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]):

$$\Delta = 2\hbar\omega \begin{cases} \exp[-1/\rho], & \mu_0 >> \hbar\omega, \\ \exp[-2/\rho], & \mu_0 << \hbar\omega, \end{cases} \tag{5}$$

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 $T_c > 100^\circ$K.

In conclusion, we are sincerely grateful to A. I. Akhiezer, V. G. Bar'yakhtar, and A. S. Davydov for a discussion of the result and useful remarks.

[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

P. S. Zyryanov, V. I. Okulov and V. P. Silin
P. N. Lebedev Physics Institute, USSR Academy of Sciences
ZhETF Pis. Red. 9, No. 6, 371-374 (20 March 1969)

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 the magnetic field greatly exceeds the density of the number of electrons n_k which take part in the oscillations. This new observed effect is a result of the spin paramagnetism of the conduction electrons of the metal, which was actually neglected in [1]. On the other hand, allowance for the interaction of electrons within the framework of the theory of the electronic Fermi liquid [2] reveals the presence of one more effect - longitudinal quantum spin waves, the analog of the already discussed transverse quantum spin waves [3]. In such waves, the nonequilibrium magnetization oscillates along the direction of the constant field, and the oscillating density of the electron gas vanishes. Under more general conditions, an appreciable interaction takes place between the quantum spin waves and the oscillations of the electron densities accompanying the spin oscillations. In this connection, such waves should be called quantum electronic spin-acoustic waves (QESAW).

We present here several characteristic results of the theory of QESAW for the case when they propagate along a constant magnetic field parallel to the z axis. The spectrum of the oscillations is determined by the equation [$\sim \exp(-i\omega t + ikz)$]:

$$X^+ + X^- + 4\psi X^+ X^- = 0, \tag{1}$$

and the ratio of the spin density to the electron-density is

$$\frac{2s_k^z}{n_k} = -\frac{4\pi e^2}{k^2}\frac{X^+ - X^-}{1+\psi(X^+ + X^-)}\,.. \tag{2}$$

Here e is the electron charge and ψ is a constant characteristic of the theory of the electron liquid and takes into account the spin dependence of the electrons on their distribution [4], and

$$X^{\pm} = \int \frac{dp}{(2\pi\hbar)^2}\frac{|e|B}{c}\sum_n \frac{f^{(\pm)}(\epsilon_{n,p}) - f^{(\pm)}(\epsilon_{n,p-\hbar k})}{\hbar\omega - \epsilon_{n,p} + \epsilon_{n,p-\hbar k}}, \tag{3}$$

where B is the intensity of the constant layer, c the velocity of light, $\varepsilon_{n,p}$ the energy of the electron in the magnetic field, and $f^{(\pm)}$ is the distribution function of the electrons with spins parallel and antiparallel to the direction of B. In (1) and (2) it is assumed that the wavelength of the oscillation greatly exceeds the Coulomb-field screening radius, and the frequency is low compared with the plasma frequency.

Bearing in mind that for long waves we have

$$\epsilon_{n,p-\hbar k} \cong \epsilon_{n,p} - \hbar k v_{n,p} + (\hbar^2 k^2/2m_{n,p}),$$

it is easy to see that, neglecting the temperature scatter, whose effect is small, there is certainly no Landau damping if $|s - v_n^{\pm}| \gg \hbar k/m_n^{\pm}$, where $s = \omega/k$ and $v_n^{\pm}$ is the velocity of the electron at the n-th discrete level of the quantizing magnetic field, corresponding to the Fermi surface for the spin parallel and antiparallel to the z axis, respectively. To simplify the formulas we shall assume that $|s - v_{n0}^{+}| \ll v_{n0}^{+} \ll v$, where v is the usual electron velocity on the Fermi surface. Let v_{m0}^{-} be the value of v_n^{-} closest to v_{n0}^{+}. Then, using the symbol

$$\Delta = (v_{mo}^{-} - v_{no}^{+})(2p/\hbar\Omega)\ ,$$

where p is the electron momentum on the Fermi surface and Ω is the electron gyroscopic frequency, we get from the dispersion equation (1) the following two expressions for the phase velocity of the QESAW and for the ratio (2)

$$s_{1,2} = v_{no}^{+} + \frac{\hbar\Omega}{4p}\left[\Delta + \frac{1+2\beta}{1+\beta} \pm \sqrt{\frac{1}{(1+\beta)^2} + \Delta^2}\right]; \tag{4}$$

$$\frac{2s_k^z}{n_k} = \frac{4e^2}{\pi\hbar v}\,\frac{p^2}{\hbar^2 k^2}\,\frac{\Delta}{-1 \pm \sqrt{1+\Delta^2(1+\beta)^2}},$$

where $\beta = \psi p^2/(\pi^2 v\hbar^3)$.

