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Coupling of electron gases in wide quantum wells

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Crossover from simple quantum-well to complex double-heterostructure behavior has been observed by magnetotransport measurements on molecular-beam-epitaxially grown GaAs/$Al_xGa_{1-x}As$ modulation-doped samples. Significant unintentional electric fields ($\simeq 30$ kV/cm) are revealed by comparison with self-consistent electronic-structure calculations.

It is well established that a quasi-two-dimensional electron gas (2D EG) can exist at the interface of a heterojunction, for example, in a GaAs/$Al_xGa_{1-x}As$ heterostructure. If the magnetoresistance approaches zero at some magnetic field (indicating that the Hall angle is nearly 90°) and if the oscillations of the magnetoresistance vanish when the magnetic field is turned towards the plane of the interface, the electron gas is generally considered to be two dimensional. Still, a 2D EG has a finite thickness. The additional degree of freedom in the third direction causes interesting effects on the properties of the 2D EG. The most obvious consequence is the possibility of occupation of higher subband levels. Störmer *et al.*[1] first demonstrated the effect of intersubband scattering by using a back-gate modulation technique to occupy the second subband. Three occupied subbands have been observed by Razeghi *et al.*[2] in $In_{1-x}Ga_xAs$/InP heterojunctions. Rötger *et al.*[3] measured magnetooptical spectra of a 50-nm-wide quantum well with three occupied subbands. They found significant effects of a magnetic field on the subband energy separation which could be explained by self-consistent calculations. Upper subband transport in heterostructures has recently been reviewed by Smith and Fang.[4]

We are interested in the question of what will happen when the two 2D EG's formed at the interfaces of a wide quantum well (also called double heterostructure) start to interact with decreasing interface separation. When the separation is very large the 2D EG's are independent while the quantum-well limit with just one 2D EG is reached for small separations. In a previous paper[5] we investigated the transport properties of a series of samples with different well widths and doping. The magnetotransport experiments gave a qualitative idea about the crossover from one to two electron gases which participate in the conduction. Furthermore, the effect of the so-called inverted interface on the electron mobility was emphasized. In this contribution we concentrate on the narrowest (25 nm) and the widest (60 nm) quantum wells from that series for a more accurate study of the electron distribution in these devices. The sample with the 25-nm-wide well was provided with a gate which allowed the carrier density to be varied. This sample was designed to check whether a spatial separation of the 2D EG could be achieved by adjusting the electron density. At the opposite limit the 60-nm well was to be used for studying the magnetoresistance in the case of double heterostructure behavior. To support the interpretation of the experiments, self-consistent local-density-functional calculations were carried out based on the code of Ando and Mori,[6] which was extended to include the effect of an electric field normal to the interfaces.[7]

The systems under study are nominally symmetrically doped, molecular-beam-epitaxy (MBE) -grown GaAs/$Al_xGa_{1-x}As$ quantum wells.[8] Starting with a semi-insulating GaAs substrate, we have a 700-nm-thick undoped and a 300-nm-thick *p*-type doped (10^{17} cm^{-3}) GaAs layer. The *p*-doped layer is inserted to improve the symmetry of the Fermi level through the well. The center part of the structure is a GaAs layer with a thickness of 25 or 60 nm with 10-nm-thick spacer layers of unintentionally doped $Al_xGa_{1-x}As$ and Si-doped (1.2×10^{18} cm^{-3}) $Al_xGa_{1-x}As$ layers of 40 nm (on both sides). On top of the structure there is an unintentionally doped GaAs cap layer of 20 nm. The 25-nm well is covered by an Al gate. Hall bars were made in the conventional way but the contacting process (Au/Ge/Ni contacts) was slightly changed to guarantee Ohmic contacts not only with the 2D EG at the normal interface but also with the electron gas close to the deep-lying inverted interface. These changes include the evaporation of a thicker Au/Ge/Ni layer and an optimized time-temperature profile during alloying. The gates on top of the samples with the 25-nm-wide well were fabricated by a lift-off process after finishing the Ohmic contacts. The 300-nm-thick Al gate had a good Schottky character at the applied voltages: the leakage current was always negligible compared with the measuring current. The experiments were carried out at a temperature of 50 mK in a dilution refrigerator mounted in a 10-T superconducting solenoid. Care was taken to avoid heating of the electron gas.

