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Spin and edge channel dependent transport through quantum dots

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Abstract

We investigate the influence of spin polarized currents and non-equilibrated edge channels on the transport properties of a single quantum dot. Polarized currents are realized by the manual depletion of edge channels in high magnetic fields via a metallic top gate covering the source contact in the system. We observe a suppression and enhancement in the conductance of the quantum dot dependent on the edge channel configuration in the leads.

Zero-dimensional electron systems, so called quantum dots, have been studied intensively experimentally and theoretically. Transport spectroscopy reveals the electrostatic properties of these systems like Coulomb blockade (CB) and single electron tunneling (SET) [1]. Beside these electrostatic features the electronic properties of such structures show quantum effects, that hint to the quantum nature of the electron. The spin of an electron confined in a quantum dot is proposed for the realization of quantum bits in quantum computers [2]. Therefore investigations on the spin physics of quantum dots are pushed forward for the realization of quantum computing [3–5].

Here we report on the influence of spin polarized currents and non-equilibrated edge channels on the transport properties of a single lateral quantum dot. The leads of the quantum dot behave as regular quantum Hall systems and therefore generate (under suitable conditions) edge channels in high magnetic fields. These edge channels can be suppressed one by one by biasing a top gate, that partly covers the surface of the quantum Hall system [6]. The reflection of edge channels at a gate leads to non-equilibrated edge channels behind the gate [7]. The amount of edge channels reflected at this gate is thereby dependent on the gate voltage and the magnetic field. This magnetic field dependency is analyzed for two different gate voltages, indicating three different regimes with different edge channel configurations. Thereby we identify one regime, where a fully unpolarized current can be converted to a fully polarized current by gate voltage. For the three regimes we investigate the changes in the conductance of the dot due to spin polarized currents and non-equilibrated edge channels compared to the initial point.

Our device is based on a GaAs/AlGaAs heterostructure consisting of a two-dimensional electron system (2DES) 57 nm below the surface. An electron density of $n = 3.7 \times 10^{15}$ m^{-2} and a low temperature mobility of $\mu = 130$ m^2 V^{-1} s^{-1} are detected in standard quantum Hall measurements. Our quantum dot is fabricated by using split gate technique: metallic gates covering the surface of the heterostructure deplete the 2DES underneath and therefore define the geometry of the device [8]. The geometry of the quantum dot allows to tune the dot from zero to more than 40 electrons. In addition to the quantum dot our device consists of two metallic top gates, covering the source and drain contact of the system in a distance of 30 μm from the quantum dot. Figure 1 shows a scanning electron micrograph of our device with top gates highlighted. Figure 1(a) demonstrates the functionality of the spin selective gates: The direction of the magnetic field is chosen in such a way that current flows along edge channels that directly connect source S and drain D via their mutual mesa edge. By biasing gate G5 single edge channels can be reflected whereas other edge channels remain unaffected. The reflected edge channels are forced back to the source contact. The non-affected edge channels pass G5 and form non-equilibrated edge channels behind the gate together with edge channels coming from a floating contact. Biasing gate G1 forces the non-equilibrated edge channels to propagate along G1 towards the quantum dot. Gate G6 covering the drain contact of the system is here not used and set to ground. In figure 1(b) the geometry of the quantum dot is presented. The quantum dot is formed by biasing gates G1, G2 and G4. Gate G3, the so called plunger gate, shifts the internal energy levels of the dot and therefore controls the electron

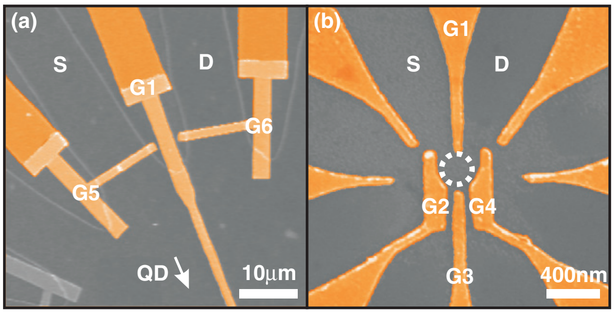

Figure 1. Scanning electron micrograph of the device (metallic top gates highlighted in color). (a) Edge channel selective gates (G5, G6) covering source and drain contacts of the quantum dot. (b) Single quantum dot defined by gates G1, G2 and G4 with two quantum point contacts (QPC) and plunger gate G3.

