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Magneto-transport in InAs/AlSb quantum wells with large electron concentration modulation

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We report measurements of magnetocapacitance, Hall resistance, and magnetoresistance of gated InAs/AlSb quantum wells. By varying the voltage between the front gate and the two-dimensional electron gas, we were able to make magneto-transport measurements at 4.2 K for electron concentrations covering a range from 3×10^{11} to 3×10^{12} cm^{-2}. A strongly modified magnetocapacitance signal and a drop in the mobility were observed as the second subband became populated. The relation of gate voltage to density of mobile carriers obtained from these measurements was in agreement with the simple capacitor model, indicating the absence of Fermi level pinning in the quantum well.

InAs/AlSb quantum wells are of interest because of the large conduction band offset of 1.3 eV between AlSb and InAs [1] and the high *intrinsic* electron mobility of InAs. The combination of high barriers and high mobility makes this material system potentially suitable for field-effect device applications as well as for the study of magnetotransport effects at low temperature [2,3]. An important issue in field-effect devices is the tunability of the mobile carrier concentration in the well over a wide range. In spite of the high mobilities and concentrations achieved, the transconductance of InAs/AlSb quantum well FET's is relatively low [4], therefore raising the question of Fermi level pinning in the well. One of the objectives of this study was to determine whether the Fermi level in the quantum well is pinned due to the possible presence of defects at the abrupt interface of InAs and AlSb. Although the high values of low temperature mobilities (more than 300000 $cm^{-2}/V\,s$) reported by Tuttle et al. [5] suggest that the InAs/AlSb interface is of high quality, the issue of carrier concentration modulation can be conclusively resolved only by direct measurements of concentration as a function of applied gate bias. Recently, Munekata et al. [2] demonstrated, via magnetocapacitance measurements, the modulation of electron concentration from 2×10^{11} to 5×10^{11} cm^{-2} in a $Al_{0.35}Ga_{0.65}Sb$/InAs quantum well with a thick top barrier. In the present work, we were able to achieve a wide range of modulation, from 3×10^{11} to 3×10^{12} cm^{-2}. The higher concentrations at the upper end of this range enabled us to populate the second subband. The magnetocapacitance with a high signal-to-noise ratio allowed us to observe the transition from one-subband to two-subband occupation clearly. Our quantum wells had unalloyed AlSb barriers to avoid complications caused by a broken-gap structure at the interface.

The samples used in this study were grown by molecular beam epitaxy on semi-insulating GaAs substrates. The quantum wells consisted of 15 nm of InAs sandwiched between two AlSb barriers. Both top and bottom interfaces were InSb-like [5]. The top barrier was a 100 nm thick layer of AlSb capped by 5 nm thick layer of GaSb to prevent the oxidation of AlSb upon exposure to

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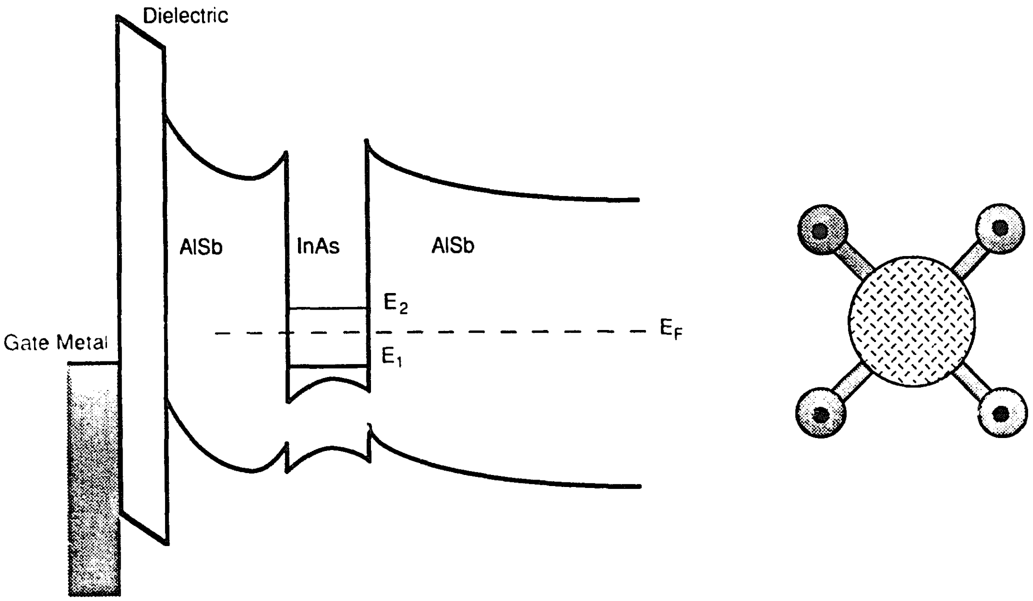

Fig. 1. Schematic energy band diagram and top view of the clover leaf gated structure used in this study. The dielectric layer can be either silicon oxide or silicon nitride.

atmosphere. Details of the growth procedure were very similar to that of Tuttle et al. [5].

