Quasithreshold character of the far-inrared absorption in GaSb/InAs/GaSb quantum wells

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Quasithreshold growth of far-infrared absorption in a GaSb/InAs/GaSb semimetallic quantum well has been observed. This effect is attributed to the existence in the energy spectrum of such structures of a region of quasi-three-dimensional electronic states near the Fermi level. The proposed model is also confirmed by the strong temperature dependence of the absorption. © *1995 American Institute of Physics.*

Quantum wells based on type-II heterojunctions, specifically, GaSb/InAs/GaSb, are distinguished by the fact that some of the allowed electronic states in the well lie in the continuous spectrum of the valence band of GaSb. This has two important consequences. First, the electron gas in the well is strongly degenerate. Second, as we shall show below, a region of quasi-three-dimensional states appears in the electronic spectrum. To this last circumstance we associate the quasithreshold character, which we observed, as well as the strong temperature dependence of the far-infrared absorption.

In the experiments we employed structures with a single GaSb/InAs/GaSb quantum well grown by the method of molecular epitaxy on (001) GaAs substrates. The well was 200 Å wide and the thickness of the top layer of GaSb was chosen to be equal to 1200 Å, which made it possible to eliminate the influence of the surface potential. The electron concentration and mobility were determined from Hall measurements. The typical values were, respectively, 1.1×10^{12} cm^{-2} and 5×10^{4} cm^2/(V·s) at $T=77$ K and 2.6×10^{12} cm^{-2} and 2.2×10^{4} cm^2/(V·s) at $T=300$ K. The well in the experimental structures contained a strong built-in magnetic field, whose existence was verified by observing beats in the Shubnikov–de Haas oscillations. The geometry of the experiment is shown in the inset in Fig. 1. The external magnetic field B was oriented in the plane of the 2D layer. The exciting radiation, whose source was an optically pumped pulsed D_2O laser ($\lambda=385$ μm), was incident along the normal direction to the plane of the sample. The photovoltaic current arising in the plane of the sample perpendicular to the direction of the field **B** was measured. In the geometry of the experiment it is described by the phenomenological relation $j_i/I\sim\alpha(I)\chi_{ikl}n_kB_l$, where I is the intensity, $\alpha(I)$ is the absorption coefficient for light, χ_{ikl} is a rank-3 tensor whose specific form is determined by the photocurrent mechanism, and n_k is a unit vector oriented parallel to the built-in field.

Figure 1 shows the quantity j/I versus the intensity of the light at $T=4.2$ K and $T=250$ K. We see that at liquid-helium temperature this dependence has a quasithreshold

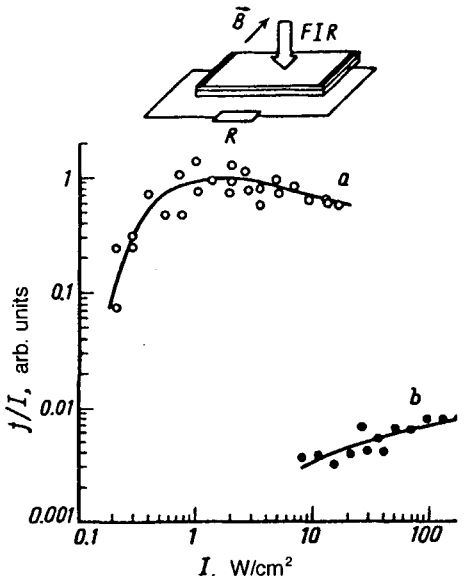

FIG. 1. Normalized photocurrent plotted as a function of the radiation intensity ($\lambda = 385$ μm, $B = 1.6$ T): a — $T = 4.2$ K; b — $T = 250$ K. Inset: Geometry of the experiment.

character. The value of I, for which the absorption coefficient increases sharply, is very low: it is equal to approximately 0.2 W/cm^2. At $T = 250$ K, the absorption depends relatively weakly on I.

