RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 39, NUMBER 15 15 MAY 1989-II

Electrical depopulation of double quantum wells

K. Ensslin,* D. Heitmann, M. Dobers,† K. v. Klitzing, and K. Ploog
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1,
D-7000 Stuttgart 80, Federal Republic of Germany

(Received 1 March 1989)

Modulation-doped n-type $Al_xGa_{1-x}As$-GaAs double quantum wells (QW's) have been prepared where the population of each quantum well can be tuned via a front gate voltage V_g in an exact and reproducible way. Using cyclotron resonance and magnetocapacitance measurements we present a detailed analysis of the depopulation behavior of each QW as a function of gate voltage and magnetic field. We find a unique type of behavior: Once the QW close to the front gate is populated the carrier density of the QW closer to the substrate becomes independent of the gate voltage. This is in excellent agreement with the results of a self-consistent calculation of the subband structure which confirms our theoretical understanding of the population process. In addition, we observe a hysteresis behavior in the magnetocapacitance measurements as a function of the gate voltage which is particularly pronounced close to the onset voltage of the QW closer to the front gate. We explain this phenomenon by the occupation of states in the Si-doped $Al_xGa_{1-x}As$ in between the two QW's.

High carrier density layered two-dimensional electron gases (2D EG), which can be prepared by piling up several 2D EG one upon another in a multi-quantum-well structure, are very interesting both for fundamental studies as well as for application. There have been a number of fundamental investigations in magnetic fields,[1-8] e.g., the g-factor enhancement was investigated in double and triple heterostructures[1] and the quantum Hall effect (QHE) was observed in a multi-quantum-well with 30 periods.[2] From the theoretical point of view it seems to be increasingly interesting to study double heterostructures because this allows the investigation of a correlated electron movement in parallel and very closely packed 2D EG.[9,10] Recently, the observation[11] of a plateau in the fractional QHE at filling factor $\nu = \frac{5}{2}$ initiated theoretical efforts[12,13] to understand this phenomenon in terms of a two-layered system. The high carrier density, which can be achieved in multi-quantum-well systems, is very interesting for application in low-channel resistance devices. Gated structures with controllable carrier density are highly desirable.

In this Rapid Communication we present a detailed investigation of a double quantum well (QW) which constitutes the first step to the realization of a two-layered system. The structures consist of two n-type modulation-doped QW's which are described in more detail in Fig. 1. The samples have semitransparent front gates which allow us to tune the carrier densities of both quantum wells in a controlled and reproducible way. We observe a unique occupation behavior of the two QW's in its dependence on the gate voltage. We have investigated the samples as a function of the gate voltage V_g by means of cyclotron resonance (CR) and magnetocapacitance versus voltage (MCV) measurements. For very low values of V_g only the back QW, which is closer to the substrate, is populated and its carrier density can be tuned such as in a single heterostructure, e.g., Ref. 14. Once the front QW, which is closer to the surface of the sample, is populated, the carrier density in the back QW becomes independent of the gate voltage. The carrier density in each QW can be determined from the minima in the capacitance when a magnetic field is applied perpendicular to the 2D EG. We performed a self-consistent calculation of the subband structure of these two coupled electron gases and find excellent agreement with the experimental results. In particular, the calculation shows the importance of the boundary conditions of the electrostatic potential and explains the higher carrier density in the back QW compared to the front QW.

For certain magnetic fields we can realize the situation at which the Fermi level lies in between two Landau levels of each QW. In this regime we observe a hysteresis in the

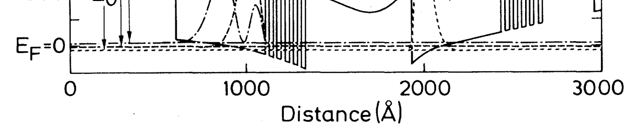

FIG. 1. Potential of the double quantum well obtained from a self-consistent calculation. The surface of the sample is on the left-hand side of the figure. For the conduction-band offsets ΔE between GaAs and $Al_xGa_{1-x}As$ we use $\Delta E = x \times 1$ eV. The dotted, dashed, and dash-dotted lines mark the wave functions and subband energies of the lowest three quantum states. The vertical arrow gives the scale for the squared wave functions.

transport measurements as a function of gate voltage and magnetic field. When both QW's are populated the conduction band in between the two QW's can be very close to the Fermi level. Therefore, we explain the hysteresis behavior by the occupation of states in the Si-doped $Al_xGa_{1-x}As$ in between the two QW's.

