A 2D Electron Gas for Studies on Tunneling Dynamics and Charge Storage in Self-assembled Quantum Dots

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

Keywords: III-V semiconductors, indium compounds, self-assembly, semiconductor quantum dots, tunnelling, two-dimensional electron gas.

For the last 15 years, self-assembled quantum dots have attracted much attention because of their special electronical behavior as *artificial atoms* [1]. These systems are of great interest, not only for studying the fundamental properties of the 0D-electron system, but also because of possible device application like flash memories, single electron devices or single photon sources [2,3,4]. To realize such possible applications the carrier charging and emission characteristics are of importance. Previous work has shown that the capacitance-voltage (C-V) spectrocopy is a valuable tool to study electronic structures und charge carrier dynamics of coupled low-dimensional electron systems [5,6]. However, these capacitance measurements have their experimental limitations in both time and spatial resolution [7] and studying single QDs with long retention times is almost impossible using C-V spectroscopy. We present here a new method that enables us to detect the tunneling dynamics with high spatial and time resolution.

The mentioned limited time resolution of the frequency-dependent capacitance measurement can clearly be identified in Fig. 1. Three samples with different coupling strenghts between the QDs and the 2DEG were investigated using C-V spectroscopy. The three samples consist of an inverted HEMT structure with embedded self-assembled InAs QDs [5]. The QD layer of the strongly-coupled sample #1 is separated from the 2DEG by a 25 nm thick GaAs-tunneling barrier

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from the 2DEG [as schematically shown in the inset of Fig. 1(a)]. The tunneling barriers of sample #2 and #3 consist of a 10 nm and 20 nm $Al_{0.34}Ga_{0.64}As$, respectively, and 20 nm GaAs [see the insets of Fig. 1(b) and (c)]. 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. At low temperature (all measurements were performed at 4.2 K) sample #1 can be well characterized by C-V spectroscopy [Fig. 1(a)]. The observed maxima in the capacity can be directly linked to the individual electron states of the QDs [5,6,7,8]. Figure 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 [6]. 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.

Figure 1(b) depicts the capacitance versus the gate bias of a weakly-coupled electron system. Using frequency-dependent C-V spectroscopy [6], 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)] allows us to identify the double-peak structure around -0.5 V and the broad feature between -0.2 V and 0.4 V with charging of the s and p shell [8], 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

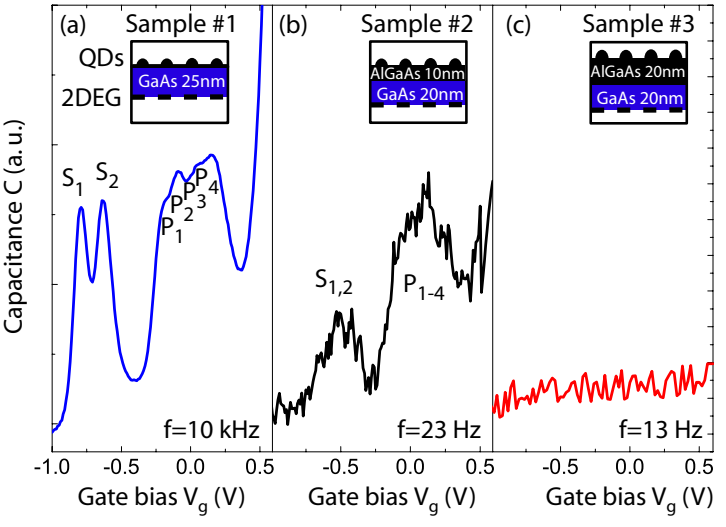

Fig. 1. C-V spectra of three samples (#1, #2 and #3) with different coupling strengths between the QDs and a 2DEG, adjusted by different thicknesses and compositions of the AlGaAs/GaAs tunneling barrier