We measured the magnetoresistance of the 25-nm sample well at several gate voltages. The results are shown in Fig. 1 and Table I. From the absence of significant effects of the gate voltage on the low-field magnetoresistance, it

TABLE I. Measured and theoretical electron densities (in 10^{15} m^{-2}) of the 25-nm quantum well as a function of gate voltage. n_H^{expt} is the total Hall density, while n_1 and n_2 are the densities in the first and second subbands determined independently from the magnetoresistance data. Two sets of theoretical results refer to calculations with internal bias of 0 and -30 kV/cm, respectively. The total electron density in the calculations is assumed equal to n_H^{expt}.

Gate voltage (meV)	n_H^{expt}	n_1^{expt}	n_2^{expt}	$n_1^{\text{theor}}(0)$	$n_2^{\text{theor}}(0)$	$n_1^{\text{theor}}(-30)$	$n_2^{\text{theor}}(-30)$
-200	8.4	7.9		6.3	2.1	7.3	1.1
0	10.2	8.2	$\simeq 2.5$	6.9	3.3	7.5	2.7
$+300$	12.5	8.4	4.3	8.1	4.4	8.1	4.4

is clear that only one mobility is resolved, no matter what the electron density is. But the second subband can be populated or emptied by only small changes in the gate voltage.[9] When the gate voltage is below -200 mV (equivalent to an electric field of $\simeq -26$ kV/cm), the carrier density determined from the Hall resistance is about equal to the one obtained from the Shubnikov–de Haas (SdH) oscillations and these oscillations are fairly regular. At more positive gate voltages the density determined from the Hall resistance is clearly larger than that obtained from the major SdH oscillations. The difference between the two densities is found to agree with the density of the second subband as determined from the additional peaks in the magnetoresistance. The carrier density is approximately proportional to the applied voltage, which means that the field ionization of neutral donors in the barrier is not important. The self-consistent calculations with an electric field perpendicular to the interface show that the electron density peaks close to the two interfaces when two subbands are occupied (see inset of Fig. 1). This can be interpreted as a precursor of the transition to the double heterostructure behavior. But because of the strong coupling between both sides the electrons feel both the normal and the inverted interface and only one averaged mobility is measured. So, for an effective separation of the 2D EG a much stronger band bending is required. Experiment and theory do not agree well when at zero gate voltage the potential profile is assumed to be symmetrical (Table I). Results are improved by assuming an internal electric field of about -30 kV/cm, which is consistent with the findings below. In this way we can model the effects of unintentional asymmetries due to small differences between the two dopant layers and the unavoidable surface depletion.

