Phase Transitions,
Vol. 79, Nos. 9–10, September–October 2006, 765–770

Quantum dot electrons as controllable scattering centers in the vicinity of a two-dimensional electron gas

M. RUSS†, C. MEIER*†, B. MARQUARDT†,
A. LORKE†, D. REUTER‡ and A. D. WIECK†

†Experimental Physics, University of Duisburg-Essen, Lotharstr. 1, D-47048
Duisburg, Germany
‡Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum,
Universitätsstr. 150, D-44780 Bochum, Germany

(*Received 9 August 2006; in final form 17 October 2006*)

Self-assembled InAs quantum dots can be controllably charged with a defined number of electrons per dot. We report on conductivity measurements of $Al_xGa_{1-x}As/GaAs$ heterostructures, where such quantum dots are embedded in the direct vicinity of a two-dimensional electron gas (2DEG). We demonstrate the controlled enhancement of the scattering rate in the 2DEG induced by charging the quantum dots with additional electrons. The resulting transport lifetimes are in good agreement with theoretical values for Coulomb scattering in two dimensions.

Keywords: Quantum dots; two-dimensional electron gas; scattering; GaAs

1. Introduction

Almost immediately after the first fabrication of uniformly sized InAs quantum dots on GaAs [1], it was realized that these islands can be used as controllable scattering centers for a two-dimensional electron gas (2DEG). The first experiments showed a drastic reduction of the 2DEG mobility with decreasing distance between the dots and the 2DEG [2]. Since then, several authors successfully used self-assembled quantum dots for novel transport experiments in the quantum Hall regime of highly disordered 2DEG [3–5]. However, the reason of the strong scattering by self assembled quantum dots is still unclear. One of the main candidates for the origin of the reduction of the mobility are the quantum dot electrons and their associated Coulomb potential. However, by comparing capacitance and transport data, Zhukov *et al*. and Kawazu *et al*. demonstrated that the charging of the quantum dots can even lead to an *enhancement* of the mobility [6, 7]. Zhukov *et al*. argue that in these experiments the quantum dot electrons are not the dominant source of scattering and in certain cases effectively screen other potential inhomogeneities. Here, we report on capacitance and conductivity measurements which show a reduction of the mobility whenever additional electrons are charged in the quantum

---

*Corresponding author. Email: cedrik.meier@uni-due.de

Phase Transitions
ISSN 0141-1594 print/ISSN 1029-0338 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01411590600960893

dot layer. The results compare favorably with calculated mobilities if the quantum dots are modelled as a sheet of Coulomb scatterers.

2. Samples and experimental setup

All samples were grown by solid-source molecular beam epitaxy on GaAs (100) semi-insulating substrates. The active part of the structure starts with 150 nm $Al_{0.34}Ga_{0.66}As$, a Si-δ-doping, a 40 nm $Al_{0.34}Ga_{0.66}As$ spacer and 40 nm GaAs. On top of the GaAs layer the InAs quantum dots were grown, followed by another 40 nm GaAs and an insulating AlAs/GaAs superlattice. Finally, the structure was capped with 5 nm GaAs. The resulting conduction band profile is depicted in figure 1. The 2DEG resides at the $Al_{0.34}Ga_{0.66}As$/GaAs interface and is coupled to the quantum dots by a tunneling barrier of 40 nm GaAs. In our experiments, the resistance of the tunneling barriers can be neglected.

Gated Hall-bar devices and large area gates were prepared on the same sample using standard photolithographic techniques. All measurements were performed in a He-cryostat at a temperature of 4.2 K, using a low frequency lock-in technique.

3. Results

Figure 2 shows the capacitance of the structure as a function of the gate voltage U_g. Starting from low gate voltages, at first the 2DEG is charged ($U_g = -1.0\,\mathrm{V}$) and the capacitance reflects the geometric position of the 2DEG. On top of this background capacitance, several charging peaks associated with the self assembled quantum dots (SAQD) can be resolved. In a simple, intuitive picture, this enhancement of the capacitance whenever a quantum dot state is filled results from the smaller distance of the quantum dots to the gate electrode (figure 2). For a more in-depth treatment, see Russ *et al.* [8] and references therein.

