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Localized superconductivity induced by an array of steps at a non-coherent twin boundary

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Abstract. A model is considered in which localized superconductivity (LS) is induced by a two-dimensional array of steps (twinning dislocations) at a non-coherent twin boundary in the bulk of a metallic crystal. It is proposed that the cores of the twinning dislocations are the sources of the local enhancement of the electron–phonon interaction parameter in superconductor. In the framework of the model the dependence of the LS critical temperature on the two-dimensional concentration of the steps and on the orientation angle of the twin boundary with respect to the crystalline plane of twinning is predicted.

During the last few years the interesting phenomenon of the enhancement of the superconducting critical parameters (critical temperature T_c and critical magnetic field H_c) in a number of the metallic crystals with twins was experimentally discovered and investigated [1, 2]. In [2–4] this enhancement was connected with the appearance of localized superconductivity (LS) in the twin-boundary region due to the local enhancement of the electron–phonon interaction parameter, but the reason for such enhancement so far is not clear.

In this paper we consider the possible mechanism of the origin of the LS, when the cores of the steps (twinning dislocations) at the non-coherent twin boundary, which does not coincide with the crystalline plane of twinning (figure 1), are the sources of the local enhancement of the electron–phonon interaction parameter. (This model was discussed briefly in [5].) As was shown by the computer simulations of the twinning dislocation core structure [6], the crystal lattice in this region is strongly stretched and therefore the electron–phonon interaction parameter can be locally increased. The long-range elastic strains of the dislocation can also assist in the localization of the superconductor order parameter near its line [7, 8]. Also near the line of dislocations (including twinning dislocations), localized electrons and phonons can exist (see, e.g., [9]), which increase the local density of the states and the dimensionless electron–phonon interaction parameter. The coherent parts between neighbouring steps of the non-coherent twin boundary do not cause additional electron scattering. Together with the local enhancement of the electron–phonon interaction parameter, it can result in the enhancement of the superconductor critical parameters in the vicinity of twin boundary, which does not coincide with the twinning of the crystal.

In the case when the distance l between the neighbouring dislocations at the non-coherent twin boundary is much smaller than the bulk coherence length of superconductor ($l \ll \xi_0 \simeq v_F/T_{c0}$), as is so in most of the investigated metallic twin crystals [1, 2],

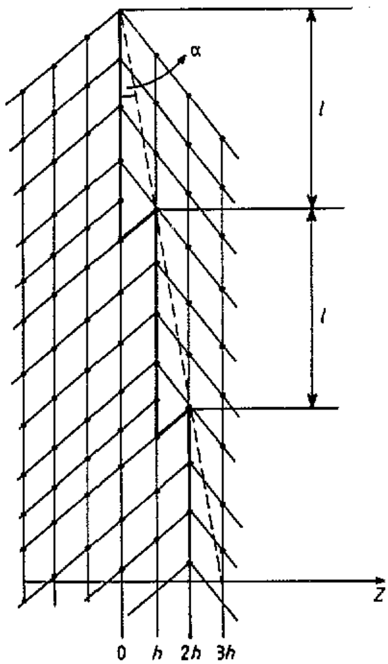

Figure 1. Configuration of the steps of the atomic height h (twinning dislocations) at the non-coherent twin boundary which is inclined (with the angle $\alpha = h/l$, $h = b$) with respect to the crystalline plane of twinning ($Z = 0$).

the array of the steps gives rise to two-dimensional LS at the twin boundary. (The case $l = \infty$ corresponds to a coherent twin boundary.) For the bulk dislocations, in contrast with the twinning dislocations, the condition $l \ll \xi_0$ cannot be realized in practice even for strongly plastically deformed superconductors (especially for the second-order superconductors). In addition to the previous theories (see, e.g., [1–4, 7, 8]), the proposed model of the origin of LS permits us to calculate the dependence of the LS critical temperature T_c on the two-dimensional concentration of twinning dislocations and consequently on the orientation angle α of the twin boundary with respect to the crystalline plane of twinning. The dependence $T_c(\alpha)$ was observed in the experiments on the LS in twinned crystals of tin [10]. The localization of the superconducting order parameter at the network of the misfit dislocations was also recently observed in superconducting superlattices [11, 12].

