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Electronic states and quantum Hall effect in GaSb-InAs-GaSb quantum wells

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The electronic states of an InAs quantum well buried a few tens of nm below a GaSb surface are described, assuming Fermi-level pinning in the lower part of the gap at this surface. This model accounts satisfactorily for a variety of experimental observations such as the imbalance of electron and hole concentrations, the relatively high electron mobility, and the appearance of quantum-Hall plateaus. Additional cyclotron-resonance measurements are also consistent with the proposed electronic structure.

InAs-GaSb heterostructures are especially interesting because of the band lineup between these two semiconductors. Indeed, the electronic properties of InAs-GaSb superlattices indicate that the top of the GaSb valence band is ~ 0.15 eV higher than the bottom of the InAs conduction band.[1] Under suitable circumstances, GaSb valence electrons are transferred to the adjacent InAs layers, generating an equilibrium concentration of spatially separated electron- and holelike two-dimensional gases. Magneto-optical experiments[2,3] have been explained by this picture, including the band-structure subtleties due to hybridization of electron- and holelike states.[4,5]

On the basis of extrapolation of the superlattice results to a single InAs well between GaSb barriers, one would expect the formation of an electron gas in the well, balanced by hole gases of equal concentration in the barriers, with the Fermi level lying in the 0.15-eV band-overlap region. However, recent experimental work[6-8] on such quantum wells contradicts this simple picture and provides other observations which are not yet explained in a consistent way. In particular, these observations are the following.

(i) A large excess concentration of electrons with respect to holes (up to $\rho_e - \rho_h \sim 7\times 10^{11}$ cm^{-2}) is observed.[7,8]

(ii) A relatively high electron mobility (in excess of 10^5 cm^2/V s) is measured[7] at low temperatures. The temperature dependence is reminiscent of that limited by phonon scattering without the presence of a large number of impurities.

(iii) The quantum Hall effect is observed in single quantum wells,[6-8] with plateau spacings corresponding to an effective carrier concentration $(\rho_e - \rho_h)$. However, it has been pointed out that, because of the peculiar band lineup of the two materials it is unlikely that electrons truly are confined in the InAs well if they are lower in energy than the GaSb valence-band edge and therefore degenerate with the three-dimensional valence-band continuum as they escape to infinity in a time of order 10^{-13} s.[9] As a result, it seems that electrons of essentially three-dimensional (3D) character take part in the quantum Hall effect, in analogy with recent observations in GaAs-$Al_xGa_{1-x}As$ systems.[10]

The present Rapid Communication adds to this list yet another experiment which is in contrast to the simple picture derived by analogy with the superlattice results. As will be seen below, our recent cyclotron-resonance measurements indicate that the Fermi level is higher than 0.15 eV when measured from the bottom of the InAs conduction band, and lies, therefore, above the top of the GaSb valence band. This observation rules out the transfer from the GaSb valence band as the only source of electrons.

These puzzling observations are of particular concern in view of the prototypical role of the InAs-GaSb system as a type-II heterostructure, and the first one in which the quantum Hall effect for an electron-hole system was reported. The purpose of the present Communication is to show that these observations can be quite naturally accounted for and reconciled with the band offsets derived from superlattice experiments if one simple and plausible assumption about the Fermi-level position at the GaSb surface of the samples is granted.

The crucial point is that in all samples under consideration the top p-type GaSb barrier is only 200 Å thick, and therefore it is less than the depletion length at moderate doping levels. It follows that if the Fermi level at the GaSb surface lies at some position in the GaSb gap, it cannot fully recover its bulk value (near the acceptor level) at the depth below the surface where the interface to InAs occurs. The quantum well is therefore in a region of strong band bending, a situation which can significantly influence its electronic structure. In this case, the surface acts as the source of electrons and, therefore, the system is a new type of modulation-doped heterostructure, with the surface playing the role of the doped layer.

