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A two-dimensional electron gas as a sensitive detector to observe the charge carrier dynamics of self-assembled QDs

Bastian Marquardt[a,*], Martin Geller[a], Axel Lorke[a], Dirk Reuter[b], Andreas D. Wieck[b]

[a] *Experimental Physics and CeNIDE, University of Duisburg-Essen, D-47048 Duisburg, Germany*
[b] *Chair of Applied Solid-State Physics, Ruhr-University Bochum, D-44780 Bochum, Germany*

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ABSTRACT

The carrier tunneling dynamics of self-assembled InAs quantum dots (QD) is studied using a time-resolved conductance measurement of a nearby two-dimensional electron gas (2DEG). The investigated heterostructures consist of a layer of QDs with different coupling strengths to a 2DEG, adjusted by different thicknesses of the spacer layers. We demonstrate a strong influence of charged QDs on the conductance of the 2DEG, even for very weak coupling between the QD layer and the 2D system, where standard capacitance (C)–voltage (V) spectroscopy is unsuitable to investigate the electronic structure of these QDs.

The electrical read-out of quantum dot states by an adjacent electron channel has become a powerful tool to study charge, spin and entanglement in confined few electron systems [1,2]. These studies were mostly performed on lateral and lithographically defined structures. No corresponding read-out scheme was demonstrated for the otherwise widely studied self-assembled quantum dots (QDs). The electronic structure and charge carrier dynamics of ensembles of self-assembled QDs can be observed in time-resolved capacitance measurements [3,4]. However, these capacitance measurements have experimental limitations in both time and spatial resolution. Therefore, studying single QDs with long retention times is almost impossible using capacitance studies.

We demonstrate here that the conductance of a two-dimensional electron gas (2DEG) can be used as an efficient and sensitive detector to study the charging dynamics of self-assembled InAs QDs with single-electron charge resolution and a time resolution ranging from microseconds to several hundreds of seconds [5]. The conceptual similarity of our sample structure to flash memories demonstrates the possibility to realize a QD memory device based on self-assembled QDs [6,7]. Finally, the favorable scaling laws regarding the conductance of a 2DEG promises high-resolution single dot spectroscopy, which has already been successfully used to study lithographically patterned QDs [8].

In this report, three different samples (#1, #2 and #3) were investigated, which consist of an inverted HEMT structure [9,10] with embedded self-assembled InAs QDs. The QD lateral size is about 20 nm and the heigth is 5 nm which results in measured quantization energies in growth direction of about 50 meV [9,11]. In order to study the influence of the charged QDs on the conductance of the 2DEG for different coupling strengths, the tunneling barriers differ in thickness and $Al_{0.34}Ga_{0.66}As/GaAs$ composition. The QD-layer of the strongly coupled sample #1 is separated by a 25 nm thick GaAs-tunneling barrier from the 2DEG (as schematically depicted in the inset of Fig. 1(a)). The tunneling barriers of sample #2 and #3 consist of a 10 and 20 nm $Al_{0.34}Ga_{0.66}As$, respectively, and 20 nm GaAs (see the insets of Figs. 1(b) and 5). This results in charge tunneling times (i.e. electron tunneling between QDs and 2DEG), which are orders of magnitudes longer than those of sample #1. Fig. 1 shows C–V spectra of samples #1 and #2 (all measurements were performed at 4 K). The observed maxima in the capacity can be directly linked to the individual electron states of the QDs [12]. Fig. 1(a) shows the C–V spectrum of a rather strongly coupled QD/2DEG-system. The average tunneling time between the QD states can be estimated to about 100 μs in frequency-dependent C–V measurements [13]. The applied high frequency (f=10 kHz) leads to a smooth curve (i.e. high signal to noise ratio), hence, every individual QD-state can be resolved. Strongly coupled heterostructures have already been characterized by different

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[*] Corresponding author. Tel.: +49 203 379 2867.
E-mail address: bastian.marquardt@uni-due.de (B. Marquardt).