Figure 1 shows the sample geometry and the result of a self-consistent calculation for the potential of the double QW. The samples were grown by molecular-beam epitaxy[15] and have the following sequence of layers: a semi-insulating GaAs substrate; a 0.4-μm nominally undoped GaAs buffer layer followed by two identical QW's, each with 26.7-nm undoped $Al_xGa_{1-x}As$, a short-period superlattice consisting of five periods [2.2-nm AlAs and 2.2-nm GaAs, 2.2-nm AlAs, 51.1-nm GaAs, 4.4-nm AlAs, and 26.7-nm Si-doped $Al_xGa_{1-x}As$ ($x=0.3$, $N_D \approx 3 \times 10^{17}$ cm^{-3})]; then 26.7-nm undoped $Al_xGa_{1-x}As$ and a 2.2-nm GaAs cap layer. The samples were mesa etched, defining gate areas of ~2 mm diameter 100-nm Al_2O_3 followed by 5-nm NiCr were evaporated onto the gate area. Outside the gate area Ohmic contacts were annealed to the 2D EG. A gate voltage V_g was applied between the gate and the channel contacts. The barrier between the two QW's is too thick to make tunneling a favorable coupling mechanism of the two QW's. However, the two QW's are directly connected in the contact regime through the annealing process and the Fermi level is aligned in both 2D EG. Cyclotron resonance was measured in a 14.5-T superconducting magnet, which was connected via a waveguide system to a Fourier transform spectrometer. Spectra were taken at fixed carrier density N_s and magnetic field B. The normal of the sample was parallel to the magnetic field. The temperature was 2.2 K and the resolution of the spectrometer was set to 0.1 cm^{-1}.

For the numerical solution of the Schrödinger equation of our double-QW structure we treat the problem as in a multiple occupied subband system, where the wave functions, in principle, extend into both QW's. Our nomenclature will be similar to a system with several occupied subbands, where in our case the lower subband marks the back QW and the maximum of the wave function of the higher subband is in the front QW. The carrier densities are then defined as N_s^0 in the back QW and N_s^1 in the front QW. These quantities were determined *in situ* under the conditions of the experiment from MCV measurements. More experimental details are included in Ref. 14. The boundary condition for the potential on top of the sample is fixed by the gate voltage whereas a depletion approximation[16] is used to describe the potential in the buffer layer. Although both QW's are exactly identically arranged, the result of the self-consistent calculation in Fig. 1 shows that the carrier distribution among the two QW's is completely asymmetric. In addition, the carrier density in the back QW is higher although the front QW is, in principle, clad by two Si-doped $Al_xGa_{1-x}As$ layers. As a consequence, the electrons in the front QW have their maximum probability on the so-called inverted interface[17] (GaAs on AlAs) where the carriers may have a lower mobility as compared to the normal interface (AlAs on GaAs).

Figure 2 shows CR spectra for a fixed magnetic field $B=9.57$ T and various gate voltages V_g. For a positive voltage, $V_g=1.0$ V, we observe two well-separated resonances. With decreasing gate voltage the higher-energy resonance shifts to lower energies, loses oscillator strength, and disappears at about $V_g=-0.8$ V. In this regime, $-0.8\text{ V} \leq V_g \leq 1.0$ V, the lower-energy resonance changes neither its position nor amplitude and linewidth: It is not at all affected by the gate voltage. However, for lower gate voltages, $V_g \leq 1.0$ V, when the higher-energy resonance has disappeared, the lower-energy resonance loses oscillator strength and shifts to higher energies according to nonparabolicity as it is expected for a single-layered 2D EG. A more detailed analysis shows a filling-factor-dependent oscillating type of behavior of the resonance amplitude, linewidth, and position which has been observed by many authors[14,18–25] for single-layered 2D EG in different material systems.

Figure 3 shows results of MCV measurements for various magnetic fields. For $B=0$ [Fig. 3(a)] we observe a threshold voltage of $V_t \sim -3.5$ V where the capacitance increases rapidly. Then, for increasing gate voltage, the capacitance remains constant, as it is known for single-layered 2D EG,[26,27] and has a second threshold near $V_{t1}=-0.6$ V. For finite magnetic fields we can observe minima in the MCV curves in all gate voltage regimes.