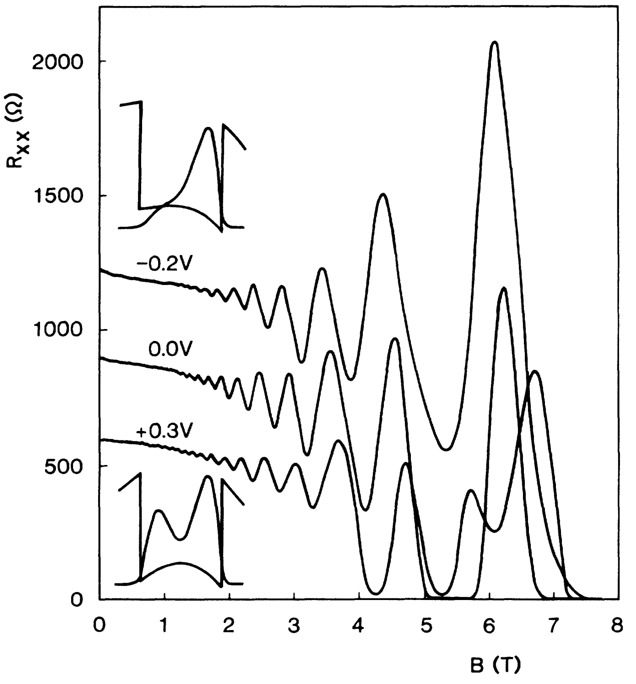

FIG. 1. Magnetoresistance of the 25-nm-wide quantum well as a function of the magnetic field, with the gate voltage as a parameter. The inset shows the calculated potential profile and electron density assuming an internal electric field of -30 kV/cm (gate on left-hand side).

The magnetoresistance of the 60-nm well exhibits a rather complex behavior, as can be seen in Fig. 2. There are altogether three different kinds of oscillations, and close to zero field the magnetoresistance is a quadratic function of the field. The quadratic behavior at low magnetic fields can be explained on the assumption that there are two carrier types with different mobilities. With the classical two-band model[10] the mobilities and the densities of both types of carriers can be determined from the low-field magnetoresistance. We find two electron systems, one with a mobility of 80 m^2/V s and a density

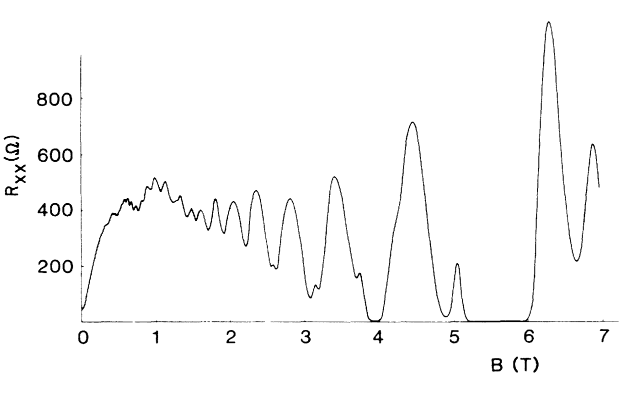

FIG. 2. Magnetoresistance of the 60-nm-wide quantum well.

$N_s = 4.3 \times 10^{15}$ m^{-2} and another with a mobility of 2.0 m^2/V s and $N_s = 8.2 \times 10^{15}$ m^{-2}. Because of the surprisingly large ratio of 40 between the two mobilities and the good quality of the fit we believe that the model describes the actual situation quite well. The existence of two types of electron gas can be interpreted in the following way. If there are two 2D EG's, each of them localized at a different interface, they act as two different carrier systems because they have different mobilities. Electrons near the inverted interface are known to have a much lower mobility than electrons close to the normal interface due to roughness scattering, Si out-diffusion, impurity trapping, and strain in the inverted interface; cf. Harris *et al.*[5] The separation of two electron gases is due to the large well thickness. This causes a considerable band bending in the well and thus separates the electron gas into two layers which are pushed against the interfaces as shown in Fig. 3.

