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Quantum dots as tunable scatterers for 2D- and 1D-electron systems

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Abstract

We investigate the influence of charged, self-assembled InAs quantum dots on nearby, weakly coupled two- and one-dimensional electron gases. While the transport properties of two-dimensional electron gases (2DEG) are only weakly affected by the tunable charge in the quantum dots, we find that in laterally patterned samples the effect of coupling to the dot states is greatly enhanced. Even negative differential conductance can be observed close to the 2D–1D transition.

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The investigation of self-assembled quantum dots (SAQD) in semiconductor-heterostructures has been an important research area for almost 15 years. This interest is based on their intriguing internal electronic structure with fully quantized, atomlike properties [1].

In this work the influence of a layer of self-assembled InAs-quantum dots on the transport properties of a nearby two-dimensional electron gas (2DEG) is investigated. Placed in a layer close to a 2DEG in a high electron mobility transistor (HEMT) device, SAQDs act as artificial and tunable Coulomb scatterers. Sakaki et al. [2] showed that the electron mobility at 77 K is significantly reduced when the plane of SAQD gets closer to the 2DEG. Recently, Russ et al. [3,4] could show that gate tunable charged dots weakly affect the transport properties of the electron channel.

Here, we report on the possibility to enhance the interaction by spatial confinement of the electron channel.

The devices were grown by solid-source molecular-beam epitaxy in a metal–insulator-semiconductor field effect (MISFET) heterostructure.

First, on a GaAs (1 0 0) semi-insulating substrate a 200 nm thick GaAs buffer was deposited, followed by 300 nm $Al_{0.34}Ga_{0.66}As$, a Si-δ-doping layer, a 10 nm thick $Al_{0.34}Ga_{0.66}As$-spacer and a 25 nm GaAs-tunneling barrier. In this structure, a 2DEG forms 5 nm away from the spacer/tunneling barrier interface. In Hall measurements, a mobility of $6000\,\mathrm{cm^2/V\,s}$ and a carrier density of $n_{2D} = 7.9 \times 10^{11}\,\mathrm{cm^{-2}}$ were determined at $T = 250\,\mathrm{mK}$. The 2DEG is coupled to the quantum dot layer by the tunneling barrier. On top of the dots, 30 nm of GaAs and a 120 nm AlAs/GaAs superlattice were grown. In order to determine the dot density, a second InAs-SAQD-layer was grown on the sample surface and imaged by atomic force microscopy. The dot density was found to be $7 \times 10^9\,\mathrm{cm^{-2}}$.

From this material, Hall bars were prepared and contacted using AuGe/Ni metallic contacts. To confine the macroscopic electron channel we use the split gate technique proposed by Thornton et al. [5]. By applying a negative voltage to the two gates the underlying 2DEG is depleted and the current flow is restricted to the ungated area (see Fig. 1(b)). The length of the narrow channel is about 600 nm, the width is varied between 400 and 1000 nm.

The electric measurements were performed in a ^{3}He-cryostat at 250 mK in a DC-setup.

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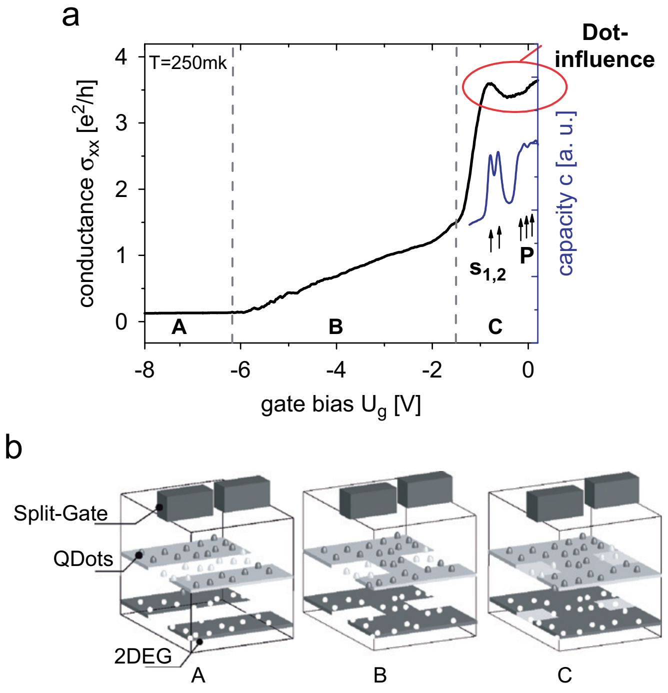

Fig. 1. (a) Conductance versus gate voltage. Observation of a conductance-drop as soon as the first dot levels becomes occupied. (b) Illustration of the different physical situations for different gate voltage ranges.