The interpretation of these measurements is straightforward. For highly negative gate voltages $V_g < V_t$ both QW's are depopulated and the CR amplitude vanishes. For increasing gate voltage, $V_t < V_g < V_{t1}$, the capacitance grows and the back QW is populated. The CR in

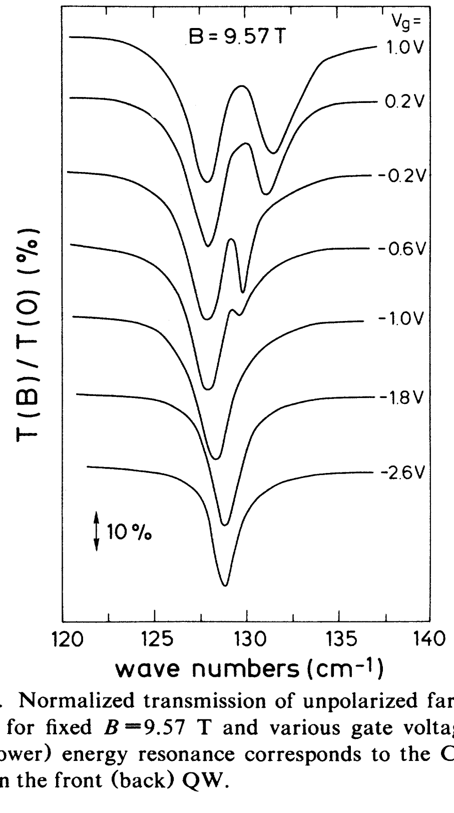

FIG. 2. Normalized transmission of unpolarized far-infrared radiation for fixed $B=9.57$ T and various gate voltages. The higher (lower) energy resonance corresponds to the CR of the electron in the front (back) QW.

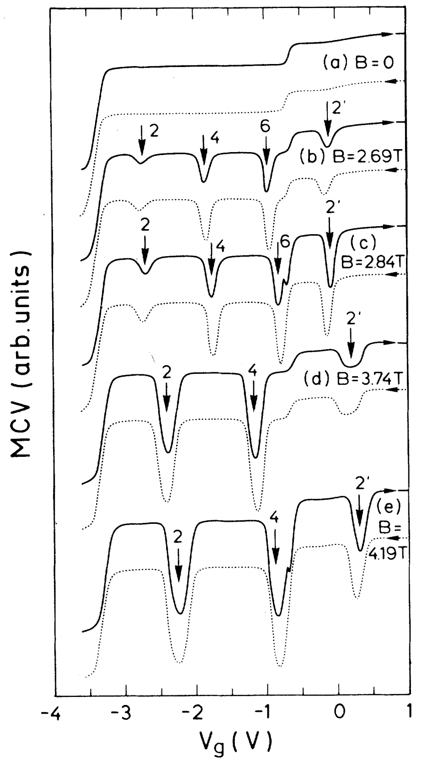

FIG. 3. Magnetocapacitance vs voltage characteristics for various magnetic fields. The filling factors in the QW are indicated by arrows. For the front QW the numbers are primed. The solid lines are for increasing V_g, the dotted lines for decreasing V_g.

this voltage regime behaves as is well known for a single-layered 2D EG.[14,18] With increasing carrier density the CR position shifts to lower energies and correspondingly higher effective masses as it is expected from nonparabolicity. The carrier density in the back QW and thus the filling factor can be determined very precisely from the minima in MCV measurements as indicated by the arrows in Fig. 3.

Around $V_{t1} = -0.6$ V we observe a second threshold in the capacitance curve for $B = 0$ in Fig. 3(a). Here the front QW is populated leading to a sudden decrease of the thickness of the effective dielectric and increase of the capacitance. If we take into account the additional Al_2O_3 on top of the sample the ratio of the capacitances with one and two occupied QW's agrees well with the thicknesses of the two different capacitances.

As we will show below all measurements clearly indicate that the carrier density N_s^0 of the back QW becomes independent of the gate voltage once the front QW is populated. We attribute the lower energy CR in Fig. 2 to the carriers in the back QW. The effective masses of the carriers in the two QW's differ considerably due to the different shapes of the potential wells and the different carrier densities. We can describe the general behavior of the two resonance positions as a function of gate voltage very well with a simple two-band model[28] and the self-consistently calculated wave functions.

