Interaction between twinning-plane superconductivity and bulk superconductivity in tin

I. N. Khlyustikov

Institute of Problems of Technology, Microelectronics, and High-Purity Materials, USSR Academy of Sciences

(Submitted 22 June 1987)
Zh. Eksp. Teor. Fiz. **94**, 314–321 (March 1988)

Magnetic measurements of the critical magnetic fields for twinning-plane superconductivity (TPS) were performed in the field and temperature region corresponding to metastable supercooled states of bulk superconductivity. It was observed that metastable states for bulk superconductivity are not excluded by the existence of TPS. It is concluded that the TPS is spatially inhomogeneous (relative to coordinate axes along the twinning plane). A critical temperature and a line of critical magnetic fields were observed and should apparently be interpreted as the critical temperature and critical magnetic field of the Berezinskiĭ-Kosterlitz-Thouless topological phase transition in a two-dimensional system of quasiparticles localized on the twinning plane.

In our preceding studies[1,2] twinning-plane superconductivity (TPS) in tin was investigated only for a region of magnetic fields and temperatures corresponding to a stable normal state of the single-crystal samples. On the (H, T) phase plane this region lies above and to the right of the thermodynamic $H_c(T)$ equilibrium line of the bulk superconductivity. This region was chosen because the magnetometric procedure cannot be used to investigate (TPS) in the case when the crystal surrounding the twinning plane (TP) is in a superconducting state and screens the external magnetic field. It is well known at the same time that the (H,T) phase plane of a type-I superconductor has below the $H_c(T)$ line a region in which the single crystal can be in a metastable normal state. The presence of metastable states of a single crystal permits magnetic investigation of the (TPS) phenomena in a wider range. The region of the supercooled states of the single crystal is bounded on one hand by the line of thermodynamic equilibrium between the normal and superconducting $H_c(T)$ phases, and on the other hand by the line of the absolute instability of the normal state $H_{c_2}(T)$. If superconductivity can be germinated on the outer surface of the sample, the region of metastable states becomes somewhat narrower and is bounded from below by the line $H_{c_3}(T) \approx 1.7 H_{c_2}(T)$. The relations between the critical fields $H_c(T)$, $H_{c_2}(T)$ and $H_{c_3}(T)$, or, in other words, the width of the metastable-state region is expressed in terms of the Ginzburg-Landau parameter $\varkappa$. A detailed description of the processes involved in superheating and supercooling in superconductors is given in Ref. 3, and the regions of metastable states on single-crystal samples of such type-I superconductor as tin were measured earlier in Refs. 4–7.

We report here measurements made in the region of supercooled metastable state of the sampel-bulk normal phase of tin containing twins. In addition, we repeated for the same samples the measurements of the TPS critical magnetic fields reported in Ref. 2. This permitted construction of a complete superconductivity phase diagram for twin-containing tin samples.

SAMPLES AND EXPERIMENTAL PROCEDURES

The bulk superconductivity of the tin investigated in the present study has the following known basic parameters: $T_{c0} = 3.722$ K,[8] $H_c(T) = 0) = 308$ Oe,[9] $\xi_0 \sim 3400$ Å,[9] and $\varkappa \sim 0.13$,[9] where T_{c0} is the critical temperature and ξ_0 is the coherence length. In the region near T_{c0} where the experiments were performed, the derivatives of the critical fields with respect to temperature can be assumed constant:

$$dH_c/dT = -164 \text{ Oe/K}, \; dH_{c2}/dT = -31 \text{ Oe/K},$$

$$dH_{c3}/dT = -52 \text{ Oe/K}.$$

The blanks for the sample preparation were tin single crystal cylinders of ~10 mm diam and ~100 mm long. The single crystal were grown from pure tin with a resistivity ratio $\rho_{300}k/\rho_{4,2}\ k \sim (1\text{-}5)\cdot 10^4$. The crystallographic (301) plane along which the twinning takes place was oriented along the cylindrical axis, while the crystallographic C_2 axis, belonging to the chosen (301) plane was perpendicular to the longitudinal axis of the blank.

