PHYSICAL REVIEW B VOLUME 57, NUMBER 19 15 MAY 1998-I

Resistance resonance induced by electron-hole hybridization in a strongly coupled InAs/GaSb/AlSb heterostructure

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(Received 27 October 1997)

We observe large resistance increases in a crossed band-gap electron-hole system owing to a coupling-induced energy gap at the point of anticrossing between the electron and hole dispersion relations. Samples with various degrees of coupling have been fabricated with front and back gates, which are able to deplete completely the electrons or holes, respectively. This has enabled a systematic study of the electron-hole coupling as a function of the total charge in the system. These results are interpreted in the light of recent theoretical predictions about two-dimensional electron-hole systems and equivalent experimental work on strongly coupled double two-dimensional electron gases. The temperature dependence of the coupling-induced resistance enhancement of the material has also been investigated, allowing us to obtain the magnitude of the resultant energy gap in the dispersion relations, which is found to be approximately 2 meV in the sample with the strongest coupling. [S0163-1829(98)02119-5]

There has been much interest, both theoretical[1–4] and experimental,[5–7] in heterostructures based on the InAs/GaSb/AlSb materials system. The band offsets are such that the conduction-band gap in InAs falls at a lower energy than the valence-band edge in GaSb, resulting in an intrinsic transfer of charge between the GaSb and InAs. Thus an electron gas forms in the InAs and a hole gas in the GaSb, allowing semimetallic systems to be created with very small separations between the electron and hole layers. This makes the system an ideal candidate for research into the possible existence of excitonic ground states and exotic pseudoparticle states. Much theoretical work has been carried out in both of these areas,[1–4,8,9] with the first experimental evidence of electron-hole hybridization having recently been published.[10]

In this paper we present results of four-terminal electrical transport measurements on a sample in which the band structure is tailored using gating, as recently suggested by Naveh and Laikhtmann.[1] In this way, the carrier densities can be altered in the InAs (electron) and GaSb (hole) layers. We present evidence for hybridization of electron and hole states in a strongly coupled electron-hole system, analogous to the energy level anticrossing in strongly coupled double two-dimensional electron gases (2DEG's). The effects of this on resistance are examined as a function of carrier density in both layers and temperature. It has been predicted that electron-hole hybridization will cause an energy gap to form at the point where the electron and hole in-plane dispersion relations cross,[1,3] the size of this gap depending on the strength of the coupling between the electrons and holes. Thus a semiconductor with nonmonotonic pseudoparticle energy-wave-vector (E-k) relations is produced in a crossed band-gap system.

The structure of the sample we discuss in this paper is shown as an inset to Fig. 1. The buffer layer (not shown) consisted of 5000 Å of GaAs followed by 10 000 Å of AlSb. The latter was necessary to take up the 7% lattice mismatch between the GaAs substrate and the InAs/GaSb/AlSb of the active region. On top of this, a thin (150 Å) layer of GaSb was grown, which contained a hole gas, followed by 300 Å of InAs, in which the electrons resided. A 500 Å barrier layer of AlSb and a 50 Å antioxidation cap layer of GaSb completed the structure. For the measurements presented here, the sample was etched into a standard Hall bar configuration using a plasma of 6% CHF_3 and 38% H_2. Front gating was achieved by evaporating a NiCr/Au gate on top of a layer of an organic insulating polymer[7] and back gating by means of direct contact to the n^+ GaAs substrate using a silver-epoxy resin. AuGeNi was deposited, and formed, without any annealing, shallow Ohmic contacts to both the electrons and the holes without shorting the layers to the conducting substrate. More details of the processing are given in Drndic *et al.*[7]

At zero applied gate bias the system behaved very much like an uncoupled system as the Fermi energy is well away from the gap. The pseudoparticles are then very much electron- and hole-like in character with densities of 7×10^{11} cm^{-2} and 2×10^{11} cm^{-2} and mobilities of 70 000 cm^2 V^{-1} s^{-1} and 5000 cm^2 V^{-1} s^{-1}, respectively. The ex-

