Giant fluctuations and gate control of the \( g \)-factor in InAs Nanowire Quantum Dots

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Abstract

We study the \( g \)-factor of discrete electron states in InAs nanowire based quantum dots. The \( g \) values are determined from the magnetic field splitting of the zero bias anomaly due to the spin 1/2–Kondo effect. Unlike to previous studies based on 2DEG quantum dots, the \( g \)-factors of neighboring electron states show a surprisingly large fluctuation: \( g \) can scatter between 2 and 18. Furthermore electric gate tunability of the \( g \)-factor is demonstrated.

Due to the precise structural control, semiconductor nanowires (NW) provide a new class of nanoscale building blocks for a broad range of disciplines like quantum optics, electronics, nanosensing and biotechnology \[1\]. Recently semiconductor NWs also attract increasing attention

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in the field of quantum transport: single electron transistor behavior [2], Pauli spin blockade [3] and
the Kondo effect [4] have already been observed in NW based devices. Furthermore, new physical
phenomena were also demonstrated, e.g. $\pi$-junction [5] or the interplay of Andreev reflection
and Kondo effect [6, 7], which are not accessible in conventional GaAs heterostructures. In this
Letter we report on a surprising behavior of InAs NW based quantum dots (QD). We investigate
the $g$-factor of the dot electron states, which is the key parameter for the manipulation of spin
information at a single electron level. The $g$-factor shows an order of magnitude variation for
neighboring discrete electron states, which highly exceeds previous observations in semiconductor
based quantum dots [8, 9]. Moreover, strong gate tunability of the $g$ value of individual charge
states is also demonstrated.

The high quality InAs nanowires were grown by molecular-beam epitaxy [4]. The nanowires
were then brought into IPA solution by short sonication of the growth substrate. The wires were
deposited by spinning a droplet of the solution on a highly doped Si substrate with 400 nm ins-
ulating SiO$_2$ cap layer. After locating the nanowires by SEM, the devices were fabricated by
standard e-beam lithography technique. We define ohmic source and drain contacts for transport
measurements (S,D) and a top gate electrode (TG) for local gating (see Fig. 1a). The Ti/Au
(10/100 nm) TG electrode is isolated from the nanowire by the native surface oxide layer [10].
Before the evaporation of the Ti/Al (10/100 nm) ohmic contacts this oxide layer is removed by
gentle Argon sputtering. The transport measurements were performed with standard lock-in tech-
nique in a dilution refrigerator at a base temperature of 40 mK in perpendicular magnetic field.
The electron density of InAs wires can be strongly varied by applying voltage on the back gate
electrode. Based on the backgate dependence the nanowires have n-type charge carriers. When
the back gate potential is decreased, barriers are generated at the contacting source and drain
electrodes, and a QD forms in the middle of the wire segment [2, 4]. In our device architecture the
topgate provides an additional knob to modify the shape of the confinement potential of the QD
besides the back gate.

A typical stability diagram measured on such a QD is plotted in Figure 1b. Since the dot is in a rather open state the differential conductance exceeds the value of \( \sim 0.7 G_0 \) \((G_0 = 2e^2/h)\) and the borders of the Coulomb blockade diamonds are rather blurred. From the size of the diamonds (see the dotted lines) the estimated charging energy is in the range of 0.5 – 1 meV, which is consistent with the length of the nanowire segment of 400 nm \([4]\). The subsequent Coulomb diamonds have alternating sizes (smaller / larger /smaller ...), and in the smaller diamonds the differential conductance shows a pronounced increase at zero source drain bias voltage (see dotted lines at \( V_{sd} = 0 \) in Fig. 1b). This type of even-odd dependence of the stability diagram is a strong indication of the spin–1/2 Kondo effect \([11]\), which was analyzed in InAs nanowire QDs by Jespersen et al. in detail \([4]\).

