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Abstract

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ON MAXIMUM CRITICAL MAGNETIC FIELDS IN SUPERCONDUCTING METALS

According to currently existing ideas (¹⁻³), the high critical magnetic fields H_k of bulk superconductors are linearly related to distortions of the crystal lattice and to the mean free path of conduction electrons. Verification of these ideas is possible on alloys (^{4,5}), on deformed metals (⁶), and also on metallic samples obtained by low-temperature condensation (^{7,10}).

The last approach seems the most convenient. A metal freshly condensed under such conditions is in an extremely nonequilibrium state, close to amorphous (^{8,9}), and the distortions that have arisen in it can be removed as gradually as desired by annealing. It is essential that all measurements can be carried out on one and the same sample. In addition, under such conditions, apparently, the maximum possible critical field can be obtained in superconductors. Indeed, very high critical magnetic fields (^{10,11}) are obtained in metals freshly condensed onto a cold substrate. A measure of the distortions in this case may be such a quantity convenient for measurements as the electrical resistance of the sample. In this way, measurements were carried out of the critical magnetic fields H_k and temperatures T_k for indium, tin, and thallium over a very wide interval of lattice distortions. The results of these measurements are presented in the present communication.

For the formation of metal layers and their investigation, a method described earlier was used. The metal layers were obtained by condensation onto a glass substrate cooled with liquid helium (¹²). H_k was determined in a longitudinal magnetic field from the appearance of the normal electrical resistance of the samples at this field value.

In Figs. 1-4 some measurement results are given for one of the indium samples with a thickness of $\sim 5000 \text{ \AA}$.

As is seen from Fig. 1, the highest values of H_k are observed for freshly condensed metal, which corresponds to the most distorted state of the lattice. As the distortions are removed, the magnetic field decreases and, for a well-annealed

sample, H_{k0} reaches a value of 340 oersted, i.e., close to the value H_{k0} of single-crystal bulk indium.

Figure 2 shows the behavior of the electrical resistance of the sample under consideration as a function of its annealing. The measure of the lattice distortions is the value of the sample electrical resistance at 4.2° K after the corresponding stepwise annealing. The annealing steps shown in Fig. 2 correspond to the curves $H_k(T)$ in Fig. 1.

The curve in Fig. 3 shows the course of H_{k0} of indium as a function of the degree of distortion of its lattice. The values of the critical magnetic fields at 0° K were obtained by extrapolating the curves $H_k(T)$ taken in fields up to $12 \cdot 10^3$ oersted; therefore these values are determined with a smaller error for those curves (Fig. 1) for which a larger temperature interval was traversed, and with a larger error for the steepest curves $H_k(T)$. However

according to preliminary measurements* on one freshly condensed sample of the same thickness at higher fields, $H_k \sim 20 \cdot 10^3$ Oe was found at $T = 1.6^\circ\text{K}$, which also confirms the correctness of the extrapolated values of H_{k0} (Fig. 3).

Measurements were carried out on In samples of thickness $\sim 5000 \text{ \AA}$ (3 samples), $\sim 400 \text{ \AA}$ (one sample), and $\sim 100 \text{ \AA}$ (one sample). In this case the values of the maximum magnetic fields $(20\text{--}25) \cdot 10^3$ Oe prove not to depend on the thickness of the sample and are considerably higher than the critical fields for the thinnest equilibrium In films (¹⁴). The behavior of the curves $H_k(\rho)$ for all these samples at large ρ is the same. The curves $H_{k0}(\rho)$, naturally, diverge only when the distortions are removed, when the H_k associated with the thickness of the samples appears.

Fig. 1

Fig. 2

Fig. 1. Dependence of the critical magnetic field H_k on the temperature T for an indium layer of thickness $\sim 5000 \text{ \AA}$. Points *a* refer to the curve $H_k(T)$ for a layer obtained by condensation on a substrate cooled with liquid helium. Points *b–zh* refer to the curve $H_k(T)$ for a layer annealed to: *b*–50°K, *v*–80°K, *g*–120°K, *d*–200°K, *e*–250°K, *zh*–300°K

Fig. 2. Behavior of the electrical resistance R as a function of temperature T for an In film of thickness 5000 Å

It is interesting to note that the character of the dependence $H_{k0}(\rho)$ is represented by a curve with saturation (Fig. 3), with saturation being observed at $\rho \sim (5\text{--}6) \cdot 10^{-6} \text{ \Omega} \cdot \text{cm}$ (which corresponds to an electron mean free path $\sim 300 \text{ \AA}$, i.e., about 100 interatomic distances).

The maximum value of the critical magnetic field does not contradict the theoretical estimates $H_k \sim 10^4 T_k$.

A completely analogous behavior of $H_{k0}(\rho)$ is also observed for another metal

Fig. 3

Figure 1: Fig. 3

Fig. 4

Figure 2: Fig. 4

–tin. For indium and tin it is difficult to isolate a linear segment of the curve. The maximum value of the critical field in tin is $(40—45) \cdot 10^3$ Oe.

A different behavior of $H_{k0}(\rho)$ is observed in Tl. In this metal H_{k0} increases linearly up to $\sim 45 \cdot 10^3$ Oe, showing no tendency toward saturation.

Along with the change in H_{k0} during annealing of the layers, a very noticeable shift of T_k as a function of ρ is observed. For In, for example, T_k changes from 4.1°K for a freshly condensed layer to 3.4°K (i.e., by a factor of 1.2) for a layer annealed at room temperature. Figure 4 gives the dependence of T_k on the degree of distortions for the same sample for which the

* In this case a solenoid with a superconducting winding and a field up to $33 \cdot 10^3$ Oe, kindly provided by L. S. Lazareva, was used.

Fig. 3 shows the behavior of $H_{k0}(\rho)$. The character of the behavior of $T_k(\rho)$ is the same as that of $H_{k0}(\rho)$.

For Sn, T_k depends on the degree of distortion in a completely analogous manner, reaching a maximum value $T_k = 4.44^\circ\text{K}$ (i.e., 1.2 times greater than T_k for tin with an undistorted lattice). For Tl, in contrast to its behavior in In and Sn, T_k increases linearly as the lattice is distorted, reaching 3.15°K (an increase by ~ 1.3 times).

Fig. 3. Dependence of the critical magnetic field at 0°K, H_0 , on the specific electrical resistance ρ at 4.2°K for an In film of thickness 5000 Å.

Fig. 4. Change in the critical temperature T_k as a function of the specific electrical resistance ρ at 4.2°K for an In film of thickness 5000 Å.

Such changes in T_k may be caused by a change (decrease) in the Debye temperature [15] and by distortion of the crystal lattice [13].

Thus, a metal formed by condensation on a very cold substrate apparently has a maximally distorted crystal lattice. Even limiting plastic deformation of these metals at liquid-helium temperature [13] produces a smaller lattice distortion—a smaller increase in T_k and ρ . Therefore, the critical magnetic fields obtained in the present work for In and Sn are maximal for these metals.

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