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Gate-controlled subband structure and dimensionality of the electron system in a wide parabolic quantum well

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Remotely doped parabolic quantum wells have been used to produce thick (> 2000 Å) layers of high-mobility electron systems. Using a front gate electrode we are able to simultaneously deplete the well and change the actual thickness of this quasi-three-dimensional system. Thus, we can successively depopulate the elecrical subbands in the well, leading to step-like changes in the gate to channel capacitance. This yields direct insight into the subband structure of the electron system and allows its spectroscopy without the need of a magnetic field. The experimental results are compared with those of a self-consistent subband calculation and we obtain a qualitative agreement.

The introduction of a new growth technique[1] has made it possible to realize high quality quasi-three-dimensional electron systems (Q3DESs). Theoretical considerations of this new construct predict a number of interesting many-body effects.[2] The concept is based on the production of an arbitrarily shaped potential well, which may be accomplished by molecular beam epitaxy (MBE) in the AlGaAs-GaAs system. The band gap in $Al_xGa_{1-x}As$ depends in the range of $0 < x < 0.3$ nearly linearly on the mole fraction x of the Al content, so that a spatial variation of x results in a corresponding spatial variation of the band gap. If the potential is chosen to be parabolic in the growth direction, one can mimic the potential of a spatially uniform 3D slab of positive charge, given by the curvature of this parabola.[1] Mobile electrons, provided through remote doping, then act to screen this fictitious charge, forming a Q3DES of nearly uniform density and high mobility. Since the potential wells can be chosen to be very wide, quantization effects play only a minor role and many electric subbands are occupied. The 3D nature of such parabolic quantum wells has been clearly demonstrated in recent experiments,[3–6] performed at low temperatures and in magnetic fields.

Here, we wish to report on the first experiment using parabolic wells with electrically tunable carrier density by use of a front gate electrode. In such samples, direct observation and spectroscopy of the subband structure in a Q3DES is possible even at zero magnetic field. The experimental method used here is the measurement of the capacitance between gate electrode and electron channel as a function of the gate voltage (*C-V* measurement). This technique has been demonstrated before to be a very powerful technique in the determination of the density of states in conventional 2D samples in the regime of the quantum Hall effect,[7,8] to study the magnetic anisotropy of a one-dimensional system,[9] and the Zeeman bifurcation of quantum dot spectra in a quasi-zero-dimensional system.[10]

The samples used are molecular beam epitaxy (MBE) grown, remotely doped parabolic quantum wells[1] with well widths between 750 and 5680 Å, respectively. Here, we wish to report on the results obtained in a nominally 4640-Å-wide well. The curvature of the parabola in this case corresponds to a fictitious charge density of $n^+ = 6\times10^{15}$ cm^{-3}. The low-temperature sheet carrier density and dc mobility at zero gate bias, as extracted from van der Pauw measurements, is $N_S = 1.35\times10^{11}$ cm^{-2} and $\mu = 185\,000$ cm^2 V^{-1} s^{-1}, respectively. Defining an effective width[1] of the Q3DES by $w_e = N_S/n^+$, the well thus is "filled" to about 50%. Indium contacts to the channel were annealed at $T = 430$ °C in reducing atmosphere. A 50 Å NiCr film is evaporated as gate electrode in a circular geometry. The capacitance voltage (*CV*) measurements were performed at $T = 4.2$ K by immersing the sample in liquid helium, and at frequencies between 10 and 1000 Hz using conventional lock-in techniques.

In Fig. 1 we present the experimental results, i.e., the measured capacitance of the 4640-Å-wide well as a function of the gate voltage V_g. At $V_g = V_{th}$, where the channel becomes depleted, a very sharp drop in the capacitance occurs. In contrast to corresponding measurements on quasi-two-dimensional samples, where the capacitance for $V_g > V_{th}$ at $B = 0$ is nearly independent of the gate bias, the overall capacitance gradually decreases with negative gate voltage V_g. This decrease is more pronounced the wider the well under investigation. In addition, we observe step-like changes in the capacitance at specific values of V_g. The lower trace depicts the simultaneously recorded in-phase signal, which is used to monitor the current flowing between gate and Q3DES. No such current is observed for $V_g < 0$, whereas for a small positive bias a strong increase occurs, indicating the alignment of the Fermi level with the donor levels in the $Al_xGa_{1-x}As$, which results in a conducting layer between gate and Q3DES.

