THE UPPER CRITICAL FIELD OF ULTRATHIN SUPERCONDUCTING FILMS AND LAYERED SUPERCONDUCTORS

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Introduction

Physical properties of disordered conductors have recently been intensively studied [1]. According to the classical BCS theory of superconductivity the critical temperature does not depend upon the elastic impurity concentration [2]. However in strongly disordered conductors when the mean free path is of order of atomic distance electron-electron interaction (EEI) effects come to be essential leading to suppression of superconductivity in low dimensional superconductors. Thin films and layered superconductors (LS) are the examples of such systems. The interest concerning LS is stimulated also by the discovery of high T_c oxides which have layered structure.

The subject of the present study is theoretical investigation of temperature dependence of the upper critical field H_{C2} in thin disordered films and layered superconductors when $\varepsilon_F\tau >> 1$ (τ - the mean free time). The problem of H_{C2} calculation in low dimensional SC was discussed previously in ref.[3], in which the EEI in the Cooper channel has not been taken into account. Meanwhile at $T < T_c$ the EEI is of more complicated nature due to mixing of the Cooper and diffusion channels [4]. We study the case of weak disorder taking account of the EEI effects both in the diffusion channel (dynamically screened Coulomb interaction) and in the Cooper channel.

Results and Disscussion

To calculate H_{C2} we use the linear integral equation for the order parameter which is valid for all temperatures:

$$\Delta(r) = |\lambda| T \sum_{\omega} \int G^{o}_{-\omega}(1,r)\Delta(1)G^{o}_{\omega}(1,r)d^3 1 \ , \qquad (1)$$

where $G^{o}_{\omega}(r,r')$ - Green function of normal metal. Here we consider orbital effect only neglecting paramagnetic one (i.e. assuming $H << H_p = \Delta/2^{1/2}\mu_B$). The

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kernel of eq.(1) may be calculated by means of diagrammatic technics, EEI being included in the first order of the perturbation theory. Calculations lead to the modified Maki - De Gennes equation for H_{C2}:

$$\ln\frac{T}{T_{co}} + \psi\left(\frac{1}{2} + \frac{1}{2\pi T\tau_H}\right) - \psi\left(\frac{1}{2}\right) = \Phi_{Coul} + \Phi_{Coop} \,, \qquad (2)$$

(where $\tau_H^{-1} = DeH/c$ for magnetic field in perpendicular direction and $\tau_H^{-1} = D(eHd/c)^2/6$ for parallel field; $D = v_F l/3$ - the diffusion coefficient). The functions Φ_{Coul} and Φ_{Coop} determine the corrections due to EEI in the diffusion and Cooper channels, respectively, and depend upon the particular electron spectra. Now we come to the cases of thin film and LS.

Thin film. Let us consider a film with thickness $d \ll L_T = (D/2\pi T)^{1/2}$. Calculating the quantities Φ_{Coul} and Φ_{Coop} we come to the equation for $H_{C2}(T)$:

$$\ln\frac{T_{co}}{T} - \frac{\rho}{24\pi}\ln^3\left[\frac{D}{2\pi T d^2}\right] - \frac{7\zeta(3)\rho}{2\pi^3}\ln\left[\frac{8\pi}{\rho}\right] =$$

$$= \left[\psi\left(\frac{1}{2} + \frac{1}{2\pi T\tau_H}\right) - \psi\left(\frac{1}{2}\right)\right]\left[1 - \frac{\rho}{8\pi}\ln^2\left[\frac{D}{2\pi T d^2}\right]\right] - \frac{\rho\,\alpha}{16T\tau_H} \,, \qquad (3a)$$

$$\text{where} \quad \alpha = \begin{cases} \ln(8\pi/\rho), & \text{for} \quad 2\pi T\tau_H \gg 8\pi/\rho \gg 1 \,, \\ \ln(2\pi T\tau_H), & \text{for} \quad 8\pi/\rho \gg 2\pi T\tau_H \gg 1 \,. \end{cases} \qquad (3b)$$

Here $\rho \equiv R_\square/R_o = 6\pi/p_F^2 ld$ ($R_\square$ is sheet resistance of the film, $R_o = h/(2e)^2$ is the quantum unit of resistanse). In large fields $2\pi T\tau_H \lesssim 1$ we have $\alpha = 0$.

