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Self-assembled quantum dots as probes for Landau-level spectroscopy

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Abstract

We report on capacitance–voltage measurements of an inverted two-dimensional electron gas (2DEG) with a layer of self-assembled InAs quantum dots in its immediate vicinity. A variable frequency approach enables us to determine the position of the Quantum dots-induced charging peaks for the first six electrons per dot in magnetic fields up to 10 T. Using the first s-electron as an energetic reference we monitor the oscillations of the 2DEG Fermi energy as a function of the applied magnetic field. Because in the present experiment, also the energy scale of the oscillations can be determined a detailed comparison with theoretical models becomes possible. We find good agreement at low and intermediate fields, when a Gaussian density of states with a constant background is assumed. The discrepancy found for highest fields investigated suggests that more sophisticated models are necessary in this regime.

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Keywords: Capacitance spectroscopy; Landau-levels; Quantum dots

1. Introduction

Capacitance–voltage(CV)-spectroscopy has proven to be a valuable tool for the investigation of self-assembled quantum dots [1]. The “quantum capacitance” (i.e. the part of the capacitance that is directly proportional to the density of states) allows for a detailed study of the energetic structure inside these fully quantized systems. In most cases, a heavily doped (three-dimensional) contact layer has been used as a back electrode to study the density of states (DoS) of the quantum dots (QD). Using such a three-dimensional back-contact the spectrum of the many-particle ground state energies of typical InAs QD was experimentally observed [2] and soon a theoretical framework based on the assumption of a harmonic dot potential and on the concept of Coulomb-blockade effects was able to explain the measured energy levels and the positions of the maxima in the CV spectra [3].

In this work, the back electrode is realized by a two-dimensional electron gas (2DEG) (see Fig. 1). Similar structures have been analysed before by different authors [4–8], but so far the emphasis in these investigations has been put on the influence of the QD layer on the 2DEG. The samples used in those studies did not allow for a detailed analysis of the electronic structure of the QD.

In our work, the positions of the first six charging maxima of the QD are determined for magnetic

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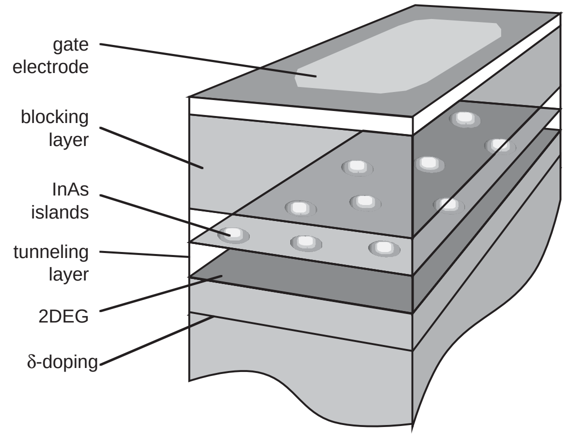

Fig. 1. Inverted MISFET structure with a layer of QD between the gate electrode and the 2DEG. The samples are provided with ohmic contacts and NiCr gates by standard photolithographic techniques.

fields from 0 to 11 T using a 2DEG as a back contact. Consequently, our heterostructure allows for magneto-transport measurements of the 2DEG with an in situ tunable scattering potential. In this paper however, we concentrate on the possibility to analyse the energetic structure of the 2DEG Landau-levels using states of the QD as an energetic reference. Tunnelling from the 2DEG into the QD leads to an increased capacitance signal when the chemical potential in the back contact, μ_{bc}, equals the QD addition energy: $\mu_{bc} = \Delta E_{n,n-1}$. In highly doped, low mobility three-dimensional back contacts, μ_{bc} is considered to be constant and this relation is the basis to investigate $\Delta E_{n,n-1}$. Here we use the almost constant position of the first *s*-electron as a reference to study the oscillations of the chemical potential in the two-dimensional back contact under quantum Hall conditions. Our work therefore consitutes a complementary technique to the landau-level spectroscopy in resonant tunneling structures of Maine et al. [15].

