinning (without the characteristic "cracking"), exhibited no M_D. Another verification test consisted of the following. A long crystal, which had no moment M_D, was bent in the middle and its central part was recrystallized in such a way that the difference in orientations of the crystals corresponded to the TP at one of its boundaries and differed by 10° to 15° at the other boundary. As a result, the first boundary was a TP and the second was a layer of dislocations. Measurements revealed an M_D only in the first boundary. Another sample was prepared by mechanical twinning: a twin with a thickness of 0.2 mm was located in the middle of the sample, which had an M_D twice as large (two TP) as the sample with one TP. We shall mention one other conclusion based on these experiments: the concentration of impurities at the boundaries of the crystals in the recrystallization process does not play a role in the effect.

The samples were fabricated in the following manner. A bicrystal (ϕ 6mm and 50 mm in length), in which the (301) TP was oriented in the direction of growth (or at right angles to it), was grown from a 99.999% pure tin melt from two seed crystals that were oriented in the required manner. The samples with a size of ~ 1 mm^3 were cut from the bicrystal with an electric arc; the surfaces of these samples were etched deeply. A sample, which was prepared in the same manner as the bicrystal but had no TP, served as a control sample which had no M_D.

An experimental trace of the measured $M_D(H)$ (with an accuracy of $\sim 10\%$, at $T =$ const) of a sample containing a TP is shown in Fig. 1a. For comparison, Fig. 1b shows a trace of the moment M_f of the fluctuations of a super conducting phase in a single crystal of the same volume. The jump M_m (Fig. 1a) at the field H_m is caused by the transition of a part of the sample—the layer containing the TP--from the metastable normal state to the superconducting state.

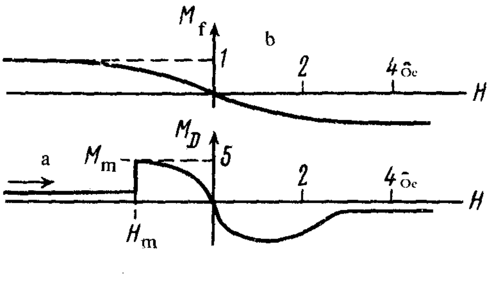

FIG. 1. (a) Trace of the magnetic moment of Sn bicrystal that contains the (301) twinning plane; the recorder pen moved from left to right. (b) Magnetic moment of fluctuations of the superconducting phase in Sn single crystal. The magnetic moment of the sample in the normal state was eliminated by compensation in the instrument.[1,2]

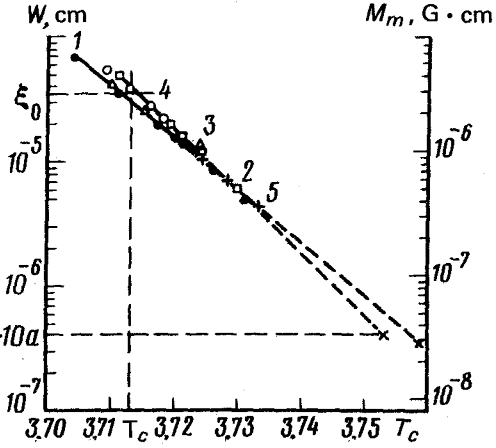

FIG. 2. Graphs of M_m values taken from traces similar to those in Fig. 1a and of the equivalent thickness w of the superconducting layer for different samples. 1, Growth twin; crystallization front ⊥ (301) and $H\,||[010]$; 2, the same, $H\,||[103]$; 3, the same, $H\,||[301]$; 4, mechanical twin with two twinning planes, $H\,||[010]$; 5, growth twin; crystallization front || (301) and $H\,||[010]$.

