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Exchange interaction in chirally coupled quantum dots

Daniel Tutuc[1], Alexander W. Heine[1], Dieter Schuh[2], Werner Wegscheider[2,3], and Rolf J. Haug[1]
[1]Institut für Festkörperphysik, Leibniz Universität Hannover, Appelstraße 2, D-30167 Hannover, Germany
[2]Institut für Experimentelle und Angewandte Physik, Universtät Regensburg, Universitätsstraße 31, D-93053 Regensburg, Germany
[3]Laboratorium für Festkörperphysik, ETH Zürich, Schafmattstraße 16, CH-8093 Zürich, Switzerland

E-mail: `heine@nano.uni-hannover.de`

Abstract. We present transport measurements on a system of two lateral quantum dots in a perpendicular magnetic field. Due to edge channel formation in an open conducting region, the quantum dots are chirally coupled. When both quantum dots are tuned into the Kondo regime simultaneously, we observe a change in the temperature dependence of the differential conductance. This is explained by the RKKY exchange interaction between the two dots. As a function of bias the differential conductance shows a splitting of the Kondo resonance which changes in the presence of RKKY interaction.

1. Introduction

Semiconductor quantum dots (QDs) are highly tunable devices and therefore have attracted much interest in the scientific community. Using the spin of the QD as a qubit in quantum information processes is one of the proposed applications [1]. For this application it is necessary to provide non-local manipulation and readout of the spin information of a QD. One possible mechanism to entangle the spins of different QDs beyond the nearest neighbour approach is the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction between magnetic moments. This indirect non-local exchange interaction is mediated by charge carriers and locks the magnetic moments in a new ground state. The latter is either ferromagnetic or antiferromagnetic depending on the distance between the magnetic moments and the Fermi wave vector of the charge carriers [2].

Another entanglement mechanism of a single QD spin to a many-body electron system is the Kondo effect [3, 4, 5]. At very low temperatures the spin of a QD is screened by the electrons in the leads and forms a new singlet ground state with the binding energy T_k. In an otherwise Coulomb-blocked situation this singlet ground state allows the electron of the highest occupied energy level to leave the dot and to be replaced by an electron from the leads with opposite spin. Therefore the dot becomes transparent at zero bias (the so-called zero bias anomaly) because its spin is constantly flipped.

In a system where the Kondo effect as well as the RKKY exchange interaction are present, one expects a competition between these two mechanisms which can be observed in transport properties [6, 7].

2. Experimental Setup

Our sample is prepared on a GaAs/AlGaAs heterostructure containing a two dimensional electron system 37 nm below the surface with an electron density of 3.95×10^{15} m^{-2}. Two lateral QDs (QD1 and QD2) are defined by local anodic oxidation using an AFM [8, 9]. Figure 1 (a) shows an AFM picture of the structure. The QDs are tunnel coupled to individual drains (D1 and D2) and to an open conducting region with a length of $\sim$ 600 nm. This region connects the QDs and is used as source contact (S). The tunnel barriers and the energy levels of the QDs can be tuned by six in-plane gates and an individual bias can be applied to each QD. The measurements were performed in a ^{3}He/^{4}He dilution refrigerator with an electron temperature of about 80 mK. Standard lock-in technique was used and the differential conductance $G_{\mathrm{i}} = dI_{\mathrm{i}}/dV$ (i $= 1, 2$) of each dot was measured individually. A magnetic field was applied perpendicular to the sample. More detailed information concerning the experimental setup can be found in Ref. [10].

3. Kondo chessboard and RKKY interaction

The measurement of the differential conductance G_1 of QD1 at zero bias as a function of gate voltage V_{G6} and perpendicular magnetic field leads to a pattern of alternating tiles of low and high differential conductance (Fig. 1 (c)). This pattern originates from the formation of Landau levels (LLs) in the QD in perpendicular magnetic field when two LLs are observable. In the presented situation the filling factor is $2 < \nu < 4$. Kondo transport then only involves energy states of the lowest LL. The number of electrons in this LL0 can be controlled by varying the number of flux quanta on the dot which redistributes the electrons between the LLs. This is achieved by a change in the magnetic field. A modulation of the total number of electrons on the dot by sweeping the gate voltage also changes the occupation of LL0. These two mechanisms lead to the so-called *Kondo chessboard* [11, 12, 13, 14], seen in Fig. 1 (c).

