New possibilities for tunneling spectroscopy in investigations of 2D states

G. M. Min'kov, A. V. Germanenko, V. V. Kruzhaev, O. É. Rut, and V. A. Larionova

Institute of Physics and Applied Mathematics at Ural University, 620083 Ekaterinburg, Russia

(Submitted 10 July 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 4, 308–312 (25 August 1995)

A development of the method of tunneling spectroscopy, which makes it possible to investigate the spectrum of two-dimensional (2D) states in a wide range of energies with a controllable surface quantum well depth, is proposed. The new possibilities of the method are demonstrated using the example of the study of 2D states in zero-gap HgCdTe. © *1995 American Institute of Physics.*

Tunneling spectroscopy is a well-known, though little-used, method for investigating the energy spectrum of semiconductors.[1] The crux of the method is illustrated in Fig. 1a, which shows an energy diagram of a metal–insulator–semiconductor tunneling contact in the presence of a surface potential in the semiconductor and localized 2D states in it. The voltage V applied to the contact shifts the Fermi level of the metal relative to the Fermi level of the semiconductor (E_F) by the amount eV, and the tunneling current $j(V)$ is determined by the number of carrier states in the semiconductor in the energy range from E_F up to E_F+eV (Refs. 2 and 3). The experimentally measured quantities are ordinarily the differential conductivity $\sigma_d(V)=dj(V)/dV$ and its derivative with respect to the voltage. In a quantizing magnetic field B the differential conductivity oscillates as a function of B and V, passing through a maximum each time that the peaks in the density of states of the semiconductor, which are associated with the Landau levels, cross the energy E_F+eV. Information about the volume and 2D states can thus be obtained in the entire energy range corresponding to the range of applied voltages, for which oscillations of the tunneling conductivity are observed.[4,5] In contrast with galvanomagnetic measurements and capacitance-versus-voltage spectroscopy, which make it possible to measure the surface potential φ and therefore the concentration of 2D carriers but yield information only about states at the Fermi energy, tunneling spectroscopy yields information about the electronic states in a wide range of energies, both above and below the Fermi level.

An important aspect of investigations of 2D states by the tunneling-spectroscopy method is the fact that by changing the applied voltage on the contact it is possible to change at the same time the quantity[5] φ_s. This change is determined by the thickness of the barrier, the charge density in the space-charge region, the density of states localized in the insulator and at the insulator–semiconductor boundary, and in the standard method of tunneling spectroscopy it is not controllable.

The development of the tunneling-spectroscopy method described in this letter

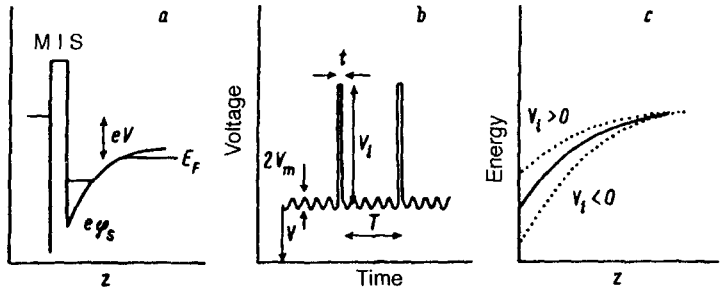

FIG. 1. a — Energy diagram of a metal–insulator–semiconductor tunneling contact; b — voltage applied to the tunneling contact versus time; c — surface bending of bands and the change introduced in the bending by the application of pulses with different polarities.

makes it possible to investigate 2D states with any fixed energy by varying independently the depth of the surface quantum well.

In the standard modulation procedure for measuring small nonlinearities of the current-voltage characteristic, in addition to a constant voltage, a modulation voltage V_m with a small amplitude is also applied to the contact (Fig. 1b). The variable component of the current at the modulation frequency f is proportional to the differential conductivity, and at the doubled frequency it is proportional to the derivative of the differential conductivity with respect to the voltage V. The additional short (duration $t \ll 1/f$) but infrequent (period $T \gg 1/f$) pulses applied to the tunneling contact recharge the localized states in the insulator and at the insulator–semiconductor boundary. If the charge relaxation time of these states is much greater than T, this will result in an increase or decrease, depending on the sign of the pulses, of the depth of the surface quantum well (Fig. 1c). By recording the alternating component of the current in the gaps between the pulses we can thus obtain information about 2D states with energy $E_F + eV$ with different depths of the potential well.

We shall demonstrate the possibilities of the proposed method for the example of spin-orbit splitting of the spectrum of 2D electronic states in a surface quantum well of the zero-gap semiconductor p-HgCdTe.

