Quantization of rotation of the polarization plane of light reflected from the surface layer of a semiconductor

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Quantization of the angle of rotation of the polarization plane of the reflected light as a function of the wavelength of the incident light in the surface layer of a cubic crystal of CdTe has been observed for the first time. This phenomenon was instrumental in detecting single quantum-size subbands of heavy and light holes in the inversion layer of n-type CdTe.

The method which we used to form quantum-size states in the inversion layer of n-type CdTe, which allowed us to detect quasi-two-dimensional surface excitons, can be summarized as follows. On a CdTe surface cleaved in air, chemisorption of oxygen atoms at 85 K was produced by light from an incandescent lamp. The spectrum of the reflection at an angle of incidence of 12° was recorded during the adsorption at various stages of formation of the monolayer which depended on the exposure time. Figure 1 shows the results for CdTe with n-type conductivity, with an electron density of 4×10^{15} cm^{-3}, and with electron mobility of 5680 cm^2/(V·s). The change in the surface resistance was measured simultaneously. On the basis of these measurements it can be concluded that the pinning of the Fermi level and the formation of the inversion layer at the surface of n-type CdTe occur in the initial stage of oxygen chemisorption. (The metallic contacts deposited on the surface form a $\sim$1-eV barrier, irrespective of the work function of the metal.) A prolonged exposure of the surface to light in the presence of oxygen is apparently necessary in order to form a chemisorbed oxygen monolayer which creates a more uniform potential well along the entire illuminated surface. As a result, the reflection minima become more clearly manifested and their displacement ($\sim$3 meV) up the energy scale is negligible. An imposition of the surface electric field gives rise to anisotropy of the optical properties in the surface CdTe layer in accordance with the Franz-Keldysh effect.

To identify the reflection minima obtained by us, we used a linearly polarized light incident at an angle of 75° with respect to the normal (**n**) to the surface (Fig. 2). In the case of polarization $\mathbf{E}\|\mathbf{n}$ (the p polarization) the optical transitions, in which the heavy-hole subbands are involved, are forbidden, according to the selection rules. We link the series of minima observed in the case of p polarization (curve 2) with the quasi-2D surface excitons which are formed because of the Coulomb interaction of electrons in the 2D surface subband with the light holes in the quantum-size subbands of the inversion layer.[1] The distribution of the reflection minima corresponds to the energy spectrum of quantized subbands of the light holes which are described by the familiar relation

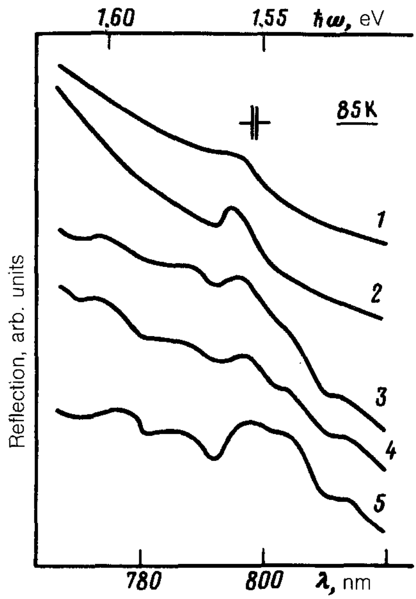

FIG. 1. Reflection spectra of n-type CdTe at an angle of 12° vs the exposure time in oxygen atmosphere (h). 1—0.4; 2—0.75; 3—1; 4—1.3; 5—2.8 h.

$$E_i = \left(\frac{\hbar^2}{2m_p}\right)^{1/3}\left[\frac{3\pi e F_s}{2}\left(i+\frac{3}{4}\right)\right]^{2/3}, \qquad i = 0, 1, 2, 3, \qquad (1)$$

where m_p is the effective mass of the holes in the **n** direction, and F_s is the effective electric field at the surface. In the case of s polarization we could not resolve the

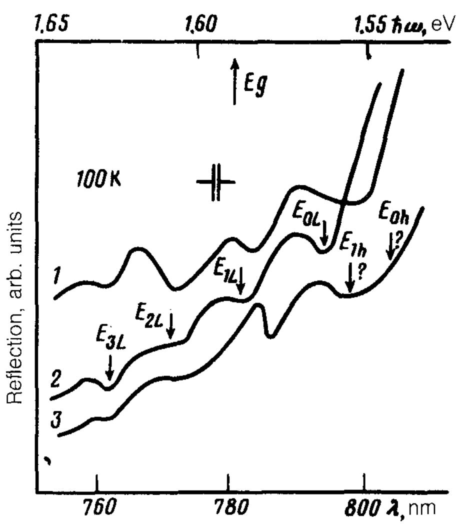

FIG. 2. Reflection spectra of n-type CdTe at an angle of 75° after a 4-h exposure. 1—Unpolarized light; 2—p-polarized light; 3—s-polarized light.