The initial single crystals were twinned by impact of a blade on the end face of a cylinder at liquid-nitrogen temperature. The blade was parallel to the (301) plane and the impact direction coincided with the cylinder axis. This impact produced in the single crystal wedge-shaped regions with twinning orientation. Measurements of the dependences of the twinning regions on the coordinate along the blank axis have shown that the angle between the wedge planes ranged from 10^{-2}–10^{-3} rad. The angle-measurement accuracy was ~5%. Assuming, as did the authors of Ref. 10, that the final angle between the TP is made up of uniformly distributed steps, each one interatomic distance in size, we find that the atomically smooth coherent sections of the TP measure ~10^2–10^3 interatomic distances. Note that the value of for bulk superconductivity in this is ~10^3 interatomic distances.

Samples in the form of $1.3 \times 1.3 \times 1.3$ mm were cut from the blank with an electric-spark lathe and the roughened surface layer was bright-dipped. Two faces of the cube were parallel within ~1° to the TP, and the two other faces were perpendicular to the crystallographic C_2 axis belonging to the TP. Each sample had a twinning liner ~50 μm thick.

Investigations of the superconducting properties of the samples were carried out with the SQUID magnetometer

 0038-5646/88/030607-06$04.00

described in Ref. 11. The sample was mounted in the magnetometer in a copper container that could be rotated around an axis perpendicular to the solenoid field. One pair of the cube faces remained parallel to the applied field when the container was rotated. The container with the sample could be rotated $\sim 180°$. The entire sample-rotating unit for was 2.3 mm in size and was placed in the magnetic-flux transformer channel. The construction of the container-rotation drive made it possible to vary the sample orientation relative to the magnetic field during the helium-experiment time, and the rotation angle was monitored accurate to $\sim 5°$. The sample-rotating unit made it possible to measure the anisotropy of the critical magnetic fields.

The magnetometer sensitivity could be continuously rotated to ensure the possibility of plotting the sample magnetization curves in the presence of bulk superconductivity. The sensitivity could be decreased five decades by decreasing the coupling between the secondary winding of the superconduting magnetic-flux transformer and the SQUID quantizing circuit.

Two methods were used in the experiment to measure the critical field. The first consistd of measuring those fields in which some singularities, kinks or jumps, could be observed on the plots of the sample magnetic moment against the magnetic field. In the second method, the hysteresis phenomena were recorded. It was used when the magnetometer sensitivity was not high enough for reliable recording of the singularities on the $M(H)$ plots at the point where the superconductivity vanished. This measurement method was used earlier in Refs. 1 and 2 to measure the critical TPS fields. The measurement procedure reduced in this case to the following: the magnetic field was increased from zero to a certain value measured in the present study accurate to ~ 0.1 Oe, and was then decreased. If the maximum attained field exceeded the thermodynamic-equilibrium field, the superconducting state was completely destroyed and supercooling of the normal phase was observed. A characteristic hysteresis loop was then produced on the plot of the magnetic moment against the field, with a jump at the point of absolute instability of the normal state. In the opposite case, no metastable cases were observed and the $M(H)$ curve was smooth and free of hysteresis. Thus, the critical thermodynamic-equilibrium magnetic field could be measured as the boundary between two magnetic-field regions in which qualitatively different $M(H)$ dependences were observed. The mutual consistency of the two methods used to measure the critical magnetic fields was verified by measuring the critical magnetic field of the bulk superconductivity.

EXPERIMENTAL RESULTS

The direct results of the experiments are plots of the samples magnetic moments vs the magnetic field, obtained at fixed temperatures. The qualitative changes of the character of the $M(H)$ plots of tin samples containing TP reveal the presence of six temperature intervals in the measurement region, and a sample of which is shown in Fig. 1.

The first two temperature intervals (I, II) corresponding to temperatures higher than T_{c0} were investigated in detail earlier in Refs. 1 and 2. At high temperatures $T \sim 3.8$ K $> T_c$ (T_c is the TPS critical temperature) a weak dimagnetism is observed, due to the bulk fluctuations of the superconductivity. At temperatures $T_c > T > T_{c0}$ one can

