SUPERCONDUCTIVITY IN QUANTIZING SEMICONDUCTING FILMS WITH A GRANULATED METALLIC COATING

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1. In connection with the problem of high temperature superconductivity (see [1]), a large number of theoretical models have been proposed recently [2, 7], indicating that in principle it is possible to effect various non-phonon mechanisms of pairing the free carriers (conduction electrons); these models are based on collective Coulomb effects. A characteristic feature of all these models is the assumed presence of an auxiliary subsystem of charges with sufficiently large polarizability (bound electrons in lateral chains of polymer molecules [2], excitons in dielectrics or in superconducting coatings of "sandwiches" [1, 3], d-electrons in transition metals and alloys [4, 5], "heavy" holes in degenerate semiconductors and semimetals [6, 7]).

In the present paper we wish to call attention to one more type of systems with high polarizability, namely granulated metallic films, consisting of individual particles (granules) with dimensions $a \sim 50$ Å, the dispersion properties of which were investigated, for example, in [8][1]. We note that the anomalously large polarizability of small metallic particles in an external electromagnetic field was pointed out also in [11].

2. As shown in [8], in a granulated metallic film there can exist proper collective oscillations of free electrons propagating along the film. In this case, an important role is played not only by the Coulomb interaction of the electrons with one another and with the ion core inside each granule, but also by the interaction between the electrons located in different granules. The latter can be taken into account in the dipole approximation (see [8]), and then the equation for the oscillations takes the form

$$\ddot{\vec{p}}_i + \omega_o^2 \vec{p}_i = -\frac{2Ve^2 n_o}{m} \sum_j \frac{\vec{p}_j |\vec{R}_{ij}|^2 - 3\vec{R}_{ij}(\vec{p}_j \vec{R}_{ij})}{|\vec{R}_{ij}|^5} \quad , \tag{1}$$

where $\vec{p}_i$ is the dipole moment of the i-th granule, due to the separation of the charges, $|\vec{R}_{ij}|$ is the distance between the i-th and j-th granules, m and n_0 is the effective mass and concentration of the electrons, $\omega_0 = [L (e^2 n_0/m)]^{1/2}$ is the frequency of the dipole oscillations of the electrons of each individual granule, and V and L are the volume and the depolarization factor of the individual granules (for simplicity the granules are assumed to be identical).

The right side of (1) describes the dipole-dipole interaction between the granules, and leads to a renormalization of the oscillation frequency (see below). We note that in (1) no account was taken of spatial dispersion effects connected with the motion of the electrons inside the granules, and also with the retardation of the electromagnetic field of the oscillations; such a procedure is valid under the following conditions:

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[1]Other interesting properties of such films were investigated both experimentally and theoretically in [9, 10].

$$v_F/\omega_o \ll a, \quad b \ll c/\omega_o, \qquad (2)$$

where v_F is the electron Fermi velocity, c the speed of light, and b the average distance between granules ($b \gtrsim a$).

In the long-wave limit ($\lambda \gg b$, where λ is the wavelength of the oscillations), by replacing the sum in (1) by an integral over the surface of the film and introducing the average density of the granule distribution $N \sim 1/b^2$, in the case when the electrons execute oscillations parallel to the plane of the film[1], we obtain the following approximate expression for the frequency [8]:

$$\omega \approx \omega_p [(L/4\pi) - (NV/2r_{min})]^{1/2}, \qquad (3)$$

where $\omega_p = (4\pi e^2 n_0/m)^{1/2}$ is the plasma electron frequency, and $r_{min} \sim b$.

On the other hand, if the electrons oscillate in a direction perpendicular to the plane of the film, then the frequency equals

$$\omega \approx \omega_p [(L/4\pi) + (NV/r_{min})]^{1/2}. \qquad (4)$$

We see that the frequency of the dipole oscillations depends strongly on their polarization, and also on the choice of the material and structure of the film (for short-wave oscillations with $\lambda \sim b$, it is necessary to take into account also the dependence of ω on $k = 2\pi/\lambda$).

It is important to note that the electric field of the oscillations outside the film penetrates at least a distance comparable with the distance between the granules ($b \gtrsim 100 \text{ Å}$).

3. All the foregoing makes the idea of using granulated metallic films as coatings for superconducting "sandwiches" quite attractive.

As is well-known [1], the main shortcoming of the model of a "sandwich" constructed in accordance with the usual dielectric-metal-dielectric (or semiconductor-metal-semiconductor) scheme is the strong screening of the electron-exciton interaction (at a distance $r \gtrsim 3 \times 10^{-8}$ cm), which imposes very strong limitations from above on the thickness of the metallic film ($d \lesssim 10 \text{ Å}$).