If the dot contains an odd number of electrons the highest occupied electron state is filled only by a single electron. Due to the strong coupling to the leads, the spin of this unpaired electron is screened by electrons of the leads forming a many-body state, the so-called Kondo cloud, which gives rise to the enhancement of conductance at zero bias voltage. The temperature dependence of the slice of the stability diagram at \( V_{sd} = 0 \) is also consistent with the Kondo effect (see Fig. 1b). Inside the diamond with even number of electrons the differential conductance decreases for decreasing temperature, while an increase is observed in odd diamonds (gray regions), where Kondo correlations take place. The spin–1/2 Kondo physics has a characteristic magnetic field dependence. The Kondo ridge at zero bias voltage splits up in a magnetic field similar to the Zeeman-splitting according to \( \Delta V = 2g\mu_B B/e \), where \( \mu_B \) is the Bohr magnetron, \( e \) is the electron charge and \( g \) is the effective \( g \)-factor of the highest discrete electron state occupied with an unpaired electron \([12, 13]\). The magnetic field dependence of a zero bias ridge is shown in Figure 2. The zero bias anomaly peak (black arrow) splits up linearly with magnetic field in agreement with Kondo physics (see inset). Note that two side peaks at low \( B \) field (gray arrows) are related to the
superconducting electrodes and they are completely suppressed by a field of $B > 50 \text{ mT}$. They will not be considered further in this paper [6]. Since the magnetic field splitting of the zero bias Kondo ridge is proportional to the Landé $g$-factor of electron state, one can evaluate the absolute value of the $g$-factor of the highest occupied discrete electron state based on the magnetoconductance data (see Fig. 2). There are different methods in the literature for the precise determination of the $|g|$ value from the Kondo splitting. In the first work the positions of the maximums of the splitted Kondo peak were used [12, 13], which yields a slight overestimation (few percent) according to later studies [14]. In our work we will determinate $|g|$ from the magnetic field dependence of the two inflection points (see orange dot and green triangle for the highest $B$ field in the main panel of Fig. 2) [15], which provides $\sim 5\%$ smaller values. The position of the inflection points are plotted as a function of the $B$ field in the inset of Fig. 2 and their difference is fitted by $\Delta V = 2|g|\mu_B B/e$.

In the following we analyze how the effective $g$-factor of individual discrete electron states behaves when the confinement potential of the QD is changed with the gate electrodes. Already the stability diagram measured at $B = 200 \text{ mT}$ in Fig. 1d shows that the magnetic field splitting of the Kondo ridge in subsequent odd Coulomb diamonds varies strongly. The extracted $|g|$ values of these three electron states are $\sim 8, 6.1$ and $1.7$. Thus adding only two extra electrons onto the dot can change the $g$-factor by over $100\%$. Fig. 3a summarizes the evaluated $|g|$ values. The colorscale plot shows the differential conductance vs. topgate and backgate voltages. Higher conductance regions appear along diagonal lines since the backgate voltage induced shift of the electron levels of the dot is compensated by opposite tuning of the topgate. At four different TG voltages the coordinates of the diamonds where Kondo ridges were observed (similar ones as in Fig. 1d) are plotted by circles. The neighboring numbers are the absolute value of the $g$-factors evaluated similar to the way in Fig. 2 $|g|$ does not show a systematic behavior as a function of the backgate voltage, but rather changes in a random fashion. The extracted $|g|$ values vary in a broad range (see also the distribution in Fig. 3d) from the lowest value of $1.7$ even up to $18$, which exceeds
the InAs bulk value of $|g| = 14.7$. By modifying the backgate and topgate voltage simultaneously along the Coulomb blockaded regions (blue stripes) the confinement potential of the dot changes while its charge state is preserved. Such a tuning of the gate voltages can also lead to marked $g$-factor variations. For instance along the dashed line in Fig. 3a the $|g|$ varies by almost a factor of two, while the number of electrons is kept fixed on the dot. Such a gate tunability of the $g$-factor of single electron state provides an efficient way for selectively addressing electron spins. Furthermore, in some of the Coulomb diamonds the magnetic field splitting of the Kondo ridge is clearly not constant over backgate voltage. As it is seen in Fig. 3b-c the splitting of the Kondo ridge varies more than 30% between the two sides of the diamond at $B = 200\text{mT}$. Thus changes of the $g$-factor are visible even inside a single Coulomb diamond. Summarizing, the $g$-factor fluctuates by an order of magnitude for neighboring electron states and it can be strongly gate-tunable even in the same charge state. We investigated the relation between the observed $g$ values and Kondo temperature ($T_K$) estimated from the full width at half maximum of the Kondo ridges [13]. As it is shown in Fig. 3i, no correlation was found between $g$ and $T_K$. Therefore we conclude that the level-to-level fluctuation of the $g$-factor is not related to Kondo physics.