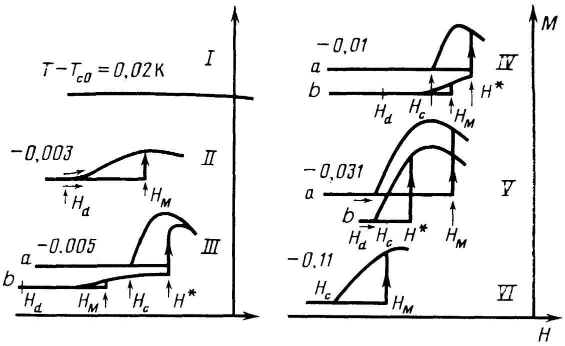

FIG. 1. Typical experimental plots of the magnetic moments of the samples vs the magnetic field at various temperatures. All the plots are directed from left to right. The scales of the plots differ. The origins of the moment are not aligned. Plot I: Nonlinearity of the magnetic-moment dependence on the field is due to bulk fluctuations of the superconducting phase at temperatures above critical. II: Diamagnetic moment M_d of TPS at temperatures higher than the critical T_{c0}. If the maximum external field exceeds in the course of plotting the value of H_d, a moment M_d is produced jumpwise in the field H_M. When the external field does not exceed H_d, the moment M_d increases smoothly with decrease of the field. IIIa: Low magnetometer sensitivity. The diamagnetism is due to superconductivity in the bulk of the sample. IIIb: High magnetometer sensitivity. The diamagnetic moment M_d of the TPS is produced jumpwise in the field H_M. The field H_d is measured by the same method as at higher temperatures. The jump of the magnetic field in the field H_M is very large. IV: Low (a) and high (b) sensitivity of the magnetometer. The plots are similar to the preceding ones, but $H_c > H^*$ in this case. V: Low magnetometer sensitivity. Depending on the maximum applied external magnetic field, the magnetic moment of the bulk superconductivity is produced jumpwise in a field either H_M or H^*. The critical magnetic field H_d is the boundary between two magnetic-field regions with different $m(H)$ dependences. VI: Typical plot for the case when TPS cannot exist in fields stronger than H_c.

observe a TPS diamagnetic moment M_d with characteristic critical magnetic fields H_d and H_M. These are the field of the TPS thermodynamic equilibrium and the field of absolute instability of the TP normal state. The arrows on Fig. 1, II demonstrate the method of measuring the critical field H_d.

The $M(H)$ plots III were obtained at temperatures somewhat lower than T_{c0}($T - T_{c0} = -0.005K, T_{c0}$ is used as the reference temperature, with plots IIIa and IIIb obtained at low and high magnetometer sensitivity, respectively. When the magnetic field was decreased in this temperature interval from large values (larger H_d, the onset of the diamagnetic moment is in two stages. First, a small jump of the moment is observed in the field H_M and corresponds to a transition to a superconducting state of a layer with "effective" thickness w near the TP. Second, with further decrease of the applied external magnetic field, a second larger jump of the magnetic moment takes place in the field H^*. The magnetic susceptibility measured in fields weaker than H^* corresponds, when the form factor is taken into account, to superconductivity of the entire volume of the sample. H^* is thus the critical supercooling field for the bulk superconductivity in the case when superconductivity already exists near the TP.

The critical fields H_c and H_d were measured by drawing trail plots and determining the maximum field reached in each plot by the method described above. The critical field H_c was also determined by measuring the location of the kinks on the $M(H)$ plots. Comparison of the fields H_c measured by different methods demonstrated the compatibility of the two experimental procedure.

All the critical magnetic fields decreased with decrease of temperature (curves IV), but they increased at different rates. The plots IVa and IVb of Fig. 1 differ from plots IIIa,b in that in case IV the critical field H_c exceeds H_M. These plots were obtained at a temperature $T - T_{c0} = -0.01K$.

The $H^*(T)$ dependence, just as $H_c(T)$, has a derivative with respect to temperature with larger absolute value than $H_M(T)$. As a result, H^* becomes larger than H_M below a certain temperature, and the $M(H)$ curves take the form shown in Fig. 1, Va,b. These plots were obtained at $T - T_{c0} = -0.031$ K. In this temperature interval, depending on the maximum magnetic field applied to the sample during each succeeding measurement cycle, two different sample supercooling-field curves are observed. The larger of the observed critical supercooling fields is recorded when the maximum field applied to the sample is larger than H_c but does not exceed H_d.

This critical field is the field of absolute instability of the normal state of the volume of the sample in the presence of TPS, denoted as before by H^*. The weaker of the critical supercooling fields is observed if the maximum applied field exceeds H_d. It must be noted that a similar superconducting transition pattern was observed in tin earlier in Ref. 4.

