Observation of the ballistic flight of hot electrons through a lead film

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A voltage across the barrier semiconductor layer, caused by the ballistic flight of energized electrons, was observed as a result of injection of electrons from a tunnel junction through a lead film. The influence of electron-electron interaction was insignificant, contrary to existing theoretical estimates.

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The most important characteristic of electrons as quasiparticle excitations that transfer electric charge is the energy ϵ measured from the Fermi level E_f. Electrons with an energy $\epsilon \lesssim kT$, where the temperature $T \lesssim 10$ K, have been studied in most known methods. Hot or energized electrons, which have a value of $\epsilon \gtrsim k\Theta$ (Θ is the Debye temperature), have not been studied in depth. The lifetime τ of such excitations can be very short even in an ideal crystal at a crystal-lattice temperature $T = 0$ K. Because of the emission of phonons, the value $\tau_{ep} \sim \hbar(k\Theta)^2/\epsilon^3$ for $\epsilon \lesssim k\Theta$ and approaches the constant limit $\tau_{ep} \sim \hbar/k\Theta$ for $\epsilon > k\Theta$. As a result of electron-electron interaction, the lifetime $\tau_{ee} \sim \hbar E_f/\epsilon^2$ within a wide range of energies $\epsilon \gg k\Theta/100$. These theoretical estimates[1] were drawn from very general considerations and give us only the order of magnitude of τ and, correspondingly, the mean free path length $l \approx v\tau$ (v is the Fermi velocity of electrons).

In this paper we discuss the preliminary results of a study of the mean free path of energized electrons in metallic lead films. The energized electrons were injected into lead by means of tunneling through the oxide layer of an auxiliary electrode—an aluminum film—to which an accelerating voltage was applied. The electrons, which were able to pass through the lead film before relaxation to the Fermi level, were detected by means of a barrier layer of the semiconductor PbTe and the lead collector electrode. Similar arrangements have been used previously to study the absorption of hot electrons in gold and silver films.[2,3]

The required layered structure with leads for connection to the measuring circuit was fabricated by a sequential evaporation of Al, Pb, and PbTe films followed by a second Pb film. These substances were evaporated in a vacuum (residual-gas pressure of $\sim 10^{-5}$ Torr) from separate evaporators and were deposited on a glass substrate through shaped openings in successively interposed masks. The Al_2O_3 oxide film formed when air was admitted into the vacuum system at a pressure of ~ 100 Torr for 1-2 min. The general appearance of the thin-film structure and the arrangement scheme of the layers are shown in Fig. 1. The thickness of the films was monitored in terms of the frequency shift of a quartz-plate-stabilized oscillator, which was placed next to the cutout in the mask. The frequency shift was assumed to be pro-

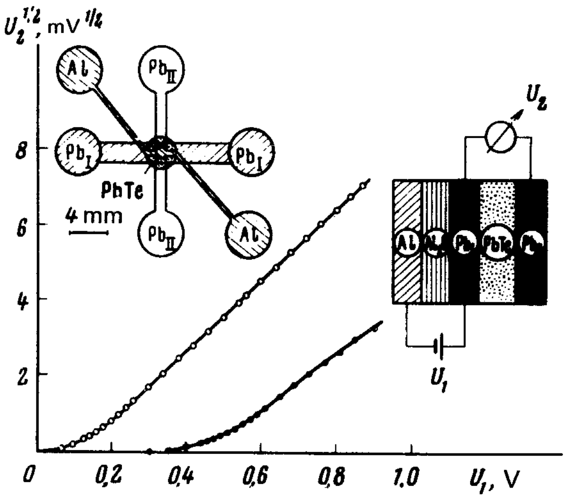

FIG. 1. Schematic of a layered structure and the dependence of induced voltage U_2 across the barrier on the injection voltage U_1. The different symbols correspond to the voltage polarities. ○–Positive polarity on Al and Pb_{II}; •–negative polarity on Al and Pb_{II} with respect to the middle electrode Pb_I. $T = 77$ K.

portional to the deposited mass. The calibration was done in a separate experiment by weighing a thick evaporated film. The weight was converted to film thickness by using the density value of the bulk metal.