Now we turn back to the discussion of the MCV measurements. We also observe minima in the capacitance for voltages above the second threshold, $V_g > V_{t1}$. In this voltage regime the carrier density N_s^0 and consequently the difference between Fermi energy and subband energy E_0 is constant, resulting in a constant density of states at the Fermi level. For this reason the maximum depth of the minima is limited by the capacitance of the sample with only the back QW being occupied. This is in agreement with the measurements in Figs. 3(b) and 3(d). However, we can realize the situation where the Fermi level is in between two Landau levels of the back QW as well as in between two Landau levels of the front QW. In this case the density of states in both QW's at the Fermi level is very low and the measured capacitance can be lower than the capacitance at $B = 0$, when only the back QW is populated. This situation is obtained when the threshold voltage V_{t1} coincides with an integer filling factor of the back QW, with $\nu^0 = 6$ in Fig. 3(c) and $\nu^0 = 4$ in Fig. 3(e). The identification of each minimum with a certain filling factor allows us to study the carrier densities in both QW's as a function of gate voltage. Figure 4 shows these results (solid circles) together with the results obtained from CR measurements (open circles). Assuming a Drude model for the 2D conductivity, it is a straightforward procedure to evaluate the carrier density of a single-layered 2D EG from CR spectra.[29] In this case the normalized transmission can be fitted with a Lorentzian whose linewidth and amplitude can be converted into a carrier density N_s and a scattering time τ. However, for two 2D EG, which give rise to two CR signals, the fit function has to be determined from the sum of two conductivities and is not just the sum of two Lorentzians.[30] The carrier densities obtained from MCV and CR measurements as displayed in Fig. 4 can well be described by the two straight lines which are results of a linear regression. This is in agreement with the self-consistent calcula-

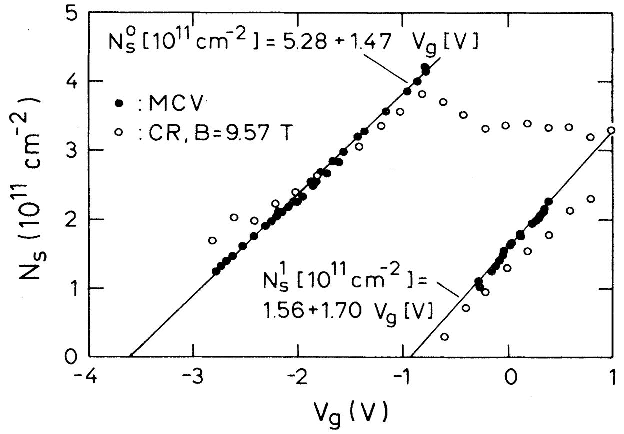

FIG. 4. Carrier densities vs V_g of both QW's evaluated from MCV (●) and CR (○) measurements. The straight lines are the result of a linear regression to the experimental points (●) of the MCV measurements. In the voltage regime $V_g > V_{t1}$ the results from the CR measurements (○) show that the carrier density N_s^0 is constant within the experimental accuracy.

tion which also gives the linear behavior for N_s^0 and N_s^1 as a function of V_g. The scattering times, which we deduce from our CR spectra, are comparable for both QW's, although the maxima of the wave functions are located on different interfaces in each QW. We conclude that our GaAs-on-AlAs interface in the front QW has a quality comparable to the opposite interface sequence.

We want to discuss another interesting finding from the MCV experiments. In Figs. 3(c) and 3(e) we observe a pronounced hysteresis behavior for increasing and decreasing gate voltage. A very similar behavior has been observed for a structure from the same wafer with a Hall geometry in the transverse and longitudinal magnetoresistance.[31] From Fig. 1 it is obvious that the part of the conduction band in between the two QW's is very close to the Fermi level. For voltages above V_{t1} it is possible to populate states in the Si-doped $Al_xGa_{1-x}As$ similar to single heterojunctions under a high forward bias. It is difficult to handle this problem in a self-consistent calculation, but we conclude from our measurements that these states can be depopulated for more negative gate voltages as the population voltage. This then gives rise to the hysteresis phenomenon.

In conclusion, we have presented a detailed analysis of the depopulation behavior of a double-quantum-well structure. The carrier density as deduced from transport (MCV) and far-infrared (CR) measurements is in agreement with the prediction of a self-consistent calculation. We observe a hysteresis behavior for increasing and decreasing gate voltage which can be explained by the population of states in the Si-doped $Al_xGa_{1-x}As$ in between the two QW's.

We would like to thank A. H. MacDonald for valuable discussions and acknowledge financial support by the Bundesministerium für Forschung und Technologie, West Germany.

---

[*] Present address: Materials Department, University of California, Santa Barbara, CA 93106.

[†] Present address: Ecole Normale Superieure, 24 rue Lhomond, 75005 Paris, France.