In the temperature intervals II and III, for which the typical $M(H)$ plots were obtained above, the onset of TPS with decrease of the external magnetic field did not cause the entire bulk of the sample to become superconducting all the way to the field H^*. In the temperature range considered here, the critical magnetic field $H_M < H^*$, so that in the case of demagnetization from strong fields, by the instant the field H_M is reached, the conditions of absolute instability of the normal state of the sample bulk are already met in the presence of TPS, and the onset of the TPS immediately leads to the spread of the superconductivity over the entire volume of the crystal. The statement that H_M is the weaker of the supercooling fields observed in this temperature interval is confirmed by the fact that on the (H,T) diagram (which will be discussed somewhat later) the H_M line does not have any discontinuities or kinks at the point of its intersection with the H^* line, the change of the method used to record the TPS critical field H_M notwithstanding.

Example VI of the sample magnetization curves in Fig. 1 corresponds to a temperature below the intersection of the $H_c(T)$ and $H_d(T)$ plots (which were obtained at $T - T_{c0} = -0.11$ K). The existence of such a point was observed earlier in Ref. 2. In this temperature interval, since TPS cannot exist in fields stronger than H_c, and H_M.

The measured critical magnetic fields for one of the samples with angle $\approx 1.4 \cdot 10^{14}$ rad at the vertex of the twinning wedge are shown on the (H,T) diagrams of Figs. 2 and 3. The phase diagram in Fig. 2 covers the entire temperature interval in which measurements were made, from ~ 3.4 to ~ 3.8 K. On the phase diagram of Fig. 3 is shown, in enlarged scale, the behavior of the critical magnetic fields in the immediate vicinity of T_{c0}. The temperature reference point is the bulk-superconductivity critical temperature T_{c0}. The following critical magnetic field lines were drawn through the experimental points on the phase diagrams: of the field $H_c(T)$ of thermodynamic equilibrium between the bulk normal and superconducting state; the field $H_d(T)$ of thermodynamic equilibrium of the superconductivity induced by the TP; the field $H^*(T)$ of the absolute instability of the normal bulk state in the presence of TPS; the field $H_M(T)$ of absolute instability of normal TP state (at temperatures between the $H^*(T)$ and $H_M(T)$ intersection point the $H_M(T)$ line is the boundary of the metastable states of the bulk sample); the field $H_{c3}(T)$ of absolute instability of the normal state of an ideal single crystal in the presence of surface superconductivity (calculated for $\varkappa = 0.13$).

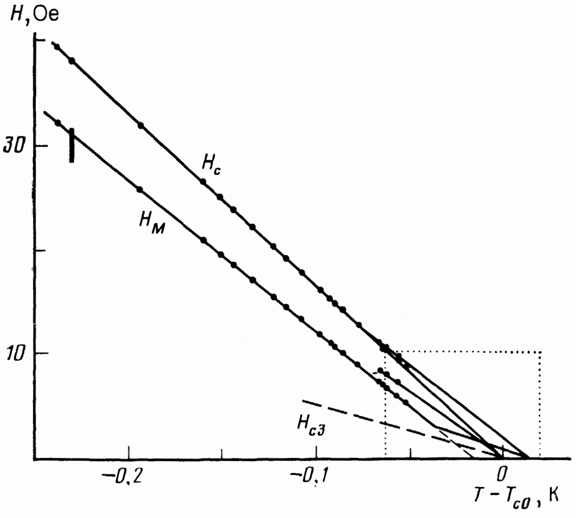

FIG. 2. (H,T) phase diagram of superconductivity of a tin sample containing a TP. The region of metastable states is bounded by the lines H_c and H_M. H_{c3} is the calculated boundary of the metastable states of the single crystal for $\varkappa = 0.13$. When the mutual orientation of the sample and of the magentic field is changed, the value of the critical field H_M changes in the range indicated by the vertical lines at $T - T_{c0} = -0.225$ K.