Fig. 1 shows the measured conductance as a function of gate bias U_g of our split gate device (split gate width $d = 1000\,\mathrm{nm}$). The three pictures under the graph illustrate the electrostatic influence of the gate voltage on the low-dimensional electron systems, quantum dot layer and 2DEG. The white circular areas in the 2DEG represent the influence of the charged quantum dots.

From the conductance data, three different transport regimes can be distinguished. For large negative voltages the electron channel between the split gates is electrostatically pinched off, therefore the conductance is approximately zero (region A). Between −6.5 and −2 V the constriction is in the quasi-1D-regime (B). The low electron mobility of the 2DEG results in a mean free path of about 80 nm. Thus, the electron transport is diffusive, which leads to a roughly linear increase of the conductance. At a gate bias of −1.75 V, the first subband of the 2DEG becomes populated and the conductance of the device increases strongly because of the parallel conduction under both gates (C). At slightly higher bias a drop of the conductance is found. We attribute this unusual negative transconductance to the influence of the dots on the transport properties of the channel. To support this interpretation the capacitance-spectrum of the device is plotted in Fig. 1 (blue curve). Capacitance–voltage (CV) spectroscopy has proven to be a valuable tool for the investigation of the internal electronic structure of self-assembled dots, embedded in MISFET structures [6]. This way the dot charge can be determined very precisely. Maxima in the CV spectra correspond to gate voltages where the dots are sequentially charged with single electrons. The region of negative transconductance can be identified as the bias at which the dots are charged with the first two electrons (corresponding to the s-shell). At the onset of parallel conduction under the gate, the occupied quantum dots affect the transport properties of the electron channel drastically. The measured conductance in region C is given by two major contributions. The first part reflects the parallel conduction under the gates and the second part results from the unaffected channel between the split gates. The charged quantum dots under the gates do not affect the conductance significantly [4]. However, they act as

