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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, amplifiers as well as single and entangled photon sources. 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 or quantum memory devices. Just recently, it has been shown that an all-electrical preparation and detection of excited many-particle spin states is possible for self-assembled QDs, an achievement that had previously only been obtained in lithographically defined quantum dots. 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., who reported on a rapid mobility decrease when the tunneling barrier, which separates the dots from the 2DEG, is reduced. Zhukov et al. 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. and Kim et al. studied the transport properties of a 2DEG containing a InAs QD layer. In prior work, we developed a general model based on self-assembled QDs. 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 carrier concentration and the mobility. The time-resolved transport spectroscopy was performed in a four point geometry, which 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...
fields (\(\mu_{2D} B \ll 1\)), the mobility \(\mu_{2D}\) 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 \(\sigma_{2D}, \mu_{2D}\), and \(n_{2D}\) with an exponential slope corresponding to the electron tunneling time. Figure 2(a) shows the measured charging transients of the conductance \(\sigma_{2D}\), carrier concentration \(n_{2D}\), and the mobility \(\mu_{2D}\) 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 \(\Delta n_{2D}\), and mobility \(\Delta \mu_{2D}\), see Fig. 2(a), are evaluated for different applied gate biases \(V_G\) and a constant pulse amplitude \(\Delta V_G = 40\) 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 \(p_{1-4}\).20

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

\[
\Delta n_{QD}(V_G) = \left(1 - \frac{1}{\lambda}\right) \Delta n_{QD}(V_G).
\]  

Here, \(\lambda = d_{2D}/d_f = 6\) represents the lever arm which is given by the distance of the 2DEG to the surface \(d_{2D}\) and the tunneling barrier thickness \(d_f\). The integration of the corrected \(\Delta n_{QD}\) spectrum over the gate bias from the empty dots \((V_G, empty = -0.8\) V\) to the fully filled dots \((V_G, full = +0.5\) V\), see Fig. 2(b), gives the total charge carrier density in the dots of \(5.7 \times 10^{10}\) cm\(^{-2}\). This corresponds to a QD density of about \(9.5 \times 10^9\) 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 \(8.3 \times 10^9\) cm\(^{-2}\), in good agreement with the measured value here.

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 \((\Delta t = 100\) ms\). Fig. 3(a) shows the obtained values for \(\sigma_{2D}, \mu_{2D}\), 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 a 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 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 \(\mu_{2D}\), 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

\[
\frac{\Delta \sigma_{2D}}{\sigma_{2D}} = \frac{\Delta n_{2D}}{n_{2D}} + \frac{\Delta \mu_{2D}}{\mu_{2D}}.
\]  

Thus, from the change in conductance \(\Delta \sigma_{2D}\) and in carrier concentration \(\Delta n_{2D}\), we can derive the change in mobility \(\Delta \mu_{2D}\). In Fig. 3(b), these three normalized quantities are
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 four electrons charged into the p-shell.

<table>
<thead>
<tr>
<th>Table I. The influence of the individually resolved charged QD states on the different transport parameters of the 2DEG.</th>
<th>Relative change per QD electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DEG-Conductance (%)</td>
<td>Carrier concentration (%)</td>
</tr>
<tr>
<td>s-states</td>
<td>3.5</td>
</tr>
<tr>
<td>p-states</td>
<td>1.6</td>
</tr>
<tr>
<td>Average</td>
<td>2.3</td>
</tr>
<tr>
<td>Total change</td>
<td>13.4</td>
</tr>
</tbody>
</table>

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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