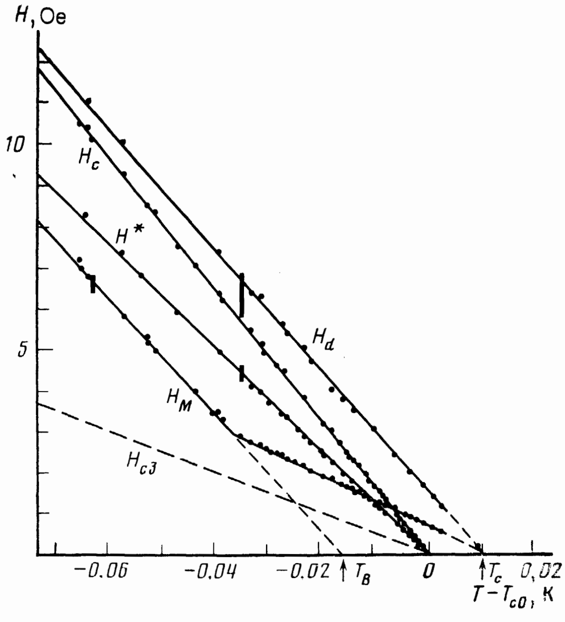

FIG. 3. Section of superconductivity phase diagram of tin with a TP in the immediate vicinity of the critical bulk-superconductivity temperature. The vertical lines at $T - T_{c0} = -0.035$ and -0.065 K represent the anisotropy of the investigated phenomenon. The critical field H_c has no anisotropy.

Recall that the investigated samples were cubes. In the study of the anisotropy, the samples were rotated in succession around the three cube axes perpendicular to its faces. This yielded both the angular dependences of the critical magnetic field and the changes of the $M(H)$ plot shapes. The measured anisotropy turned out to be small. The results are shown in the form of vertical lines on the phase diagrams of Figs. 2 and 3. They show the ranges of variation of the corresponding critical magnetic fields with change of the relative orientation of the sample and the magnetic field.

The investigations were made in a temperature interval ~ 0.3 K near T_{c0}. In this interval, all the critical magnetic field lines on the phase diagrams except $H_M(T)$ are straight to within experimental accuracy. The line $H_M(T)$ consists of two linear segments with a break at $T - T_{c0} = -0.037$ K. The linearity of the plots shown in the phase diagrams in Figs. 2 and 3 offer evidence that in all the investigated effects the changes of the external parameters (temperature and magnetic field) are small compared with the critical values of these parameters. If the low-temperature part of the $H_M(T)$ line is extrapolated to its intercept in the temperature axis we obtain a characteristic point, viz., the temperature T_B. For the temperature used to obtain the foregoing data, the difference $T_B - T_{c0}$ turned out to be -0.016 K.

The numerical parameters describing the phase-diagram lines in Fig. 2 and 3 are listed in the table. Note that the table lists the maximum values of the temperature derivatives of the critical fields observed in the anisotropy measurements.

The characteristic temperatures T_B and T_c, and also the slope of the $H^*(T)$ line, vary somewhat from sample to sample (the variation of T_c was already noted earlier in Ref. 1). At the same time, the character of the superconductivity phase diagram of twin-containing tin samples remains unchanged in both cases. Neither did the experiments reveal any variation of the slopes of the lines $H_c(T)$, $H_d(T)$ and $H_M(T)$ from sample to sample. Unfortunately, the presently available experimental data to do not connect the TPS critical parameters with the structural crystallographic characteristics of the TP (e.g., with the density of steps on the TP).

DISCUSSION OF RESULTS

We investigated in our experiments the dependence of the sample magnetization on the applied magnetic field for a number of fixed temperatures. An estimate of the sensitivity of the apparatus used shows that the onset of the superconducting phase in the sample can be revealed in the following two manners:

TABLE I.

Critical magnetic fields,	$\frac{dH_i}{dT}$, Oe/K	Intercept on the temperature axis $T_i - T_{c0}$, K	Anisotropy, %
H_c	-164	0	–
H_d	-148	0.011	~ 15
H^*	-129	0	~ 5
H_M; $T-T_{c0}>-0.037$ K	-63	0.011	~ 5
H_M; $T-T_{c0}<-0.037$ K	-143	-0.016	~ 5
H_{c3}	-52	0	–

a) By the Meissner effect, if the total volume of the sample regions from which the magnetic field is expelled exceeds $\sim 10^{-8}$ cm^3. It is assumed here that the expulsion is complete. Recalculating in terms of the TP in the sample, we obtain ~ 100 Å for the minimum recordable effective thickness of a continuous superconducting film near the TP.

b) By the trapping of magnetic flux by a superconducting loop of macroscopic size, if the critical current in this loop is more than $\sim 10^{-8}$ A. The estimate was made for a loop with dimensions equal to those of the sample cross section.

We list now the main experimental facts established for the investigated system.

