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The influence of charged InAs quantum dots on the conductance of a two-dimensional electron gas: Mobility vs. carrier concentration

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Using time-resolved transport spectroscopy, we investigate the influence of charge-tunable InAs quantum dots (QDs) on the conductance of a nearby two-dimensional electron gas (2DEG). Loading successively electrons into the self-assembled QDs decreases the carrier concentration and mobility in the 2DEG. We are able to quantify how these transport properties change for each additional charge in the s- or p-shell. It is found that mobility and carrier concentration contribute equally to the overall change in conductance. © *2011 American Institute of Physics*. [doi:10.1063/1.3665070]

Many applications based on self-assembled semiconductor quantum dots (QDs) have been realized in recent years, such as for instance high-performance QD lasers,[1,2] amplifiers[3] as well as single and entangled photon sources.[4,5] Furthermore, these nanometer-sized islands in a solid state environment may be used in more visionary future applications, such as building blocks in quantum information processing[6,7] or QD memory devices.[8] Just recently, it has been shown that an all-electrical preparation and detection of excited many-particle spin states[9] is possible for self-assembled QDs, an achievement that had previously only been obtained in lithographically defined quantum dots.[10,11] A crucial point for electrically controlled quantum and memory devices based on self-assembled QDs is the read-out of their charge and spin state. Coupling the zero-dimensional dots to a two-dimensional electron gas (2DEG) by Coulomb interaction enables such a read-out by a measurement of the conductance of the 2DEG. Hence, a detailed understanding of the interfacing between self-assembled QDs and a 2DEG is essential for the development of such devices.

Many investigations were performed over the last years in order to study how charged QDs influence the transport properties of a nearby 2DEG. One of the first experiments was done by Sakaki *et al.*,[12] who reported on a rapid mobility decrease when the tunneling barrier, which separates the dots from the 2DEG, is reduced. Zhukov *et al.*[13] have shown that the mobility can even be enhanced when the electrons inside the dots are not the dominant scattering source in the system. Ribeiro *et al.*[14] and Kim *et al.*[15] studied the transport properties of a 2DEG containing a InAs QD layer. In prior work, we developed a general model to determine the charging states of coupled low-dimensional systems[16] and calculated the influence of charged QDs as Coulomb scatters on the mobility of the 2DEG.[17]

Until now, however, it is not clear which properties of the QD electrons affect the conductance of the 2DEG dominantly. Is the change in the conductance in the 2DEG mainly due to a change in the mobility or charge carrier concentration? It is the purpose of this letter to address this question. Using time-resolved transport spectroscopy, we are able to individually determine the contributions of charge and mobility to the overall change of conductivity of the 2DEG. Even though the experiments are performed on an ensemble of QDs, we achieve single electron resolution: The characteristic finger-print, corresponding to the filling of the s- and p-shell with individual electrons, is clearly observed in all transport parameters.

The investigated sample was grown by molecular beam epitaxy and consists of an inverted high electron mobility transistor structure with embedded self-assembled InAs QDs.[16] The active region is sketched in Fig. 1(a). From previous atomic force microscopy (AFM) studies on uncapped QDs grown under similar conditions, an average dot diameter of 23 nm and an average height of 7 nm with a standard deviation of approximately 10% were obtained. The layer of self-assembled InAs QDs is separated from the 2DEG by a tunneling barrier of 30 nm thickness. The 2DEG has two functions: (a) It supplies the electrons which occupy the different many-particle states in the dots and (b) its conductance serves as a sensitive QD charge detector.[18] On this heterostructure, we have prepared a macroscopic Hall-bar device with a metallic top gate using standard photolithographic techniques (see Fig. 1(b)). The top gate electrode controls the occupation level of the dots electrostatically. The gated electron channel area is $5 \times 10^3\ \mu m^2$ which corresponds to about 4×10^5 probed QDs.

