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From two-dimensional to three-dimensional quantum dots

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Abstract

Laterally defined quantum dot structures have been fabricated on the basis of $Al_xGa_{1-x}As$ parabolic quantum wells which allow the occupation of more than one subband in growth direction. Magneto-Coulomb oscillations allow the determination of a gate parameter regime where the states of the second subband are occupied in the quantum dot. The occupation of the second subband in the dot comes along with fluctuations in the conductance peaks at zero magnetic field which we characterize with time dependent measurements. We discuss the possibility that the fluctuations are an intrinsic property of the dot at the threshhold to two occupied subbands. © 2002 Elsevier Science B.V. All rights reserved.

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The Coulomb-blockade effect in metallic single-electron transistors and in semiconductor quantum dots has been an intriguing topic in quantum transport over many years [1]. Experimental studies have focussed on Coulomb-blockade in semiconductor quantum dots with a single subband occupied in growth direction (two-dimensional dots) and on metallic islands where the electrons have a Fermi-wavelength much smaller than all geometrical dimensions (three-dimensional dots). Marked differences exist between these two types of systems. In metallic dots, for example, conductance peaks are equidistant in gate voltage while in semiconducting systems the energy quantization within the dot leads to statistical fluctuations of conductance peak spacings. The heights of neighboring conductance peaks exhibit fluctuations in semiconductors while in the metallic systems they are nearly constant. In this paper, we set out to investigate the Coulomb-blockade effect in a semiconducting parabolic quantum well structure which has the unique property that more than one subband can be controllably occupied in growth direction. This system can be regarded as being tunable from a strictly two-dimensional to an almost three-dimensional dot.

The quantum dot samples are based on MBE-grown parabolic $Al_xGa_{1-x}As$ quantum wells (PQWs) with x varying parabolically between 0 and 0.1 [2]. The 760 Å wide wells are sandwiched between 200 Å thick undoped $Al_{0.3}Ga_{0.7}As$ spacer layers and remotely doped with Si on both sides. A three monolayer thick $Al_{0.05}Ga_{0.95}As$ layer in the center of the well leads to a potential spike which is used to monitor the position of the wave functions with respect to the parabolic confinement [3]. However, this is of minor importance for the present study. A back-gate electrode consists of a 150 Å thick n^+-doped layer located 1.35 μm below the well. Using the back-gate electrode the density of the two-dimensional

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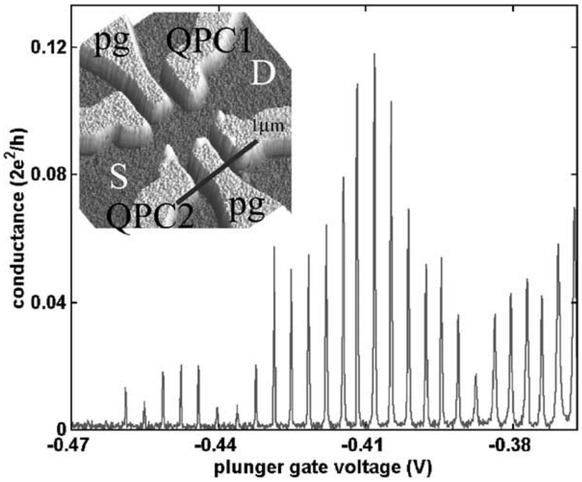

Fig. 1. Coulomb-blockade oscillations at a backgate voltage $V_{bg} = -2.5$ V. Inset: Atomic-force microscope image of the top gate electrodes defining the quantum dot.

electron gas (2DEG) in the PQW can be varied from $n_s = 1 \times 10^{15}\ \mathrm{m}^{-2}$, where only one subband is occupied in the well, up to $5 \times 10^{15}\ \mathrm{m}^{-2}$, where three subbands are occupied. Doing this, the mobility changes from 4 m^2/Vs at the lowest to 12.5 m^2/Vs at the highest densities. The occupation of the second subband starts at $n_s = 2.4 \times 10^{15}\ \mathrm{m}^{-2}$.