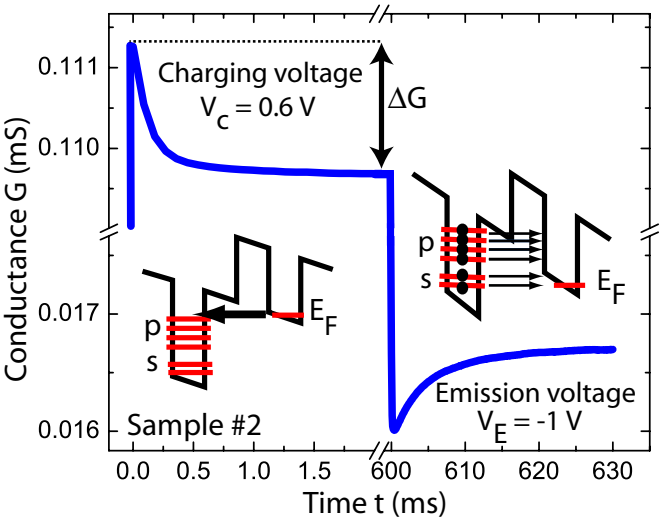

Fig. 2. Charging and emission transient of sample #2

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 [see Fig. 1(c)], 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 such very weakly-coupled QD/2DEG system as for sample #3. Hence, a different *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 is altered 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. Figure 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 2DEG [schematically depicted in the left inset in Fig. 2]. The charging of the QDs depletes the nearby 2DEG which results in decrease of the 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, an emission bias of V_E= -1 V is applied, such that the

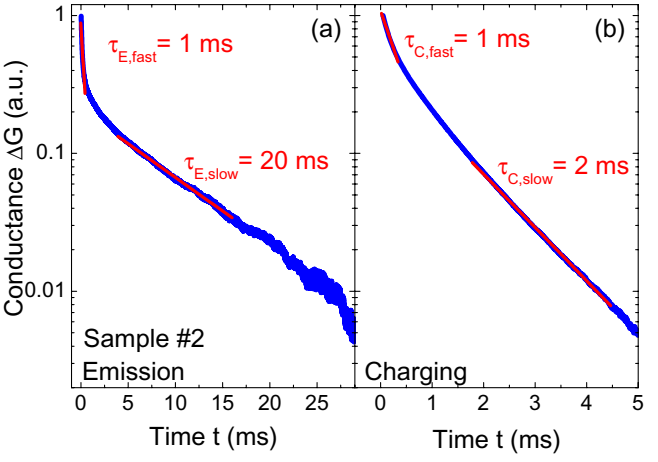

Fig. 3. Charging and emission transient of sample #2 in a semi-logarithmic plot

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.

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 fast for high-energy states and slow for low-energy states, we attribute the escape rate of $\tau_{E,fast}$= 1 ms to tunneling out of the p-states. The tunneling times of the s-states can be determined to be $\tau_{E,slow}$= 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 [9].

The charging process [Fig. 3(b)] also reflects a multi-exponential transient. Surprisingly, however, only time-constants τ_c between 1 ms and 2 ms are observed (see corresponding linear fits in red). This discrepancy can be understood as a result of 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. 2, right). During the charging process, on the other hand, because of the large positive bias, the electrons can be all injected into high-lying states with short tunneling times. The subsequent relaxation processes (p→s) are known to be of the order of picoseconds for electrons in self-assembled QDs [10].

To compare the time-resolved measurements with standard CV data [see Fig. 1(b)] we have used in the past the *charge-selective* method [11] and evaluated the transients to obtain a high-quality charging spectrum of the dots [12]. A similar operation, which is based on time-dependent conductance measeurments

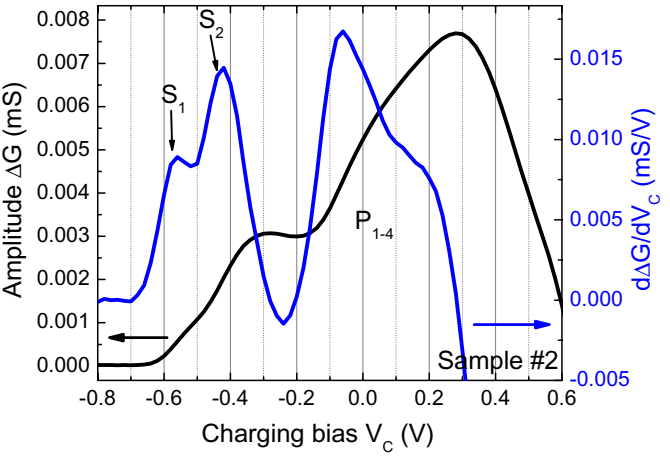

Fig. 4. Conductance amplitude ΔG (black line) and its derivative (blue)

is described in the following. The operation cycle starts with a QD depletion pulse (depletion bias V_{depl}= -1 V) and a following charging pulse (charging bias V_C= 0.6 V). The depletion bias is constant, whereas the charging bias is scanned from 0.6 V (fully occupied dots) to -1 V (empty dots).