An appropriate pulse sequence (pulse amplitude $\Delta V_G = 40$ mV) applied to the gate electrode in combination with the simultaneously time-resolved recorded conductivity of the 2DEG enables us to prepare and probe individual many-particle ground states with different numbers of electrons.[18,19] Here, we report on an experimental extension of the measurement technique that makes it possible to probe both transport parameters of the 2DEG separately, i.e., the carrier concentration and the mobility. The time-resolved transport spectroscopy was performed in a four point geometry at liquid He temperatures (see Fig. 1(b)) by applying a constant source-drain current ($I_{SD} = 3.2\ \mu$A) and measuring the longitudinal (V_x) and transverse (V_y) voltages in an applied magnetic field of $B = 0.5$ T. For small magnetic

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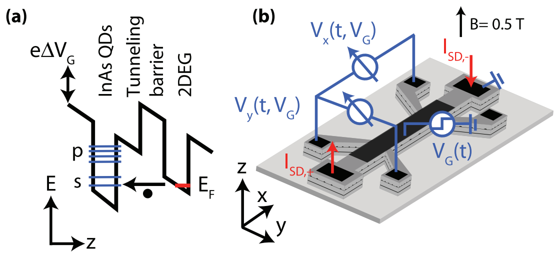

FIG. 1. (Color online) (a) Schematic conduction band profile of the active region. (b) Schematic of the gated Hall-bar device.

fields ($\mu_{2D}B \ll 1$), the mobility μ_{2D} and the carrier concentration n_{2D} of the 2DEG are easily determined using the standard Drude equations.

The gate voltage V_G can be adjusted so that the Fermi level of the 2DEG is set in resonance with an individual empty QD state (as depicted in Fig. 1(a)). The resulting charge transfer between both electron systems will affect both the carrier concentration and mobility of the 2DEG resulting in a change of the conductance. This can be monitored as a time-dependent decrease of σ_{2D}, μ_{2D}, and n_{2D} with an exponential slope corresponding to the electron tunneling time. Figure 2(a) shows the measured charging transients of the conductance σ_{2D}, carrier concentration n_{2D}, and the mobility μ_{2D} for a situation where the QD s_1-states become occupied. For details of the measurement technique and evaluation, see Refs. 18 and 19.

The absolute transient amplitudes for the change in the conductance $\Delta\sigma_{2D}$, carrier concentration Δn_{2D}, and mobility $\Delta\mu_{2D}$, see Fig. 2(a), are evaluated for different applied gate bias V_G and a constant pulse amplitude $\Delta V_G = 40\,\text{mV}$. We obtained three spectra, see Fig. 2(b). Due to the inhomogeneous size distribution of the QDs, the charging peaks are energetically broadened with a full width at the half maximum (FWHM) of about 10 meV. Nevertheless, both s-states ($s_{1,2}$) can be clearly distinguished as well as a broad shoulder attributed to the four p-states ($p_{1\text{–}4}$).[20]

Using the measured spectrum Δn_{2D} (middle panel of Fig. 2(b)) enables us to calculate the buried QD density. First, we have to calculate the density of electrons Δn_{QD} which are stored in the QD layer from the measured Δn_{2D} in the 2DEG. Because an electron stored inside the QD will not fully deplete an electron inside the 2DEG, the value of Δn_{2D} is not *a priori* equal to Δn_{QD}. Following the approach by Russ *et al.*,[16] we find for the given 3-layer system (gate, QDs, 2DEG)

$$\Delta n_{2D}(V_G) = \left(1 - \frac{1}{\lambda}\right)\Delta n_{QD}(V_G). \tag{1}$$

Here, $\lambda = d_{2D}/d_T = 6$ represents the lever arm which is given by the distance of the 2DEG to the surface d_{2D} and the tunneling barrier thickness d_T. The integration of the corrected Δn_{2D} spectrum over the gate bias from the empty dots ($V_{G,empty} = -0.8\,\text{V}$) to the fully filled dots ($V_{G,full} = +0.5\,\text{V}$), see Fig. 2(b), gives the total charge carrier density in the dots of $5.7 \times 10^{10}\,\text{cm}^{-2}$. This corresponds to a QD density of about $9.5 \times 10^{9}\,\text{cm}^{-2}$, taking into account the number of electron states involved ($N = 6$). Scanning electron microscopy studies of similarly grown samples containing InAs QDs on the surface determined a QD density of about $8.3 \times 10^{9}\,\text{cm}^{-2}$, in good agreement with the measured value here.