Unfortunately, we are not aware of any experimental determinations of the Fermi level at the (100) surface of molecular-beam-epitaxially (MBE) grown GaSb. Photoemission studies[11] of the oxygen-exposed (110) cleavage surface show that the Fermi level is pinned in the lower

part of the gap. Although the orientation and the growth mechanism may alter the nature of surface defects and therefore influence the pinning level, it appears quite reasonable to assume a similar pinning level $\Delta V \sim 0.1$–0.2 eV above the valence-band top for the case of interest here as well. It is easy to show that even without recourse to fully self-consistent calculations this assumption is sufficient to obtain the essential features of the observed behavior of the quantum wells. In fact, a Fermi-level pinning $\Delta V \sim 0.2$ eV, say, above the valence band corresponds to a depletion length $d_\rho \simeq (\epsilon \Delta V / 2\pi e^2 n_a)^{1/2} \sim 1800$ Å, for an acceptor concentration of 10^{16} cm^{-3}, as typical for these systems.[6] The InAs quantum well, which is only 200 Å away from the surface, accumulates electrons, be it in a continuum of resonant states (below the GaSb valence-band edge), or in genuine bound states (above the GaSb valence-band edge), with a density far exceeding that of the depleted acceptors in GaSb. This is illustrated in Fig. 1 for three different thicknesses of the InAs quantum wells.

Consider first the thinnest InAs well (of thickness $d_2 = 60$ Å) between a $d_1 = 200$-Å-thick GaSb layer, and a very thick GaSb substrate of which a thickness d_3 is also depleted. The electron concentration in the well and the resulting potential profile should be calculated self-consistently. As a starting guess, we take the experimental electron concentration $\rho_e \sim 4 \times 10^{11}$ cm^{-2} (Ref. 6) and assume that the corresponding charge is distributed uniformly in the well. Simple electrostatic considerations give then the equation

$$(d_1+d_2+d_3)^2 = \frac{\epsilon \Delta V}{2\pi e^2 n_a} - \frac{(n_e - n_a)}{n_e}(d_2^2 + 2d_2 d_1) \ , \quad (1)$$

where $n_e \equiv \rho_e / d_2$ is the 3D electron concentration in the well. For $\Delta V \sim 0.2$ eV, Eq. (1) gives $d_3 \sim 800$ Å, showing therefore that the depletion goes far beyond the quantum well. To make specific examples, we (arbitrarily) assume a band bending of 0.18 eV, and remember that the bulk position of the Fermi level is at the GaSb acceptor level[12] ~ 30 meV above the valence-band top. The potential profile is then obtained by purely electrostatic considerations and is shown in Fig. 1(a). Notice that for such a thin well there are no hole subbands, that the Fermi level lies ~ 0.23 eV above the InAs well bottom, and that the electron population is solely derived from surface depletion.

When the subband position in the potential given in Fig. 1(a) is evaluated (nonparabolicity is approximately accounted for by taking an effective mass $m^* = 0.03m$ for InAs) one occupied subband E_1 located 51 meV below the Fermi energy is obtained. This corresponds to an electron density $\rho_e = 6.4 \times 10^{11}$ cm^{-2} in the well, sufficiently close to the input value $\rho_e \sim 4 \times 10^{11}$ cm^{-2} to see that self-consistency could be readily achieved in a few iterations. However, the aim of this Communication is to elucidate the basic physics, leaving detailed numerical calculations to future work.

Consider now the more interesting case of thicker wells [$d_2 = 150$ Å, Fig. 1(b) or $d_2 = 200$ Å, Fig. 1(c)], where the electron subbands are degenerate with the valence-band continuum and where hole subbands are also populated.