Figure 4 depicts the charging transient amplitude ΔG [see Fig. 2] and its derivative (blue curve) as a function of the applied charging bias. The conductance amplitude ΔG of the charging transient depends on the number n_{QD} of the involved QDs and the average number N of occupied QD states. By changing the charging bias V_C, the number of occupied states N(V_C) can be tuned. From the C-V data [see Fig. 1(b)] the charging voltage of the QD states is known. Between -0.8 V and -0.7 V no QD states will be charged, hence, no transient (amplitude) can be measured. When the ground state s_1 becomes occupied at about V_c= -0.6 V the transient amplitude increases. A small change in the curve can be observed if the second s-state is charged with electrons at -0.5 V. This change in the conductance amplitude due to the s-state charging can be well resolved in the first derivative [blue curve in Fig. 4]. The amplitude ΔG saturates between -0.3 V and -0.2 V as the number of involved QD states N is now constant (N=2) and start to raise again while the p-states are charged with electrons. The maximum ΔG is observed when all QD states are filled (V_c= 0.3 V). For a charging bias V_c>0.3 V the amplitude decreases again as no further QD states can be charged. The derivative of the amplitude offers a much better resolved charging spectrum (with two s-states maxima and a broad peak of the p-states) than the C-V curve in Fig. 1(b).

As mentioned above, capacitance studies can not 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. Figure 5 shows the time-resolved charging and emission transients of the 2DEG of sample #3 on a semi-logarithmic scale and indeed we are able to observe conductance

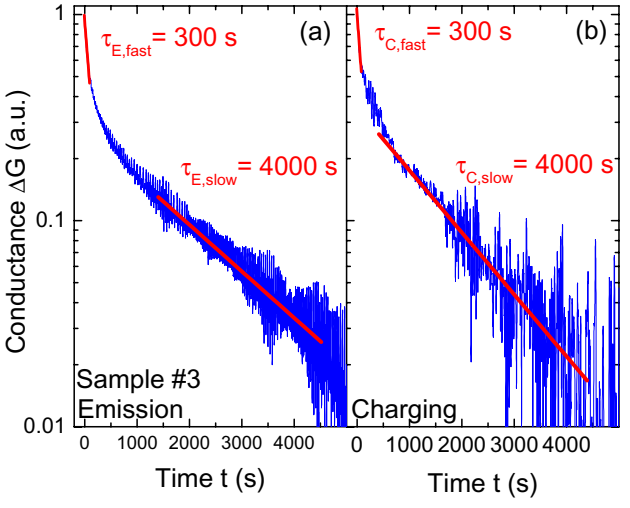

Fig. 5. Charging and emission transient of sample #3 in a semi-logarithmic plot

transients which are six orders of magnitudes slower than the transients of sample #2 [see Fig. 3].

In Fig. 5 two different time constants of the charging and the emission transients of sample #3 can be observed. The 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. We attribute the fast conductance decay to tunneling into and out of the InAs wetting layer and the slow decay to tunneling into and out of the highest p-level. The main difference to measurements of sample #2 [see Fig. 3] is the fact that the tunneling times of the charging process do not differ from the emission process. One possible explanation is that the emission transient in Fig. 5 are not only be given by tunneling but also by thermal excitation of the carriers. At 4.2 K (kT≈0.4 meV) thermal excitation of the order of 50 meV is extremely weak, which explains why it is not observed for sample #2. For sample #3 however, the extremely long retention times may allow electrons from the s-state to escape by a combined process of thermal excitation into the p-state and successive tunneling to the 2DEG. Further measurements and calculations are needed to test this model.

The present devices with very weakly coupled low-dimensional electron systems together with real-time conductance measurements enable us to decouple the applied gate bias from QD charge occupation.

The fact that non-equilibrium states can be prepared in the present sample makes them promising for charge storage as discussed in the following. Figure 6 shows the transfer characteristics of the sample, i. e. the conductance of the 2DEG versus the gate bias for three different scan times. The measurement cycle starts with a 200 ms long discharging pulse (V_{depl}= -1 V), which depletes