The first pair of maxima around $U_g = -0.6\,\mathrm{V}$ can be attributed to the charging of the lowest spin degenerate quantum dot state, which, in analogy to atom physics, is labelled as the *s*-shell. The difference in gate voltage between these two *s*-states

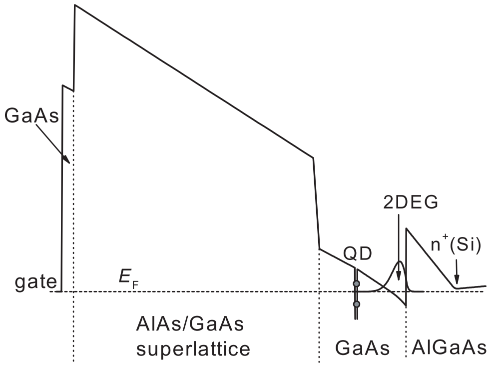

Figure 1. Calculated conduction band edge of sample studied in this work.

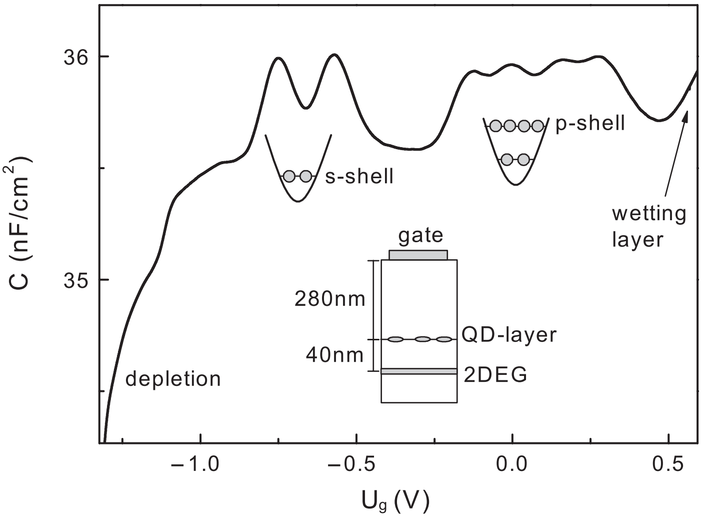

Figure 2. Capacitance of a sample with a two-dimensional back contact and embedded self-assembled InAs quantum dots.

results from the additional Coulomb energy for the second electron. Around $U_g = 0\,\mathrm{V}$, the SAQD *p*-shell is charged with four electrons. Because of the different orientations of the relevant wave functions, these electrons are separated by a smaller Coulomb energy than the *s*-electrons. Therefore, the four peaks of the *p*-shell are usually not resolved in capacitance measurements (e.g. [6]). At a gate voltage of ($U_g = 0.4\,\mathrm{V}$) each SAQD is occupied with six electrons and a further increase in gate voltage leads to a charging of the InAs wetting layer surrounding the dots.

The area of the capacitance enhancement is a measure for the number of simultaneously charged dots. In our case, we calculate a value of approximately $4 \times 10^9\,\mathrm{cm}^{-2}$ for the dot density. Therefore, capacitance measurements enable us to determine the number N_{qd} of Coulomb scatterers and their gate voltage dependent charge $Z_{qd}(U_g)$. Additionally, the electron density of the 2DEG n_{2d} can be determined from such capacitance measurements. If no dots were present, this density would be a linear function of the applied gate voltage. It can be assumed that the SAQD charging leads to a reduction of n_{2d} due to tunneling of carriers in the QD layer. This way, also n_{2d} is known for each gate voltage.

In figure 3 the gate voltage dependent conductance and its derivative are compared to the capacitance measurement. The conductance itself (figure 3b) shows only a small change in the slope of the gate voltage region where the quantum dots are charged. Therefore, the quantum dot electrons are not the origin of the rather short scattering times in samples with embedded self assembled dots.