(This figure is in colour only in the electronic version)

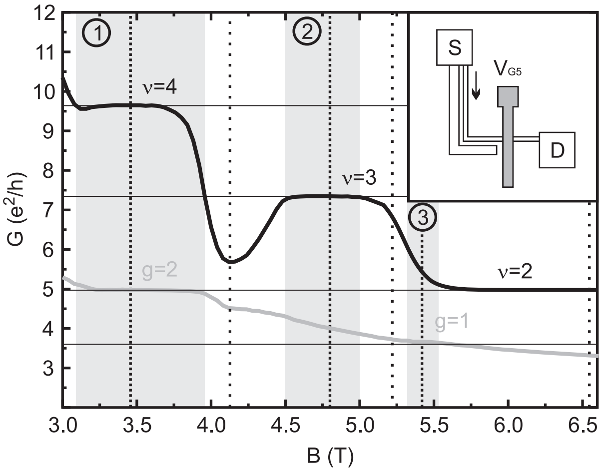

Figure 2. Conductance of the 2DES as a function of the magnetic field for two different gate voltages $V_{G5} = 0$ mV (black) and $V_{G5} = -235$ mV (gray). Three different regimes with different edge channel configurations are identified: (1) $\nu = 4$, $g = 2$ (2) $\nu = 3$ (3) $\nu = 2$, $g = 1$.

number on the dot. All measurements are done in a ^{3}He/^{4}He dilution refrigerator at a base temperature of 20 mK. We measured the conductance with standard lock-in technique in high magnetic fields applied perpendicular to the surface of our device. In all our measurements we apply a constant ac-voltage of 30 μV to the device and measure the current by two-point measurements.

In a first step we analyze the influence of gate voltage V_{G5} and magnetic field B on the conductance of the 2DES in the leads of the dot. A schematic of the experimental setup is given in the inset of figure 2. A constant voltage is applied between source S and drain D. We measure the current of the 2DES dependent on the gate voltage V_{G5} and the magnetic field B. Edge channels can be depleted manually by applying negative voltages to gate G5. Here we introduce the local filling factor g, that describes the edge channel configuration underneath the gate. Such a depletion of edge channels can be realized by sweeping gate voltage V_{G5} at a fixed magnetic field as well as sweeping the magnetic field at a fixed gate voltage. Figure 2 shows the comparison between the conductance G (in units of e^2/h) of the 2DES at zero gate voltage $V_{G5} = 0$ mV (black curve) and the conductance of the 2DES at a gate voltage of $V_{G5} = -235$ mV (gray curve) dependent on the magnetic field B. The former case shows typical Hall plateaus in the conductance for filling factors $\nu = 4$, 3 and 2. The latter case shows plateaus for the local filling factor $g = 2$ and 1. The plateau belonging to local filling factor $g = 2$ is clearly visible and can be identified by the value of the conductance, that is equal to the conductance of $\nu = 2$. The plateau, belonging to local filling factor $g = 1$, is not strongly pronounced. It can be nevertheless identified with the value of the conductance for Hall plateau $\upsilon = 1$ from standard quantum Hall measurements.

