Phase diagram of superconductivity localized near a twinning plane

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The phase diagram of superconductivity localized near a twinning plane in tin is obtained experimentally and theoretically in the (H, T) plane. The localized superconductivity exists only in a narrow range of temperatures near the critical temperature of bulk tin. The possibility of a sharp increase in the critical temperature in small particles with a twinning plane is examined.

The appearance of localized superconductivity (LS) near a twinning plane (TP) in tin, as well as in indium, rhenium, and thallium, was discovered and investigated in Refs. 1–3. In the absence of a magnetic field the LS is observed in the temperature range $T_c > T > T_{c0}$, where T_{c0} is the temperature of the superconducting transition in the bulk metal (in tin $T_{c0} \simeq 3.72$ K and $T_c \simeq T_{c0} + 0.04$ K).

1. Figure 1 shows the measurements of the critical field $H_d(T)$—a first-order transition to the state of LS in the entire region of its existence, and the temperature dependence of $H_c(T)$—the field of the first-order transition of bulk tin to the superconducting state. The procedure used for the measurements is analogous to that in Ref. 3. Normalized units are used in the plot: temperature, $t = (T - T_{c0})/(T_c - T_{c0})$, and field H/H_0, where $H_0 = H_c(t = -1)$.

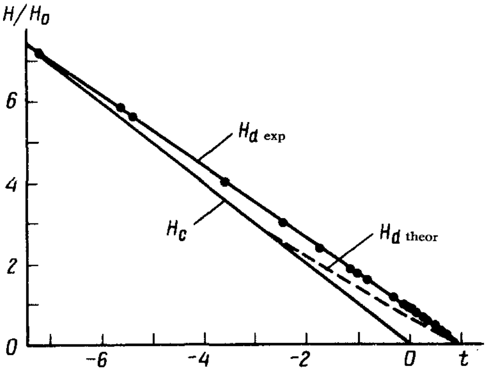

FIG. 1.

The interval of existence of LS is bounded by the region of temperatures near T_{c0}. This is not an accident: The small increase in T_c compared to T_{c0} is due to proximity effects, and the vanishing of LS in a field as the temperature is reduced is caused by the fact that the loss in the inhomogeneity energy in the LS state is of the same order of magnitude as the energy of superconducting condensation.

The theoretical description of the transition to the LS state in a field can be obtained on the basis of the modified Ginzburg-Landau theory with the density functional[4]

$$F = \frac{(B-H)^2}{8\pi} + \frac{1}{4m} \left| \left(\nabla - \frac{2ie}{c} A \right) \psi \right|^2 + a\psi^2 + b\psi^4 - \gamma\delta(x)\psi^2 , \tag{1}$$

where H is the external field; a standard notation is used here (see, for example, Ref. 5): $a = (T - T_{c0})/\eta T_{c0}$, $b = 1/N\eta$, N is the electron density, and $\eta = 0.12\epsilon_F/T_{c0}^2$ for a clean superconductor. The difference between functional (1) and the usual functional lies in the last δ-function term, which describes the amplification of Cooper pairing near a TP ($x = 0$). The constant γ is related to the temperature at which LS appears by the relation $\gamma = [(T - T_{c0})/\eta m T_{c0}]^{1/2}$.

We shall restrict our analysis to the case of a type-I superconductor ($\kappa \ll 1$). The field is directed along the TP (otherwise, a transition will occur to an intermediate state). The solution of the equation for ψ in this case can be written in quadratures and the transition field H_d, normalized by $H_0 = (2\tau_0/\eta)\sqrt{\pi/b}$, where $\tau_0 = (T_c - T_{c0})/T_{c0}$, is determined from the equations

$$\int_0^1 \sqrt{4 - 4t(1-x^2) + 2Z(x^4-1)}\, dx = 1,$$
$$h_d = H_d/H_0 = \sqrt{2(1-t)Z - Z^2}. \tag{2}$$

The phase diagram of the LS, obtained by solving (2), (the dashed curve in Fig. 1) must have the identical shape for all metals exhibiting this phenomenon.

There is good qualitative agreement between theory and experiment. Both methods of investigation indicate the existence of a lower temperature of the LS boundary, t_c. However, the theoretical value of t_c is -2.75, whereas the experimental value is $t_c \simeq -7$. Analogously, for (dH_d/dT) and (dH_c/dT) we find 0.63 and 0.75, respectively. This discrepancy stems from the fact that 1) the calculations were carried out to within terms $\sim\kappa^{1/2}$ and 2) under experimental conditions the magnetic field was not exactly parallel to TP.

We point out the fact that the existence of a lower limit on the temperature at which LS exists (t_c) is peculiar to type-I superconductors. In type-II superconductors, on the other hand, the LS must be observed in a field slightly higher than H_{c2}, down to $T = 0$ K.[6,7]

2. In bulk samples of tin an increase in T_c over T_{c0} is not large and, as shown in Refs. 4 and 8, is given by the relation

$$(T_c - T_{c0})/T_{c0} = 12\,[\textstyle\int \delta\lambda(x)dx]^2\, T_{c0}^2/\lambda_0^4 v_F^2\,,$$

where λ_0 is a dimensionless constant for Cooper pairing, and $\delta\lambda\,(x)$ is its increase near the TP. In small samples the effect of the TP on the superconductivity must increase markedly: the critical temperature T_{cR} of spheres in the central TP, whose radius is $R \ll \xi_0$, is determined by the volume average of the constant $\bar{\lambda} = \lambda_0 + 3(\int \delta\lambda\,(x)dx)/4R$.[9] If $(\bar{\lambda} - \lambda_0)/\lambda_0 < 1$ we find the dependence of T_{cR} on the size of the sphere

$$\ln(T_{cR}/T_{c0}) = 1{,}2\,\xi_0\,[(T_c - T_{c0})/T_{c0}]^{1/2}/R. \qquad (3)$$

The increase in T_{cR} with decreasing radius of the sphere is limited by dimensional quantization effects (they suppress superconductivity, when the distance between the size-quantized levels becomes on the order of the critical temperature). An estimate shows that for tin this corresponds to $R \lesssim 100$ Å. However, even for larger values $R \sim 200$–400 Å, the effective constant $\bar{\lambda}$ is on the order of unity (when the weak-coupling approximation no longer applies). Thus, in small samples of tin with a TP, it is possible to achieve a situation in which $\bar{\lambda} \sim 1$, which must correspond to an increase in T_c by an order of magnitude compared to T_{c0}.

A several-fold increase in T_c in microscopic particles of tin with a TP has indeed been observed experimentally[10] and, possibly, in Ref. 11.

We note finally that a superconductivity can, in principle, be observed in small particles of nonsuperconducting metals with a TP.

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