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Time-resolved detection of many-particle hole states in InAs/GaAs quantum dots using a two-dimensional hole gas up to 77 K

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We demonstrate the detection of many-particle hole states in self-organized InAs/GaAs quantum dots (QDs) using an adjacent two-dimensional hole gas (2DHG) as detector for temperatures up to 77 K. capacitance-voltage (C-V) measurements as well as time-resolved current measurements in the 2DHG resolve a structure of six distinct peaks which are related to the many-particle hole states in the QD ensemble. The time constants of the capture and emission processes for each individual many-particle hole state are extracted and the underlying emission processes are identified. An equivalent circuit model yields the gate voltage depedent lever-arm and the level-splittings of the many-particle hole states.

1 Introduction The storage capacity in semiconductor memories has increased in the last decades by an aggressive downscaling of the feature size, reaching for the market driver (the Flash memory [1]) 19 nm in 2011, and a few hundred electrons per bit. If the trend continues [2], length scales will reach a few nanometers soon and the read-out of the few storage electrons via a two-dimensional electron channel will become important. Due to their discrete density of states and their small sizes self-organized quantum dots (QDs) [3] are ideal systems to study the coupling of confined carriers to an adjacent two-dimensional system (2DEG or 2DHG). QDs facilitate carrier confinement also at temperatures higher than some mK and are also advantageous to study many-particle effects, such as Coulomb charging or spin states in non-equilibrium [4,5] at higher temperatures. Furthermore, QDs are very promising for memory units with nano-scale feature sizes. The feasibility of such a QD-based Flash memory has been demonstrated recently [6,7].
In this paper, we study the coupling between self-organized InAs/GaAs QDs and an adjacent two-dimensional hole gas (2DHG) at temperatures ranging from 4 K to 100 K. Capacitance-voltage (C-V) measurements and time-resolved measurements of the source-drain current in the 2DHG reveal the discrete electronic structure of the InAs/GaAs QDs and give access to the many-particle hole states of the QD ensemble.

2 Many-particle hole states

2.1 Samples We have studied two MBE-grown samples which are identical except for their tunneling barrier width. A single InAs/GaAs QD layer is embedded into a GaAs quantum well (QW) inside a nominally undoped $Al_{0.9}Ga_{0.1}As$ matrix. Underneath the QD layer a 2DHG is formed inside another GaAs QW. The holes are provided by a 30 nm wide p-doped (2×10^{18} cm^{-3}) layer which is separated by a 7 nm spacer from the QW. Structure A has a tunnel barrier between the QD layer and the 2DHG with a width of 18 nm (5 nm $Al_{0.9}Ga_{0.1}As$ and 13 nm GaAs) while the tunnel barrier width in struc-

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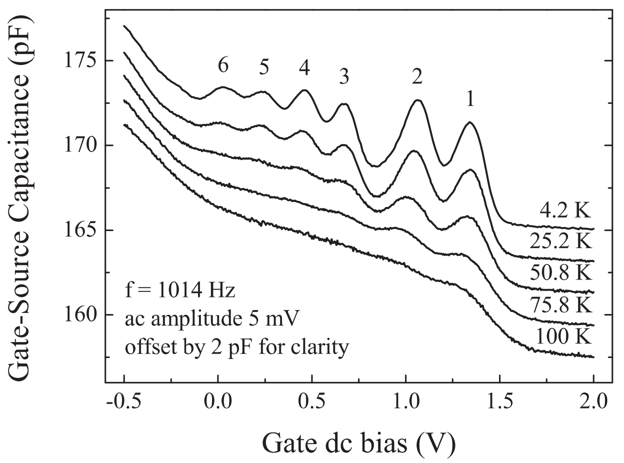

Figure 1 Structure A: C-V measurements at different temperatures showing the distinct peaks of the many-particle hole states.