In order to obtain a large signal-to-noise ratio in the magnetocapacitance measurement for this structure, it was necessary to have a large-area gate as one of the electrodes. Furthermore, the total leakage current must be, in general, well below 1 μA to accurately measure the magnetoresistance and to observe the quantum Hall effect. Schottky diodes formed by evaporating Ti/Au on top of the GaSb capping layer were found to have a prohibitively large leakage current density in the order of 10 mA cm^{-2} for applied voltage greater than 1 V in both directions. We believe that this large leakage was caused by isolated defects acting as filamentary shorts between the two-dimensional electron gas and the metallic gate. By inserting a layer of either silicon dioxide or silicon nitride between the capping GaSb layer and the gate, we could practically stop the leakage current.

The dielectric layer was grown on the GaSb capping layer by plasma-enhanced chemical vapor deposition. The circular gate of 2 mm in diameter was photolithographically defined, and the metal gate was formed by the lift-off technique. Using the deposited metal as a mask, we removed the dielectric outside the gate area with CF_4 plasma. The clover-leaf mesa was then defined and patterned with chemical etching. Contacts to the quantum well were made by alloying indium dots at 200 °C for 10 min. Fig. 1 shows the schematic energy band diagram of the gated structure and its top view.

The results of low-field Hall measurement at 12 K are shown in fig. 2. The carrier concentration at zero gate bias was 1.4×10^{12} cm^{-2} with a mobility of 1.17×10^5 cm^2/Vs. By varying the gate voltage from -7 to $+10$ V, we could adjust

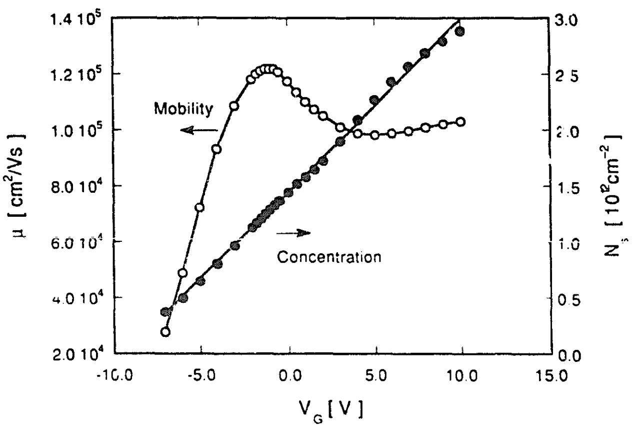

Fig. 2. Electron concentration and mobility versus gate voltage extracted from low-field Hall measurement.

the carrier concentration N_s both up and down over the range from 3×10^{11} to 3×10^{12} cm^{-2}. The concentration changed linearly with gate voltage, and the slope of the line was in agreement with a simple capacitor model. In the range below 1.2×10^{12} cm^{-2} the mobility increased with increasing concentration (increasingly positive gate bias) and peaked at 1.22×10^5 cm^2/Vs at $N_s = 1.3 \times 10^{12}$ cm^{-2} for a gate voltage of -1.25 V. With a further increase in the gate voltage, the mobility dropped to a minimum of 98000 cm^2/Vs at $N_s = 2.3 \times 10^{12}$ cm^{-2}. Beyond this point the mobility increased again slowly with concentration. A simple envelope wave function calculation which takes into account the nonparabolicity of InAs but ignores complications caused by the interaction with the valence bands of AlSb predicts the beginning of the filling of the second subband at 1.4×10^{12} cm^{-2}. We therefore believe that the drop in mobility beginning at $N_s = 1.3 \times 10^{12}$ cm^{-2} is caused by the onset of inter-subband scattering.

Although it is evident from the carrier concentration modulation that the Fermi level was not pinned in the quantum well, the mobile electron concentration depended on the thermal cycling history of the sample. After the sample had been warmed up to room temperature and cooled down to 12 K again, both the electron concentration and mobility versus gate voltage curves were shifted to a more positive gate bias. However, the slope of the concentration versus voltage line remained unchanged. This behavior suggests that there might be deep levels in the barrier which can trap electrons, but are not modulated by the gate voltage.

