Application of tunnel spectroscopy in a magnetic field to the investigation of the dispersion law of a heavily-doped *n*-InAs

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(Submitted 14 February 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 7, 402–407 (5 April 1979)

The method of tunnel spectroscopy in a magnetic field was used to investigate the dispersion law of *n*-InAs at different doping levels. We established that doping leads to changes in the dispersion law which may be described by taking into account the exchange interaction of the free carriers.

PACS numbers: 71.55.Ht, 71.70.Gm

Conventional experimental methods (magneto-thermo-emf, magneto-plasma reflection, Faraday effect, etc.) are used to measure parameters of the energy spectrum of a semiconductor at the Fermi level. In order to determine the energy dependence of these parameters, specimen with different carrier concentrations are investigated. It is generally assumed that the doping alters only the position of the Fermi level but not the dispersion law. However, investigations dealing with the effect of doping on the semiconductor energy spectrum examine a region of states in the vicinity of band edges ("tails" of density states). As regards changes in the dispersion law inside the allowed energy bands, this question is insufficiently understood, especially on the experimental side.

The most feasible experimental method for this study is tunnel spectroscopy in a magnetic field. As we know,[1] tunnel conductivity (TC) in a metaloxide-semiconductor system to which a voltage (bias) V is applied is proportional to the semiconductor density at the energy $\epsilon_F + eV$ and the tunneling probability (in the case when anomalies in the density states near the Fermi level of a metal are nonexistent). The dependence of the tunneling probability on energy is, as a rule, not well known which makes derivation of the numerical results from TC measurements difficult. The situation changes when a quantizing magnetic field is applied which induces singularities in the density states of a semiconductor and, subsequently, the occurrence of oscillations in the bias-dependent TC function. In this case at a constant bias V the dependence of the conductivity on the magnetic field exhibits the de Haas–van Alfven-type oscillations whose periods are coupled thru the reverse field to the area of the least intersection of the isoenergetic surface with the energy $\epsilon_F + eV$ surface which is perpendicular to the magnetic field, by the relationship $\Delta(1/H) = 2\pi e/c\hbar S$. If the semiconductor conduction band is isotropic, $S = \pi k^2$ and, consequently

$$k^2(\epsilon_F + eV) = \frac{2e}{c\hbar\Delta(1/H)}. \tag{1}$$

Thus, the investigation of TC oscillations in a magnetic field provides direct experimental means for determining the dispersion law of a semiconductor.

We investigated *n*-InAs–oxide–Pb tunnel junctions which were prepared by

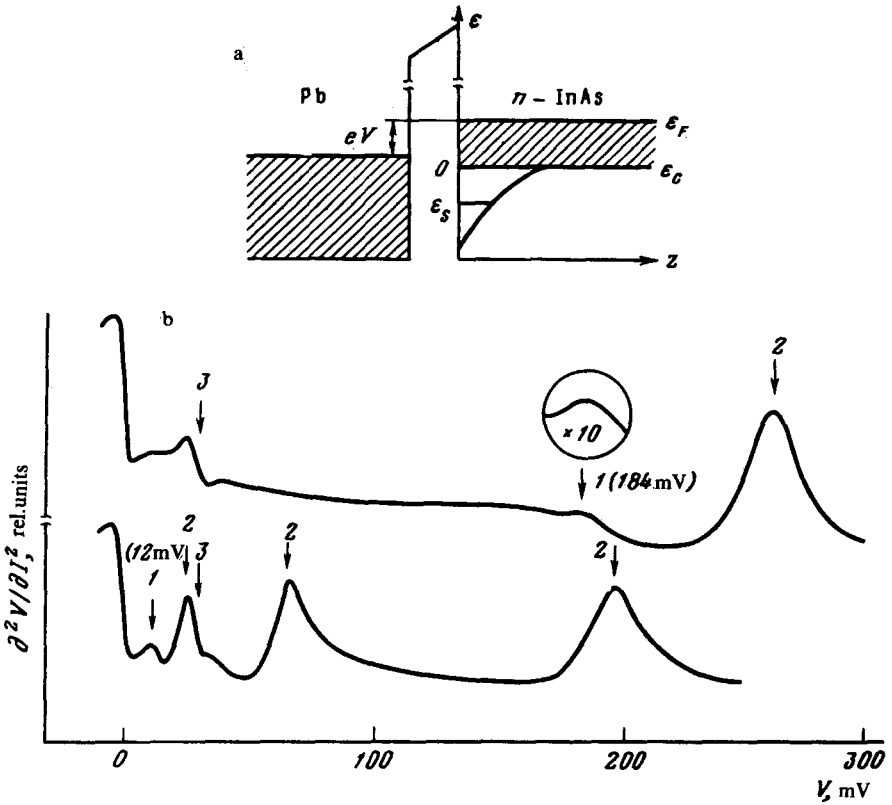

FIG. 1. (a)–Energy diagram of a tunnel junction at bias $V>0$ (the sign of the bias corresponds to the sign of the potential at the Pb electrode). ϵ_F—Fermi energy, ϵ_c—bottom of conduction band, ϵ_s—bottom of surface electron band; (b)–function $\partial^2 V/\partial I^2(V)$ at $H=2$ kOe for specimen with $n=2.2\times10^{16}$ cm^{-3} (lower curve) and $n=2.1\times10^{18}$ cm^{-3}. Arrows indicate special features associated with: 1—bottom of conduction band, 2—bottom of surface bands, 3—inelastic tunneling in the presence of an optical phonon.