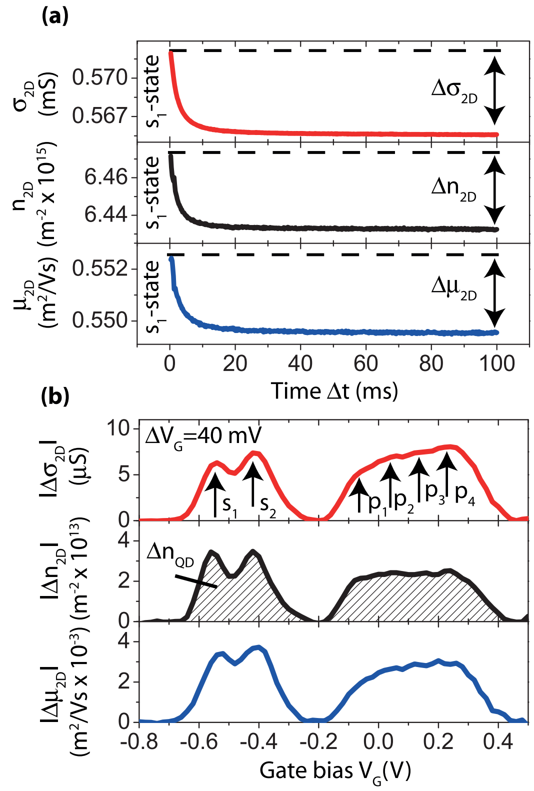

FIG. 2. (Color online) (a) The measured conductance σ_{2D}, charge carrier concentration n_{2D}, and mobility μ_{2D} transients when the QD s_1-states are being charged. (b) Transient amplitudes as a function of gate bias V_G. The many-particle ground states with different numbers of electrons ($N = 1 \ldots 6$) can be distinguished.

In order to quantify the influence that a single electron has on the transport parameters, we evaluate the transients shown in Fig. 2(a) for an elapsed time when the system has reached equilibrium ($\Delta t = 100\,\text{ms}$). Fig. 3(a) shows the obtained values for σ_{2D}, μ_{2D}, and n_{2D} plotted as a function of the gate bias V_G. The shaded areas in Fig. 3(a) indicate the voltage ranges where the dots are being charged. As expected, the conductance, mobility, and charge carrier concentration increase almost linearly as a function of gate bias,[16] i.e., the linear increase of the charge carrier concentration and mobility results in an linear increase of the conductance. Note that the mobility is affected by the charged QDs in two ways: (i) Charged QDs act as Coulomb scatters for the electrons in the nearby 2DEG[17] and (ii) The change in the carrier concentration in the 2DEG due to the charged QDs reduces its screening ability, hence, the Coulomb scattering is indirectly enhanced.

Using these equilibrium spectra in Fig. 3(a) and the amplitudes of the transients in Fig. 2(b), we can now calculate the influence caused by a single electron loaded into a QD state. The conductance of the 2DEG depends on the carrier concentration n_{2D} and mobility μ_{2D}, which again depends on n_{2D}. Taking the derivative of the conductance in the Drude model $\sigma_{2D} = e n_{2D}\mu_{2D}$ leads to

$$\frac{\Delta\sigma_{2D}}{\sigma_{2D}} = \frac{\Delta n_{2D}}{n_{2D}} + \frac{\Delta\mu_{2D}}{\mu_{2D}}. \tag{2}$$

Thus, from the change in conductance $\Delta\sigma_{2D}$ and in carrier concentration Δn_{2D}, we can derive the change in mobility $\Delta\mu_{2D}$. In Fig. 3(b), these three normalized quantities are