Figure 2 depicts the result of our self-consistent subband calculation,[11,12] namely, the potential and the corresponding probability amplitudes in the different subbands for three different carrier densities N_S. With increasing N_S the potential well becomes wider and flatter, approaching the ideal case of a wide square well. Also shown is the density distribution $N(z) = \Sigma N_s^i|\xi_i|^2$. Even if the well is not completely filled, the electrons screen the parabolic potential, and create a thinner slab of the approximate width w_e. Using a mean dielectric constant of $12.5\epsilon_0$ for the layers between the gate and the Q3DES, the measured capacitance at $V_g = 0$ agrees very well with the one calculated in simplest approximation, using the known thicknesses $d = 1800$ Å between the gate and the edge of the MBE-grown parabola, the thickness

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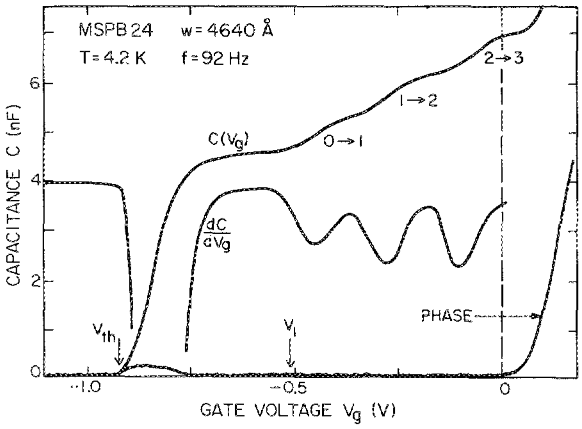

FIG. 1. Experimentally obtained capacitance $C(V_g)$ vs gate voltage for a nominally 4640-Å-wide parabolic quantum well. With decreasing gate voltage, the well is depleted of mobile carriers, leading to a decrease in the effective thickness of the quasi-three-dimensional electron system, which in turn results in a decreasing capacitance. At particular gate voltages subsequent subbands become depopulated, as indicated by steps in the $C(V_g)$ curve. These steps are more clearly visible in the differential capacitance dC/dV_g. The transition from subband 0 to subband 1 marks the transition from quasi-2D to quasi-3D behavior of the electron system. The simultaneously recorded signal which is in phase with V_g indicates no perpendicular conductance of the sample for gate voltages $V_g < 0$, and demonstrates that the obtained signal is purely capacitive. Both the phase signal as well as the differential capacitance are given in arbitrary units.

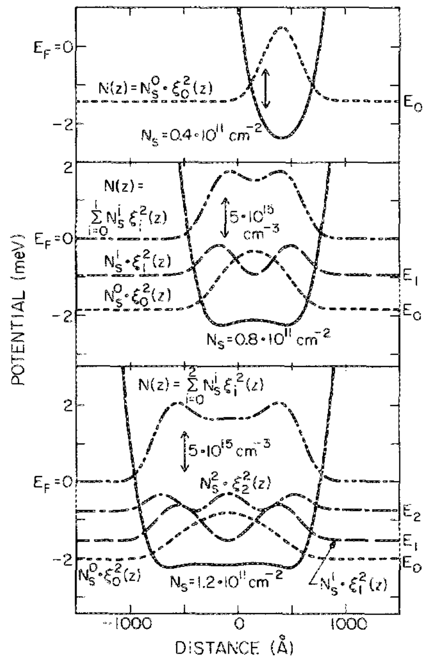

FIG. 2. Calculated self-consistent potential for a quasi-three-dimensional electron system in a parabolic quantum well of thickness $w = 4640$ Å. The potential and the probability amplitudes of the electron distributions are shown for three different carrier densities N_S or gate voltages V_g within the well. Increasing carrier density leads to a flattening of the bottom of the well and to an increase in the thickness of the electron distribution, whereas the intersubband spacings decrease. Typical subband energies are of the order of meV.

$w = 4640$ Å of the well itself, and the actual thickness $w_e = 2250$ Å of the Q3DES as defined above. The capacitance at $V_g = 0$ thus is determined by the thickness $d_{\text{tot}} = d + (w - w_e)/2$ between the gate and the leading edge of the Q3DES, which we define by the point where $N(z) = \Sigma N_S^i |x_i|^2$ drops to half its maximum value. The total capacitance per unit area at gate bias V_g is then expected to be given by three terms,[7,8] namely,

$$\frac{1}{C_{\text{tot}}} = \frac{1}{C_{\text{ins}}} + \frac{1}{C_{PBW}(V_g)} + \frac{1}{e^2 \Sigma \partial n_i / \partial \mu_i}. \tag{1}$$

Here, e is the electronic charge, n_i is the carrier density in the ith subband, and μ_i is the corresponding chemical potential. The first two terms describe the contribution of the geometrical capacitance of the dielectric insulating layer between the gate and the Q3DES, given by

$$C_{\text{ins}} = \epsilon \epsilon_0 / d$$

and

$$C_{PBW} = \frac{\epsilon \epsilon_0}{\{[w - w_e(V_g)]/2\} + z_0(V_g)}, \tag{2}$$

where ϵ and ϵ_0 are the electric permittivities of the semiconductor and the vacuum and d, w, and w_e the thickness of the layers as defined above. The most important difference from the 2D case is in the expression for C_{PBW}, taking into account the width $w_e(V_g)$ of the electron system and the shift $z_0(V_g)$ of the center of the wave function. The third term in Eq. (1) contains the thermodynamic density of states[8] at the Fermi energy. While the channel is being depleted, $w_e(V_g)$ decreases, resulting in a decrease of C_{PBW}. This is unique to the Q3DES and is due to a decreasing sheet carrier concentration whereas the space-charge density remains constant.

