Possible use of tunnel spectroscopy for determining the energy dependence of the effective mass in semiconductors

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A method is proposed for determining the effective mass in semiconductors at energies not equal to the Fermi energy, from the temperature dependence of the oscillation amplitude of the tunnel conductivity in a magnetic field. The potential of this method is illustrated using *n*-InAs as an example.

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The traditional methods of measuring the effective mass (m_e) of charge carriers in semiconductors (the Shubnikov-de Haas oscillations, Faraday effect, magnetothermal emf, cyclotron resonance, etc.) yield m_e values either at energies equal to the Fermi energy (in a degenerate material), or near the band bottom (in the case of nondegenerate statistics). Thus, measurement of the effective mass at various energies calls for the use of samples with different Fermi energies that are determined by free carrier concentrations. Moreover, the energy dependence $m_e(\epsilon)$ is actually replaced by the concentration dependence $m_e(n)$ and, accordingly, the possible change in the energy spec-

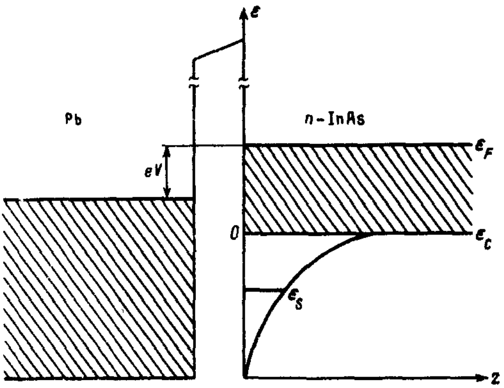

FIG. 1. The energy diagram of a tunnel junction at bias $V>0$ (the sign of the bias corresponds to the sign of the potential at the Pb electrode). ϵ_F—Fermi energy, ϵ_c—bottom of conduction band, ϵ_s—bottom of surface electron band.

trum with the doping level due to interelectron and electron-impurity coupling may be neglected.

Earlier,[1] we demonstrated the possibility of using tunnel spectroscopy in a magnetic field for the experimental determination of the dispersion law $\epsilon(k^2)$ in semiconductors. In this work we show that the investigation of the temperature dependence of the oscillation amplitude of the tunnel conductivity in a magnetic field provides a way of determining the differential characteristic of the energy spectrum—the effective mass—at energies differing from the Fermi energy by an amount eV, where V is the voltage applied to a tunnel junction and e is the electron charge.

The tunneling current in the metal-dielectric-semiconductor structure whose energy diagram is shown in Fig. 1 is expressed as follows:[2]

$$I(V) \sim \int_{-\infty}^{\infty} \rho_s(\epsilon)\, W[f(T,\epsilon) - f(T, \epsilon + eV)]d\epsilon, \tag{1}$$

where $\rho_s(\epsilon)$ is the semiconductor state density, W is the tunneling probability, and $f(T,\epsilon)$ is the Fermi-Dirac distribution function. In a magnetic field as a result of the quantization of carrier mobility the semiconductor state density oscillates, which leads to the occurrence of oscillations in the tunnel conductivity.[1] Actually, it follows from Eq. (1)

$$\sigma(V) = \frac{\partial I}{\partial V} \sim e \int_{-\infty}^{\infty} \sum_n \rho_{sn}(\epsilon)\, W_n \frac{\partial f(T, \epsilon + eV)}{\partial \epsilon} d\epsilon, \tag{2}$$

where n is the number of the Landau level in a semiconductor. Equation (2) is similar with respect to structure to an expression that describes the Shubnikov-de Haas oscillations[3] (under the integral sign we have a product of a function $\Sigma_n\, \rho_{sn}\, W_n$ which is periodic in energy with the period $\hbar\omega_c$ and a derivative of the distribution function $\partial f(T,\epsilon + eV)/\partial\epsilon$). Consequently the temperature dependence of oscillations of the tunnel conductivity has a similar form[3]