The rather large $g$-factor of bulk InAs ($g = -14.7$) is due to the presence of strong spin-orbit coupling and the contribution of the orbital degree of freedom. If the electrons are confined in a small constriction the large $|g|$ value decreases even down to the free electron value of 2 because of the quenching of the angular momentum [16, 17]. This phenomenon was reported by Björk et al. for InAs nanowires [18]. They studied quantum dots formed between two (few nanometer thin) InP tunnel barriers. Decreasing the distance between the barriers to 8nm the $|g|$ value decreased down to $\simeq 2$. However, they did not observe measurable changes in $|g|$ varying the number of electrons on the quantum dot. The size of the QD in our study is relative large, $L \simeq 350\text{nm}$ and the occupation number is also significantly higher. Therefore, a considerable orbital angular momentum is preserved. This is supported by the average value of the measured
$g$-factors of $\langle |g| \rangle = 7.4 \pm 3.6$. The elastic mean free path and spin orbit (SO) length ($l_e \approx 80$nm, $l_{SO} \approx 125$nm [19]) are significantly smaller than the size of the dot, thus the electrons cover diffusive-like trajectories and several SO scattering events are expected to take place in the dot.

Although the strong fluctuation of the $g$ value of neighboring discrete electron states is surprising for semiconductor nanostructures, it was observed in metallic nanoparticle based QDs in the presence of spin orbit interaction [20]. The $g$-factor of the discrete electron levels for e.g. silver nanoparticles (diameter of $\approx 5\,\text{–}\,10$nm) varies between $0.25\,\text{–}\,1$. The $g$-factor of a particular state contains contributions from the SO matrix elements with all other discrete levels. Since the precise nature of the wave function of electron states is fluctuating and the level spacing is also varying the SO induced correction exhibits fluctuation. The observed fluctuation agrees quantitatively with random matrix theory (RMT) calculations [21, 22], which describe the SO interaction with the parameter $\lambda = (\hbar \pi / t_{SO} \delta)^{0.5}$ ($t_{SO}$ and $\delta$ are the SO scattering time and the level spacing, respectively). In our InAs NW measurements a rough estimation of the SO strength is $\lambda \approx 0.4$ based on $\delta \approx 0.1$ meV and $t_{SO} \approx 100$ ps (bulk value) [23]. This is close to the range of $\lambda \approx 0.7\,\text{–}\,10$, where $g$ fluctuation was observed in metallic grains [20]. RMT provides an analytic expression for the distribution of the $g$-factor in the strong SO coupling regime ($\lambda \gg 1$):

$$P(g) = 3 \left( \frac{6}{\pi} \right)^{1/2} \frac{g^2}{\langle g^2 \rangle^{3/2}} \exp \left( -\frac{3g^2}{2\langle g^2 \rangle} \right),$$