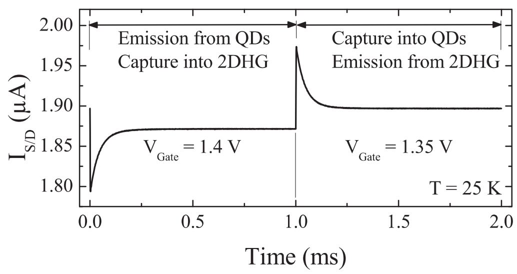

Figure 2 Emission and capture transients in the source/drain current for structure A.

ture B is 23 nm (10 nm $Al_{0.9}Ga_{0.1}As$ and 13 nm GaAs). Hall-bar mesa structures were fabricated using standard wet-chemical etching. Ohmic source/drain contacts were formed depositing a Ni/Zn/Au alloy and subsequent annealing to contact the 2DHG layer. The gate contact was formed by Ni/Au.

2.2 C-V measurements Capacitance-voltage measurements (C-V) have been a valuable tool to determine the electronic properties of QDs [8–13]. The differential capacitance ($C = dQ/dV$) is equivalent to the number of charges which is transferred by the applied ac voltage during the measurement at a constant dc bias. Here, the samples are designed in such a way that the Fermi level can be energetically aligned to the ensemble broadened peaks in the density of states of the QDs by applying an appropriate gate bias. When such an alignment occurs the tunneling probability is enhanced and the increase in the tunneling current leads to an increase in the differential capacitance C.

Figure 1 depicts the gate-source capacitance measurement of structure A. The dc gate bias was swept from 2 V to -0.5 V, subsequently filling up the QDs. The measurement ac voltage was 5 mV and the frequency 1014 Hz. The measurements were taken at temperatures ranging from 4.2 K to 100 K. A total of six peaks can be seen in the C-V curves up to a temperature of 50 K. At temperatures above 50 K only the first two peaks are observed. At a voltage of 1.34 V the Fermi level is aligned with the ground state in the density of states in the QD ensemble, so one hole per QD is transferred between the 2DHG and the QDs. In the unoccupied QDs the ground state is two-fold degenerate. By decreasing the gate bias a second hole is transferred to the QDs. Since the QDs already contain one hole, the next quantum state is a two-hole state with an energy difference to the one-hole state due to the Coulomb repulsion. The Coulomb repulsion leads to a lifting of the degeneracy of the ground state, and the energy level is shifted to higher energies with respect to the unoccupied ground state energy level [14]. Hence, the second hole transfers to the QDs at a gate voltage of about 1.1 V. A further decrease of the gate bias leads to the filling of the higher energy levels. Thus, the C-V peaks are caused by the many-particle hole ground states in the QD ensemble and resemble the difference between the n-th and (n+1)-th many-particle hole ground state (including quantization energy, Coulomb and exchange interaction) [14]. At gate voltages lower than -0.25 V the holes start to tunnel into the states of the GaAs QW into which the QDs are embedded, and the capacitance increases.

2.3 Current measurements C-V measurements are only possible for a certain range of time constants and are here limited to static measurements. Thus the carrier dynamics were studied with time-resolved measurements of the 2DHG current, using a method that has successfully been applied already to a similar structure based on electrons [4]. For structure A the gate pulse bias offset is swept in 10 mV steps and at each step a pulse of 50 mV is applied to change the energetic position of the QDs relative to the Fermi level. Holes that are transferred by the pulse from the 2DHG to the QDs (or vice versa) reduce (increase) the conductance in the 2DHG, an effect that can be directly measured via the source/drain current. A time-resolved measurement of the source/drain current of structure A is shown in Fig. 2. The transients resemble the emission and capture processes between the QD ensemble and the 2DHG. The amplitudes of the transients are a measure for the number of holes that are transferred during each pulse. Plotting the amplitudes versus the gate dc bias at which the transient was measured, a structure equal to the one observed in the C-V measurements can be observed (Fig. 3). Due to the parasitic device cut-off frequency the time constants cannot be analyzed in structure A. In structure B the situation is different. Due to the thicker tunnel barrier, the time constants of the emission and capture processes are about six orders of magnitude larger. While the device cut-off frequency is in the same range as for structure A, the time constants are in the range of seconds. Hence, the time constants involved are related to the emission and capture processes and can be analyzed. Again, we sweep the gate pulse offset in 10 mV steps, while setting

