Proximity effect and phase diagram of twinning-plane superconductivity in metallic crystals

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

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The phase diagram of twinning-plane superconductivity in tin single crystals is investigated in the (H, T) plane. It is found that the critical parameters of a pair of parallel twinning planes depend on the distance between them and the dependence of the phase diagram of the pair of planes on this distance is investigated. Twinning-plane superconductivity in indium and thallium single crystals is observed.

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1. In experiments,[1,2] in which the superconductivity of the twinning plane (TP) of a tin bicrystal was discovered, it was noted that regions of stable and metastable phases exist. An example of a trace of the magnetic moment of a specimen $M_D(H)$, demonstrating this circumstance, is presented in the upper right-hand corner in Fig. 1. If the trace of M_D begins at a sufficiently high value of the field H (arrow a), then the moment M_D arises discontinuously at a field H_m (in a good uniform specimen, a single jump is observed, while in other cases, several jumps are observed). With the opposite change in field, the trace of the moment M_D follows the dashed curve and M_D disappears at $H \approx H_d$.

If the direction of change in the field H is again reversed without reaching H_D (i.e., along arrow b), then M_D changes reversibly (along the dashed line). If, on the other hand, the region $H > H_d$ is entered and H is decreased, then the trace of M_D again follows the arrow a. By decreasing the interval (a, b), it is possible to measure the field H_d, namely, the upper boundary of the region of metastable states, to within $\sim 5\%$; the lower boundary H_m is reproduced with the same accuracy in repeated experiments.

The phase diagram shown in Fig. 1 was obtained as a result of the measurements of H_d and H_m described at different temperatures and with different specimens. The scales along the axes are chosen using the empirical equation $M_D \propto H \exp[-H/h] \exp[-(T-T_c)/\tau]$, obtained in Ref. 3, which describes the dependence $M_D(H,T)$ over the entire range of H and T studied (an example of such a dependence is presented at the top of Fig. 1) The quantities h and τ depend on the quality of the specimen, but their ratio, which remains constant, is $h/\tau = 110$ Oe/K (several dozen specimens were studied). The characteristic values of the constants h and τ are presented in Table 1. A similar phase diagram is proposed in Ref. 4; more accurate calculations of the phase diagram that we performed later, led to good quantitative agreement with the experimental results presented.

In the phase diagram in Fig. 1, the line without the points with slope -164 Oe/

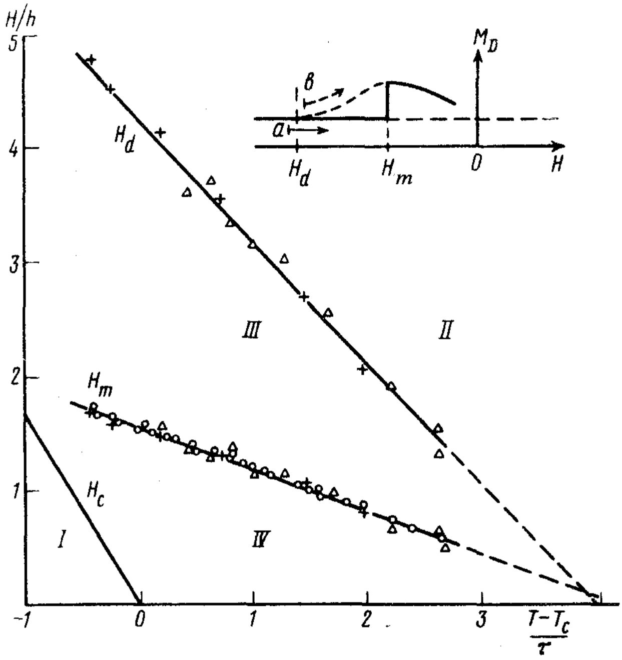

FIG. 1.

K indicates the region where bulk superconductivity exists in the tin specimen $H_c(T)$. Interpolating straight lines $H_d(T)$ with slope -120 Oe/K and $H_m(T)$ with slope -40 Oe/K are drawn from the experimental points. These lines separate the (H, T) plane into the following regions:

I) region of bulk superconductivity;

II) region of the normal state;

III) region of metastable states of TP superconductivity;

IV) region of stable states of TP superconductivity.

The first dashed sections of the straight lines $H_d(T)$ and $H_m(T)$ represent an extrapo-

TABLE I.

	Sn	In	Tl	Al
structure	tetragonal	tetragonal	hexagonal	face-centered cubic
twinning plane	(301)	(101)	$(10\bar{1}2)$	(111)
τ, K	~ 0.01	~ 0.001	~ 0.001	—
h, Oe	~ 0.8 – 1	~ 0.1	~ 0.1	—

lation into the region where there are no measurements (the signal turns out to be much weaker than the noise). We note that the straight $H_d(T)$ and $H_m(T)$ intersect near the point with coordinates (4,0).