methods described by Tsui.[1] The electron concentrations in n-InAs were: 2.2×10^{16}, 2×10^{17}, 7×10^{17}, 1.1×10^{18} and 2.1×10^{18} cm^{-3}. The functions $\partial V/\partial I(V,M)$ and $\partial^2 V/\partial I^2(V,H)$ were measured at a temperature of 4.2 K in a magnetic field up to 55 kOe. Figure 1(a) shows the junction energy diagram. This system contains two-dimensional regions of surface electrons due to the presence of an enriching layer on the n-InAs surface (investigation of the electron spectra in a magnetic field was carried out in Ref. 1). The dependence of $\partial^2 V/\partial I^2$ on V in a 2-kOe magnetic field (which eliminates the TC singularities associated with the superconductivity of lead) for specimen with carrier concentrations of 2.2×10^{16} and 2.1×10^{18} cm^{-3} are shown in Fig. 1(b). Arrows indicate special features associated with the bottom of the surface electron and conduction bands and also the inelastic tunneling in the presence of an optical phonon.

In a magnetic field directed along the junction surface ($I\perp H$) surface electron bands remain unquantized[1] and oscillations which occur in a TC are associated with

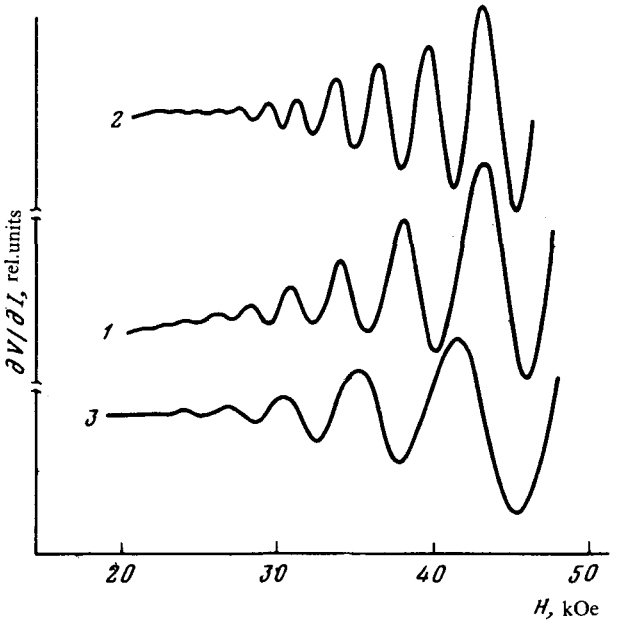

FIG. 2. The function $(\partial V/\partial I)(H)$ for specimen with $n = 1.1\times10^{18}$ cm^{-3} at biases: 1—0, 2— -40 mV, 3—30 mV.

the quantization of the conduction band of volume carriers; therefore, all measurements were carried out with the above field orientation.

Figure 2 shows the dependence of $\partial V/\partial I$ on the magnetic field for three bias values. The observed oscillations are periodic with respect to the inverse field, and their period at $V = 0$ coincides with the period of the Shubnikov-de Hass oscillations which was measured using the same specimen. The dependence of $\epsilon = \epsilon_F + eV$ on k^2, determined by means of Eq. (1) from the period of TC oscillations at a bias V (the anisotropy of the conduction band of InAs does not exceed 1%[2]) is shown in Fig. 3(a) for specimen with $n = 2.2\times10^{16}$ cm^{-3} and $n = 2.1\times10^{18}$ cm^{-3}. The experimental values of ϵ_F were determined from the position of the tunnel current singularity associated with the edge of the conduction band [Fig. 1(b)].