1. The TP influences the superconducting properties of the crystal. The action of the TP on the crystal facilitates the onset of the superconductivity in the bulk of the sample (at least in the case of tin, indium, rheium, thallium, and niobium).[12] The reason is, first, that in the presence of a TP in the sample the region of metastable states becomes narrower than in a single crystal and, second, that a relatively large diamagnetic moment M_d is observed in samples with TP even at temperatures higher than the critical one for bulk superconductivity. If it is assumed that the diamagnetic moment M_d is due to electrons localized on the TP, whose number is of the order of the number of TP atoms, we find that the observed value of M_d corresponds to motion of these electrons superluminal velocities. It follows hence that the diamagnetic moment M_d is due to three-dimensional conduction electrons located near the TP and therefore under the influence of the latter.

2. An estimate of the "effective" thickness of the superconducting layer produced near the TP was obtained in Ref. 13 from measurements of the TPS diamagnetic moment M_d. This thickness was found to be $\sim \xi_0$ at $T = T_{c0}$. This result is natural, since ξ_0 is the characteristic interaction length for ordinary three-dimensional superconductivity.

3. Closely spaced (spacing $\sim \xi_0$ and less) TP interact with one another through the single-crystal layer. The TPS critical parameters are increased by this interaction.[1] This is additional evidence that it is precisely ξ_0 which determines the characteristic distance at which the interaction with the TP is affected.

4. The action of the superconducting state of the TP on the bulk superconducting properties of the crystal makes possible the existence of supercooled metastable states of the sample. For tin, a finite distance between the lines $H_c(T)$ and $H^*(T)$ on the (H,T) phase plane is always observed. According to the theoretical results,[14] however, such metastable states are impossible, and the superconductivity should extend immediately over the entire volume as soon as the external magnetic field becomes weaker than H_c.

5. We have investigated here experimentally both the anisotropy of the $M(H)$ dependences and the anisotropy of the critical magnetic fields. It was found that the anisotropy of the investigated phenomenon is low, substantially less than what might be expected if a continuous superconducting layer of thickness $\sim \xi_0$ were to be produced near the TP.

6. The electric resistance, from edge to edge, of a solitary TP in tin always remains finite at temperatures higher than T_{c0}. This follows from the fact that there is no trapping of the magnetic flux by some closed loop, as well as from direct measurements of the TP resistance. This fact was verified for tin up to temperatures $T - T_{c0} \sim 10^{-4}$ K. In niobium, a small zero-resistance TP region is observed at $T > T_{c0}$ (Ref. 12).

7. The presence of a break on the supercooling line $H_M(T)$ (at $T - T_{c0} = -0.037$ K, Figs. 2 and 3) seems to indicate that a new mechanism that causes instability of the normal sate of the sample bulk, comes into play at temperatures below T_B.

8. The effect of the TP on the bulk superconductivity depends on the density of the steps on the TP. This was pointed out also in an earlier paper,[2] where it was noted that if bends, i.e., sections with different step densities, are present at the emergence of the TP to the outer surface of the sample, a large number of critical magnetic fields H_d and H_M are observed. The concentration dependences of the TPS parameters have not yet been completely and reliably established.

The foregoing set of facts is quite complicated and, at first glance, even contradictory. For example, the facts in items 1–3 above indicate that the well-known "proximity effect" exists in a twin-containing system. At the same time, the absence of continuous "germination" of the superconducting phase from the TP into the bulk of the sample on crossing the line $H_c(T)$ (item 4) in analogy with the evolution of bulk superconductivity from the outer surface is evidence that there is no proximity effect in the investigated system.

This "contradiction," and also the effects formulated in items 5 and 6, indicate that the superconducting state initiated by the TP is spatially inhomogeneous (referred to coordinate axes along the TP). It should be noted that the possible onset of a spatially inhomogeneous TPS state was not considered in Ref. 14.