The "splitting" of the electron gas also plays an important role in the interpretation of the oscillations in the magnetoresistance. Three oscillations can be distinguished: a slow one up to 1 T, a fast one superposed on the slow oscillation (up to 1.25 T), and another fast one from 1.25 T up to maximum field. From their periodicities on the inverted magnetic field scale the electron densities can be determined as, respectively, 0.7×10^{15}, 4.0×10^{15}, and 7.3×10^{15} m^{-2}. The total density is 12.0×10^{15} m^{-2}. Identifying the two fast oscillations with the two spatially separated electron gases, we attribute the third oscillation to a populated third electron subband which is delocalized in the well. In spite of the delocalization this electron gas still behaves two dimensionally. At high magnetic fields the third oscillation is not observed anymore, which could indicate a magnetic depopulation effect.[3] The two highest densities agree roughly with the densities obtained from the low-field analysis, where the few electrons in the third subband could not be observed. The small additional peaks at high field in the magnetoresistance are thought to belong to the same electron gas that causes the fast oscillation up to 1.25 T. This is the high-mobility 2D EG and the peaks representing the depopulation of the lower Landau levels are spin-split and superposed on the oscillation of the low-mobility electron gas. The validity of this picture depends strongly on the subband energies in the well and on the position of the Fermi level. These energies have been calculated self-consistently for zero magnetic field assuming a total carrier density of 1.2×10^{16} m^{-2}. The calculations were carried out with an electric field perpendicular to the interface as an adjustable parameter. Using an applied field of -26 kV/cm three subbands are populated by, respectively, 0.72×10^{15}, 4.04×10^{15}, and 7.23×10^{15} e/m^2, which fits the experiment very well. The magnitude of the field agrees with the internal bias found for the gated sample. Since according to the magnetoresistance data at low magnetic fields the high-density channel is located at the inverted interface, the direction of the electric field is also the same. We may conclude from these two independent estimates that in spite of the p-type doping layer still quite significant asymmetries in the potential profiles exist, which can give rise to, e.g., strong enhancement of forbidden transitions in luminescence spectra.[11]

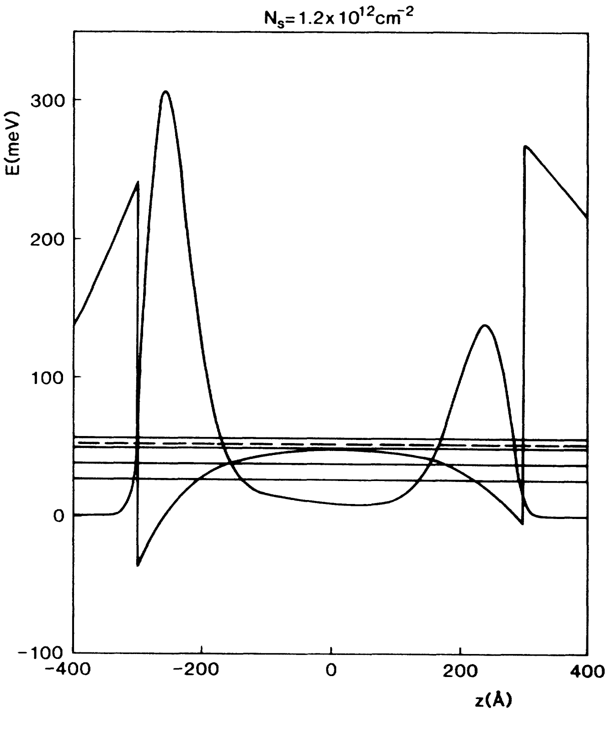

FIG. 3. Calculated potential profile, electron distribution, and subband energies for a 60-nm-wide quantum well subject to an electric field of 26 kV/cm. The dashed line denotes the Fermi energy. The left one is the "inverted" interface.

In conclusion, we have analyzed the transport properties of wide-quantum-well samples in detail. By varying the electron density in a 25-nm well, it is possible to fill and empty the second subband. But only one mobility is resolved, thus indicating that the well contains just one 2D EG. The complex magnetoresistance of the 60-nm well can be interpreted in the following way. There are two electron gases localized at the two interfaces of the quantum well and there is a third electron gas that extends throughout the well. This picture is consistent with the results of a classical low-field analysis and with self-consistent calculations. In both cases unintentional electric fields of about 30 kV/cm distort the symmetry of the well.

Note added in proof. We would like to point out relevant work by K. Ensslin *et al.* [Proceedings of the 19th International Conference on the Physics of Semiconductors, Warsaw, 1988, edited by T. Kossut (unpublished)] and P. E. Simmons *et al.* [Solid State Commun. **67**, 115 (1988)], which appeared after submission of the manuscript.

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