The inset of Fig. 1 shows the TiPtAu top-gate electrodes fabricated using electron-beam lithography and a lift-off process. These electrodes define a lateral quantum dot with geometric dimensions of 600 nm × 600 nm connected to source and drain contacts via the two quantum point contacts (QPCs) QPC1 and QPC2. Two plunger gates allow tuning the number of electrons in the quantum dot by varying the voltage V_{pg}. DC-conductance measurements were carried out with an applied source-drain voltage $V_{SD} = 6\ \mu\mathrm{V}$ at an electron temperature of 100 mK in a dilution refrigerator.

At a given back-gate voltage $V_{bg} = -2.5$ V the top gate electrodes were used to pinch off the 2DEG and thereby to define the quantum dot. With the QPCs in the tunnelling regime the Coulomb-blockade effect could be observed as depicted in Fig. 1. From an analysis of the Coulomb-blockade diamonds measured in the V_{SD}–V_{pg} plane [1] we determine a charging energy $e^2/C = 600\ \mu\mathrm{eV}$ and from the dot size a typical single-particle level spacing $\Delta \approx 20\ \mu\mathrm{eV}$. Using a simple capacitance model we estimate the electronic size of the dot to be typically 580 nm in diameter.

In order to determine the two-dimensional electron density, n_d, in the dot which is typically smaller than the density in the unbound 2DEG at the same back-gate voltage, we measure magneto-Coulomb oscillations [4] as a function of V_{pg} for a set of back-gate voltages. For quantum dots on PQWs all top-gate voltages have to be readjusted when V_{bg} is significantly changed. This is due to the soft confinement of the electron gas in the PQW: for example, an increase in V_{bg} will pull the electron distribution in the well towards the back gate and the QPCs tend to become more leaky. As a consequence the front-gate voltages have to be decreased in order to establish the necessary conditions for the observation of Coulomb blockade again. We found empirically that a front-gate voltage change of 24 mV per 100 mV change in V_{bg} is required. The densities as a function of V_{bg} determined from such a procedure are depicted in Fig. 2a. For $V_{bg} < -0.5$ V the density in the dot increases linearly with gate voltage. At $V_{bg} = -0.5$ V the electron density reaches the value where the second subband becomes populated in the 2DEG. Beyond this back-gate voltage the density increase shows clear deviations from linearity and at $V_{bg} > 0.5$ V it increases more rapidly. This behavior can be qualitatively understood on the basis of changes of the dot-gate capacitances. An increase in V_{bg} accompanied by a decrease of the top-gate voltages will tend to increase the capacitance $C_{\text{dot-bg}}$ slightly but it will more strongly decrease $C_{\text{dot-topgates}}$. This implies that at positive V_{bg} the same decrease in the top-gate voltages will have a smaller compensating effect on the density than at negative V_{bg} and $n_d(V_{bg})$ is bound to have a concave curvature. Due to the small value of Δ in our dot we can safely assume that the occupation of the second subband in the dot starts at $V_{bg} = -0.5$ V, where $n_d = 2.4 \times 10^{15}\ \mathrm{m}^{-2}$, i.e. at the same density where the second subband becomes occupied in the 2DEG.

With this information we now proceed to a comparison of the Coulomb-blockade effect at zero magnetic field for the cases of one and two occupied subbands. Most surprisingly, the prominent effect of the second subband occupation in the dot turned out to be fluctuations in the V_{pg}-positions of the conductance peaks observed at fixed $V_{bg} > -0.5$ V. The fluctuations occurred on a typical time scale > 10 s,