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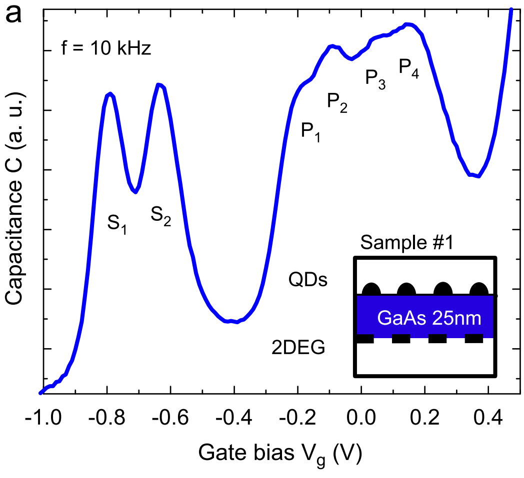

Fig. 1. (a) C–V spectrum of a rather strongly coupled sample (sample #1). (b) C–V spectrum of a relatively weakly coupled sample (sample #2).

experimental techniques which are based on capacitance and static conductance measurements [9,11].

Fig. 1(b) depicts the capacitance versus the gate bias of the weakly coupled electron system. Using frequency-dependent C–V spectroscopy [13], the tunneling time of the first s-state is determined to be $\tau_{s1} \approx 6$ ms and the tunneling time of the p-states to be $\tau_p \approx 1.4$ ms. The very weak coupling between the 2DEG and the QDs requires low-frequency modulation (f=23 Hz), which makes it difficult to obtain high-quality C–V spectra (see Fig. 1(b)). However, a comparsion with C–V studies of sample #1 (see Fig. 1(a)) and the better resolved conductance measurements (Fig. 4, see discussion below) allows us to identify the double-peak structure around -0.5 V and the broad feature between -0.2 and 0.4 V with charging of the s and p shell [12], respectively. Accordingly, at a gate bias smaller than the charging voltage of the first s-state ($V_{g,s1} \approx -0.6$ V) the QDs are empty, and they are fully occupied (6 electrons per dot) at a gate bias larger than 0.4 V. In C–V studies performed on sample #3, no charging peaks could be observed even for frequencies down to 1 Hz because of the height and thickness of the tunneling barrier. Corresponding to the exponential dependence of the tunneling process on the thickness and height of the barrier a much longer retention time is expected and C–V measurements can not be used to characterize the internal electronic structure of the weakly coupled QD/2DEG system of sample #3. Hence, a *frequency-independent* measurement tool has to be used to investigate this structure as described in the following.

We use a time-resolved measurement technique, where the charging state of the QDs can be tuned by a gate voltage, while the conductance of the 2DEG is measured in a two-terminal geometry. Using different charging and emission voltages, applied to the gate contact, allows us to observe the electron tunneling between the 2DEG and the QDs time-resolved. Fig. 2 shows the conductance of sample #2 as a function of time when the gate bias is changed abruptly. For instance, the operation starts with a 600 ms long QD-charging pulse (V_c=0.6 V) applied to the top gate of the macroscopic electron channel. In this case, the Fermi-level E_F is energetically above the highest p-state, tunneling occurs from the 2DEG to the QD states, and hence the QD states are filled with electrons by the nearby 2DEG (schematically depicted in the left inset in Fig. 2). The charged QDs deplete the nearby 2DEG which results in a smaller conductance. This can be understood either as screening of the gate potential by the QD charges or (equivalently) as QD charge induced image charges in the 2DEG. At t=600 ms, a emission bias of V_E=-1 V is applied, such that the Fermi-level E_F is now below the s-states (depicted in the right inset of Fig. 2) and tunneling from the QD states to the 2DEG takes place.