Our experiments thus yield a first direct observation of this shrinkage of the width of a Q3DES as a function of the carrier density. This and the shift of the center of the wave function, as shown in Fig. 2, results in an increase of the distance of the dielectric layer between gate and Q3DES and thus in a decrease of the measured capacitance. The value for the capacitance just above inversion threshold, i.e., $w_e \approx 0$, reveals a total change in thickness of $(w - w_e)/2 + z_0 = 1845$ Å. In this model, the center of the wave functions thus has been shifted by approximately 700 Å between $V_g = 0$ and $V_g = V_{\text{th}}$.

We attribute the steps in the capacitance at particular gate voltages to the subband structure within the well. Depleting the channel is accompanied by a successive electrical depopulation of these subbands, and thus by step-like changes in the density of states, leading to step-like changes in the third term of Eq. (1). In addition, the effective width of the Q3D slab changes in a step-like way, since the leading edge according to its definition changes its position rapidly once a subband becomes depopulated and the character of the wave function changes. The occurrence of three steps in the capacitance besides the large one at $V_g \sim V_{\text{th}}$ leads to the conclusion that four subbands are occupied at $V_g = 0$. For comparison, the calculated carrier densities N_s^i in the subbands and subband energies E_i as a function of the gate voltage are depicted in Fig. 3. Even though the absolute voltage scale in the figure does not exactly coincide with one of the experiments, the calculation predicts a fourth subband to become occupied at a total carrier density $N_S = 1.3 \times 10^{11}$ cm^{-2}, which is in good agreement with the experiment. The subband spacings in this case are consistent

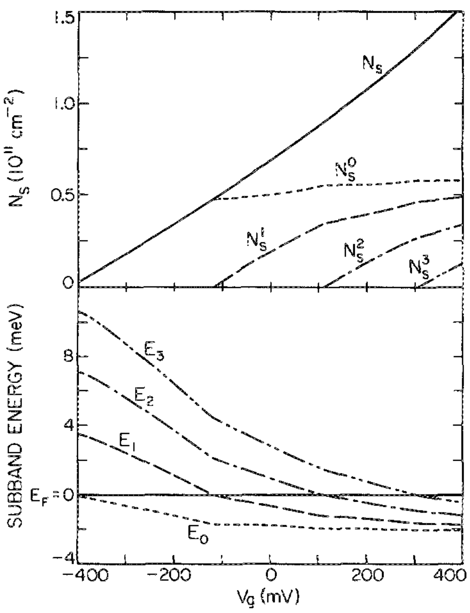

FIG. 3. Calculated carrier density and subband spacing as a function of the applied gate voltage V_g for a 4640-Å-wide parabolic quantum well. At a total carrier density of $N_S = 1.3\times10^{11}$ cm^{-2} four electrical subbands are occupied. The subband energies vary from those of a harmonic oscillator in the empty well to those of a rectangular square well for the partially filled well. In the region, where only one subband is occupied, the system behaves quasi-two-dimensionally, as indicated by a linear dependence of $(E_F - E_0)$ on N_S, whereas for higher carrier densities $(E_F - E_0)$ remains nearly constant.

with those expected for a wide rectangular well, i.e., the subband energies E_i vary as i^2 with the lowest one of the order of 0.3 meV. At $V_g = V_1$, only one subband remains occupied and the system undergoes the transition from quasi-3D to quasi-2D. In the calculation, this transition is indicated by a linear dependence of $(E_F - E_0)$ on N_s for voltages $V_{th} \leqslant V_g \leqslant V_1$, as expected for a 2DES. For voltages $V_g > V_1$ however, $(E_F - E_0)$ remains nearly constant, in agreement with the concept of a Q3DES. An offset in the voltage scale may be introduced in the calculation by changing the effective donor concentration, leaving the physical content of the calculation unchanged.

We are thus able to calculate the capacitance as a function of the gate voltage, combining both the geometrical considerations as presented in Eqs. (1) and (2) and the results of our self-consistent calculations. The overall decrease of the capacitance can be clearly demonstrated, whereas the magnitude of the steps at gate voltages, where subsequent subbands become depopulated, is underestimated in the calculations by a factor of the order of 5. The voltages at which the steps in the capacitance occur, however, are in good agreement with the ones obtained in the experiment, taking into account a fixed offset in the gate voltage. The height of the steps in the capacitance may strongly depend on the actual population process of the subbands, which can be influenced by exchange and correlation effects.[13-15] These contributions are presently under investigation.

In conclusion, we directly observe for the first time the electric depopulation of subbands in a high quality quasi-three-dimensional electron system. It manifests itself in step-like changes in the capacitance of the device, allowing the spectroscopy of the electronic levels in a very simple manner. We can tune the carrier density within the well and change its dimensionality from quasi-2D to quasi-3D behavior. An increase in the carrier density results in an increase of the actual thickness of the Q3DES, whereas the intersubband spacings decrease. This is in complete contrast to the situation in a 2DES.[15,16] The results of a self-consistent subband calculation are in very good agreement with the experiment, although the influence of a spatially varying effective mass,[17] dielectric permittivity, and nonparabolicity effects is not yet taken into account. The influence of exchange-correlation effects seems to be important in these systems.

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