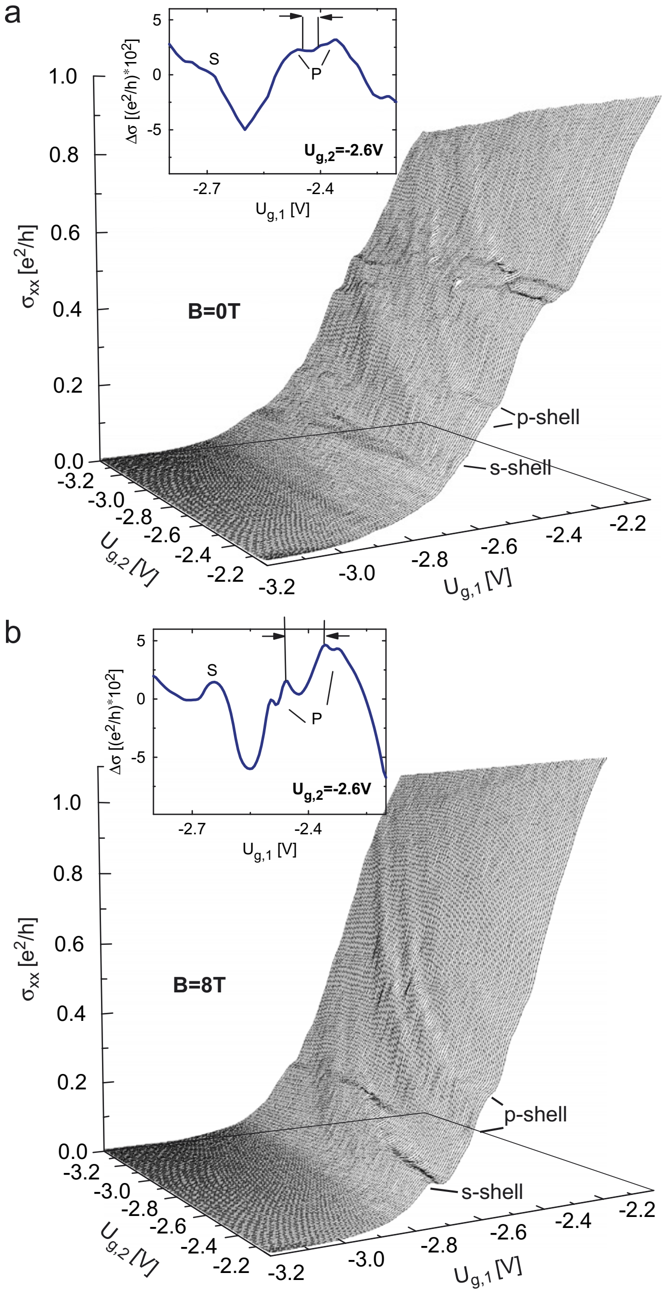

Fig. 2. (a) Conductance versus both gate voltages (split gate width $d = 400\,\mathrm{nm}$, $B = 0\,\mathrm{T}$). (b) Conductance versus gate voltages ($B = 8\,\mathrm{T}$), we observe a Zeemann splitting.

repulsive scatterers, which reduce the conductance of the nanoscopic ungated electron channel drastically.

Due to the statistical nature of the InAs island formation, the dots are randomly positioned with respect to the 1D channel.

By applying independent and asymmetric voltages on the split gates a lateral translation of the 1D-conductance channel between the split gates can be achieved. This way, the 1D-channel and the repulsive quantum dot potential can be brought into spatial alignment. Fig. 2 shows the 1D-conductance of a split gate device (width $d = 400\,\mathrm{nm}$) as a function of both gate voltages with (b) and without (a) an applied magnetic field. Due to the smaller split gate distance of this device the electron channel is pinched off at higher gate voltage ($U_{\mathrm{PinchOff,400\,nm}} \approx -3.1\,\mathrm{V}$). The asymmetry of the conductance with respect to $U_{g,1} = U_{g,2}$ results from structural and geometric inhomogeneities of the gates. The overall gate voltage dependence is roughly linear, which reflects the diffusive 1D-transport (see Fig. 1(a), region B). A small increase in conductance on the linear 1D-conductance background is found when the dots get occupied (see labels s-shell and p-shell). The peak positions on the $U_{g,2}$-scale depend approximately parabolically on $U_{g,1}$. This indicates that the quantum dot, which dominates the transport properties is located closer to gate 1 than gate 2. While for $B = 0\,\mathrm{T}$ the splitting between the p-states of different angular momentum is hardly discernible, (Fig. 2(a)), these states become clearly separated at $B = 8\,\mathrm{T}$. The insets show conductance plots with a constant gate voltage $U_{g,2}$ ($U_{g,2} = -2.6\,\mathrm{V}$) to clarify the conductance enhancement and p-level-splitting induced by a high magnetic field. Here, the approximately linear conductance background is subtracted. This orbital Zeemann splitting of the p-shell is a strong indication that the conductance modulation originates from the energy levels of the InAs-quantum dots and not other effects such as strain or random disorder, which would not exhibit such a characteristic behavior in a high magnetic field.

The increase of conductance observed in Fig. 2 when the dots become occupied is somewhat surprising. A possible explanation bases on the additional screening effect of the injected quantum dot charge. If the attractive disorder potential, which originates from the nearby ionized Si-donators, dominates the scatter potential of the device, the negative charge of the quantum dots screens the attractive disorder potential in the electron channel. This leads to an enhancement of the conductance of the constricted channel. Zhukov et al. [7] reported about an increasing of mobility in similar devices.

In summary, we have investigated a constricted 2DEG, coupled (by tunneling) to a layer of SAQDs. We have shown that the influence of charged quantum dots on the transport properties of a nearby 2DEG can be enhanced by a spatial electron channel confinement. Also we could show that in special cases the occupation of quantum dots leads to a weak increase of the conductance.

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