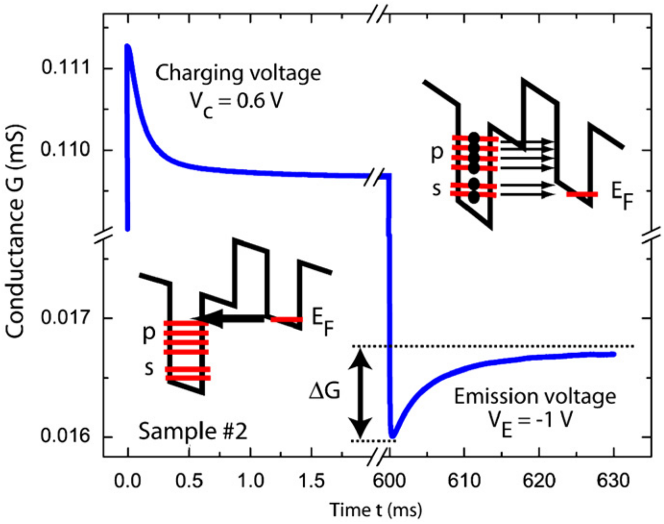

Fig. 2. Emission and charging transients from tunneling events between self-assembled QDs and a 2DEG, measured via the conductance of the 2DEG. The schematic pictures illustrate the corresponding charging and emission process into and out of the QDs, respectively.

To quantitatively evaluate the transient times, Fig. 3 shows the emission and charging transients of Fig. 2 on a semi-logarithmic scale. The emission transient (Fig. 3(a)) shows a multi-exponential decay with time-constants between $\tau_{E,fast} = 1$ ms and $\tau_{E,slow} =$ 20 ms. Because tunneling is fastest out of high-energy states and slowest out of the low-energy states, we attribute the escape rate around $\tau_{E,fast} = 1$ ms to tunneling out of p-state, the tunneling times of the s-states can be roughly limited up to $\tau_{E,slow} = 20$ ms. This is in acceptable agreement with the frequency-dependent C–V measurements mentioned above with $\tau_p \approx 1.4$ ms and $\tau_{s1} \approx 6$ ms if the difficulties of estimating multi-exponential decays are considered [14].

The charging process (Fig. 3(b)) also reflects a multi-exponential transient. Surprisingly, however, only time-constants τ_c between 1 and 2 ms are observed (see corresponding linear fits in red). This discrepancy can be understood as a result of

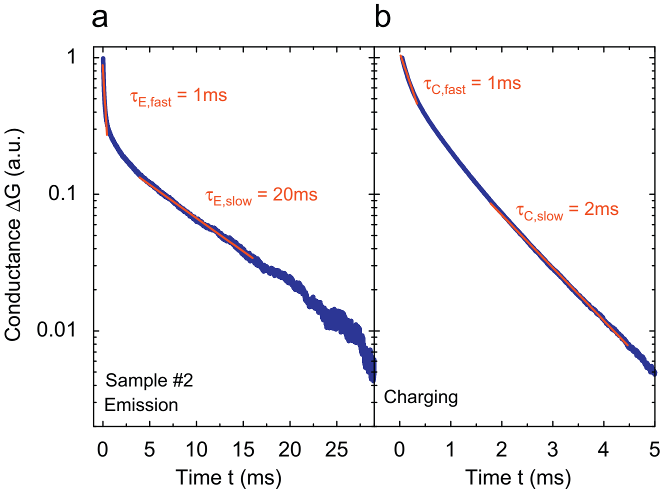

Fig. 3. The normalized amplitude ΔG of the emission (a) and charging transient (b) from Fig. 2 on a semi-logarithmic scale. The charging and emission transients show a multi-exponential behavior, however with different tunneling times.

