New possibilities of the tunnel effect in high-pressure physics

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Electronic standing waves in a thin film of lead were observed at pressures up to 10 kbar, thus indicating that the tunnel effect can be used in research on the characteristic of the electron spectrum of strongly compressed metal.

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In research on the energy spectra of electrons under pressure, principal attention is being paid to the change of the extremal sections of the Fermi surface. This is due to the extensive application of methods that employ the effects of quantization of the electron energy in a constant magnetic field.[1] The purpose of the present paper is to point out that new possibilities in the study of the effect of pressure on the band structure of metals are provided by tunnel effects. The premise for the consideration of these questions were the successful tunnel experiments on superconducting film systems under strong compression.[2]

Particular interest attaches to tunnel-conductivity oscillations, due to the existence of electronic standing waves in metals.[3] The realization of this effect is connected with certain difficulties, since the electron wavelength in a metal is comparable with the lattice parameters, and pure single-crystal plates of small dimensions are needed. Nevertheless, we have also succeeded in observing this phenomenon in many samples, so that we were able to study it systematically at hydrostatic pressures up to 10 kbar produced by the procedure of[4]. In addition, starting from the qualitative model of[3], we have developed a theory of the effect. We present here only an analytic expression for the oscillating part of the derivative of the tunnel conductivity.

$$d^2 I(u)/du^2 = I''(u).$$

The experiments were performed at 4.2 °K on Al-I-Pb tunnel junctions produced by depositing the metals on a glass substrate cooled to 80 °K. In contrast to[3], the samples were prepared in a working vacuum $\sim 10^{-6}$ Torr obtained by ordinary oil-diffusion pumping. The lead film thickness t was monitored with a quartz meter and amounted to ~250 Å. The contact resistances were 0.5–5 kΩ. Pronounced oscillations were produced (Fig. 1) in samples annealed for several days at $T = 330$ °K. An x-ray structure analysis has revealed that they have a clearly pronounced texture of the Pb films in the [111] direction.

An indisputable explanation of the observed oscillation amplitude can be obtained by assuming that the ends of the blocks making up the film and having perfect crystal lattices are atomically smooth. The spread of the block thickness is assumed to have a Poisson distribution with variance ξ. We denote by d the distance between planes in the tunneling direction (the Z axis), and by k_z the value of the quasimomentum **k** in this direction. In the case when the oscillations are most noticeable at k_z

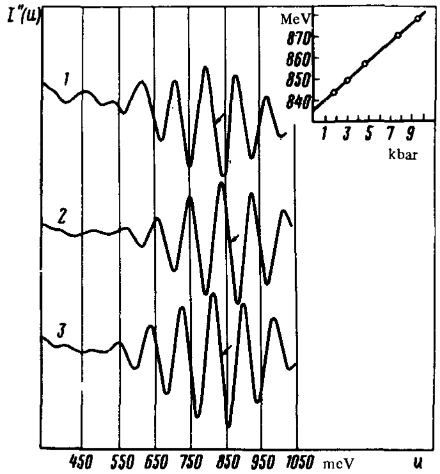

FIG. 1. Plots of $I''(u)$ at various pressures: 1—1.5 kbar, 2—10.1 kbar (after relieving the pressure). The arrows indicate the position of the point u_0. The insert shows the dependence of u_0 on the pressure.

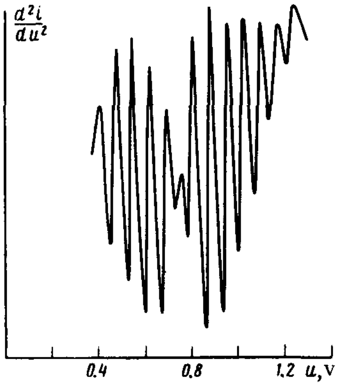

FIG. 2. Interference of the oscillations of $I''(U)$ from film sections textured in the directions [111] and [110].