To explain this result, we calculated the energy spectrum of the electrons on the basis of Kane's model. For simplicity, we ignored the spin-orbit splitting of the valence bands of the two semiconductors. The corresponding Schrödinger equations for InAs (index 1) and GaSb (index 2) are

$$E u_1 = -i\hbar\gamma(\vec{\nabla}\cdot\mathbf{v}_1), \quad (E-\Phi)u_2 = -i\hbar\gamma(\vec{\nabla}\cdot\mathbf{v}_2),$$
$$(E+E_{g1})\mathbf{v}_1 = -i\hbar\gamma\vec{\nabla}u_1, \quad (E-\Phi+E_{g2})\mathbf{v}_2 = -i\hbar\gamma\vec{\nabla}u_2.$$

Here u_1, u_2 and $\mathbf{v}_1$, $\mathbf{v}_2$ are envelopes of the s- and p-type wave functions, E_{g1} and E_{g2} are the band gaps in InAs and GaSb, Φ is the splitting between the edges of the conduction bands of these semiconductors, and γ is the Kane matrix element. The energy E is measured from the bottom of the conduction band of InAs. The energy diagram of the structure is shown on the left side in Fig. 2.

In what follows, we shall assume that the z axis is perpendicular to the plane of the well. According to Ref. 1, the boundary conditions at the interfaces are

$$u_2|_{z=\pm L/2} = u_1|_{z=\pm L/2}, \quad v_{z2}|_{z=\pm L/2} = v_{z1}|_{z=\pm L/2},$$

where L is the width of the quantum well. The following results are obtained by solving these equations simultaneously. In the energy interval $E_{c1} \leqslant E \leqslant E_{v2}$, there exists a region

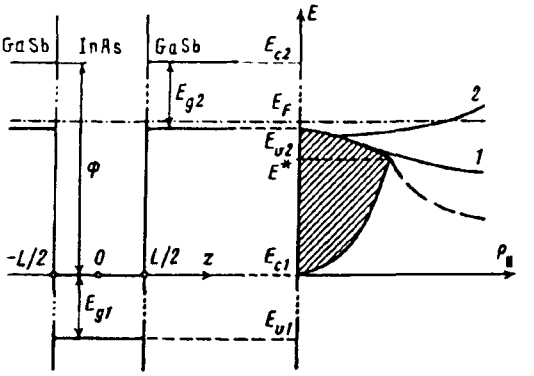

FIG. 2. Band diagram and energy spectrum of a GaSb/InAs/GaSb quantum well. The hatched region corresponds to quasi-three-dimensional electronic states in the well. The curves *1* and *2* correspond to the first and second quantum-size levels. Dashed line — level of the surface states.

that corresponds to quasi-three-dimensional states with wave functions that oscillate outside the quantum well. In the energy spectrum (see the right side in Fig. 2) this region is hatched. Its boundaries are determined by the equations

$$E=\Phi-\frac{E_{g2}}{2}-\sqrt{\frac{E_{g2}^2}{4}+\gamma^2 p_\parallel^2} \quad \text{for } E^*<E<E_{v2},$$

$$E=-\frac{E_{g1}}{2}+\sqrt{\frac{E_{g1}^2}{4}+\gamma^2 p_\parallel^2} \quad \text{for } E_{c1}<E<E^*,$$

where $p_\parallel$ is the component of the electron momentum in the plane of the well. For $E_{g1}=0.4$ eV, $E_{g2}=0.8$ eV, and $\Phi=0.95$ eV, E^* is equal to approximately 0.1 eV. The dashed line represents the level to which the states localized on the boundaries of the well correspond. These states are similar to those investigated in Ref. 1 for the case of a single type-II heterojunction. If the well is sufficiently wide; specifically, if the following condition is satisfied:

$$-\frac{E_{g1}}{2}+\sqrt{\frac{E_{g1}^2}{4}+\frac{\gamma^2\hbar^2\pi^2}{2mL^2}}<\Phi-E_{g2}$$

(here m is the electron mass in InAs), then we have a quantum-well level, which is described by curve *1* in Fig. 2. If the following condition is satisfied:

$$-\frac{E_{g1}}{2}+\sqrt{\frac{E_{g1}^2}{4}+\frac{4\gamma^2\hbar^2\pi^2}{2mL^2}}<\Phi-E_{g2},$$

then we have another quantum-size well, which is described by curve *2* in Fig. 2. Using the value $m=0.023m_0$, it is easy to see that both quantum-size levels are present in a well whose width exceeds 160 Å. The bottom level, just as the level of the surface states, lies entirely below the Fermi level, and the electrons filling it do not participate in