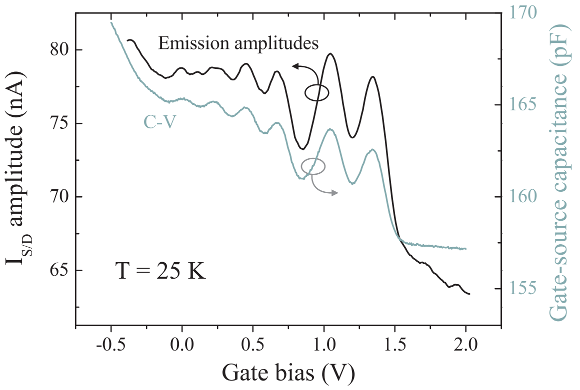

Figure 3 Structure A: Emission transient amplitudes versus the respective gate bias (black curve). The amplitudes resemble a curve similar to the C-V measurement (grey curve).

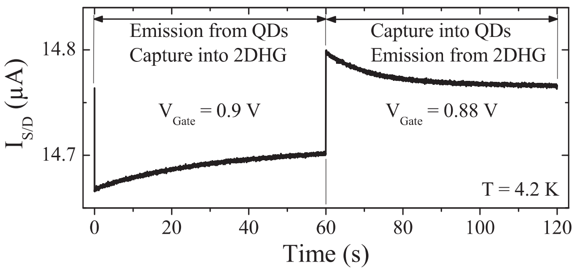

Figure 4 Emission and capture transients in the source/drain current for structure B corresponding to Peak 1.

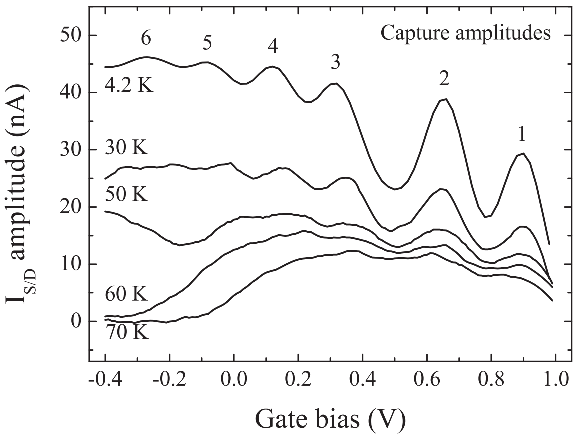

Figure 5 Structure B: Capture amplitudes versus the respective gate bias. The curves show a peak structure similar to structure A.

the pulse amplitude to 20 mV. The source/drain voltage is kept at 30 mV. The emission and capture transients for a pulse bias offset of 0.88 V are shown in Fig. 4. The amplitudes of the transients being equivalent to the number of charges that are transferred during the pulses, yield a peak structure similar to the one obtained for structure A (Fig. 5). Similar to Fig. 1 for structure A a total of six peaks can be seen in Fig. 5. When increasing the temperature the peak structures vanish. Up to 30 K all peaks can still be seen while at 50 K only the first few peaks can be distinguished. The strong decrease of the amplitudes with higher temperatures at voltages below 0.2 V is the result of decreasing time constants of the capture process which becomes too fast for the measurement window.

2.4 Emission and capture time constants The emission and capture transients measured for structure B are mono-exponential and the time constants can be easily extracted. The time constants for the capture and emission processes in the QD ensemble are depicted in Fig. 6, showing the evolution of the time constants for each individual peak with temperature. At 4 K the time constants of the peaks are all in the same order of magnitude. At this temperature the dominating emission and capture process is tunneling. Increasing the temperature, the time constants for the many-particle states with higher energy begin to decrease. Here, thermally-assisted tunneling is the dominating process, where the holes are thermally activated to a higher state and then tunnel through the barrier [15, 16]. Further increasing the temperature increases the contribution of the thermal energy to the emission and capture processes, such that also the time constant of the ground state begins to decrease.