The results from figure 2 allow to identify three different regimes, which are pointed out by a slight gray background. Regime one ranges from $B = 3.12$ to 3.96 T and depicts the situation where, from the starting point of four edge channels ($\nu = 4$), two edge channels are suppressed by gate G5 (local filling factor $g = 2$). This leads to a current that flows in four edge channels in front of the gate and in the two outer edge channels behind the gate. Regime two ranges from $B = 4.52$ to 5.0 T. Here the comparison between filling factor $\nu = 3$ and local filling factor g between $g = 1$ and 2 is made. The third regime is located at local filling factor $g = 1$ and spreads from $B = 5.24$ to 5.52 T. In this regime a comparison between an unpolarized current at $\upsilon = 2$ and a spin polarized current at $g = 1$ is possible. At filling factor $\upsilon = 2$ the lowest Landau level is fully occupied, whereby the total polarization is vanishing. Due to the spin splitting of the Landau level, a full spin down polarization can be achieved by reflecting the inner lying edge channel at the gate. In between these three regimes transport is dominated by scattering effects, leading to equilibrated transport. This classification allows us to compare the conductance of the quantum dot in these three named regimes and in the intermediate ranges.

We now analyze the influence of spin polarized currents and non-equilibrated edge channels on the transport properties of our quantum dot. Therefore we show the conductance of the quantum dot in dependence of gate voltage V_{G3}, tuning the quantum dot from approx. 10 electrons to around 40 electrons, for the three different regimes named above and for the intermediate ranges. The magnetic field values, at which the comparison between $V_{G5} = 0$ and -235 mV is accomplished, are marked in figure 2 by dotted lines. Figure 3 shows the conductance of the quantum dot for these values of the magnetic field and compares it to the conductance with gate voltage $V_{G5} = -235$ mV applied at the same magnetic fields. In regime one (figure 3, 3.48 T) the suppression of two edge channels at gate G5 leads to an enhancement in the conductance of the quantum dot for an interval of $V_{G3} = [-1.0\ \text{V}, -0.3\ \text{V}]$. At a gate voltage of $V_{G3} = -0.3$ V the two graphs intersect and following, the conductance for $V_{G5} = -235$ mV develops to a suppression in the interval $V_{G3} = [-0.3\ \text{V}, 0\ \text{V}]$. Beside this behavior an overall suppression of the amplitude of the conductance peaks is visible. The discrepancy of these two curves decreases for higher magnetic fields and vanishes in the magnetic field range between

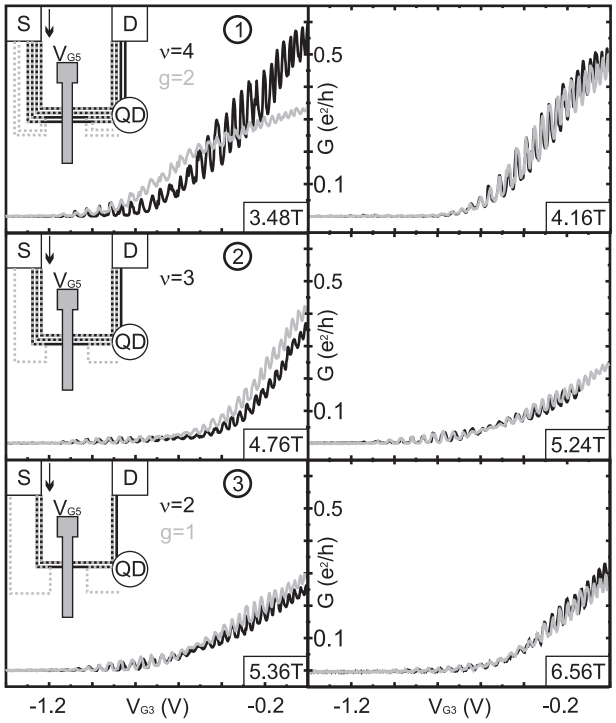

Figure 3. Spin and edge channel dependent transport. Left: conductance G of the quantum dot for three different regimes: (1) equilibrated edge channels at filling factor ($\nu = 4$) compared to non-equilibrated edge channels at local filling factor $g = 2$. (2) Equilibrated edge channels at filling factor $\nu = 3$ compared to non-equilibrated edge channels. (3) Unpolarized current at filling factor $\nu = 2$ compared to polarized current at local filling factor $g = 1$. Right: conductance G of the quantum dot in between the allocated regimes.