To further study the origin of the observed minima in the derivative of the conductance (figure 3b) whenever additional electrons are charged into the quantum dot layer, the effects of the SAQD on the 2D carrier concentration and on the mobility have to be distinguished. We have therefore extracted the carrier concentration of the 2DEG from Hall measurements at a magnetic field of $B = 0.3T$, which has no noticeable influence on the quantum dot charging positions.

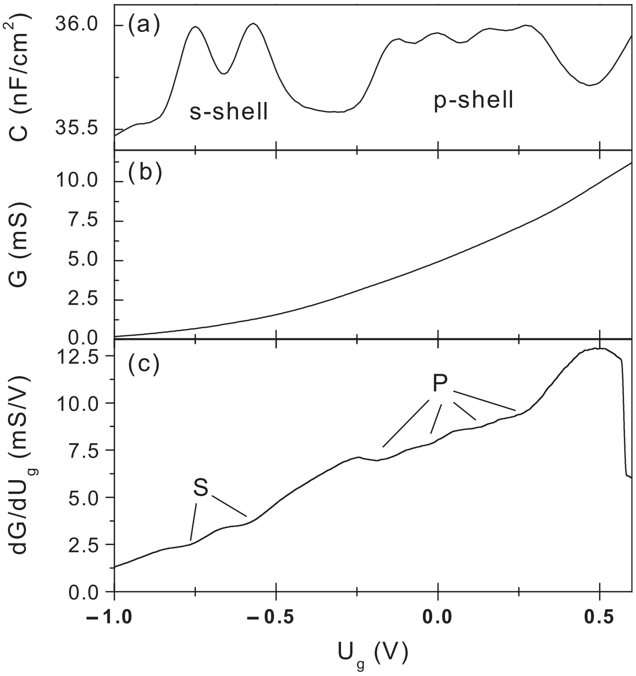

Figure 3. Capacitance (a), conductance (b) and derivative of the conductance (c).

Using this carrier concentration n_{2d}, the mobility μ can be calculated from the conductance σ:

$$\mu = \frac{\sigma}{e n_{2d}} \tag{1}$$

To compare the mobility with theoretical values we use the Stern–Howard model [9, 10] and calculate the dot induced scattering time τ for each gate voltage using the expression [11]

$$\frac{1}{\tau} = \frac{1}{2\pi\hbar E_{\mathrm{F}}} \int_0^{2k_{\mathrm{F}}} \frac{q^2}{\sqrt{4k_{\mathrm{F}}^2 - q^2}} \frac{\langle U(q)\rangle^2}{\epsilon(q)^2} \mathrm{d}q. \tag{2}$$

Here, the values for the *Fermi* energy E_{F} and the respective wavevector k_{F} can be calculated from the actual carrier concentrations. If the quantum dot electrons act as individual scatterers and are located at a distance d from the plane of the 2DEG the resulting screened potential $U(q)$ can approximated by [11]

$$\langle U(q)\rangle^2 = N_{qd} Z_{qd}(U_g) \left(\frac{2\pi e^2}{\kappa q}\right)^2 F(q, d), \tag{3}$$

where κ denotes the static dielectric constant of GaAs and $F(q, d)$ is a form factor describing the actual position of the scatterers and the extension of the 2D wave function.

As a second source of scattering we introduce the sheet of ionized Si donors, which supply the carriers for the 2DEG. The charge of these donors is constant for

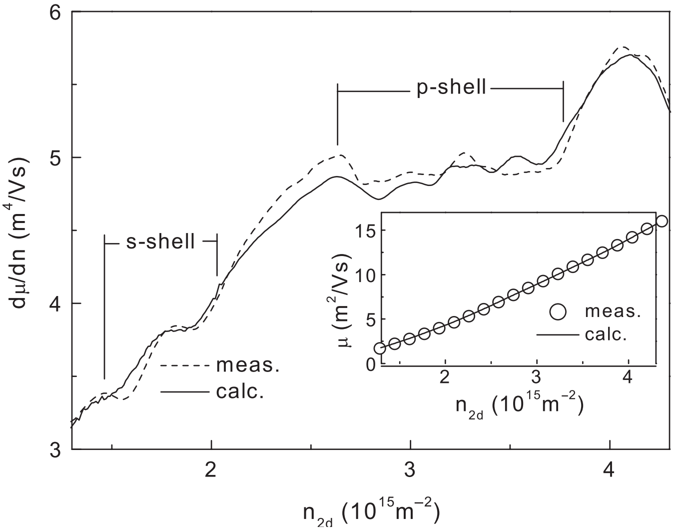

Figure 4. Measured and calculated mobility (inset) and the respective derivatives.