2. Experimental details

Fig. 1 shows a sketch of our inverted metal insulator semiconductor field effect transistor (MISFET) heterostructure. The following layers were grown by molecular beam epitaxy on a GaAs (1 0 0) substrate: a 200 nm GaAs buffer, a short period superlattice (40 × (2/2)nm GaAs/AlAs), 300 nm $Al_{0.35}Ga_{0.65}As$, a Si delta-doping layer (5×10^{12} cm^{-2}), a 10 nm $Al_{0.35}Ga_{0.65}As$ spacer, 25 nm GaAs, InAs quantum dots (2 ML InAs), 30 nm GaAs, a short period superlattice (29 × (3/1)nm AlAs/GaAs) and a 5 nm GaAs cap layer. The 2DEG is located at the (inverted) interface between the AlGaAs spacer and the following GaAs layer (see Fig. 1). The sample capacitance was measured in lock-in technique for frequencies ranging from 63 Hz to 20 kHz, all measurements were performed at liquid helium temperature (4.2 K).

3. Results and discussion

Fig. 2 shows a capacitance spectrum taken at $B = 0$ T. At $V_g = -2$ V the 2DEG is depleted and only a background capacitance (cables, etc.) of 3 pF is visible, which is substracted in all further calculations. At about $V_g = -1.8$ V the 2DEG becomes occupied and the capacitance of the system (2DEG-gate) is measured. The capacitance value at $V_g = -1.25$ V of 255 pF is in good agreement with the geometric value C_{geo} of approximately 267 pF.

In the range from $V_g = -0.9$ to 0.4 V the QD are successively filled with electrons and the additional density of states of the QD between the gate and the 2DEG gives rise to six maxima in the total capacitance. Contrary to the case of a highly doped low mobility back contact [9], in the present case the total capacitance is expected to be affected by both the DoS in the dots, D_{QD}, and—particularly at high magnetic fields—the varying DoS of the 2DEG, D_{2D}. To account for this, we have extended the model in Ref. [9] to include also the quantum nature of the back contact.

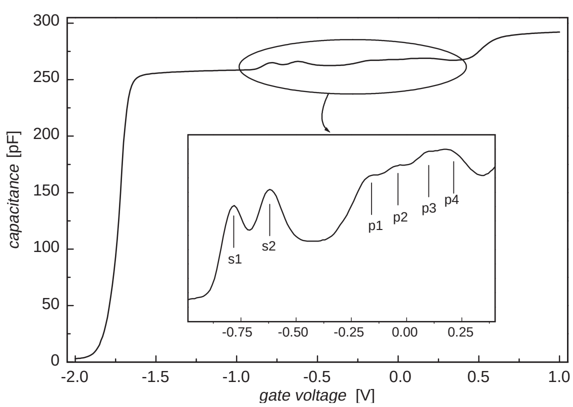

Fig. 2. Capacitance spectrum for $B = 0$ T and $f = 1063$ Hz. The inset shows the dot-induced charging peaks for the first six electrons per dot.

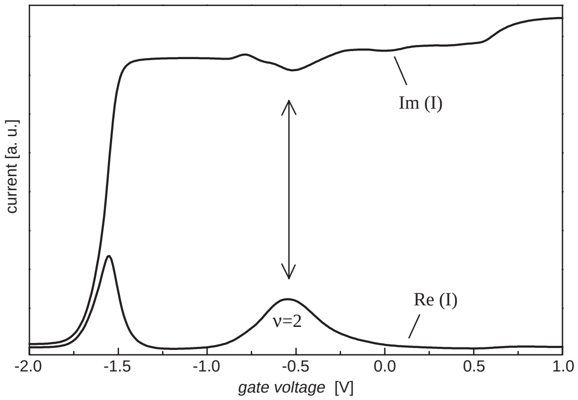

Fig. 3. Real and imaginary part of the complex current signal for $B = 10.5$ T and $f = 2063$ Hz. The maximum in Re(I) (filling factor $\nu = 2$) corresponds with a capacitance minimum which obscures the positions of the dot-induced charging peaks (arrow).