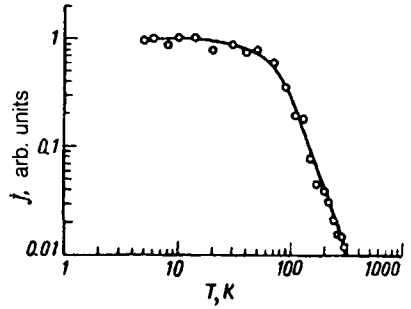

FIG. 3. Photocurrent versus the temperature of the sample for $I = 15$ W/cm^2 ($\lambda = 385$ μm, $B = 1.6$ T).

conduction and absorption processes. At low temperatures the band of quasi-three-dimensional states is also completely filled with electrons. However, the second quantum-size level is only partially filled and the electron gas in it is strongly degenerate. This is the level that is responsible for the semimetallic properties of the quantum well GaSb/InAs/GaSb.[1)]

Let us now discuss the experimental results on the basis of the energy spectrum obtained. We start at liquid-helium temperatures. In this case the Fermi level lies slightly above the top of the valence band of GaSb, and therefore above the top of the region of quasi-three-dimensional states. Therefore, if the electron gas is not heated, this region is completely filled and transitions of electrons inside it cannot occur. Absorption occurs as a result of indirect transitions within the second quantum-size level. As the light intensity increases, the electron gas heats up and vacancies appear near the top of the region of quasi-three-dimensional states. This makes possible direct optical transitions inside this region. In such transitions the longitudinal momentum $p_\parallel$ of an electron is conserved, and an increase in energy is accompanied by a change in the transverse momentum p_z. The latter change is possible as a result of the strong interaction of an electron with the interfaces. It is obvious that the probability of such transitions is much higher than the probability of indirect transitions As a result, the absorption should increase rapidly.

At $T = 250$ K, the situation is markedly different. Simple estimates show that in this case the Fermi level in the volume layers of GaSb, and therefore in the entire system, lies approximately 100 meV above the top of the valence band of GaSb. The number of vacancies in the region of quasi–three-dimensional states is now small and is determined mainly by the lattice temperature. The absorption coefficient is therefore much smaller than in the case of low temperatures, and it does not depend on the intensity.

The considerations presented above agree well with the temperature dependence of j shown in Fig. 3. We see that at temperatures ranging from 4.2 up to 70 K the absorption is virtually independent of T, and as the temperature increases from 80 to 300 K, the absorption drops by two orders of magnitude. This is explained as follows. At low temperatures the position of the Fermi level is virtually independent of the temperature and at $T < 70$ K the Fermi level lies near the edge of the valence band of GaSb. In this situation, as a result of the heating, the number of vacancies in the band of quasi-three-dimensional states is comparatively large and virtually independent of the lattice tem-

perature. At higher temperatures, the Fermi level rises rapidly and the number of vacancies, and therefore the absorption decrease rapidly.[2)]

In conclusion, we note that the spectrum of the well CsSb/InAs/GaSb was calculated in Ref. 3 on the basis of the Kohn–Luttinger model. The result obtained there is different from the classical result in that the quantum-size levels are somewhat broadened and form combined electron-hole states. However, it seems to us that Kane's model is better applicable to the system studied in the present work. The main result of our calculation, which for the time being ignores the heavy holes, consists of the appearance of a band of quasi-three-dimensional electron states. It is our opinion that, just as in Ref. 3, the effect of the heavy holes leads only to a slight broadening and shift of the quantum-size levels. We also underscore the fact that our spectrum is consistent with the main experimental results that we know now.

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[1)]It is well-known that the metallic properties of the well disappear at thicknesses less than 75 Å . This is markedly different from 160 Å given above. This disagreement could stem from the fact that in our calculations we ignored the spin-orbit splitting of the valence bands, the bending of the energy bands near the heteroboundary, and the built-in electric field in the well.

[2)]In Ref. 2 we proposed a different mechanism for the decrease in j with increasing E_F. However, this mechanism cannot explain the dependence of the absorption on the light intensity.

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