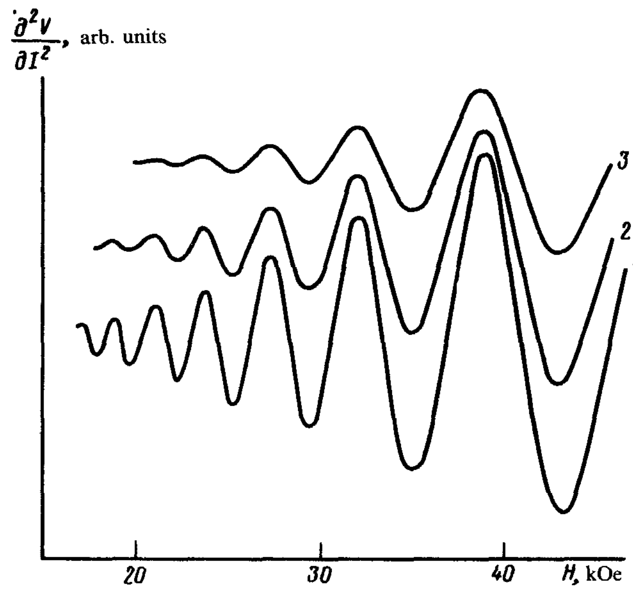

FIG. 2. The function $\frac{\partial^2 V}{\partial I^2}(H)$ for a specimen with $n = 2\times 10^{17}$ cm^{-3} at bias voltage $V = -30$ mV. Temperature, K: 1—4.2, 2—13.4, 3—19.1.

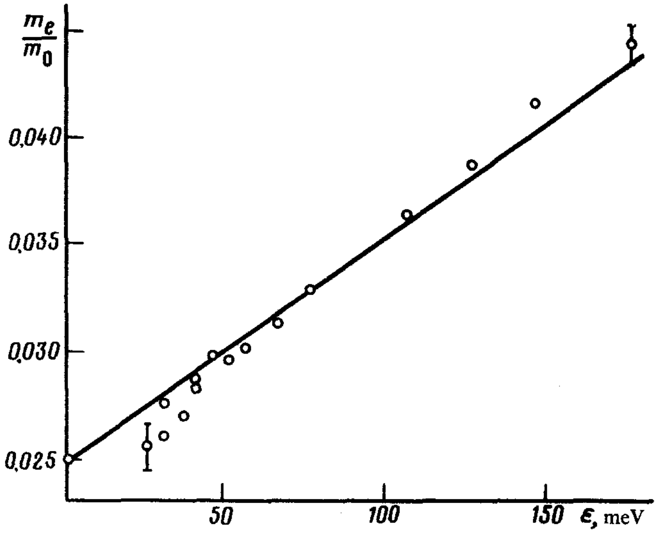

FIG. 3. The energy dependence of the effective mass in n-InAs: circles—experiment for specimen with $n = 2\times 10^{17}$ cm^{-3}, solid line—the Kane law with parameters $m_n = 0.0245\, m_0$, $\epsilon_g = 0.418$ eV, $\Delta = 0.38$ eV.[1]

$$A(T) \sim \frac{T}{\mathrm{sh}\left(\frac{2\pi^2 k_B T m_e(\epsilon_F + eV)c}{\hbar eH}\right)}, \tag{3}$$

where k_B is Boltzmann's constant, c is the speed of light in vacuum and H is the magnetic field strength.

In contrast to the Shubnikov-de Haas oscillations, Eq. (3) contains the effective mass at the energy $\epsilon_F + eV$; therefore, when measuring the temperature dependence of the amplitude of oscillations of the tunnel conductivity at various voltages V, $m_e(\epsilon_F + eV)$, i.e., $m_e(\epsilon)$ may be determined.

The essence of the method may be explained as follows. In the Shubnikov-de Haas effect the temperature dependence of the amplitude of conductivity oscillations arises because the temperature increases the Fermi step of the electron distribution function in a semiconductor—which, as the magnetic field increases, is intersected by the state density maxima associated with the Landau levels—is washed out. In this case, electrons near the semiconductor Fermi level contribute to the conductivity, and Eq. (3) is used to determine their mass, i.e., $m_e(\epsilon_F)$. In the case of tunnel conductivity the temperature dependence of the oscillation amplitude is due to the smearing out with increasing temperature of the Fermi step in the electron distribution in a metal (see Fig. 1). For a fixed voltage V, contribution to the differential conductivity of a tunnel junction derives from states with energy $\epsilon_F + eV$; therefore, Eq. (3) yields a value for the mass at precisely this energy.

The measurements were carried out in the temperature interval 4.2–30 K using Pb-oxide-n-InAs tunnel junctions prepared by a method described in Ref. 4. To exclude the effect of surface electron bands the magnetic field was directed along the surface of a junction ($I \perp H$). Figure 2 shows the dependence of $\partial^2 V/\partial I^2$ on the magnetic field at constant voltage V and different temperatures. The tunnel conductivity oscillation is well described by Eq. (3) over the entire range of temperatures, magnetic fields (to 55 kOe) and bias voltages investigated. Figure 3 shows the energy dependence of the effective mass determined by means of Eq. (3). The experimental results agree well on the whole with the Kane function having the following parameters: m_n (effective mass at the band bottom) $= 0.0245\ m_0$, $\epsilon_g = 0.418$ eV and Δ (spin-orbit splitting) $= 0.38$ eV.[1]

In our opinion, the proposed method may be used for investigating a broad class of semiconductors.

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