2. It is well known that the critical temperature and critical field of a thin superconducting layer decrease due to the proximity of a normal metal. This proximity effect evidently also influences TP superconductivity. The purpose of the experiments described below was to observe the reverse effect: An increase in the critical temperature and field of two close-lying TP as the distance between them is decreased.

In order to observe the effect, we prepared a single crystal of tin, in which a thin $\sim 3 \times 10^{-3}$ cm crystal-twin intersecting it was formed by means of mechanical twinning. With careful preparation (selection, annealing), it was possible to obtain a specimen in which a transition to the superconducting state of the TP was observed with a single jump, similar to that illustrated in the graph at the top of Fig. 1. The results of measurements of H_d and H_m on this specimen are shown by the straight lines B and b, respectively, in Fig. 2. For comparison, the straight lines A and a, which reproduce the straight lines H_d and H_m in Fig. 1, are also presented in this figure. It can be seen that the presence of two TP increased the values of their critical parameters. Similar results were obtained for several other specimens. These are represented for one of them by the straight lines C and c, and for the others only by the points of intersection of the corresponding straight lines H_d and H_m, lying near the straight line E. Unfortunately, it was not possible to measure the thickness of the twin interlayer in these specimens. The straight lines D and d represent the results of measurements for a uniformly deformed specimen, in which the average density of the TP sections was determined from the magnitude of the diamagnetic moment; the average distance between these sections[5] was estimated as $\sim 10^{-4}$ cm. As can be seen from Fig. 2, the temperature range in which the effect investigated exists increased by a factor of 2 compared to the single TP.

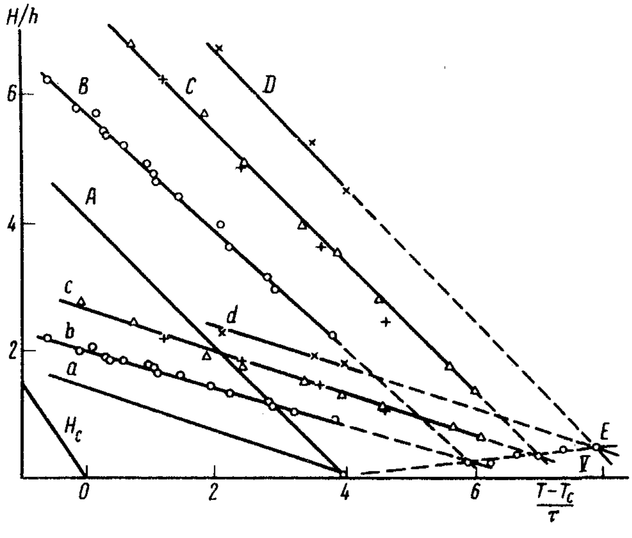

FIG. 2.

The experiments described indicate the very interesting possibility of greatly increasing the critical parameters of a metal in a specimen with a periodic structure, namely, in the form of many thin, parallel, single-crystalline layers with the mutual orientation of twins.

We note that the straight line E in Fig. 2, on which the points of intersection of the straight lines H_d and H_m lie, delineates another part of the phase diagram, namely, the region V, in which there is an inverse relation between the upper and lower critical fields $H_d < H_m$; however, it has not yet been possible to make any measurements in this curious region.

3. In addition to the experiments with Sn described above, we performed experiments on observation of TP superconductivity in In, Tl, and Al; the effect was not observed in Al. The characteristics of these metals are presented in Table I.

We note once again that the TP is the mirror symmetry plane of the bicrystal. It was stated in Refs. 1 and 2 that the symmetry of a bicrystal relative to TP is the reason for the appearance of an extermal group of electrons in the twin, which do not exist in the single crystal. These electrons, which move parallel to the TP, interact strongly with phonons in the TP, which also do not exist in the single crystal. Thus, a "two-dimensional metal" arises in the bicrystal near the TP,[1,2] whose properties can differ greatly from the properties of a three-dimensional crystal of the same metal. In particular, the phonon spectrum of a "two-dimensional metal" is all the more softer, compared to the three-dimensional metal, the more obliquely is the twinning plane oriented due to its small population of metal atoms. The latter is what leads to the increase in the critical temperature of the TP, which is greatest for Sn.

Indeed, the softening of the phonon spectrum is one way to increase the critical temperature T_c of the superconductor.[6] Thus, compression of the lattice of a Sn crystal by 1% decreases[7] T_c(Sn) by ~1 K; stretching the lattice leads to a corresponding increase in T_c(Sn). The interatomic distances in the (301) plane, which is the twinning plane, are ~50% (on the average) greater than the dimensions of the unit cell in Sn. This justifies completely the appreciable increase in T_c (TP Sn), which is decreased only by the proximity of the Sn crystal located in the normal state with $T > T_c$(Sn).

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