Oscillations of the tunneling conductivity of Yb-oxide–p-HgCdTe contacts with $E_g = -120$ meV and uncompensated acceptor concentration of 2×10^{18} cm^{-3} were investigated in magnetic fields up to 5.5 T at a temperature of 4.2 K. In such structures the low work function of Yb results in surface bending of bands in the semiconductor and the appearance of 2D states. The Fermi energy in the semiconductor was determined according to Ref. 3. It is equal to $-(5 \pm 2)$ meV in the test sample (the energy is measured from the bottom of the conduction band).

Typical curves of the oscillating part of the tunneling conductivity as a function of the magnetic field are shown in Fig. 2a. We see that they consist of a superposition of several types of oscillations with different frequency, which are well resolved in the Fourier analysis (Fig. 2b). The fundamental frequency is determined by the area of the extremal section of the isoenergetic surface S with energy $E = E_F + eV$:

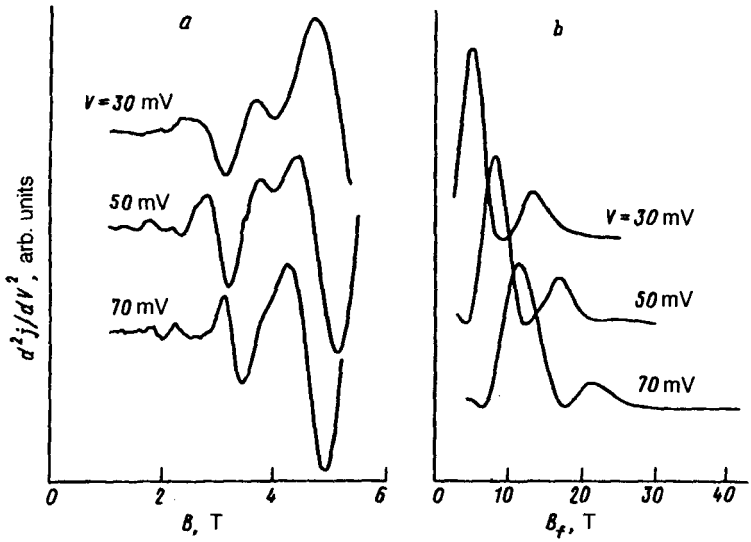

FIG. 2. d^2j/dV^2 versus the magnetic field (a) and results of a Fourier transformation which were obtained for different applied voltages (b). The magnetic field is oriented along the normal to the surface of the tunneling contact.

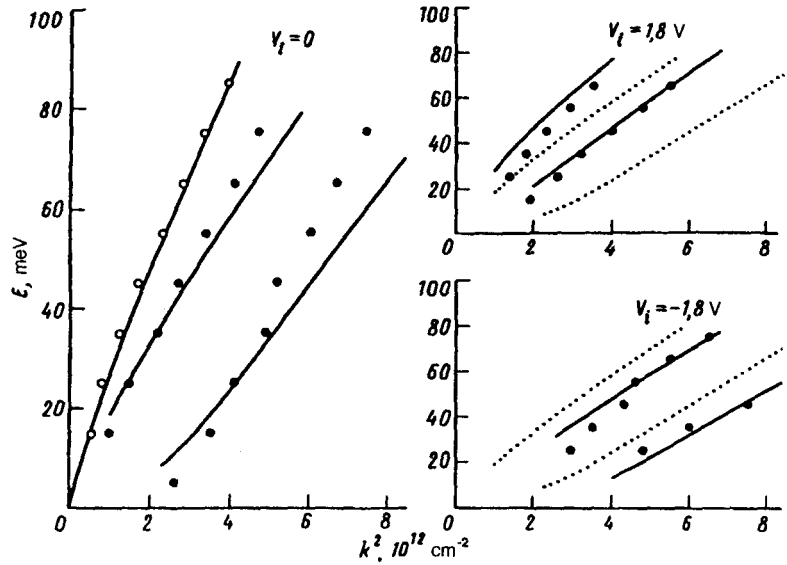

FIG. 3. Dispersion relation obtained by the standard method ($V_i=0$) and by applying additional voltage pulses of different polarities for volume and two-dimensional surface states. ○ and ● — Experimental dispersion relations for volume and 2D states, respectively. Lines — theoretical calculations with $\varphi_s=200$ ($V_i=0$), 200 ($V_i=-1.8$ V), and 155 mV ($V_i=1.8$ V). The dispersion relation for 2D states with $V_i=0$ is shown for comparison by the dotted lines in the figures on the right-hand side.