2.5 Level splittings The level splitting of the many-particle hole states in the InAs/GaAs QDs can be extracted from the peak structures by using an equivalent circuit model, in which the QD ensemble and the GaAs QW, into which the QDs are embedded, are treated as quantum capacitance and the rest of the device as two geometrical capacitances. The quantum capacitance is $C_q(E) = C_{QD} + C_{QW} = e^2(D_{QD}(E) + D_{QW}(E))/A$, where e is the elementary charge $D_{QD,QW}(E)$ the density of states of the QD ensemble and the QW, respectively, and A the active gate area. The geometric capacitances from the gate to the QD layer and from the QD layer to the 2DHG, respectively, are $C_{1,2} = \epsilon_r \epsilon_0 A/d_{1,2}$ with the relative dielectric constant ϵ_r, the vacuum electric constant ϵ_0, the active gate area A, and the distance $d_{1,2}$ between the respective layers. The total capacitance is then[17]

$$C_{tot}(E) = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2 + C_q(E)}}. \tag{1}$$

The density of states of the QD ensemble is assumed to consist of six Gaussians, while the density of states of the QW consists of only a broad Gaussian (Fig. 7a). The peak positions of the Gaussians in the density of states are manually adjusted until they fit the peak positions of the measurement (Fig. 7c). The width of the Gaussians gives an estimate of the inhomogeneous broadening in the QD ensemble of 9 meV. Figure 7b gives the lever-arm which is the ratio of the change of gate voltage to change in the energetic position of the QD ensemble. Due to the accumu-

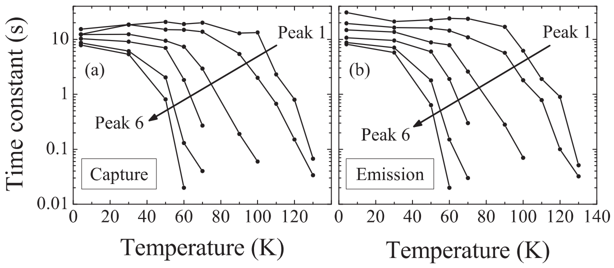

Figure 6 Structure B: Time constants of the (a) capture of holes into the QDs and (b) emission of holes from the QDs.

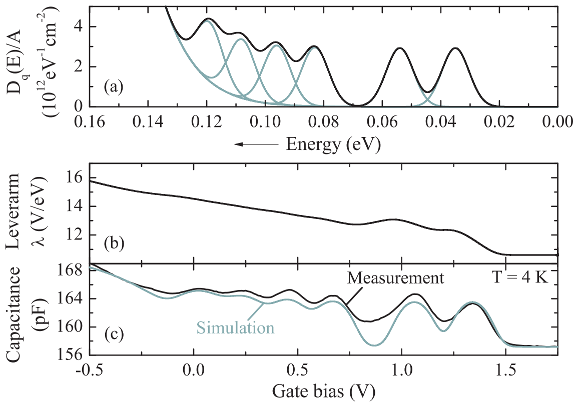

Figure 7 Structure A: (a) The density of states in the QD ensemble and the QW. (b) Calculated lever-arm in dependence of gate voltage. (c) Calculated and measured C-V curves of structure A at 4 K.

Table 1 Level-splittings of the many-particle hole states in structures A and B derived from the eauivalent circuit model.

Peaks	Structue A (meV)	Structure B (meV)
1,2	19(1)	21(1)
2,3	29(1)	31(1)
3,4	13(1)	14(1)
4,5	12(2)	13(2)
5,6	11(2)	12(2)

lation of holes in the QDs with decreasing gate voltage the lever-arm increases from about 11 for unoccupied QDs to about 14 after six holes have been captured into the QDs. The level-splittings of the structures A and B are listed in Table 1.

3 Conclusion We have studied the coupling between an ensemble of self-organized InAs/GaAs QDs with an adjacent 2DHG. A structure with strong coupling (small tunneling time constants) was studied by static C-V measurements yielding a distinct structure of six peaks, caused by the many-particle hole ground states in the QD ensemble. Another structure with weak coupling (large tunneling time constants) was studied by transport spectroscopy, where the tunneling dynamics is monitored by a conductance change in the 2DHG. From the amplitudes of such measurements a curve similar to the one obtained from the C-V measurements could be derived, which also shows six distinct peaks of the many-particle hole states in the QD ensemble. The time constants of the capture and emission processes at each individual peak were extracted and analyzed, and show a transition from pure tunneling to thermally-assisted tunneling. From an equivalent circuit model the level splittings of the many-particle hole states in both structures were extracted.
The C-V and time-resolved current measurements have shown that the 2DHG is sensitive to detect many-particle hole states in a QD ensemble at temperatures up to 77 K.

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