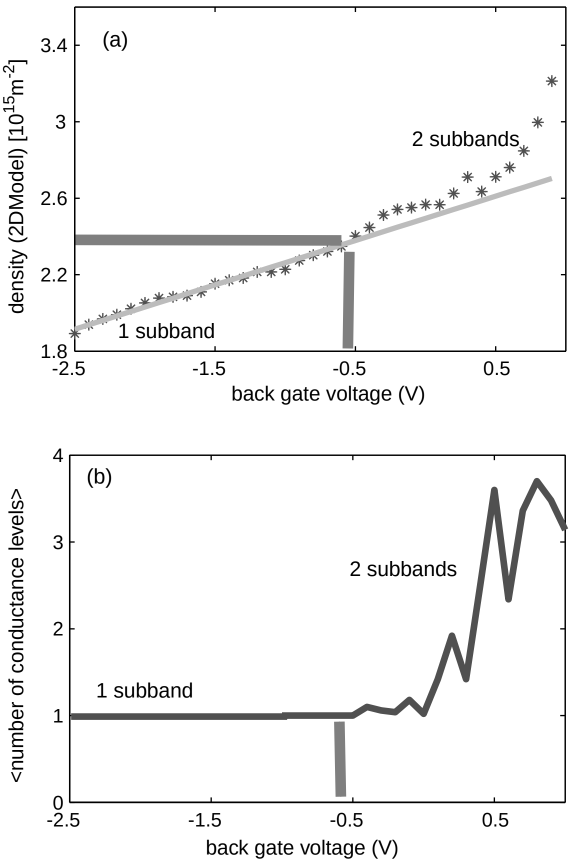

Fig. 2. (a) Density n_d in the dot as determined from magneto-Coulomb-oscillations as a function of V_{bg}. (b) Average number of conductance levels as a function of V_{bg} as determined from time-dependent measurements on a conductance maximum. The onset of the fluctuations of the conductance peaks coincides with the onset of the occupation of the second subband.

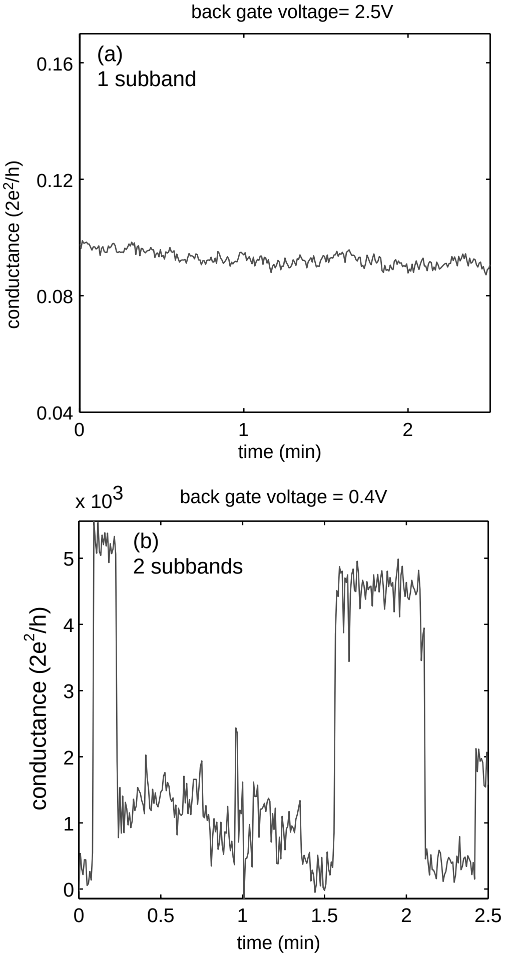

Fig. 3. Time dependent conductance measured at the maximum of a conductance peak in the case of one (a) and two (b) occupied subbands.

i.e. the time needed to sweep across a conductance peak, but < 10 min, i.e. the time needed for the total V_{pg}-sweep. In order to characterize these fluctuations we measured the conductance as a function of time for given V_{bg} at many V_{pg}-values within the range of three conductance peaks. Fig. 3 shows two typical examples; Fig. 3a for the case of a single subband in the dot ($V_{bg} = -2.5$ V), and Fig. 3b for the case of two subbands ($V_{bg} = -0.4$ V). In the latter case a clear random-telegraph-noise type switching between two conductance levels is observed while in the former case the current is constant within the noise level of the measurement setup. Similar switching was observed at $V_{bg} > -0.4$ V but the number of conductance levels increased steadily with increasing V_{bg}. Fig. 2b shows a plot of the number of switching levels as a function of back-gate voltage. Comparison with Fig. 2a reveals the striking correlation between the onset of the occupation of the second subband in the dot and the onset of the fluctuations.