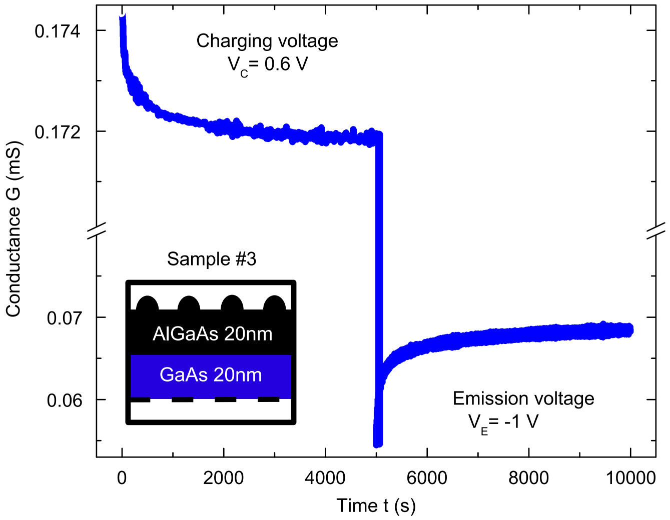

Fig. 5. Emission and charging transients from tunneling events between self-assembled QDs and a 2DEG (for sample #3) at 4 K.

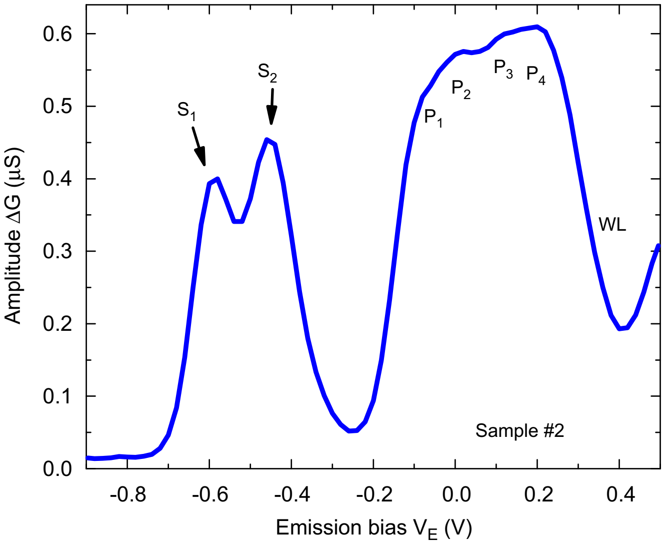

Fig. 4. The amplitude ΔG of the transients versus emission bias. The six individual charging peaks confirm that the transients are caused by electron tunneling from the QD states into the 2DEG.

non-equilibrium tunneling processes as depicted by the insets in Fig. 2. During the emission process, the s-electrons have to penetrate a relatively high tunneling barrier (lowest arrows in Fig. 3, right). During the charging process, on the other hand, because of the large positive bias, the electrons are all injected into high-lying states with short tunneling times. The subsequent relaxation processes ($p \rightarrow s$) are known to be of the order of picoseconds for electrons in self-assembled QDs [15].

To compare the time-resolved measurements with standard CV data (see Fig. 1(b)) we use a boxcar evaluation method [16]. This method is similar to the previously discussed operation. However the pulse amplitude is now $\Delta V = 40\,\text{mV}$, so that only an individiual QD state is probed. The emission bias V_E is scanned from -1 (depleted QDs) to 0.6 V (competely filled QDs). Fig. 4 shows the transient amplitudes ΔG (see Fig. 2) versus the applied emission bias V_E. Six individual charging peaks related to the occupation of the s and p shells of the dots can be observed with a resolution comparable to the best C–V spectra (see Ref. [9] and Fig. 1(a)). Furthermore, these data confirm, that the observed transients are indeed caused by tunneling between the 2DEG and the QDs.

As mentioned above, capacitance studies cannot be used to probe the sample #3 because of the very long tunneling times of the charge carriers. Charging transients, however, can be recorded on time scales well above 10^4 s. Fig. 5 shows the time-resolved conductance of the 2DEG of sample #3 when the gate voltage is changed abruptly and indeed we are able to observe conductance transients which are six orders of magnitudes slower than the transients of sample #2 (see Fig. 2).