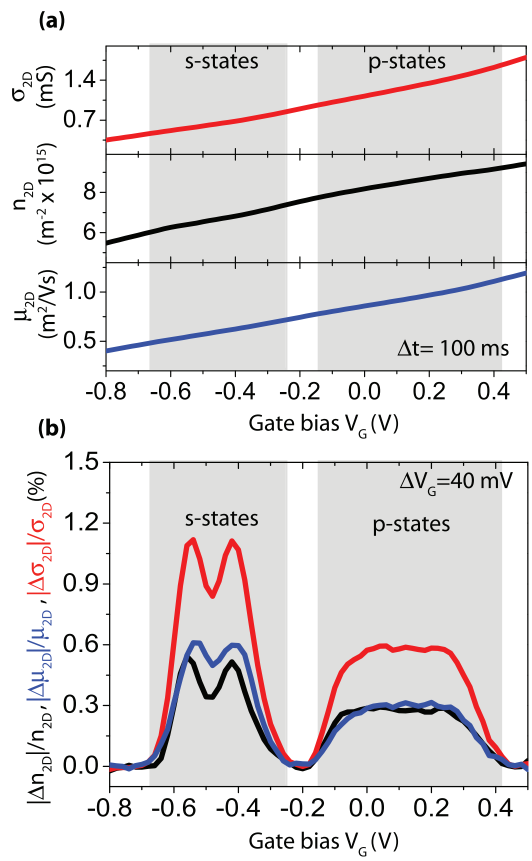

FIG. 3. (Color online) (a) The equilibrium conductance σ_{2D}, carrier concentration n_{2D}, and mobility μ_{2D} of the 2DEG versus gate bias after an elapsed time of 100 ms. (b) The relative change of the three transport parameters in percent for a pulse amplitude of $\Delta V_G = 40$ mV.

shown versus the applied gate bias V_G for a given pulse amplitude $\Delta V_G = 40$ mV. From a comparison of the curves, we find that surprisingly, both charge and mobility contribute equally to the change in conductance.

To obtain the influence of a single confined charge in the s- or p-shell on the 2D transport properties, the curves in Fig. 3(b) have to be integrated over the corresponding voltage range. The results are listed in Table I. For the s-states, the relative change of the 2DEG conductance is about 3.5% per electron. This reduction is composed in almost equal parts from a change in carrier concentration and mobility of about 1.5% and 2.0%, respectively. The influence of the p-states on the transport properties is almost a factor of two smaller mainly due to the overall increase of σ_{2D}, n_{2D}, and μ_{2D} with increasing gate voltage (cf. Fig. 3(a)). The total change in the conductance of 13.4% (two electrons in the s-shell and four electrons in the p-shell) is in perfect agreement with hysteresis measurements performed on the same sample.[18]

In summary, we have reported on the influence of charged InAs QDs on the transport properties of a nearby 2DEG. Using time-resolved transport spectroscopy in a four-point geometry, we were able to quantify the change in the conductance, carrier concentration, and mobility of the 2DEG resulting from adding successively electrons into the s- and p-shell of the dots. The influence of charged QDs on the 2DEG conductance has its origin in almost equal contributions from a change in the mobility and carrier concentration. We believe that these measurements of the different

TABLE I. The influence of the individually resolved charged QD states on the different transport parameters of the 2DEG. The total change results from the sum of the different QD states for two electrons charged into the s-shell and 4 electrons charged into the p-shell.

	Relative change per QD electron		
2DEG-	Conductance (%)	Carrier concentration (%)	Mobility (%)
s-states	3.5	1.5	2.0
p-states	1.6	0.8	0.8
Average	2.3	1.0	1.3
Total change	13.4	6.2	7.2

contributions to the overall conductance can serve as a valuable input for detailed theoretical treatment of coupled zero-dimensional and two-dimensional electron systems. Furthermore, our findings show that coupled QD-2DEG systems may be suitable for velocity modulated transistors (VMT), where the change in conductance is given by gate voltage dependence of mobility rather than the carrier density.[21,22]

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