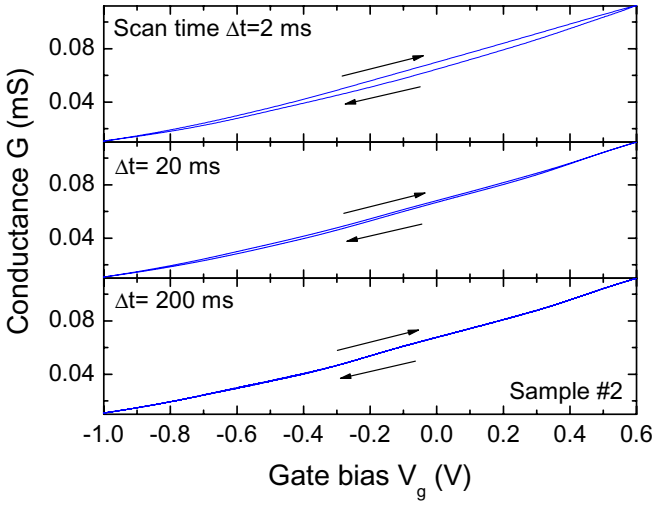

Fig. 6. Hysteresis measurements of sample #2 with different scan times Δt

the InAs QDs as discussed above. Fast bias sweeps (Δt= 2 ms, 20 ms and 200 ms) from the depletion voltage upward to the filling voltage (V_{fill}= 0.6 V) follow. As a consequence, during the fastest sweep [$\Delta t \geq \tau$, see Fig. 6(a)] the QDs remain empty during the entire upward sweep and the 2DEG remains unaffected by the (empty) states of the QDs. Next, during a 200 ms long charging period at a gate bias V_{fill} of 0.6 V, the QDs become completely charged. The reduction in the charge carrier density lowers the conductance of the 2DEG, resulting in the observed hysteresis. The hysteresis decreases by increasing the scan time and, hence, vanishes for sweep times longer than 200 ms, the longest charge carrier storage time in the QD ensemble [see Fig. 6(c)]. The measured hysteresis opening $\Delta G/G$ in Fig. 6(a) for a gate bias of 0 V is about 10 %. In comparison, the relative change in 2D carrier density between fully charged dots (6 electrons per dot) and empty dots amounts to $\Delta n/n \approx 7$ % at V_g= 0 V. Using an approximately constant mobility [5] leads to $\Delta G/G \approx 7$ %, in good agreement with the measured value. Thus, we are able to switch between two different QD charge occupation levels (completely full and empty QDs) for the same applied gate bias. This further supports the conclusion that the observed hysteresis is indeed given by the different QD charging states.

Using Gauss' law to model the three layer system (gate, dot layer, 2DEG) [5] it can easily be shown that for every electron transferred into the QD layer roughly one electron will be depleted from the 2DEG. Equivalently this can be understood either as screening of the gate potential by the QD charges or as QD-charge-induced image charges in the 2DEG. The reduction of the charge carrier density lowers the conductance of the 2DEG, resulting in the observed hysteresis [15].

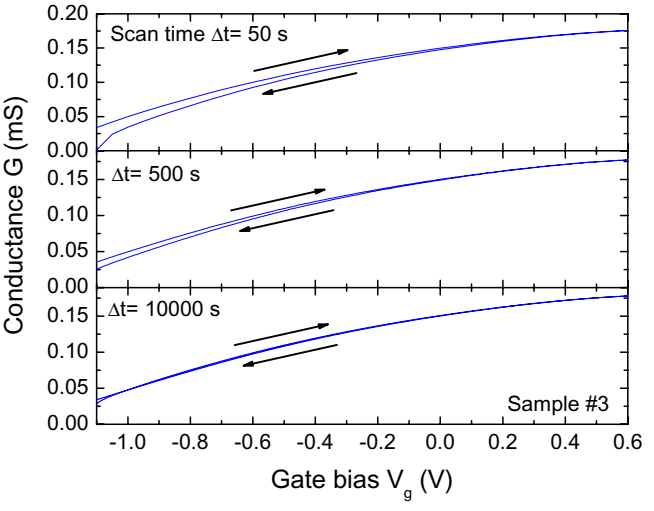

Fig. 7. Hysteresis measurements of sample #3 with different scan times Δt

Figure 7 shows hysteresis measurements of sample #3 for three different scan times Δt. Similar to hysteresis meaurements of sample #2 [see Fig. 6], the hysteresis opening becomes smaller if the scan time Δt is raised. For scan times slower than 10 000 s the hysteresis opening completely vanishes. This is in good agreement with the observed time constants of the transients [see Fig. 5]. This confirms the assumption that the charge storage in the QDs causes the measured hysteresis also for sample #3. Furthermore, because of the low 2DEG charge carrier density of sample #3 ($n_{2DEG}= 3\times10^{11}cm^{-2}$), the hysteresis opening can be enhanced to about 30 % which is of central importance for using a 2DEG as a sensitive read-out in future QD-based memories [16].

In conclusion, we introduced a novel technique which enables to extend the experimental range regarding both tunneling dynamics and number of probed QDs. We have 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 QD-layer. 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.

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