Figure 2 illustrates the $M_m(T)$ dependence for several samples, which can be expressed, as in Ref. 1, by the equation

$$M_m(T) = M_c \exp\left[-(T - T_c)/\tau\right]$$

For $M_c = 3\times 10^{-6}$G“Q13”cm,$\tau = 0.01$K. The M_m values are normalized to a unit area of the TP, which is determined from the dimensions of the sample. Since M_m depends on the magnetic susceptibility of the layer that contains the TP, we determine the “equivalent” layer thickness w by assuming that it has the diamagnetic susceptibility of a superconductor $\chi_s = -1/4\pi$ (the total Meissner effect ignoring the form factor). The w scale in Fig. 2 shows that

$$\max w(T) \approx w(T_c) \approx \xi_0,$$

where ξ_0 is the coherence length.

We determine min $w(T)$ in the following manner. The $H_m(T)$ dependence measured experimentally is linear[1]; by extrapolating this dependence to $H_m(T_0) = 0$, we obtain the values of T_0 (measurements are impossible in this region because of the weak signal). Then we extrapolate the graphs in Fig. 2 to T_0 and obtain

$$\min w(T) \approx w(T_0) \approx 10\,a,$$

where a is the lattice period.

We shall now discuss the reason for the occurrence of the effect. We propose the following hypothesis. The TP (x,y) is the symmetry plane of the bicrystal in which the twins occupy the half-spaces z and $-z$. Therefore, the energy spectrum of the electrons, which are moving near the TP (almost) parallel to it, is depicted by a small band of the

Fermi surface, which is symmetrical to its midline that lies in the (p_x,p_y) plane. There can be several such bands: they are formed along the intersection lines by the (p_x,p_y) plane of the two Fermi surfaces of the bicrystal. The proximity in z of many electrons to the TP (x,y) is determined by the large spatial extent of the wave packets of electrons that have a long free path length. Thus, an isolated, two-dimensional, extremal group of electrons (not present in a metal single crystal), whose velocities are almost parallel to the TP, appears in the bicrystal's layer of thickness $\sim\xi_0$. At the same time, a two-dimensional phonon branch—TP oscillations—appears in the phono spectrum of a bicrystal. As a result of these two effects, a layer of a "two-dimensional metal" tied to the TP is formed in the bicrystal; this layer has its own electrons and phonons, whose interaction does not remove them from this two-dimensional system. Specifically, this can be a Cooper interaction, which also produces superconductivity of the metal in the TP observed by us.

We note that other effects can also play a role in the examined case: magnetic surface levels[3] and Tamm levels.[4] The energy levels and the effects produced because of the interaction of electrons with the metal surface have been examined in Stern's theoretical paper.[5]

We must emphasize one other fact indicated by the results of this work. Twinning planes, rather than dislocations, play the major role in the normal increase of T_c of a metal because of its deformation; this is generally attributed to its dislocations.

In conclusion, we note that the appearance of a "two-dimensional metal" in the twinning plane must be observed in crystals that are twins of any metal, both superconducting and nonsuperconducting, and it must also be observed, together with superconductivity, in other effects. These results indicate that the "two-dimensional metal" should be studied in greater detail.

The authors thank P. L. Kapitsa for his interest in this work, L. P. Pitaevskiĭ and V. S. Edel'man for a discussion, and G. S. Chernyshev for his technical assistance.

[1] I. N. Khlyustikov and M. S. Khaĭkin, Zh. Eksp. Teor. Fiz. **75**, 1158 (1978) [Sov. Phys. JETP **48**, 583 (1978)].
[2] I. N. Khlyustikov and M. S. Khaĭkin, Prib. Tekh. Eksp. No. 2, 184 (1980).
[3] M. S. Khaĭkin, Usp. Fiz. Nauk **96**, 409 (1968) [Sov. Phys. Usp. **11**, 785 (1968-69)].
[4] I. M. Lifshitz and S. I. Pekar, Usp. Fiz. Nauk **56**, 531 (1955).
[5] E. A. Stern, Phys. Rev. **162**, 565 (1967).

Translated by Eugene R. Heath
Edited by S. J. Amoretty