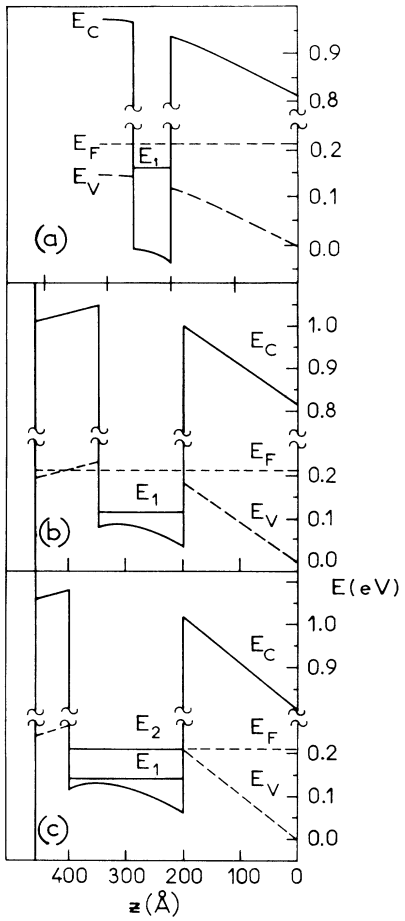

FIG. 1. Band-bending profiles obtained by solving an approximate Poisson equation for (a) a 60-Å InAs quantum well holding 4×10^{11} electrons cm^2 (see Ref. 8). E_1 denotes the position of the occupied electron band. (b) A 150-Å InAs well holding 9.6×10^{11} cm^{-2} electrons, while the GaSb layer on the left holds 2.2×10^{11} holes cm^2 (see Ref. 7). (c) A 200-Å InAs quantum well holding 1.2×10^{12} electrons cm^2, while the GaSb layer on the left holds 3.5×10^{11} holes cm^2 (see Ref. 8). Notice the E_2 second subband lying very close to the Fermi level. The hole subbands are not shown.

In fact, as the well becomes thicker and contains more electrons, Eq. (1) at some point can no longer be satisfied by positive values of d_3. This indicates a qualitative change in the potential profile with respect to Fig. 1(a), as electron states in the well are now more than sufficient to balance the surface charge and accept electrons coming from the thick GaSb substrate as well. For the sample with $d_2 = 150$ Å in Ref. 7, with experimental input values $\rho_e \sim 9.6 \times 10^{11}$ cm^{-2} and $\rho_h \sim 2.2 \times 10^{11}$ cm^{-2}, the potential in Fig. 1(b) results (the band bending in the GaSb substrate, $z \leftarrow 350$ Å, cannot be determined by pure electrostatic considerations and is estimated in the Thomas-Fermi approximation). The electron subband E_1 lies 97 meV below the Fermi energy and holds therefore 1.2×10^{12} electrons cm^{-2}, again in fair agreement with the input value of ρ_e. For the sample with $d_2 = 200$ Å in

Ref. 8, the input values are $\rho_e = 1.2 \times 10^{12}$ cm^{-2} and $\rho_h = 3.5 \times 10^{11}$ cm^{-2}. The potential profile in Fig. 1(c) is obtained, with one subband E_1, 70 meV below the Fermi energy and a second one, E_2, lying almost exactly at the Fermi energy. The first one can hold 8.8×10^{11} electrons cm^{-2} and it is impossible, within the accuracy of this crude estimate, to assess if any carriers are actually present in the second subband. This requires more accurate self-consistent calculations.

Further confirmation of the proposed electronic structure comes from cyclotron-resonance measurements performed on 150- and 200-Å InAs quantum wells. These experiments determine the effective mass, in the direction parallel to the layers, of carriers at the Fermi energy, and, in view of the significant energy dependence of the InAs conduction mass,[13] determine the Fermi-level position with respect to the bottom of the conduction band. For a strongly distorted well with a slanting bottom, such as those in Figs. 1(b) and 1(c) an average of the energy difference between the Fermi level and the well bottom is measured, weighted by the subband wave function squared. For the 150-Å sample, we observe $m^* = 0.049$, corresponding to a Fermi energy ~ 230 meV above the well bottom, and for the 200-Å sample $m^* = 0.038$, corresponding to 130 meV. This is in reasonable agreement with the potential diagrams of Fig. 1; notice that a Fermi energy more than 0.15 eV above the InAs conduction band is incompatible with the simultaneous presence of holes unless strong band bending is involved.

It should be mentioned that in calculating the Fermi energy from the observed cyclotron masses the effect of the hybridization of the electron and hole subbands on the Landau levels has been neglected. As has been shown for InAs-GaSb superlattices,[5] this effect is characterized by an anticrossing of electron- and holelike levels which leads to a strongly nonlinear field dependence of the Landau levels. Here, however, a simple linear dependence of the resonant field on the radiation energy has been measured and we must conclude that we are already well above the anticrossing.