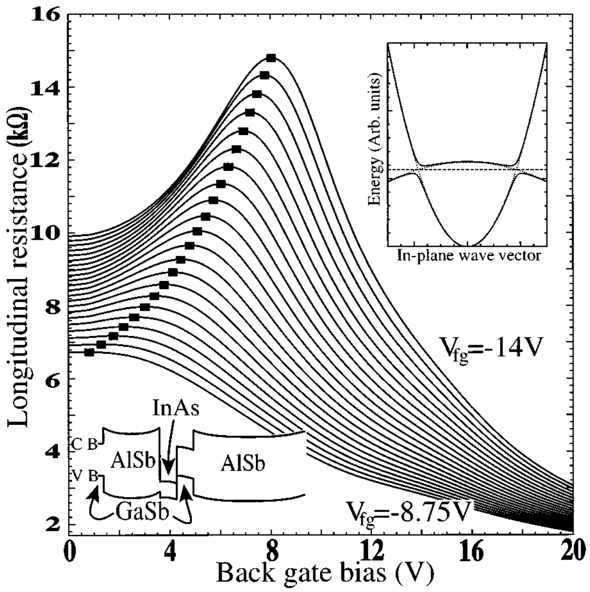

FIG. 1. Longitudinal resistance of the barrierless sample as a function of back gate bias for different fixed front gate biases stepped in units of 0.25 V. Bottom inset: Band structure of our sample in the growth direction, showing the crossed band line-up between the adjacent InAs and GaSb layers. Top inset: Diagrammatical representation of the energy bands without (dotted lines) and with (solid lines) a small coupling perturbation. The Fermi level is included to show the situation at resonance for the coupled case, where there are no available *k* states at the Fermi energy.

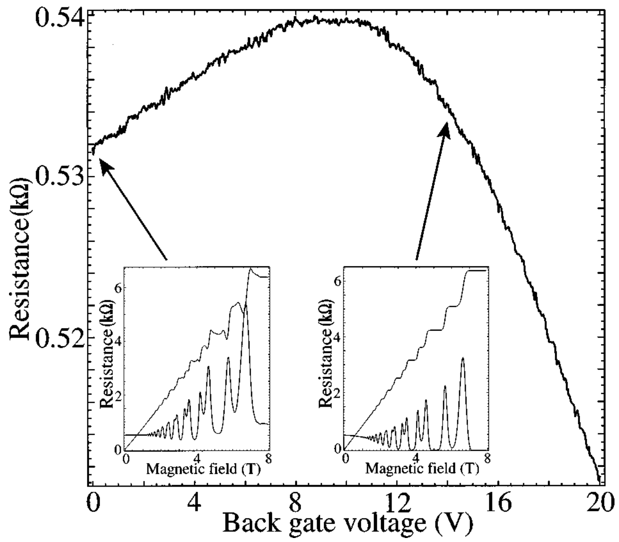

FIG. 2. Longitudinal resistance of structure with a 50 Å barrier between InAs and GaSb as a function of back gate voltage with a front gate voltage of 0 V applied. Left inset: Longitudinal and transverse resistance as a function of field at 0 V back gate voltage. Right inset: Longitudinal and transverse resistance as a function of field at 14 V back gate voltage.

cess of electrons over holes is due to the presence of surface donors,[11] deep donors in the AlSb,[12] and interface donor states.[13] The density of the higher mobility carriers (electrons in this case) at any particular gate bias can be easily determined from the period of the Shubnikov–de Haas (SdH) oscillations in a magnetic field. The hole density can be ascertained accurately by performing back gate bias sweeps at fixed magnetic fields. In these the weaker magneto-oscillations of the holes can be seen. A linear dependence of electron carrier density with front gate bias of 2.5×10^{10} cm^{-2} V^{-1} was found. Owing to the imperfect screening of the electron layer, the hole density is altered by application of front gate bias by an amount -3.7×10^{9} cm^{-2} V^{-1}. Application of bias to the back gate caused a change in the hole density of 2.5×10^{10} cm^{2} V^{-1}. In this case, the high density of states in the hole layer means that it acts as a good screen for the electrons from the back gate.[14] Over the entire back gate voltage range, no electron density change was measurable in the experiment ($<1\times10^{9}$ cm^{-2}) until the holes were depleted.

Figure 1 shows traces of the longitudinal resistance as a function of back gate voltage at a temperature of 1.5 K for different front gate voltages; an individual trace shows how the longitudinal resistance of the sample varies with hole density changed using the back gate (no measurable change in electron density) for a particular electron density (different front gate biases). At extreme positive back gate bias the holes are depleted, and what is seen is the resistivity of the electron layer. For all other biases both types of carrier coexist, and thus their interactions can be studied. There is a peak in resistance as a function of back gate bias that moves to more positive values as the front gate is made more negative. In a sample with no coupling between electrons and holes the resistance would be expected to fall as the positive back gate bias is decreased, simply owing to the increase in the number of holes (and thus the hole layer's conductivity). In fact, the opposite is seen, with enhancement of holes causing an increase in the resistivity provided the number of holes is exceeded by the number of electrons.