In the limit of small values of Δ we get hence

$$s_1 = v_{no}^{+} + \frac{\hbar\Omega}{4p}\left(\frac{2\beta}{1+\beta} + \Delta\right); \quad \frac{2s_k^z}{n_k} = \frac{4e^2}{\pi\hbar v}\left(\frac{p}{\hbar k}\right)^2 \frac{2}{\Delta(1+\beta)^2}.$$

When $\Delta = 0$ these formulas describe longitudinal spin waves, which can exist only when account is taken of the interaction between the electrons. The second solution has at $(1 + \beta)\,\Delta \ll 1$ the form

$$s_2 = v_{no}^{+} + \frac{\hbar\Omega}{4p}(2+\Delta); \quad \frac{2s_k^z}{n_k} = \frac{4e^2}{\pi\hbar v}\left(\frac{p}{\hbar k}\right)^2 \frac{\Delta}{2}.$$

Waves that are accompanied by spin oscillations exist only in the limit when $\Delta = 0$; this corresponds to the results of [1].

In the opposite limit $1 \ll \Delta\,(1 + \beta) \ll v/v_{n0}^{+}$, the QESAW phase velocities differ from v_{n0}^{+} and v_{m0}^{-} by $(h\Omega/4p)\,(1 + 2\beta)\,(1 + \beta)$. Here

$$\frac{2s_k^z}{n_k} = \pm\frac{4e^2}{\pi\hbar v}\left(\frac{p}{\hbar k}\right)^2 \frac{1}{1+\beta}.$$

It is seen from this expressions that inasmuch as $e^2/\hbar v \geq 2$ for real metals it follows that for QESAW with wavelength much larger than the interelectron distance the oscillations of the spin density greatly exceed the oscillations of the electron-number density. We note that at $\Delta = \pm 2\,\beta\,(1 + 2\beta)^{-1}$ the QESAW phase velocity coincides with v_{n0}^{+} or v_{m0}^{-} respectively when the wave propagation becomes forbidden as a result of the Cerenkov effect on the electrons. If the QESAW phase velocity is not small compared with the Fermi velocity, it may not be close to one of the values of $v_n^{\pm}$, so that $|s - v_{n0}^{+}| \sim |v_{n0}^{+} - v_{n0\,\pm\,1}^{+}|$. Then $(2s_k^z/n_k) \sim (\Omega p/\hbar k^2 v)$. Comparing this expression we (7), we can state that the relative role of the spin oscillations decreases, although even here they predominate for wavelengths λ (cm) $> 3 \times 10^{-4}\ B^{-1/2}$, where B is in Gauss. We note in conclusion that since $\hbar\Omega$ does not equal the energies of the electron with spin parallel and antiparallel to B, the QESAW will occur in metals under the same conditions as the wave observed in [1].

[1] A. L. McWhorter and W. G. May, IBM J. Res. Dev. 8, 285 (1964); O. V. Konstantinov and V. I. Perel', Zh. Eksp. Teor. Fiz. 53, 2034 (1967) [Sov. Phys.-JETP 26, 1151 (1968)]; A. S. Kondrat'ev, Candidate's dissertation, Leningrad State University, 1969.

[2] V. P. Silin, Zh. Eksp. Teor.Fiz. 33, 495 (1957) [Sov. Phys.-JETP 6, 387 (1958)].

[3] P. S. Syryanov, V. I. Okulov, and V. P. Silin, ZhETF Pis. Red. 8, 489 (1968) [JETP Lett. 8, 300 (1968)].

[4] V. P. Silin, Zh. Eksp. Teor. Fiz. 55, 697 (1968) [Sov. Phys.-JETP 28 (1969)].