where $\langle g^2 \rangle$ is the mean square value of the distribution. For our experimental distribution function of $|g|$ (see bar graph in Fig. 3d) $\langle g^2 \rangle = 67$. Using this mean square value, the RMT predicted distribution is plotted as a line graph in Fig. 3d. Although we are not in the strong SO coupling regime, the distribution functions show a good agreement without fitting parameters. Based on the theory, $\langle g^2 \rangle = 3/\lambda + \langle g_o^2 \rangle$, where the first term is the spin contribution and $\langle g_o^2 \rangle$ is the orbital part [21]. In the case of metallic nanoparticles the spin contribution dominates the $g$-factor. In contrast, for InAs QDs the orbital part is expected to be the main contribution due to the small effective mass and relatively large dot size. This is consistent with the large broadening of the
distribution of $g$. However RMT calculations [21, 22] focus mainly on the spin contribution. Thus a proper estimation of the $g$-factor fluctuation for our InAs NW QD would require new model calculation, which takes into account the orbital contribution induced by the QD geometry and the SO interaction of InAs.

In conclusion, we have analyzed the $g$-factor of discrete electron states of InAs nanowire based quantum dots. The $|g|$ values were evaluated from the magnetic field splitting of zero bias Kondo ridges. The evaluated values show an order of a magnitude large level-to-level fluctuation. Furthermore the $g$-factor can be tuned up to a factor of two for the same charge state by gate electrodes. A possible explanation is drawn: the random nature of the wavefunction of the discrete electron states generates different orbital contribution and spin-orbit correction to their $g$-factors. The observed gate tunability of the $g$-factor of confined electrons can be used to drive the spin in and out of resonance with a static magnetic field induced ESR condition, which could provide a fast and selective manipulation of quantum dot based spin qubit.

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Figure 1: (a) SEM picture of the device: The quantum dot forms between the two Ti/Al ohmic contacts (S,D) with Ti/Au topgate (TG) deposited on top of it. The nanowire (blue) has a diameter of 80 nm. The bar is 0.5 µm. (b,d) Colorscale plots of the differential conductance vs. backgate and source drain voltage measured at $V_{tg} = 0.07$ V. The stability diagram at $B = 0$ T (b) clearly shows the even/odd filling of the quantum dot. There is a Kondo ridge at zero bias voltage in every second Coulomb diamond (dotted lines at $V_{sd} = 0$). At $B = 200$ mT (d) the Kondo ridges split up differently. (c) Differential conductance versus backgate voltage at $T = 45$ mK and 500 mK. The conductance increases inside every second Coulomb diamond for decreasing temperature (gray regions) in agreement with Kondo physics. Measured at $V_{tg} = 0.06$ V and $V_{sd} = 0$ mV.
Figure 2: Magnetic field splitting of the Kondo zero bias anomaly. (main panel): Differential conductance vs. source drain voltage at different perpendicular magnetic field values $B = 0, 5, 10, ... , 240 \text{ mT}$ (back to front). Measured at $V_{bg} = -2.64 \text{ V}$ and $V_{tg} = 0.08 \text{ V}$. The curves are shifted for clarity. Note that the two side peaks (gray arrows) are superconducting features induced by the Ti/Al electrodes. (inset): The position of the inflection points of the $G_d(V_{sd})$ curves from the main panel (orange dot and green triangle) as a function of the magnetic field. Linear fit (line) with the extracted $|g|$-factor.
Figure 3: (a) Summary of the evaluated $|g|$ values. Color scale plot of the differential conductance vs. backgate voltage and TG voltages (at $V_{sd} = 0$ V and $B = 0$ T) with the absolute value of the $g$-factors determined from the magnetic field splitting of the Kondo ridges. (b,c) Stability diagram of a Coulomb diamond with a Kondo zero bias anomaly, where the magnetic field induced splitting is changing inside the diamond. Measured at $V_{tg} = 0.6$ V. (d) Distribution of the evaluated $|g|$-factors (bar) and a parameterless fit (line), see text. (e) Extracted $|g|$ values vs. estimated Kondo temperature from the full width at half maximum of the Kondo zero bias anomaly at $B = 0$ T ($\text{FWHM}=2k_B T_K/e$).