In order to understand this observation, the longitudinal resistance in a structure identical to that given above except for a 50 Å AlSb barrier between the wells has been measured as a function of back gate bias (Fig. 2). In this sample there is no coupling between the electron and hole layers; therefore, its behavior should correspond to the standard semimetallic picture of such a crossed band-gap system: our results show this to be the case. At low biases, making the back gate bias more positive (and thus decreasing the density of holes) causes the longitudinal resistance to rise, but only very slightly. This change is small, because the holes have a much lower mobility than the electrons in parallel with them. Two sets of SdH and Hall data are shown in the insets to Fig. 2, while the prominent oscillations in the longitudinal resistance being due to the high mobility electron gas. It can be seen that at zero back gate bias (left inset) there is a low-mobility hole parallel conducting channel that manifests itself in the nonzero resistance minima of the longitudinal resistance and the low quality of the Hal plateaus. Applying 14 V back gate bias is sufficient to deplete the holes and thus see single-layer magnetotransport data. From this we infer that the fall in zero-field resistance above 10 V is due to the enhancement of electrons after the hole layer has become completely depleted. The conclusion is that the resistance peak that is seen in the first (barrierless) sample with the overall drop in the resistance as holes are removed is due to the effects of coupling. The introduction of a 50 Å barrier between the GaSb and InAs layers containing the electrons and holes is sufficient to remove this coupling to within the sensitivity of the experiment.

The dependence of the resistance feature on front and back gate bias allows the determination of its physical origin. The peak in the longitudinal resistance corresponds closely to the point of equal carrier densities in the two layers. Such a peak is exactly what is expected if there were a coupling induced semiconducting energy gap present, since the Fermi energy would lie in the gap defined by the point of the anticrossing (see inset, Fig. 1) and hence there would be no states available to carry current, minimizing the conductivity. Note that this occurs when the Fermi wave vectors of both type of carrier are equal, and, assuming that neither Fermi surface is extremely anisotropic, this point is close to matched carriers.

The resistance peak becomes stronger as the densities of both types of carrier are reduced; this could be due to a reduction in the *k*-space band anisotropy at lower carrier densities resulting in the position of the anticrossing point becoming better defined in energy (band anisotropy would make the energy of the anticrossing point wave-vector direction dependent). Alternatively, since the applied electric field is altering the band bending in the electron and hole potential wells (especially in the InAs electron well, which is relatively wide), the average electron-hole separation is reduced as the carrier densities are reduced. Thus the interaction effects, including coupling, and hence energy gap magnitude, are strengthened as the wave functions are forced towards the common boundary of the wells: this would also cause a strengthening of the resonance in the low-density limit. We would also expect an enhancement of the resonance at lower carrier densities simply owing to the reduction in electrostatic screening of particles in one layer by their intralayer neighbors from the Coulomb potentials of charges in the other layer, and also if the pseudoparticles themselves were interacting to create excitons as exciton formation becomes energetically more favorable as the interparticle distance within a layer increases.[15] An important point to note is that the resistance of the sample does not diverge as one might expect in the ideal case of a perfectly hybridized system; this is likely to be due both to hole band anisotropy (which would result in the gap being at different energies dependent on the direction of the in-plane wave vector) and the possible presence of states in the gap itself—perhaps being due to impurities—which are numerous enough to cause a conduction path to exist even when the Fermi level is in the gap.

Back gate sweeps were then carried out as a function of temperature with the front gate bias fixed (see Fig. 3). It can be seen from these data that we have a rapid decrease in the prominence of the resonance feature as the temperature is increased. If a gap were present in the system and this was the origin of our resonant feature, then the disappearance of this feature is exactly what we would expect. As the temperature is increased, the distribution of the fermions (i.e., the pseudoparticles) becomes more smeared and the probability of finding carriers at an energy greater than the Fermi energy increases; thus it becomes possible to excite carriers across the gap in the density of states analogous to the situation in a normal intrinsic semiconductor. At temperatures much greater than the gap temperature (given by E_g/k_B, where E_g is the gap energy and k_B is the Boltzmann constant) any effects of the gap will not be seen in the conduction.