Measurements were made at temperatures $T = 77$ K and $T = 4.2$–1.3 K. A constant voltage U_1 was applied between the Al and Pb_I films, and the voltage U_2 that appeared between the Pb_I and Pb_{II} films was recorded (see Fig. 1). The injecting voltage $U_1 \lesssim 1$ V was within the nearly linear portion of the I-V characteristic of the Al-Al_2O_3-Pb_I tunnel junction, which had a resistance $R_1 = 1\ k\Omega$. The induced voltage U_2 was also within the limits of the linear portion of the I-V characteristic of the Pb_I-PbTe-Pb_{II} barrier layer, which had a resistance $R_2 = 300\ k\Omega$. We attribute the voltage U_2, which appears when U_1 is turned on, to the ballistic flight through the Pb_I film of electrons with an energy sufficiently high to surmount the energy barriers in the Pb_I-PbTe-Pb_{II} structure. The observed polarity of U_2 corresponds to hole injection for a positive polarity of the Al film and electron injection for the opposite polarity of the injector.

To be specific, we shall examine the injection of electrons in the simple case of an isotropic dispersion law at $T = 0$ K. We introduce coordinates with the x axis directed normally to the plane surface of the tunnel junction into Pb_I, so that the point $x = 0$ lies at the Al_2O_3-Pb_I boundary. As a result of elastic tunneling, a nonzero correction f to the equilibrium distribution function of electrons appears for states in the interval $0 \leqslant \epsilon \leqslant U_1$ (region I in Fig. 2). The total current through the junction is $J_1 \sim \int_I v_x f dp$ (see, for example, Ref. 4). The function $f(x) = f \exp(-x/l)$ with the penetration depth into the bulk of the metal. If an energy barrier of height U_0 exists at the depth $x = d$, then the current injected through the barrier must be $J_2 \sim \int_{II} v_x$

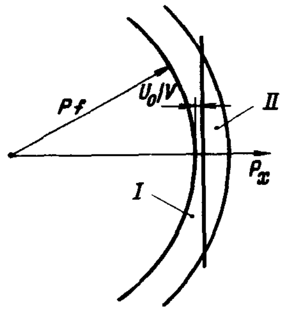

FIG. 2. Diagram of the regions in momentum space which correspond to the total tunnel current–spherical layer I and to the recorded injection current–spherical segment II.

$f(d)dp$, where the integral is taken over region II in Fig. 2, as defined by the condition $p_x \geqslant p_f + U_0/v$. By leaking backward into the Pb_I film, the injected charges cause the voltage drop $U_2 = R_2 J_2$ with a negative sign on the collector electrode Pb_{II}.

The rather wide linear portion of the IV characteristic $J_1 = U_1/R_1$ of the tunnel junction makes it possible to assume that for a large fraction of the states in region I the tunneling probability does not depend on U_1, and the value of J_1 is determined by the volume of region I, which is proportional to $p_f^2 U_1$. We can assume, therefore, that the value of J_2 is proportional to the volume of region II, i.e., $p_f(U_1 - U_0)^2/v^2$, if the mean free path l does not depend on the excitation energies. The experimental results are in agreement with these considerations. The barrier height for the holes $U_{0h} = 0.10$ V turned out to be different from that for the electrons $U_{0e} = 0.45$ V presumably because of the presence of a forbidden band of width ~0.3 eV in the PbTe. The current ratio $J_2/J_1 \approx 10^{-4}$ at $U_1 \approx 1$ V and the Pb_I film thickness $d = 5000$ Å enabled us to estimate the mean free path $l \approx 700$ Å by using the ratio $J_2/J_1 \approx \exp(-d/l)(U - U_0)/E_f$, where the ratio of the volumes of regions I and II was assumed to be equal to $\sim(U - U_0)/E_f$ in order of magnitude. This estimate of l is in agreement with the theoretical estimate $l_{ep} \sim 1000$ Å for $\epsilon > k\Theta \approx 10^{-2}$ eV. It remains unclear why the electron-electron interaction does not produce the predicted relaxation of electrons. This interaction is responsible for the fast falloff of $f(x) \sim \exp(-a\epsilon^2 x)$, where a is a constant. On the U_2 vs U_1 plot this leads to a slowing down of the increase of U_2 and a saturation in the range of U_1 values corresponding to the condition $l(\epsilon = U_1) \approx d$. We can see in Fig. 1 that the length l_{ee} remains greater than 5000 Å even at $\epsilon = 1$ eV, although according to theoretical order-of-magnitude estimates for lead $E_f = 10$ eV and the length $l_{ee} \approx 100$ Å. The reason for such a large discrepancy is nebulous. A decrease of the temperature to $T = 1.3$ K, as expected, did not alter significantly the dependence of U_2 on U_1, since the characteristic ratio $(kT/\epsilon) \sim 10^{-2}$ indicates that the pathlength of electrons of such high energies has a weak temperature dependence.

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