The amplitude of the charging transients of sample #2 and #3 are both of the order of 1% for different thicknesses of the spacer layer. This observation and hysteresis measurements (see Ref. [5]) predict, that every charge carrier stored inside the QDs depletes one charge carrier inside the 2DEG if the spacer layer is undoped, hence no depletion layer is formed. Increasing the thickness of the spacer layer will consequently not affect the amplitude of the conductance signal in the time-resolved measurements and could enable very sensitive measurements even for very weakly coupled systems. Furthermore, the transients measurements offer the possibility to study the carrier dynamics of single self-assembled QDs, as the conductance of the 2DEG is determined by its length-to-width ratio rather than the total area. The observed signal $\Delta G/G = N \times n_{QD}/n_{2DEG}$ (where N is the average charge occupation number per dot) is constant for a given QD density n_{QD} and carrier density n_{2DEG} in the 2DEG.

In the semi-logarithmic plot of the charging and the emission transients of sample #3 (see Fig. 6) two different time constants can be monitored. The measured emission and the charging transients are very similar. The fast decay has a time constant of about 300 s, whereas the slow decay has a time constant of 4000 s. Since the dominate tunneling time of 4000 s is the same for both charging and emission, we attribute it to tunneling into and out of the p-states. From a comparison with the results in Fig. 3, we expect tunneling out of the s-state to have a ten times longer decay time of 40 000 s. Because of the averaging process of many transient to get a good signal-to-noise ratio, such a time scale is not accessible in this experiment. The fast decay time of 300 s in sample #3 is not yet fully understood and could be attributed to tunneling into the wetting layer. In principle, tunneling into the wetting layer could also be present for sample #2 with an estimated time scale of 0.2 ms. This decay,

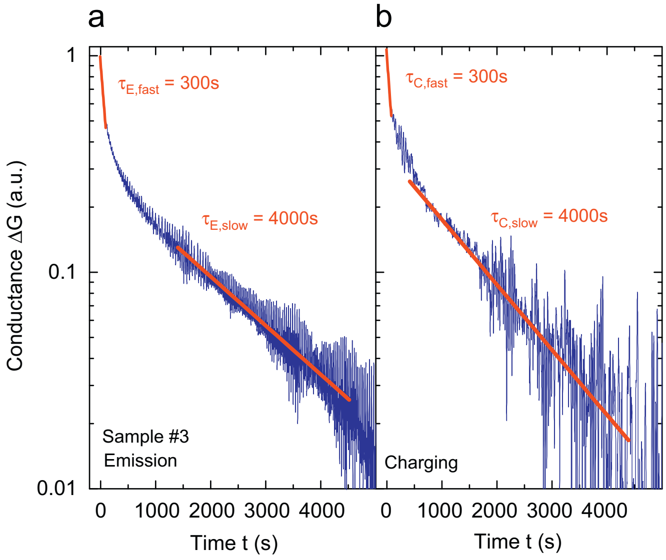

Fig. 6. The normalized amplitude ΔG of the emission (a) and charging transient (b) from Fig. 5 on a semi-logarithmic scale (sample #3).

however, would be masked by the RC-time constant of the present sample which is roughly 1 ms. Further studies with an improved setup that allows measurements with extended time scales are needed to clarify the role of tunneling into the wetting layer.

In conclusion, we introduced a novel technique which enables to extend the experimental range regarding both tunneling dynamics and number of probed QDs. We could shown that the conductance of the 2DEG can be used as an efficient detector to study the charge tunneling dynamics of the nearby self-assembled QDs. The observed signal ΔG is independent on the coupling strength of the heterostructure. Therefore, the technique can be used as a characterization tool for the investigation of very weakly coupled low-dimensional electron systems with long retention times and single QD resolution in the future.

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