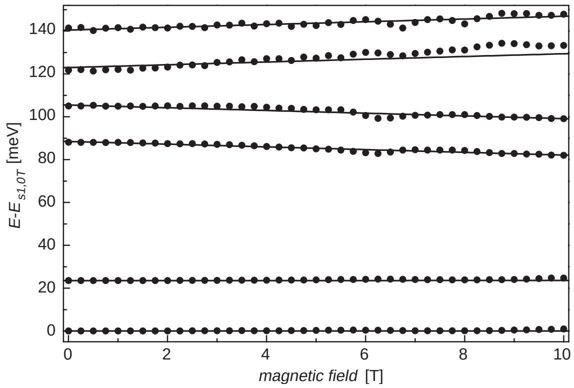

Fig. 4. Positions of the charging maxima of the first six electrons per dot (symbols). The lines are calculated functions for a harmonic oscillator with constant interaction.

The resulting total capacitance C_{tot} is given by

$$\frac{1}{C_{\text{tot}}} = \frac{1}{C_{\text{QD}}} + \frac{1}{C_{\text{qQD}} + \cfrac{1}{\cfrac{1}{C_{\text{2D}}} + \cfrac{1}{C_{\text{q2D}}}}}. \tag{1}$$

Here, C_{QD} is the geometric capacitance between the QD layer and the gate electrode and C_{2D} is the geometric capacitance between the 2DEG and the QD. The respective quantum capacitances are $C_{\text{qQD}} = \mathrm{e}^2 D_{\text{QD}}$ and $C_{\text{q2D}} = \mathrm{e}^2 D_{\text{2D}}$. An important result is that by defining a combined back contact capacitance $C_{\text{bc}}^{-1} = C_{\text{2D}}^{-1} \cdot C_{\text{q2D}}^{-1}$ Eq. (1) is for low measurement frequencies f and zero magnetic field mathematically identical to the formulas derived in Ref. [9]. Therefore, it is plausible that the 2DEG can be used as a back contact to map out the QD energy levels in the same manner as standard 3D back electrodes.

For high magnetic fields the situation is further complicated by additional resistive effects of the 2DEG (Fig. 3). To determine the positions of the dot-induced capacitance maxima, the resistive effects at integer filling factors have to be minimized using a low measurement frequency $f < 1$ kHz (see Ref. [10] for an analysis of the influence of the resistivity of a 2DEG in capacitance measurements). Since on the other hand a high value of f is desirable to obtain a better signal-to-noise ratio, the optimum value should be chosen according to the actual strength of the magnetic field, i.e. the position of the Landau-levels.

This way, we are able to determine a complete addition spectrum for the first six electrons per dot (Fig. 4). For low magnetic fields ($B < 4$ T), the positions of the capacitance maxima are described very well by a simple, constant interaction harmonic oscillator approach [11]. The measured Coulomb energies are $E_{\text{cb}}^{\text{s-s}} = 23.75$ meV for the s-electrons and $E_{\text{cb}}^{\text{p-p}} = 19.7$ meV for the p-electrons. While the value for the s-electrons is in acceptable agreement with previous measurements utilizing three-dimensional back contacts, the Coulomb energy for the p-electrons is exceptionally high.

The most remarkable feature of Fig. 4, however, is the apparent oscillation of the charging energies at high magnetic fields, particularly for the higher p-electrons. We attribute this variation to the oscillations of the 2DEG Fermi energy with the magnetic field.

The magnetic-field dispersion of the s-electrons is smooth and shows only a small and well-known diamagnetic shift. Therefore, and because of the large Coulomb blockade between the two s-electrons, these dot levels can be employed as tools to analyse the fluctuations of the Fermi energy in the 2DEG and ultimately as an instrument to analyse the shape of the 2DEG density of states.