The question of the 3D vs 2D nature of the electron states and its relationship with the observation of the quantum Hall effect remains to be discussed.

To this aim, we examine the electronic states near the Fermi energy, in low and in high magnetic fields. The k dispersion of subbands in the plane parallel to the interfaces is characterized by strong hybridization and anticrossing of holelike and electronlike states.[4] For the thin InAs wells [see Fig. 1(a)] a purely 2D subband only crosses the Fermi level, and no problems arise. In the thicker samples [Figs. 1(b) and 1(c)] with both "electrons" and "holes" present, the band dispersion is schematically shown in Fig. 2. The lower part of the electron subband is broadened into a resonance and the Fermi surface is ring shaped in the k plane, with inner radius k_{Fh} and outer radius k_{Fe}. States near k_{Fh} are localized in GaSb, states near k_{Fe} in InAs and have mobilities which are accordingly different. Notice that the states are 2D in an energy region at least as large as the acceptor binding energy. The low-field magnetotransport is well described[14,15] by two-carrier formulas,[16] corresponding to

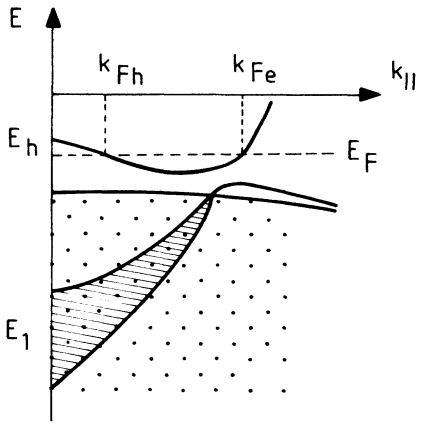

FIG. 2. Schematic subband $k_{\parallel}$-dispersion for the quantum well of Fig. 1(a). The pointed region denotes the GaSb valence-band continuum, and the broadening of the E_1 electron subband into a resonance is indicated by the striped zone. E_h denotes the $k = 0$ position of the hole subband.

electron and hole concentrations

$$\rho_{e,h} = 2\pi k_{Fe,h}^2/(2\pi)^2 \ . \tag{2}$$

For high magnetic fields, the system is in the quantum limit and we must consider the Landau-level structure which has been computed in detail for InAs-GaSb superlattices[5] and which is characterized by anticrossing of electron- and holelike levels. This is a result of the same electron-hole mixing which accounts for the partially 3D (resonancelike) character of states degenerate with the valence-band continuum. However, it is important to notice that in our model of band bending the Fermi energy lies on or between purely 2D Landau levels, in the sense that these Landau levels under consideration are separated by a gap in which no (delocalized) states are present. Whenever the Fermi level lies between 2D Landau levels, the Hall conductivity can be expressed by Streda's formula,[17]

$$\sigma_{x,y} \sim \frac{\partial n}{\partial B} \ , \tag{3}$$

where $n(E_F,B)$ is the total number of occupied electron states at given field and Fermi energy values. If we neglect hybridization for a moment, $n(E_F,B)$ can be expressed as

$$n(E_F,B) = n_{\rm val} - \rho_e(E_F,B) - \rho_h(E_F,B) \ , \tag{4}$$

where the first B-independent term represents the density of the electrons in the fully occupied valence band, while the following terms add to this the excess electrons in the conduction states and subtract those missing from the valence states. Their contribution yields the quantized Hall conductivity with effective carrier density $\rho_e - \rho_h$, a result which is not altered by the hybridization that simply blurs out the distinction between the three terms on the right-hand side, but does not alter their sum.

Further clarification of the situation could of course

come from a direct measurement of the Fermi-level position of this surface, and from other measurements, such as the carrier concentration as a function of the top GaSb layer thickness. Also, it should be mentioned that the structure in Fig. 1 can be operated as a new kind of field-effect device if a metal electrode is placed on top of the outer GaSb layer and properly biased to modulate the carrier density in the high-mobility InAs channel. We hope that this work will stimulate experimental efforts in these directions.

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