regime one and regime two (figure 3, 4.16 T). Furthermore an adjustment of the conductance peak amplitudes occurs. In regime two a difference in the conductance is visible again. Here an overall enhancement of conductance at $V_{G5} = -235$ mV is revealed (figure 3, 4.76 T). This enhancement regresses up to a magnetic field of $B = 5.24$ T (figure 3, 5.24 T) and recurs at a magnetic field of $B = 5.36$ T (figure 3, 5.36 T) within regime three. Beyond this point, the situation is not well defined. We see an alternating appearance and disappearance of the discrepancy. Also a slight suppression of conductance appears for some magnetic field values. Overall a trend of disappearance of discrepancy (figure 3, 6.56 T) is observed.

Transport in the leads of the dot at the magnetic fields around $B = 4.16$ T (between regime one and regime two) and 5.24 T (between regime two and regime three) is dominated by scattering effects. Here transport is equilibrated. In these areas the conductance of the quantum dot is not affected by the voltage applied to gate G5. From this it follows, that the resistance of the gate G5 is negligible compared to the resistance of the quantum dot (as expected from the resistance values). In the emphasized regimes one to three we compare the transport properties of the quantum dot through equilibrated edge channels and non-equilibrated edge channels. For a fixed voltage applied to the system the current in the leads is determined only by the resistance of the quantum dot because the resistance of the spin selective gate is negligible. We therefore can assume the same current in the leads of the dot both for equilibrated edge channels and non-equilibrated edge channels. In the former case the full current propagates through the full amount of edge channels, corresponding to the applied magnetic field, whereas in the latter case the full current is transported only through the outermost edge channels. The given current therefore distributes among the available edge channels. The current per edge channel thus depends on the number of current-carrying edge channels. It is higher for non-equilibrated edge channels than for equilibrated edge channels due to the reduced number of edge channels. In addition to that effect we need to take into account different transmission probabilities through the dot for different edge channels, due to the spatial arrangement of these edge channels close to the dot. The outermost edge channel in the leads lies closest to the quantum dot. The second outermost edge channel is located further inwards. Transport through the quantum dot and the outermost edge channel is, as a result of the vicinity of that edge channel to the quantum dot, favored to transport through the dot and an inner lying edge channel. Considering both effects hints at the origin of enhanced conductance for non-equilibrated transport: The total transmission coefficient of the quantum dot is composed of the transmission coefficients of all paths. For a configuration where current flows through a large number of equilibrated edge channels the total transmission coefficient is lower than for a configuration where the total current flows in a small number of non-equilibrated edge channels. For equilibrated edge channels we have smaller currents for paths with high transmission probabilities than for non-equilibrated edge channels. The additional inner paths for equilibrated edge channels do not significantly add to the total transmission coefficient because of their very low transmission probability. Due to that higher transmission coefficient transport for non-equilibrated edge channels is enhanced. In addition to that favored transport through the quantum dot, we have to assume a different effect that is responsible for the partly suppressed transport in regime one. But here we have already a very high conductance and practically an open quantum dot, whereas in the area where we see the enhancement the coupling to the leads is already strong, but the quantum dot is not yet open.

In conclusion we showed the transport properties of a single quantum dot dependent on different configurations of non-equilibrated edge channels in the vicinity of the quantum dot. We showed that the edge channel configuration of the quantum dot can be tuned by biasing a metallic top gate that covers the source contact of the system. In that process we identified three regimes with different edge channel configurations. For these three regimes we compared the conductance of the quantum dot to the initial situation, with no gate voltage applied. Thereby we found a change of conductivity in all three regimes, due to different possible paths, in which current propagates.

To clarify the detailed influence of spin in this experiment it would be nice to combine the transport experiment with optical measurements in the future.

Acknowledgments

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