$B_f = c\hbar S(E)/2\pi e$. In materials with isotropic dispersion relation we have $S(E) = \pi k^2$. The energy dependence of the quasimomentum can thus be determined by measuring the oscillations with different applied voltages. Figure 3 shows the experimental curves $E(k^2)$ obtained for the volume and surface states by the method described on the same tunneling contact. The energy spectrum of the volume states was obtained by performing measurements in the orientation $\mathbf{B} \perp \mathbf{n}$ ($\mathbf{n}$ is the normal to the plane of the tunneling contact), for which there are no oscillations associated with the 2D states, since their energy spectrum is not quantized for this orientation of the magnetic field. The dispersion relation for the 2D states was obtained with the orientation $\mathbf{B} \parallel \mathbf{n}$. The same figure also shows the dispersion relations obtained for the 2D states by applying to the structure additional pulses of different polarity with $t = 1$ μs, $T = 30$ ms, and an amplitude of 1.8 V with modulation frequency $f = 740$ Hz. We see that the additional pulses change the dispersion relation. When positive pulses are applied to the semiconductor electrode, the energy of the 2D states with a fixed value of the quasimomentum increases, whereas it decreases when negative pulses are applied. It follows, therefore, that positive pulses decrease the surface potential and negative pulses increase it.

Figure 3 also shows the computational results for the spectrum of 2D states which are localized in a surface quantum well at the zero-gap semiconductor–insulator bound-

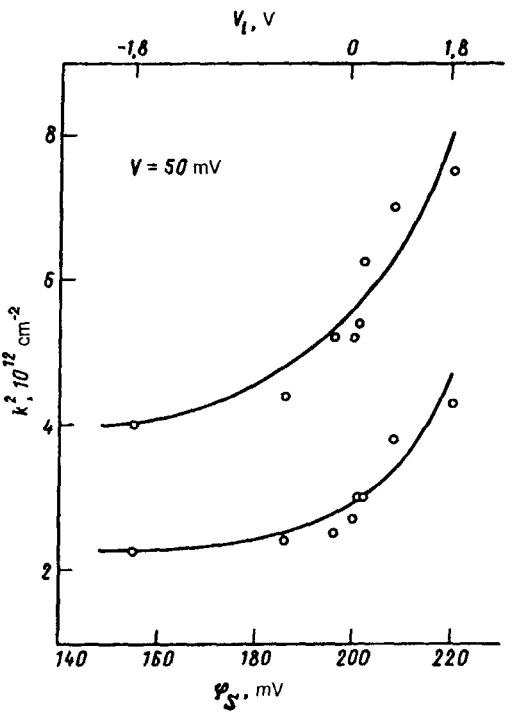

FIG. 4. Quasimomentum for two branches of the energy spectrum of 2D states as a function of the magnitude of the surface potential with $V = 50$ mV, which corresponds to energy $E = 45$ meV. The curves are drawn through the experimental points.

ary. In the calculations it was assumed that the insulator is a Kane semiconductor with a large band gap.[5] The problem was solved by direct integration. As one can see from the figure, the theoretical curves $E(k^2)$ agree satisfactorily with the experimental results when the surface potential φ_s is used as the adjustable parameter. The calculation showed that the dispersion branches which we observed are two branches of the same quantum-size band which is split by the spin-orbit interaction in an asymmetric quantum well. In addition, the depth of the surface quantum well can be determined as a function of the amplitude of the applied pulses by comparing the computational and experimental results. For the experimental tunneling contact a change of the amplitude of the pulses in the range from -1.8 to $+1.8$ V resulted in a change of the depth of the surface quantum well in the range 220–150 meV.

This method of measurement makes it possible to determine experimentally for a fixed energy the ratio of the magnitudes of the quasimomenta of the 2D branches as a function of the magnitude of the surface potential (Fig. 4). In contrast with the capacitance-versus-voltage spectroscopy and galvanomagnetic investigations, which yield such a dependence for only one energy — the Fermi energy, in the method described here the energy of the investigated states is determined by the voltage applied to the tunneling contact and can be arbitrary within the limits for which oscillations of the tunneling conductivity in a magnetic field are observed (this range generally is 100–300 meV).

In summary, the development of the tunneling-spectroscopy method makes it possible to combine the advantages of galvanomagnetic and capacitance-versus-voltage measurements with the advantages of tunneling spectroscopy, i.e., it makes it possible to obtain information about 2D states in a wide range of energies with different surface quantum well depths.

This work was supported by the program "Universities of Russia" and the State Committee of the Russian Federation on Higher Education.

[1]E. L. Wolf, Solid State Phys. **30**, 1 (1975).
[2]D. C. Tsui, Phys. Rev. B **8**, 2567 (1973).
[3]L. P. Zverev, V. V. Kruzhaev, G. M. Min'kov, and O. É. Rut, Zh. Éksp. Teor. Fiz. **80**, 1163 (1981) [Sov. Phys. JETP **53**, 595 (1981)].
[4]R. Winkler, U. Kunze, and U. Rössler, Surf. Sci. **263**, 222 (1992).
[5]G. M. Min'kov, O. É. Rut, V. A. Larionova, and A. V. Germanenko, Zh. Éksp. Teor. Fiz. **105**, 719 (1994) [J. Exp. Theor. Phys. **78**, 384 (1994)].
[6]P. Sobkowicz, Semicond. Sci. Technol. **5**, 183 (1990).

Translated by M. E. Alferieff