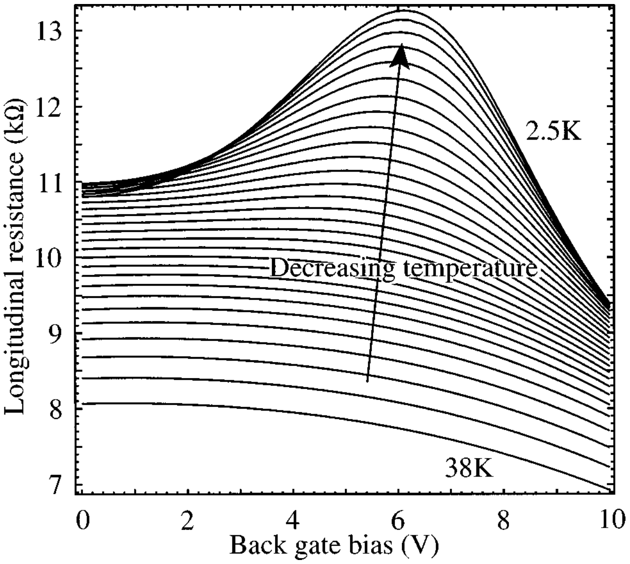

FIG. 3. Resistance as a function of back gate bias as the temperature is increased with a bias of −12 V applied to the front gate. The temperatures range from 2.5 to 38 K in equal increments of approximately 1.2 K.

Figure 4 shows the conductivity as a function of temperature at resonance and on either side of resonance. The behavior of the conductivity off-resonance is similar whether electrons or holes are the majority carrier, the different conductivity levels simply reflecting the difference between the electron and hole mobilities. In contrast, the temperature dependence of the conductivity at the matched carrier point is very different; the conductivity shows a marked decrease at temperatures below 25 K. Resonance disappears at higher temperatures and the temperature dependence of the conductivity is similar to that of the nonresonant case. Thus we infer that our gap magnitude is of order 2 meV. The fact that we

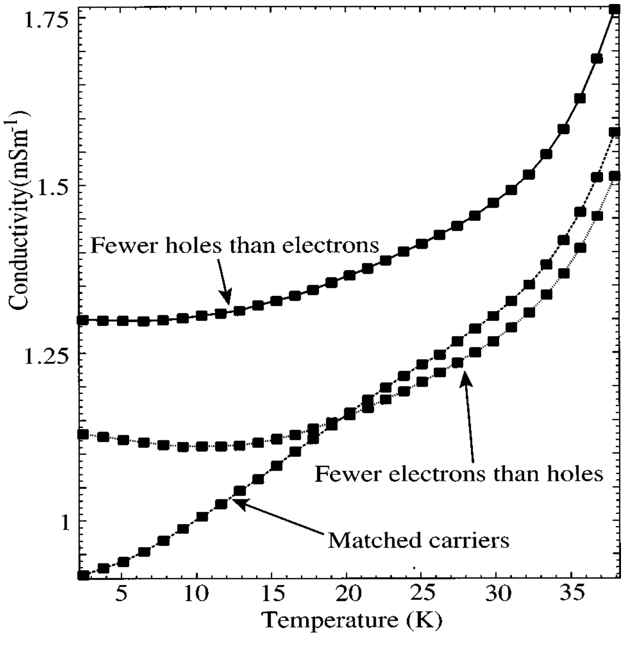

FIG. 4. The behavior of the conductivity as a function of temperature on-resonance and also the situation when electrons or holes are the majority carrier.

do not have conductivity which has an ‘‘activated’’ (i.e., $e^{-E/kT}$) dependence on temperature is to be expected since the band anisotropy in the hybridized system and the possible existence of gap conduction states would make the temperature dependence more complex.

In conclusion, the resistance of a strongly coupled electron-hole gas in an InAs/GaSb/AlSb structure has been studied as the densities of both types of carrier were altered by gating. A peak in the longitudinal resistance that is found near matched carrier densities disappears when the temperature is raised above approximately 25 K. The resistance peak height increased as the carrier density of the electrons and holes was reduced. These results indicate that we have a strongly coupled system in which the electron and hole levels have hybridized, causing an anticrossing to appear in the in-plane dispersion relation. At energy gap in the density of states where the two hybridized states are close in energy and wave vector is formed as a consequence. Using the temperature dependence data, we have shown the magnitude of this gap in our heterostructure to be approximately 2 meV.

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