A known large group of papers (see, e.g., the review[15]) dealing with the behavior of systems in which superconducting inclusions with high critical parameters are placed in a matrix comprising a superconductor with relatively low critical parameters. It was shown for such systems as the matrix critical temperature is approached from above, when $\xi_{\rm matr}(T) = \xi_0[(T - T_{c0})/T_{c0}]^{1/2}$ (T_{c0} is the critical temperature of the matrix) becomes approximately equal to the distances R between the regions with high critical parameters as a result of interaction through the matrix material, a single coherent state is established in the entire system of superconducting inclusions. A feature of the appearance of such a coherent superconducting state is that an undamped electric current can flow in the sample (zero resistance), but the matrix remains normal nevertheless. It was also shown that if the matrix consits of type-I superconductors, the appearance of a coherent superconducting state in a system of inclusions with high critical parameters forbids the existence of metastable supercooled states of the matrix. These experiments have shown that no such coherent state occurs for TPS in tin. We emphasize once more that the verification in a zero magnetic field was made up to temperatures $T - T_{c0} \sim 10^{-4}$ K, corresponding to $\xi(T) \sim 10^{-2}$ cm. At the same time no structural singularities of this and larger scale were observed in the investigated samples. It must therefore be concluded that there exists some special mechanism that upsets the coherence of the TPS state. Since the matrix (the single crystal surrounding the TP) is homogeneous at the indicated scale 10^{-2}, the loss of TPS coherence should be determined indeed by the properties of the TP.

It was indicated in Ref. 13 that a TP in a twin metallic crystal should be regarded as a most unique two-dimensional metal with its own electrons and phonons localized on the TP. According to Ref. 16, a two-dimensional superconducting system has two special temperature points, $T_{\rm ct}$ and $T_{\rm BCS}$, with $T_{\rm ct} < T_{\rm BCS}$. T_{ct} is the critical temperature of the topological Berezinskiĭ-Thouless-Kosterlitz phase transition, and T_{BCS} is the stability limit of the Cooper-paired state of the electrons of this two-dimensional system.

At temperatures below $T_{\rm ct}$ superconducting order parameter differs from zero within the range of the macroscopic regions. Under these conditions the superconductivity of the two-dimensional system can be revealed by the presence of diamagnetism, by vanishing of electric resistance between two remote points of the system, and by the trapping of electromagnetic flux by closed superconducting loops of macroscopic size.

In the intermediate temperature region at $T_{\rm ct} < T < T_{\rm BCS}$ the state in which the two-dimensional electrons form Cooper pairs remains stable, but the thermal fluctuations upset the coherence of the order parameter over macroscopic scales. The order parameter remains nonzero within microscopic regions with dimensions on the order of or less than the superconducting correlation length. In this state the two-dimensional system has excess diamagnetism, but its electric resistance turns out to be finite. It is known also that in the presence of a magnetic field the critical temperature of the topological phase transition and the temperature of the Cooper pairing in a two-dimensional superconducting system both are lowered.

It is natural to state that the response of the three-dimensional metal surrounding of the two-dimensional superconductor must depend on the state of the two-dimensional superconductor. A system comprising a two-dimensional superconductor surrounded by a three-dimensional type-I superconductor can reveal all the properties recorded for tin samples containing TP. The necessary condition is satisfaction of the relation $T_{\rm ct} < T_{c0} < T_{\rm BCS}$ between the temperatures. Here as above, $T_{\rm ct}$ and $T_{\rm BCS}$ are the characteristic temperatures of the two-dimensional superconductor, and T_{c0} the critical temperature of the three-dimensional one. The appearance of a two-dimensional-metal superconducting state that is coherent over macroscopic scales must inevitably make the supercooled three-dimensional metal superconducting. On the other hand, the existence of superconductivity only on microscopic scales in a two-dimensional system does not impose so stringent a condition on the possibility of observing metastabilities. In other words, the line of the critical magnetic fields of the topological phase transitions, plotted in the coordinates H and t, is the limit below which no supercooled states are observed under any conditions. These properties are possessed by the critical temperature T_B and by the low-temperature part of the $H_M(T)$ line with a slope -143 Oe/K; we shall designate it henceforth by $H_B(T)$ (see Figs. 2 and 3).

The observed value of the critical temperature T_B of the topological phase transition and the position of the critical-magnetic-field lines $H_B(T)$ are determined both by the properties of the two-dimensional metal (by the temperature $t_{\rm ct}$) and by the action of the three-dimensional metal that surrounds the TP on the two-dimensional one. It is precisely this interaction which makes the temperatures T_B and T_{c0} close to each other.

The interaction between the two-dimensional and three-dimensional metals alters the superconducting characteristics of not only the two-dimensional metal but also of the three-dimensional one in a certain layer, apparently of thickness $\sim\xi_0$, directly adjacent to the TP. The temperature T_c is the critical temperature of just this relatively thin layer. Accordingly, $H_d(T)$ and $H_M(T)$ are respectively the critical magnetic fields of the superconductivity localized near the TP. It must be noted that the properties of just such a metal layer adjacent to the TP which were considered in Refs. 14 and 18.