The exceeding of the critical temperature, i.e. $\Delta T_c = T_c - T_{c0} > 0$, of the onset of LS over the bulk critical temperature T_{c0} is rather small ($\Delta T_c \ll T_{c0}$) [1, 2] and the diameter b of the dislocation core region with increased Cooper pairing interaction is of the order of several interatomic spacings, which is much less than the coherence length: $b \ll \xi_0$. Therefore the phenomenon of LS in the array of parallel twinning dislocations (steps) can be described in the framework of the Landau–Ginzburg theory with the additional δ-functional term ΔF_S in the expression for the bulk density of the superconducting free energy F [13]:

$$\Delta F_S(r) = -\gamma \sum_i \delta(\rho - \rho_i)|\Psi(r)|^2 \tag{1}$$

where ρ_i is the two-dimensional radius vector of the ith step, $\Psi(r)$ is the bulk superconducting complex order parameter and the phenomenological parameter $\gamma > 0$ describes the local enhancement of the electron–phonon interaction parameter near the step line (see also [4]). In the framework of the model we can estimate the parameter γ as

$$\gamma \simeq (T_c^{(L)} b)^2 / E_F^{(L)} \tag{2}$$

where $T_c^{(L)}$ and $E_c^{(L)}$ are the local critical temperature and the local Fermi energy in the region of twinning dislocation core (of the diameter b). In equation (2) it is proposed that the local critical temperature greatly exceeds the bulk critical temperature: $T_c^{(L)} \gg T_{c0}$.

By solving with logarithmic accuracy (when $l \gg b$) the standard Landau–Ginsburg bulk equations [13] with the additional term (1) we obtain the following interpolation equation for the determination of the critical temperature T_c of the LS:

$$\exp[-2l/\xi(T_c)]/\xi(T_c) = (m\gamma/l)[1 - (m\gamma/\pi)\ln(l^*/b)] \tag{3}$$

where $\xi(T)$ is the temperature-dependent bulk superconductor coherence length [13] ($\xi(T) \simeq \xi_0[T_{c0}/(T - T_{c0})]^{1/2}$), $l^* = \min\{l, \xi(T_c)\}$ and m is the effective mass of the Cooper pair.

In the case $l \gg \xi(T_c)$ from equation (3) we obtain the expression for T_c of the LS near the single defect line, which is analogous to the expression for the energy of the bound state in the two-dimensional shallow potential well (see, e.g., [14]). In this case the exceeding ΔT_c of the LS critical temperature T_c over the bulk critical temperature is exponentially small with respect to the dimensionless parameter $1/\gamma m \gg 1$:

$$\Delta T_c \equiv T_c - T_{c0} \propto \exp[-2\pi/\gamma m]. \tag{4}$$

In the opposite limit $l \ll \xi(T_c)$ from equation (3) the expression for T_c of the LS near the slightly non-homogeneous planar defect, which is analogous to the expression for the energy of the bound state in one-dimensional shallow potential well (see, e.g., [14]), follows. In this case the critical temperature difference ΔT_c is quadratic with respect to the parameter $\gamma m/l$:

$$\Delta T_c \propto (\gamma m/l)^2[1 - (2\gamma m/\pi)\ln(l/b)] \simeq (\gamma m/l)^2 \tag{5}$$

$$\Delta T_c/T_{c0} \sim (T_c^{(L)}/T_{c0})^4 (b^2/l\xi_0)^2. \tag{5a}$$

The inter-step distance l (the inverse two-dimensional concentration n_S of dislocation) is connected with the angle of the inclination $\alpha \ll 1$ of the non-coherent twin boundary with respect to the crystalline plane of twinning and with the step height $h \simeq b : l = h/\alpha$. Therefore, for the single twin boundary in the case $l \ll \xi(T_c)$ this mechanism of the origin of the LS causes the following $\Delta T_c(\alpha)$ dependence:

$$\Delta T_c \propto (\alpha\gamma)^2[1 - (2m\gamma/\pi)\ln(1/\alpha)] \simeq (\alpha\gamma)^2. \tag{6}$$

In this limit of the high two-dimensional density of the steps ($l \ll \xi(T_c)$), not only their lines but also the kinks and the mutually crossed network of the twinning dislocations make a contribution to the local enhancement of the electron–phonon interaction parameter and to the origin of the LS at the planar defect of crystal.

In the system of parallel twin boundaries with interplane distance D (superlattice of twins) in the limit $l \ll \xi(T_c)$ we obtain the following equation for the critical temperature T_c of the LS with the symmetric distribution of the order parameter between twin boundaries:

$$\tanh[D/2\xi(T_c)]/\xi(T_c) = m\gamma/l. \tag{7}$$

For a single twin boundary ($D \gg \xi(T_c)$), equation (7) coincides with equation (3) in the case $b \ll l \ll \xi(T_c)$. However, in the limit $D \ll \xi(T_c)$, when the effect of proximity is suppressed, from equation (7) it follows that

$$\Delta T_c \propto \gamma/lD \propto \alpha\gamma/D \qquad (8)$$

i.e. the exceeding of the LS critical temperature over the bulk critical temperature is larger, than in the case of the single twin boundary (equations (3) and (6)), when $\Delta T_c \propto \alpha^2$.

Thus the compact distribution of dislocations (either a surface dislocation, when $D \gg \xi(T_c) \gg l$ or a bulk dislocation, when $D, l \ll \xi(T_c)$) can induce LS above the bulk critical temperature (and the critical magnetic field) at non-coherent twin boundaries in metallic crystals.

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