The first term in the right hand side of eq. (3a) corresponds to the EEI in the diffusion channel, the second term - to the contribution of the Cooper channel and is essential provided $2\pi T\tau_H \gg 1$ only, i.e. at temperatures $T_c - T \ll T_c$. The second and the third terms in the left hand side of eq.(3a) determine T_c of a film, which coinsides with the result of ref.[5]:

$$\ln\frac{T_c}{T_{co}} = -\frac{\rho}{24\pi}\ln^3\left[\frac{D}{2\pi T_c d^2}\right] - \frac{7\zeta(3)\rho}{2\pi^3}\ln\left[\frac{8\pi}{\rho}\right] \,, \qquad (4)$$

The parameters ρ and $\gamma = D/2\pi T_c d^2$ determine character of the temperature dependence of H_{C2}. The main effect of EEI on H_{C2} in the Cooper channel manifests in qrowing of the slope of the dependence $H_{C2}(T)$ at $T \sim T_c$. EEI in the diffusion channel does not affect the slope near T_c but for large enougph ρ it may lead to a positive curvature of the dependence $H_{C2}(T)$ when the temperature decreases.

In ultrathin films the EEI contribution in the diffusion channel prevails. In Fig.1 curves H_{C2} vs T taking account this contribution only are given for a number of values of the parameter ρ ($\rho = 0$ (a) - the Maki-De Gennes universal curve, $\rho = 0.1$ (b), 0.2 (c), 0.3 (d), 0.4 (e) and 0.5 (f)). We have used the relation $\gamma = C\rho^2$, where the constant C is determined by the material parameters $p_F l$, T_c/ε_F and the typical value $C \approx 10^3$ was taken).

Layered Superconductor. Layered metals usually consist of metallic layers separated by dielectric layers with thickness approximately of several A. Below the perpendicular to the layers H_{C2} is discussed.

If probability of electron hopping between layers is not very high then the Fermy surface takes form of a goffered cylinder:

$$\varepsilon_p - \varepsilon_F = v_F(p_{\parallel} - p_F) + W\cos(p_{\perp}d), \tag{5}$$

where $p_{\parallel}$ - electron momentum projection in layer plane, v_F and p_F - the Fermi velocity and momentum in this direction, $p_{\perp}$ - the electron momentum in the perpendicular direction, d - the distance between layers, W/ε_F - small goffering parameter.

The calculation procedure is analogous to the one in the previous chapter. The fact that $W \ll \varepsilon_F$ and the value of d is of the atomic scale makes the following condition valid: $Wd/v_F \sim W/\varepsilon_F \ll 1$. As a result the EEI contribution in the diffusion channel is the same as in a film of thickness d.

In calculating of Φ_{Coop} let us consider the limit $d \gg \xi_{\perp} = \xi_{\parallel}Wd/v_F$ ($\xi_{\perp}$ and $\xi_{\parallel}$ are the coherence lengths normal and parallel to the layers respectively). We have $\xi_{\perp} \ll \xi_{\parallel}$, i.e. the limit of Josephson coupling between layers holds. In this case we obtain:

$$\Phi_{Coup} = \left[\frac{21\zeta(3)}{\pi^2 p_F{}^2 l d}\, 2\ln\frac{d}{\xi_{\perp}} - \frac{3\pi\alpha}{8p_F{}^2 l d}\, \frac{1}{T\tau_H} \right], \tag{6a}$$

$$\text{where} \quad \alpha = \begin{cases} 2\ln\dfrac{d}{\xi_{\perp}}, & \text{for } 1 \ll d/\xi_{\perp} \ll 2\pi T\tau_H, \\ \ln(2\pi T\tau_H), & \text{for } 1 \ll 2\pi T\tau_H \ll d/\xi_{\perp}. \end{cases} \tag{6b}$$

One can see from eq.(6) that depending on the relations between parameters $d/\xi_{\perp}$ and $2\pi T\tau_H$ different regimes occur for the temperature dependence of H_{C2}.

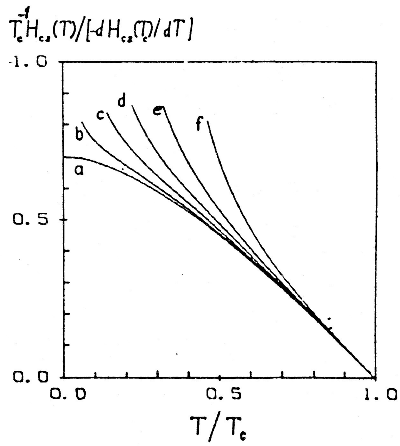

Figure 1

Conclusions

It is shown that EEI below T_c leads to considerable deviations of $H_{C2}(T)$ dependencies for thin films and LS from the predictions of the Maki - De Gennes theory. The main qualitative feature is the presence of the upward curvature in $H_{C2}(T)$ curves at low temperatures which is due to the suppression of the dynamically screened Coulomb interaction with magnetic field qrowth. Moreover, electron-electron interaction in the Cooper channel gives rise to the increase of the $H_{C2}(T)$ curve slope near T_c with the increase of the sheet resistance of a film ρ.

Experimentally the upward curvature in $H_{C2}(T)$ dependencies in films and LS (for magnetic field perpendicular to the layers) was observed (see refs. [6-8]). For making quantitative comparison of the theory with these data Pauli limiting and possibly spin-orbit coupling should be taken into account.

References

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