We determined the exact position of the first dot-induced capacitance peaks for magnetic fields between 0–10 T. The conversion from gate voltage positions V_{G} to a 2DEG Fermi energy E_{F} is carried out by evaluating

$$E_{\text{F}} - E_{\text{F}}(B = 0\ \text{T}) = e(V_{\text{G}} - V_{\text{s1,0 T}})/\lambda, \tag{2}$$

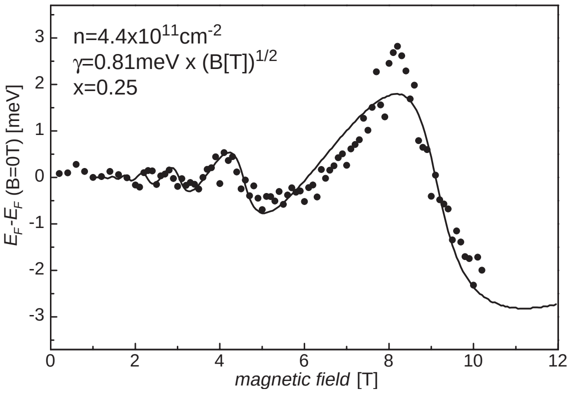

Fig. 5. Energetic positions of the first QD s-electron (dots) and simulated curve using a Gaussian model with a variable width ($\propto B^{1/2}$) and a constant underground of 25% (line). Note that no adjustable parameters are used to determine the experimental data.

where λ is the so-called "lever arm" [11]. The simulated curve in Fig. 5 is calculated assuming for the Landau-level DoS $D(E)$ a Gaussian broadening with a constant underground x and variable width $\Gamma(B)$:

$$D(E) = x\frac{2eB}{h} + (1-x)\frac{2eB}{h}\sum_{i=-t}^{t}\frac{1}{\sqrt{\pi}\Gamma}\,\mathrm{e}^{-\frac{(E-E_i)^2}{\Gamma^2}}. \tag{3}$$

Here $E_i = \hbar\omega_c(i+\frac{1}{2})$ is the position of the ith Landau-level and t has to be chosen high enough to limit numerical errors, especially for large values of Γ. E_F can easily be obtained by numerically integrating this function until the carrier concentration n is reached.

Eq. (3) is derived following the work of Gornik et al. [12] and Eisenstein et al. [13]. At moderate fields our data is in a very good agreement with this model, when $x = 25\%$ and $\Gamma = 0.81$ meV $\times (B[\mathrm{T}])^{1/2}$ are assumed. Still, at high magnetic fields we find a significant disagreement between the model and the experimental data. We believe that a more sophisticated model like the self-consistent theory by Xie et al. [14] is necessary to reproduce the dispersion over the entire range of magnetic fields.

It is interesting to note, that the so-derived carrier concentration $n = 4.4 \times 10^{11}$ cm^{-2} is approximately the same as the value determined from the maxima of the resistive current in capacitance measurements (4.2×10^{11} cm^{-2}, see Fig. 3). Because the resistive signal is sensitive to the whole sample area, while the values determined from the energetic positions of the QD s-electrons are only sensitive to the area in the direct vicinity below each dot, this leads to the conclusion that for our geometry the (singly charged) dots are not strongly affecting the local carrier density of the 2DEG.

Summary

We have investigated a two-dimensional electron gas, coupled (by tunnelling) to a layer of self-assembled quantum dots. We have shown, that the first QD electron level can serve as an energetic reference to probe the position of the Fermi energy in the 2DEG. This enables us to compare the measured shape of the 2DEG DoS with existing models. We found a good general agreement with a Gaussian model with a constant background of $x = 25\%$ and a variable width $\Gamma = 0.811$ meV $\times (B[\mathrm{T}])^{1/2}$. However, some features of our data cannot be explained by standard models for the 2DEG density of states.

Additionally, we found no evidence for a strong inhomogeity of the 2DEG carrier concentration due to the charging of the quantum dot layer.

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