all gate voltages and their density can be calculated from the growth parameters of the sample. Finally, we use a homogeneous, constant 3D background of scatterers as a fitting parameter to align our calculated mobility with the measured values prior to the occupation of the quantum dots ($U_g = -0.9\,\mathrm{V}$).

Figure 4 shows the resulting calculated mobility and its derivative in comparison to the experimental data. In our calculation, we achieve an almost perfect reproduction of the measured mobility (inset in figure 4). Also, the general features of the derivative of the mobility can be modelled extremely well. The charging of the quantum dots leads to six distinct minima in the derivative of the mobility. However, in the calculation a value of $3.2 \times 10^{10}\,\mathrm{cm}^{-2}$ had to be assumed for the dot density, which is eight times higher, than the value extracted from the capacitance. We attribute this increased scattering by the quantum dot electrons to the resonant interaction with the 2DEG, which is well known to enhance scattering in similar systems [12].

We note that the observed behavior in figure 4 is a justification of our assumption to treat the quantum dot electrons as uncorrelated scatters. If all Z_{qd} electrons of a single dot would scatter like a single point charge, their *total* potential would enter equation (2) quadratically and not linearly as in our calculation. This, however, would lead to an enhancement of the scattering of the p-electrons with respect to the s-electrons, which is not observed in the experiment.

4. Conclusion

We have measured the capacitance and the transport parameters of a sample, which contains a layer of self assembled InAs quantum dots in the direct vicinity of a two-dimensional electron gas. We have demonstrated that in our samples the quantum dot electrons can be modelled as uncorrelated Coulomb scatterers using the Stern–Howard model and the charging of the dots leads to well resolved minima in the derivative of the mobility. It can be assumed that resonant interaction of the quantum dots with the 2D electrons is the reason for the observed enhancement of the scattering with respect to the Stern–Howard model. To further strengthen this assumption, samples with smaller tunneling barriers and therefore stronger coupling should be investigated in future work.

Acknowledgements

Financial support by the Bundesministerium für Bildung und Forschung (BMBF) under grants 01BM461 and 01BM465, as well as by the Deutsche Forschungsgemeinschaft (DFG) under grant GRK384 is gratefully acknowledged.

References

[1] D. Leonard, M. Krishnamurthy, C.M. Reaves, *et al*., Appl. Phys. Lett. **63** 3203 (1993).
[2] H. Sakaki, G. Yusa, T. Someya, *et al*., Appl. Phys. Lett. **67** 3444 (1995).
[3] E. Ribeiro, R.D. Jäggi, T. Heinzel, *et al*., Phys. Rev. Lett. **82** 996 (1999).
[4] Q. Wang, N. Carlsson, P. Omling, *et al*., Appl. Phys. Lett. **76** 1704 (2000).
[5] G.H. Kim, J.T. Nicholls, S.I. Khondaker, *et al*., Phys. Rev. B **61** 10910 (2000).
[6] A.A. Zhukov, Ch. Weichsel, S. Beyer, *et al*., Phys. Rev. B **67** 125310 (2003).
[7] T. Kawazu, T. Noda and H. Sakaki, Phys. Stat. Sol. (c) **4** 1325 (2003).
[8] M. Russ, C. Meier, A. Lorke, *et al*., Phys. Rev. B **73** 115334 (2006).
[9] F. Stern and W.E. Howard, Phys. Rev. **163** 816 (1967).
[10] A. Gold, Phys. Rev. B **38** 10798 (1988).
[11] E. Ribeiro, E. Müller, T. Heinzel, *et al*., Phys. Rev. B **58** 1506 (1998).
[12] M.A. Fisher, A.R. Adams, E.P. O'Reilly, J.J. Harris, *et al*., Phys. Rev. Lett. **59** 2341 (1987).