These limitations can be greatly relaxed in semiconductor "sandwiches" [7] as a result of the increase of the effective screening radius, on the one hand, and the quantization of the transverse momentum of the conduction electrons, on the other. In this case, however, new difficulties arise, connected with the satisfaction of definite requirements imposed on the band structure of strongly doped semiconductors and on the character of reflection of the electrons from the heterojunctions (see [7]).

A sandwich made of a thin (quantizing) film of a degenerate n-semiconductor (semimetal),

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[1] Inasmuch as the interaction between dipoles decreases with distance like $1/r^3$, all the dipole moments can be in our approximation ($\lambda \gg b$) regarded as equal in both magnitude and direction.

on whose surface a granulated metallic coating is deposited, is practically free of the indicated shortcomings and constitutes a relatively simple (from the point of view of experiment) system with easily controlled parameters. The interaction between the conduction electrons in the film of the n-semiconductor and the aforementioned dipole oscillations of the electrons in the granules can lead to a pairing effect, and consequently to the occurrence of two-dimensional superconductivity along the film. If the parameters of the semiconducting film are such that only one two-dimensional subband is filled in momentum space, then the width of the gap characteizing the binding energy (correlation) of the electron pairs in the film is given by (see [7, 12]):

$$\Delta = 2\hbar\omega \begin{cases} \exp[-1/\rho], & \mu_o \gg \hbar\omega, \\ \exp[-2/\rho], & \mu_o \ll \hbar\omega, \end{cases} \tag{5}$$

where $\rho = e^2/\varepsilon_n d\hbar\omega$, ε_n is the high-frequency dielectric constant of the semiconductor, d is the film thickness, $\mu_0 = \hbar^2/2m_n[2\pi N_n d + (\pi^2/d^2)]$ is the limiting (Fermi) energy of the conduction electrons, and m_n and N_n are their effective mass and concentration.

It is easy to see that when $\hbar\omega \sim e^2/\varepsilon_n d$ the gap reaches a maximum, $\Delta_{max} \sim \hbar\omega$. Thus, for example, for films with $d \simeq 10^{-6}$ cm and $\varepsilon_n \simeq 3$ at a dipole-oscillation frequency $\omega \simeq 10^{14}$ sec^{-1} we obtain as an estimate $\Delta_{max} \gtrsim 3 \times 10^{-2}$ eV, which corresponds to a superconducting-junction critical temperature $T_c \gtrsim 100°K$.

[1] V. L. Ginzburg, Contemp. Phys. 9, 355 (1968)[Usp. Fiz. Nauk 95, 91 (1968)
[2] W. A. Little, Phys. Rev. A135, 1416 (1964)
[3] V. L. Ginzburg and D. A. Kirzhnits, Dokl. Akad. Nauk SSSR 176, 553 (1967) [Sov. Phys.-Dokl. 12, 880 (1968)].
[4] J. W. Garland, Phys. Rev. Lett. 11, 111, 114 (1963).
[5] B. T. Geilikman, Zh. Eksp. Teor. Fiz. 48, 1194 (1965)[Sov. Phys.-JETP 21, 796 (1965)]; Usp. Fiz. Nauk 88, 327 (1966) [Sov. Phys.-Usp. 9, 142 (1966)].
[6] E. A. Pashitskii, Zh. Eksp. Teor. Fiz. 55, 2387 (1968) [Sov. Phys.-JETP 28 (1969)].
[7] E. A. Pashitskii, ibid. 56, 662 (1969) [ibid. 29, (1969)].
[8] S. Yamaguchi, J. Phys. Soc. Japan 5, 1577 (1960).
[9] P. G. Borzyak, O. G. Sarbei, and R. D. Fedorovich, Phys. Stat. Sol. 8, 55 (1965).
[10] P. M. Tomchuk and R. D. Fedorovich, Fiz. Tverd. Tela 8, 276, 3131 (1965) [Sov. Phys.-Solid State 8, 226 (1966)].
[11] L. P. Gor'kov and G. M. Eliashberg, Zh. Eksp. Teor. Fiz. 48, 1407 (1965) [Sov. Phys.-JETP 21, 940 (1965)].
[12] V. Z. Kresin and B. A. Tavger, ibid. 50, 1689 (1966) [23, 1124 (1966)].

QUANTUM ELECTRONIC SPIN ACOUSTIC WAVES

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It is shown in [1] that in a metal, in the presence of a quantizing magnetic field, there exist longitudinal oscillations of electron-gas density with an acoustic dispersion law. In the present communication we show that similar oscillations of the electron density are connected with oscillations of the magnetization, and as a rule the difference between the oscillating density of the number of electrons $2s_k^z$ with spins parallel and antiparallel to