The spatial homogeneity or inhomogeneity of the superconducting state produced near a TP is determined by the state of the two-dimensional superconductor. For tin we have $T_B < T_{c0}$, therefore the superconducting state localized near the TP turns out to be spatially inhomogeneous everywhere in the region where the diamagnetic moment M_x is observed. For niobium,[12] $T_B > T_{c0}$ and it becomes possible to observe a macroscopically coherent TPS state at $T > T_{c0}$.

The observed value of the critical temperature depends on how the two- and three-dimensional metals interact. The slope of the $H^*(T)$ phase diagram should also be determined by the interaction between the metals contained in the considered system.

The maximum of the critical temperature T_c is limited in principle within the framework of the described model by the temperature T_{BCS}. On the basis of the results of Ref. 17, where experiments were performed on with high twin density, T_{BCS} of a TP in tin can be estimated at not less than ~ 10 K.

We indicate, finally, how the positions of the phase-diagram lines of the investigated phenomena can become dependent on the crystallographic structure (on the density of the steps) of the TP. Violation of translational invariance of the TP causes scattering of the quasiparticles of the two-dimensional metal. Thus, changes of the TP defect density should lead to changes of the parameters (mean free path, lifetime) of quasiparticles localised on the TP. A change should take place simultaneously also in the coupling of the two- and three-dimensional systems. This must be accompanied by a change of the experimentally recorded response of the three-dimensional system to action by the TP.

The author is grateful to Ch. V. Kopetskiĭ and A. S. Borovik-Romanov for interest and attention, to M. S. Khaĭkin, V. S. Édel'man, A. I. Buzdin, and V. V. Lebedev for numerous helpful discussions, to V. E. Grigorov for devising a procedure for preparing the samples and for preliminary measurements, and to G. S. Chernyshev for technical help.

[1]I. Khlyustikov and M. S. Khaĭkin, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 132 (1982) [JETP Lett. **36**, 164 (1982)].
[2]A. I. Buzdin and I. N. Khlyustikov, *ibid*, **40**, 140 (1984) [**40**, 893 (1984)].
[3]H. J. Fink, D. S. McLachlan, and B. Rothberg-Bibby, Progr. Low Temp. Phys. Vol. Y11B, Chap. 6, p. 435, 1978.
[4]T. E. Faber, Proc. Roy. Soc. London **214**, 392 (1952).
[5]T. E. Faber, *ibid*, **241**, 531 (1957).
[6]H. Parr, Phys. Rev. **B12**, 4886 (1975).
[7]J. Feder and D. S. McLachlan, Phys. Rev. **177**, 763(1969).
[8]Superconducting Materials [in Russian], E. M. Savitskiĭ, ed., Metallurgiya, 1976.
[9]I. N. Khlyustikov and M. S. Khaĭkin, Zh. Eksp. Teor. Fiz. **75**, 1158 (1978) [Sov. Phys. JETP **48**, 583 (1978).
[10]A. M. Kosevich and V. S. Boiko, Usp. Fiz. Nauk **104**, 201 (1971) [Sov. Phys. Usp. **14**, 286 (1971)].
[11]I. N. Khlyustikov and M. S. Khaĭkin, Prib. Tekh. Éksp. No. 2, 184 (1980).
[12]I. N. Khlyustikov and S. I. Moskvin, Zh. Eksp. Teor. Fiz. **89**, 1846 (1985) [Sov. Phys. JETP **58**, 1065 (1985)].
[13]M. S. Khaĭkin and I. N. Khlyustikov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 167 (1981) [JETP Lett. **33**, 158 (1981)].
[14]A. I. Buzdin and N. A. Khvorikov, Zh. Eksp. Teor. Fiz. **89**, 1857 (1985) [Sov. Phys. JETP **54**, 158 (1981).
[15]*Percolation, Localization, and Superconductivity*, A. M. Goldman and S. A. Wolf, eds., NATO ASI Ser. B., VOl. 109, Plenum, 1983.
[16]S. Doniach and B. A. Huberman, Phys. Rev. Lett. **42**, 1169 (1979).
[17]I. N. Khlyustikov and M. S. Khaikin, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 191 (1983) [JETP Lett. **38**, 324 (1983)].
[18]A. F. Andreev, *ibid*. **46**, 463 (1987) [**46**, S84 (1987)].

Translated by J. G. Adashko