Experimental determination of the change of the electron fermi velocity under pressure

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Experiments were performed aimed at observing the Tomasch tunnel effect under pressure up to 9 kbar. The experiments have made it possible to observe directly the increase of the Fermi velocity in lead, and uncover new possibilities of determining details of the characteristics of the electron spectrum under changes in volume.

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A study of the oscillatory de Haas—van Alphen and Shubnikov—de Haas phenomena under conditions of strong compression are so far the main source of information on the energy spectrum of the conduction electrons when the lattice parameters are changed.[1] Prospects of investigating the band structure of metals and alloys under pressure with the aid of electron tunneling have recently been noted.[2] In this article we demonstrate a new possibility of using the tunnel effect to obtain information on the change that hydrostatic compression introduces in such an important characteristic of the electron spectrum as the velocity of normal electrons. This possibility stems from a study of the Tomasch geometric tunnel resonances in thick ($t > 2$ μm) superconducting films.[3] The maxima in the oscillations of the tunnel conductivity are determined from the formula[3]

$$\epsilon_j = j\frac{h}{4t}V_F, \tag{1}$$

where $j = 1, 2, \ldots,$ is the number of the singularity, h is Planck's constant, V_F is the electron velocity on the Fermi surface, $\epsilon_j = [(eU - \Delta_1)^2 - \Delta_2^2]^{1/2}$, e is the electron charge, U is the voltage on the barrier, and Δ_1 and Δ_2 are the energy gap of the superconducting injector and the superconducting object of the investigation, respectively. Thus, the gist of an experiment aimed at determining the changes of the electron velocity reduces to a measurement of the period of the Tomasch tunnel oscillations at zero and finite pressures.

The Tomasch effect in Al-Al$_2$O$_3$-Pb-Ag tunnel junctions was investigated at hydrostatic pressures up to 9 kbar.[1)] The samples were prepared by condensing the metals on a glass substrate in a vacuum $P = 10^{-6}$ Torr. The aluminum and lead films were respectively 100—300 Å and 2.5—3.2 μm thick. The barrier layer was produced by oxidizing the aluminum film. The temperature condition under which the lead film was produced was chosen such as to obtain a clearly pronounced texture in the [111] direction, and the quality of the texture was monitored by x-ray structure analysis. The resistances of the tunnel junctions in the range of investigated energies (2—4 meV) were 100—3000 Ω/mm^2. To eliminate edge effects, the film were deposited through magnetically clamped masks. The measurements were made at a temperature 1.4 °K with the aid of

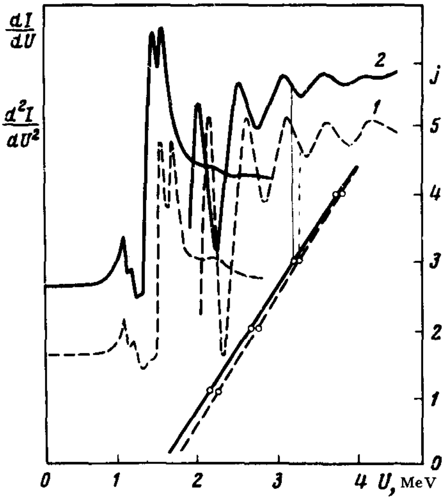

FIG. 1. The characteristics $(dI/dU)(U)$ and $(d^2I/dU^2)(U)$ and plots of $\epsilon(j)$ for an $Al\text{-}Al_2O_3\text{-}Pb\text{-}Ag$ tunnel junction at $P=0$ (dashed) and at $P=8.8$ kbar (solid line).

the well known modulation technique. The pressure in the "bomb" with kerosene-oil mixture was monitored against the change of superconducting transition temperature of indium. The data discussed below, obtained with samples clearly exhibiting anisotropy of the gap of lead, Tomasch oscillations, and a conductivity ratio $(\sigma_N/\sigma_S)(U=0)=10^{-3}$ in the entire indicated pressure range. The last circumstance guarantees that quantitative results will be reliably obtained, since it excludes the presence of leakage currents of non-tunnel origin through the barrier.