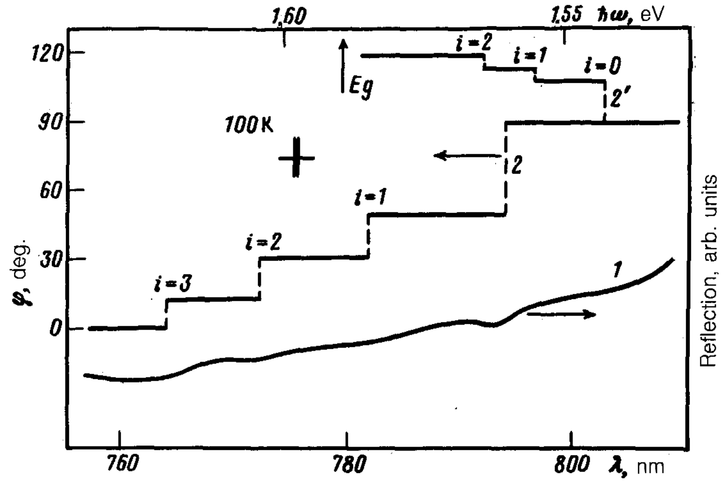

FIG. 3. Reflection spectra at an angle of 75° (1) and of the angle of rotation of the p-polarization plane (2 and 2′) for n-type CdTe after a 1-h exposure.

minima corresponding to the quantum-size heavy holes (E_{0h} and E_{1h}) which are expected to be present in the region 797–804 nm (curve 3).

The spectrum of the oblique reflection from the surface, which was subjected to a preliminary excitation of light for 1 h, was initially measured with an unpolarized light (curve 1 in Fig. 3). Two polarizers were then placed in front of the CdTe sample and behind it and the intensity of the reflected light was measured as a function of the angle of rotation φ of the second polarizer relative to the first polarizer (curve 2 in Fig. 3). When the polarized light is incident on the sample, the maximum intensity of the reflection is measured in the region $\lambda \sim 750$–760 nm at an angle $\varphi = 0$, i.e., the reflected light remains p polarized. At $\lambda = 764$ nm, however, the maximum of the reflection intensity appears at $\varphi = 12°$ and the angle of the polarization plane rotates abruptly. The second abrupt rotation through an angle $\varphi = 18°$ occurs at 772.2 nm, the third occurs at 782.1 nm, and the largest rotation, $\varphi = 42°$, occurs at 794.4 nm. The abrupt rotations of the angle φ (represented by the dashed lines) occur in a narrow interval, $\Delta\lambda \lesssim 0.1$ nm. The particular features of the behavior of φ cannot be ascertained in this interval, because the error margin of the method we are using is of the same order of magnitude. The energies corresponding to the wavelengths λ at which the abrupt changes in the angle φ occur can be accurately described by expression (1) for light holes ($m_{p1} = 0.135 m_0$) and give the value of 3.3×10^4 V/cm for F_s. In the approximation of the triangular potential well, the thickness of the inversion layer is estimated to be $z_i = 2E_i/3eF_s$, according to Ref. 2, which gives the values $z_0 = 6$ nm and $z_3 = 19$ nm.

In the region 790–804 nm we see, in addition to the abrupt changes in the angle φ described above, a similar behavior of the angle of rotation of the polarization plane at 803.4, 797.2, and 792.4 nm as a result of variation in the angle φ between 90° and 120°. The intensity of reflected light is, however, much weaker for this series than for the first series (curve 2′ in Fig. 3). The corresponding values of the energy are described by relation (1) with effective masses of the heavy holes $m_{ph} = 1.4m_0$, consistent with the estimates of Ref. 3. We have thus observed for the first time quantum-size heavy holes in CdTe by measuring the abrupt change in the angle of rotation of the polarization plane during the reflection.

In summary, the quantized rotation of the polarization plane of reflected light which we have observed describes exactly the energy spectrum of the quantized states in the surface layer of CdTe. Application of this new method showed that its sensitivity is much greater than that of the known methods. Evidence pointing to its superior sensitivity is the detection of quantum-size heavy holes in CdTe. This observation would not have been possible on the basis of the absorption[2] and reflection spectra in which rotation of the polarization plane is ignored (Fig. 2).

Such quantized rotation of the angle of the polarization plane in the case of reflection has also been observed in other regions of the spectrum at 300 K, e.g., at $\lambda = 810$–890 nm.

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