Magnetocapacitance measurements were done at 4.2 K for magnetic fields up to 8 T. All four contacts to the quantum well, depicted in fig. 1, were shorted together and the electron gas served as the counter electrode. Each curve in fig. 3 is the magnetocapacitance measured in a constant magnetic field as the gate bias was swept. The curves are vertically offset in this figure for clarity. On successive sweeps of the gate voltage in opposite directions, we observed a slight hysteresis in the magnetocapacitance versus gate voltage signal. For negative bias, only the first subband

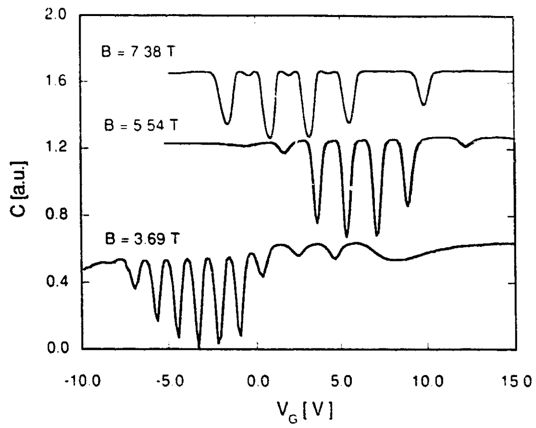

Fig. 3. Typical magnetocapacitance signals showing the transition from one-subband to two-subband occupation.

was populated, and the minima in the magnetocapacitance corresponding to successive filling factors were equally spaced. The topmost curve also showed incipient minima resulting from spin-splitting. As noted by Hopkins et al. [3] in their study of the quantum Hall effect in similar InAs/AlSb quantum well structures (without a gate and with higher mobility), this is not surprising in light of the large g-factor of bulk InAs. From the magnetic field, we calculated the change ΔN_s in electron concentration between two filled levels. The ratio between ΔN_s and the change in the corresponding gate voltages in this regime was independent of magnetic field and agreed with the simple capacitance model.

As shown clearly in the magnetocapacitance signal at $B = 3.69$ T, the minima that occurred at positive gate voltages were no longer equidistant. It has been shown [6] in a self-consistent calculation for (Al, Ga)As/GaAs quantum wells that this occurs in the regime where population spills over into the upper subband, at which point the electron density in each subband becomes a nonlinear function of gate voltage. We believe that this explanation also applies qualitatively to InAs/AlSb quantum wells, although a quantitative understanding of the strongly modified shape of the magnetocapacitance observed in our quantum wells in this regime would probably require a detailed calculation taking into account the peculiar band lineup of InAs and AlSb as well as the nonparabolicity of InAs. We also found that, in

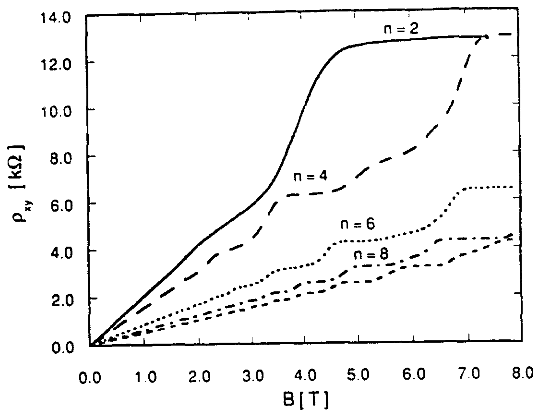

Fig. 4. Two-dimensional Hall resistivity R_{xy} at 4.2 K for different gate voltages.

contrast to previous experiments [6] on GaAs heterostructures with two occupied subbands, some of the minima were shifted to lower magnetic field for increasing gate voltage. The cause of this effect is not clear at present.

We also measured the magnetoresistance and Hall resistance for different gate voltages. As shown in fig. 4, well-defined Hall plateaus were obtained. The carrier concentration modulation efficiency extracted from the periodicity of the Shubnikov–de Haas oscillations again agrees with magnetocapacitance and low-field Hall measurements.

In conclusion, we have demonstrated carrier concentration modulation over a wide range in InAs/AlSb quantum wells and were able to populate the second subband. The agreement between the parallel plate capacitor model and the modulation of mobile carriers confirms the absence of Fermi level pinning at the InAs/AlSb interfaces of these wells.

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