Application of pressure leads to a change in the tunnel characteristics (dI/dU) and $(d^2I/dU^2)(U)$; this change is due to the decrease of the energy gaps of the junction electrodes and to the increase in the period of the oscillations (see Fig. 1). The experimental $\epsilon(j)$ is a straight line (Fig. 1 shows $\epsilon(j)$ at $P=0$ and $P=8.8$ kbar), the slope of which changes noticeably with pressure, reflecting the increase of the Fermi velocity. By averaging the data of experiments with six tunnel samples and with different lead-film thicknesses at pressures 1.5, 2.8, 4.7, 6.9, 7.2, 8.8 kbar we obtained $d[\ln V_F]/dP \approx d[\ln\epsilon]/dP = +(7.7\pm 0.7)\times 10^{-6}\ \text{bar}^{-1}$.

This increase of the period, and consequently also of the electron velocity, is primarily due to the decrease of the electron-photon interaction (EPI). In fact, it is well known[4] that EPI in metals leads to an electron-spectrum renormalization that manifests itself in a decrease of the electron velocity $V_F = V_0/Z_n$ near the Fermi surface, where V_0 is the velocity in the absence of electron-phonon interaction and Z_n is a renormalization coefficient. We then obtain for the change of the period of the Tomasch oscillations under pressure

$$\frac{d\ln\epsilon}{dP} = -\frac{d\ln Z_n}{dP} + \frac{d\ln\frac{V_0}{t}}{dP}. \qquad (2)$$

The contribution of the last quantity is small, as can be easily determined from the free-electron model: $d[\ln(V_0/t)]/dP = 2\kappa/3$, where κ is the compressibility of lead. On the other hand, it is also possible to obtain experimentally data on the dependence of V_0/T on P, by studying in detail, under pressure, another type of tunnel oscillations considered by us earlier.[2] The period $\Delta E = (\pi\hbar/2)(V_0/t)$ of such a structure does not contain a renormalization due to the EPI (we recall that the structure is observed far from the Fermi level). Reduction of a large number of experimental plots of d^2I/dU^2 against U at various pressures (up to 10 kbar) for different samples has yielded

$$\frac{d\ln\frac{V_o}{t}}{dP} = (1.6 \pm 0.4)\times 10^{-6}\ \mathrm{bar}^{-1}.$$

This agrees with the results of Anderson's calculations$^{2)}$ of the band structure of lead under pressure, from which it follows also that $d[\ln(V_0/t)]/dP$ depends very little on the band energy, so that we can use for $d[\ln(V_0/t)]/dP$ in (2) the experimental results[2] obtained for this quantity at the energy $E = E_F + 0.8$ eV.

Taking all the foregoing into account, we obtain from the experiment on the Tomasch effect on the pressure the following relation for the renormalization coefficient $Z_n(P)$:

$$\frac{d\ln Z_n}{dP} = -6.1\times 10^{-6}\ \mathrm{bar}^{-1}.$$

This value agrees well with the data on the change of the state density[5] and conforms fully to the tunnel experiments and calculations performed on the effect of pressure on the electron-phonon interaction function.[6] To our knowledge, these are the first experiments in which the electron velocity and the parameter of renormalization of the electron spectrum were measured under pressure. The results can serve as a confirmation of the prediction of H. Brandt and N. B. Brandt,[7] that the cyclotron effective mass of the electrons decreases under pressure, an effect that is likewise determined by the change of the EPI: $M^* = m_0 Z_n$.

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$^{1)}$A thin ~1000 Å layer of silver helps amplify the oscillations in this case.

$^{2)}$We take the opportunity to thank J. R. Anderson for supplying the calculations prior to their publication, and for a useful discussion of the problems touched upon here during his stay in the USSR.

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