Switching of the conductance between discrete levels (for reviews see Ref. [5]) is a well-known phenomenon in electronic transport in small-area [6] and large area devices [7]. Usually, these switching events are attributed to electron trapping and detrapping in localized states or to the existence of two-level fluctuators in the vicinity of the current carrying path. However, inspired by the intriguing correlation of the onset of the fluctuations with the onset of the population of the second subband, we suggest that the origin of the fluctuations may be found *within* the quantum dot and that its occurrence is closely related to second subband states. A similar explanation of fluctuations in the Coulomb-blockade regime of a quantum dot exposed to magnetic fields was given by the authors of Ref. [8]. In their sample the magnetic field served to decouple a compressible region within the sample from a ring shaped compressible stripe at the edge of the dot. At a fixed gate voltage the conductance switched between two values due to electrons tunnelling from the inner to the outer Landau-level. We speculate that a similar type of switching between two states could occur in our dot when the second subband plays the role of the inner Landau level. It is well known that localized states exist in the low-energy tail of the two-dimensional density of states. Such states within the dots could, for example, play the role of trapping centers for electrons that are sufficiently decoupled from the extended states to achieve long switching times. Alternatively, switching between degenerate many-body ground states with different charge distributions could be responsible for the observed fluctuations. However, since we cannot discriminate the actual origin of the instable behavior on the basis of the present data, further investigations are planned on these systems, which are expected to give more insight into the issue.

In conclusion, we have presented an investigation of a quantum dot fabricated on a parabolic quantum well which, in contrast to conventional semiconductor quantum dots, allows the controlled occupation of more than one occupied subband in the dot via a back-gate electrode. The onset of the second subband population is clearly correlated with the occurrence of time-dependent fluctuations of conductance peaks which may well be an intrinsic property of the dot.

References

[1] H. Grabert, H. Devoret (Eds.), Single Charge Tunnelling, Plenum Press, New York, 1991.;
hM.A. Kastner, Rev. Mod. Phys. 64 (1992) 849;
L.P. Kouwenhoven, C.M. Marcus, P.L. McEuen, S. Tarucha, R.M. Westervelt, N.S. Wingreen, in: L.P. Kouwenhoven, G. Schön, L.L. Sohn (Eds.), Mesoscopic Electron Transport, Kluwer, Dordrecht, 1997.

[2] A.C. Gossard, IEEE J. Quant. Electron. 22 (1986) 1649.

[3] G. Salis, B. Graf, K. Ensslin, K. Campman, K. Maranowski, A.C. Gossard, Phys. Rev. Lett. 79 (1997) 5106.

[4] A.A.M. Staring, B.W. Alphenaar, H. van Houten, L.W. Molenkamp, O.J.A. Buyk, M.A.A. Mabesoone, C.T. Foxon, Phys. Rev. B 46 (1992) 12 869.

[5] M.J. Buckingham, Noise in Electronic Devices and Systems, Ellis Horwood Ltd., New York, 1983.;
M.J. Kirton, M.J. Uren, Adv. Phys. 38 (1989) 367;
Sh. Kogan, Electronic Noise and Fluctuations in Solids, Cambridge University Press, Cambridge, UK, 1996.

[6] T. Rogers, Phys. Rev. Lett. 53 (1984) 1272;
R.T. Wakai, Appl. Phys. Lett. 49 (1986) 593;
E.R. Nowak, R.D. Merithew, M.B. Weissman, I. Bloom, S.S.P. Parkin, J. Appl. Phys. 84 (1998) 6195;
K.S. Ralls, Phys. Rev. Lett. 52 (1984) 228;
V.V. Kuznetsov, JETP Lett. 49 (1989) 453;
J.C. Smith, C. Berven, S.M. Goodnick, M.N. Wybourne, Physica B 227 (1996) 197.

[7] Th. Ihn, A.K. Savchenko, M.E. Raikh, R. Schwarz, J. Non-Cryst. Solids 137&138 (1991) 523;
R. Arce, J. Non-Cryst. Solids 114 (1989) 696.

[8] N.C. van der Vaart, M.P. de Ruyter van Stevenick, L.P. Kouwenhoven, A.T. Johnson, Y.V. Nazarov, C.P.J.M. Harmans, C.T. Foxon, Phys. Rev. Lett. 73 (1994) 320.