[1] R. J. Nicholas, M. A. Brummel, and J. C. Portal, Surf. Sci. **113**, 290 (1982).

[2] H. L. Störmer, J. P. Eisenstein, A. C. Gossard, W. Wiegmann, and K. Baldwin, Phys. Rev. Lett. **56**, 85 (1980).

[3] L. L. Chang, Surf. Sci. **73**, 226 (1978).

[4] R. Dingle, Surf. Sci. **73**, 229 (1978).

[5] R. Dingle, H. L. Störmer, A. C. Gossard, and W. Wiegmann, Surf. Sci. **98**, 90 (1980).

[6] D. C. Tsui, H. L. Störmer, A. C. Gossard, and W. Wiegmann, Phys. Rev. B **21**, 1589 (1980).

[7] L. L. Chang, E. E. Mendez, N. J. Kawai, and L. Esaki, Surf. Sci. **113**, 306 (1982).

[8] S. Washburn, R. A. Webb, E. E. Mendez, and L. L. Chang, Phys. Rev. B **31**, 1198 (1985).

[9] A. C. Tselis and J. J. Quinn, Phys. Rev. B **29**, 3318 (1984).

[10] S. T. Chui, Phys. Rev. B **36**, 6486 (1987).

[11] R. Willet, J. P. Eisenstein, H. L. Störmer, D. C. Tsui, A. C. Gossard, and J. H. English, Phys. Rev. Lett. **59**, 1776 (1987).

[12] T. Chakraborty and P. Pietiläinen, Phys. Rev. Lett. **59**, 2784 (1987).

[13] D. Yoshioka, A. H. MacDonald, and S. M. Girvin, Phys. Rev. B **39**, 1932 (1989).

[14] K. Ensslin, D. Heitmann, H. Sigg, and K. Ploog, Surf. Sci. **196**, 263 (1988).

[15] K. Ploog, H. Fronius, and A. Fischer, Appl. Phys. Lett. **50**, 1237 (1987).

[16] K. Ensslin, D. Heitmann, and K. Ploog, this issue, Phys. Rev. B **39**, 10879 (1989).

[17] K. P. Martin, R. J. Higgins, J. J. L. Rascol, Hyong Mo Yoo, and J. R. Arthur, Surf. Sci. **196**, 323 (1988).

[18] K. Ensslin, D. Heitmann, H. Sigg, and K. Ploog, Phys. Rev. B **36**, 8177 (1987).

[19] B. A. Wilson, S. J. Allen, and D. C. Tsui, Phys. Rev. Lett. **44**, 479 (1980).

[20] Th. Englert, J. C. Maan, Ch. Uihlein, D. C. Tsui, and A. C. Gossard, Solid State Commun. **46**, 545 (1983).

[21] D. Heitmann, M. Ziesmann, and L. L. Chang, Phys. Rev. B **34**, 7463 (1986).

[22] E. Batke, H. L. Störmer, A. C. Gossard, and J. H. English, Phys. Rev. B **37**, 3093 (1988).

[23] F. Thiele, U. Merkt, J. P. Kotthaus, G. Lommer, F. Malcher, U. Rössler, and G. Weimann, Solid State Commun. **62**, 841 (1987).

[24] S. Narita, K. Muro, S. Mori, S. Hiyamizu, and K. Nanbu, in *Application of High Magnetic Fields in Semiconductor Physics,* edited by G. Landwehr, Lecture Notes in Physics, Vol. 177 (Springer-Verlag, Berlin, 1983), p. 194.

[25] Z. Schlesinger, W. I. Wang, and A. H. MacDonald, Phys. Rev. Lett. **58**, 73 (1987).

[26] T. P. Smith III, B. B. Goldberg, M. Heilblum, and P. J. Stiles, Surf. Sci. **170**, 304 (1986).

[27] D. Weiss, V. Moser, V. Gudmundsson, R. R. Gerhardts, and K. v. Klitzing, Solid State Commun. **62**, 89 (1987).

[28] U. Merkt, in *Festkörperprobleme,* Advances in Solid State Physics, Vol. 27, edited by P. Grosse (Vieweg, Braunschweig, 1987), p. 109.

[29] K. W. Chiu, T. K. Lee, and J. J. Quinn, Surf. Sci. **58**, 182 (1976).

[30] K. Ensslin and D. Heitmann (unpublished).

[31] M. Dobers, Ph.D. thesis, University of Stuttgart, 1987 (unpublished).