It is evident from Fig. 3(a) that in a specimen with concentrations of 2.2×10^{16} cm^{-3} the experimental function $\epsilon(k^2)$ is well described by the three-band Keino model with $\epsilon_g = 0.418$ eV,[3] $\Delta = 0.38$ eV [4] and the effective mass at the band bottom $m_n = 0.0245m_0$. Moreover, the theoretical value of ϵ_F coincides with the experimental. In contrast with this, the experimental value of ϵ_F (which is 10 meV times greater than the theoretical) for a specimen with $n = 2.1\times10^{18}$ cm^{-3} and the function $\epsilon(k^2)$ over the entire energy interval fail to follow the Keino law with the aforementioned parameters. In order to describe the dispersion law of a heavily-doped material in the first approximation[5] we shall take into consideration the exchange interaction of the free carriers. Thus,

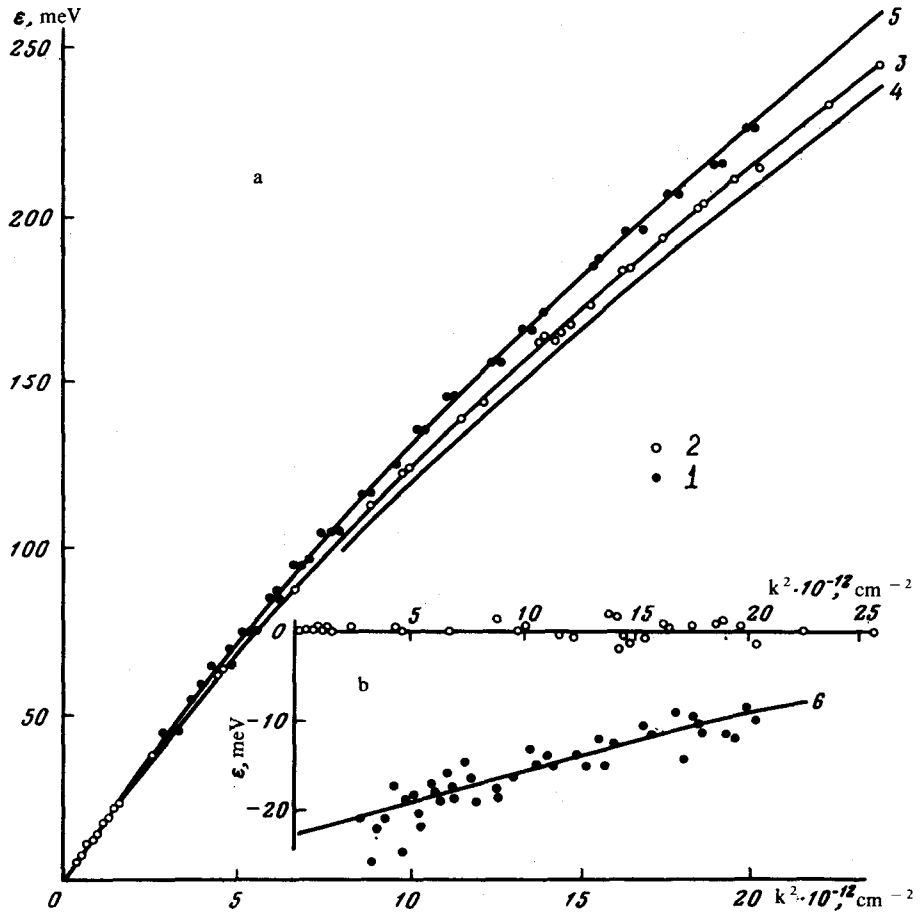

FIG. 3. (a)–The function $\epsilon(k^2)$ for specimen: 1—$n = 2.2\times 10^{16}$ cm^{-3}, 2—$n = 2.1\times 10^{18}$ cm^{-3}. Curves 3 and 4—Keino dispersion laws with parameters: $\epsilon_g = 0.418$ eV, $\Delta = 0.38$ eV, $m_n = 0.0245m_0$ and $m_n = 0.0255m_0$, respectively, 5—theoretical function $\epsilon(k^2)$ with allowance for transfer energy; (b)–energy deviation from the Keino law which describes a dispersion law of a weakly-doped materials, for the same specimen; 6—function described by Eq. (2).

$$\epsilon(k) = \epsilon_1(k) + \epsilon_2(k), \tag{2}$$

where $\epsilon_1(k)$ is the Keino law for a weakly-doped material and $\epsilon_2(k)$ is the transfer energy with allowance for screening.[5] Figure 3(a) shows the dependence in Eq. (2) (for both materials the energy is measured from the bottom of the conduction band). In order to better demonstrate a difference in the dispersion laws for the weakly- and the strongly-doped specimen, Fig. 3(b) shows the deviation of energies—that correspond to a given value of k^2—from the Keino law with parameters $\epsilon_g = 0.418$ eV, $\Delta = 0.38$ eV and $m_n = 0.0245m_0$. This figure takes into account the fact that the bottom of the

conduction band of a heavily-doped material is actually displaced down the energy scale by an amount $\epsilon_2(0)$.

Thus, we have shown that doping leads to changes in the semiconductor dispersion law which is satisfactorily described by taking into account the exchange interaction of the free charge carriers.

We believe the method used in this work may be useful in investigation of the special features of the energy spectrum of a broad class of materials.

The authors thank G.I. Kharus for useful discussions.

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