$=\frac{1}{2}\pi/d=k_q$[3] and the electron dispersion law $E=E(\mathbf{k})$ is close to the "free" one, we obtain

$$I''(u)=A\exp[-\kappa(u-u_q)^2]\sin[2\pi(u-u_0)/\Delta u)], \qquad (1)$$

where $\Delta u=(1/2)\pi V_{\text{ph}}/t$ is the period of the oscillations ($\hbar=1$), $V_{\text{ph}}=\partial E/\partial k$ is the phase velocity at $\mathbf{k}=\mathbf{k}_q=\mathbf{k}(0,0,k_q)$, $u_q=E(\mathbf{k}_q)-E_F$, E_F is the Fermi energy, $\kappa=2\xi d(\pi/t\Delta u)^2$, $A=C\exp[-2\pi\gamma(E(\mathbf{k}_q),\mathbf{k}_q)/\Delta u]$, C is a function that varies slowly over Δu, $\gamma(E,\mathbf{k})$ is the damping of the quasiparticles in the standing-wave state,[1)] and $u_0=u_q+\delta v$. The value of δv is determined by the difference between the tunneling matrix element and a constant, by the imperfection of the film texture, by the boundary conditions for the formation of the electronic standing waves, etc. As a result, the oscillatory picture should shift when the external potential barrier in the lead film changes, something attainable with an electrostatic field, by sputtering dielectrics having different forbidden-band widths, etc. The scattering by the boundaries between the grains of the film, which include large structural distortions, preserves only the standing waves whose quasimomenta are almost perpendicular to the barrier. It must therefore be expected that the amplitude of the oscillations will decrease and their period will increase in strong magnetic fields (estimated at ~100 kOe). The observation of the described effects serves as a good confirmation that the physical nature of this phenomenon has been well understood.

According to (1), the band energy at the point k_q can be determined from the zero of $I''(u)$ situated between the two largest amplitudes. The error δE in the determination of $E(k_q)$ is small; for example, $\delta E=3$ to 5 mRy for lead. This accuracy of $E(k_q)$ is sufficient for a numerical comparison with the band-structure calculations. It was found that $\delta E\leqslant\Delta u/2$ and decreases if the picture of the oscillations is closer to symmetrical, if the film is thicker, and if the dependence of the usual junction conductivity on the barrier bias is weaker.

The connection between $I''(u)$ and the band structure of the metal was confirmed by experiments on the influence of high and hydrostatic pressure (p) on the behavior of the oscillatory picture. The value of δE is practically independent of the pressure, and therefore these experiments yield, with good accuracy, $\eta=\partial[E(k_q)-E_F]/\partial p$. The obtained value $\eta=4.0\pm0.2$ meV/kbar is in satisfactory agreement with our calculations of the band structure of lead in the nonrelativistic approximation. The pressure dependence of E_F was taken from[5].

It is well known that the greatest difficulty in the interpretation of the behavior of the Fermi surface as a function of the pressure lies in the determination of E_F at different pressures. Any theoretical model of the band structure makes it possible to calculate the electron energy at one point k_q in a symmetrical direction of the Brilluoin zone much more accurately and several thousand times more rapidly than E_F. Therefore a high-accuracy measurement of the pressure-induced shift of the oscillation picture makes it possible, within the framework of a theoretical model, to determine the function $E_F=E_F(p)$, thus ensuring unambiguous interpretation of the experiments on the effect of pressure on the Fermi surface of a metal. The nonlinearities in the dependence of η on p can serve as an indication of the presence of phase transitions.

Interference of the oscillations of $I''(u)$ from film sections textured in the directions [111] and [110] were observed in a number of samples (Fig. 2). A frequency analysis of these curves makes it possible to obtain in a single experiment the characteristics of the band structure for various crystallographic directions and will contribute both the refinement and to the study of the band structure of the metals and alloys.[2)]

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[1)] The impossibility of observing oscillations of the type $k_z=2\pi d^{-1}/3$, mentioned in[3], is due to the increase of the quasiparticle damping below the Fermi level.

[2)] Oscillations were also observed in $Pb_{1-x}Bi_x$ alloys ($x<2$ at.%).

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