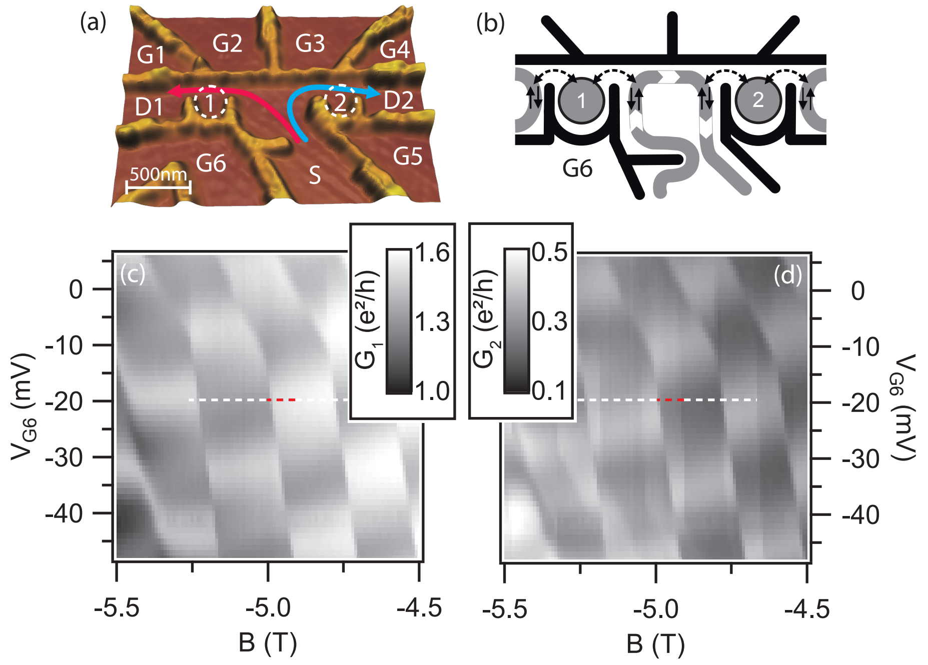

Figure 1. (a) AFM picture of the sample. The oxide lines in bright colour define the structure. (b) Schematic of the edge channels for perpendicular magnetic field with negative polarity. (c)+(d) Differential conductance of QD1 (c) and QD2 (d) as function of magnetic field and gate voltage.

The differential conductance G_2 of QD2 in Fig. 1 (d) shows a more complicated pattern: a negative of the Kondo chessboard in QD1 is visible that is superimposed by a stripe pattern. The reason for that is the formation of edge channels in the open central region. For the given magnetic field polarity a schematic of transport through the edge channels is shown in Fig. 1 (b). QD2 lies "downstream" and the changes of the electrostatic potential at the site of QD1, e.g. by onset of the Kondo effect, can be seen in the transport properties of QD2. Thus the coupling between the QDs is chiral and the chirality can be changed by reversing the magnetic field polarity [10].

The intervals where both QDs are tuned into the Kondo region simultaneously can be easily identified in the superimposed pattern exhibited by QD2. In QD1, Kondo transport can be observed between -4.97 T and -4.77 T, while QD2 exhibits the Kondo effect between -5.05 T and -4.92 T. Therefore between -4.97 T and -4.92 T transport through both QDs is Kondo enhanced (marked in red). A detailed temperature analysis in this region yields a strong change in the behaviour of the Kondo temperatures compared to the case when only one QD is tuned into the Kondo regime (see [10]). This change indicates a modulation in the ground state of the system. Since this effect can be observed in both QDs for both magnetic field polarities, it is not caused by any electrostatic effect. Instead it is attributed to the quantum mechanical interaction mediated by the electrons in the edge states, the RKKY exchange interaction.

4. Bias dependence

To probe the influence of the RKKY interaction on the zero bias anomaly, a bias V_{sd1} was applied at drain 1 and the differential conductance G_1 was measured along the dashed line in Fig. 1 (c). The result is shown in Fig. 2 (a). The region of Kondo transport can be seen clearly and between -4.9 T and -4.8 T a splitting can be observed in Fig. 2 (b). In traces taken along the coloured lines in Fig. 2 (a) the detailed evolution of this splitting is revealed. For the trace of -4.83 T two peaks at about ±0.24 mV are clearly visible. When QD2 enters the Kondo regime at -4.92 T, this splitting decreases to ±0.12 mV and the peaks are considerably smaller. In the centre of the overlap region at -4.96 T the peaks vanish completely.

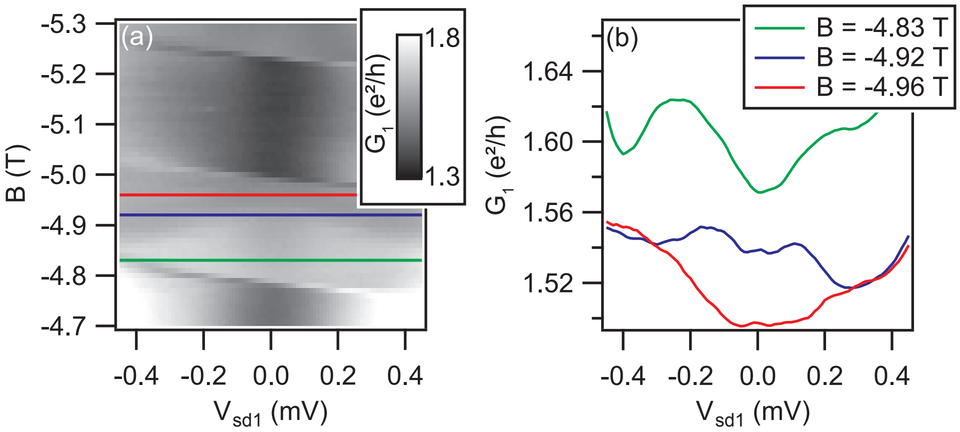

Figure 2. (a) Differential conductance G_1 as function of magnetic field and bias voltage for fixed gate voltage $V_{\mathrm{G6}} = -20\mathrm{mV}$ (dashed line in Fig. 1 (c)). (b) Traces measured along the coloured lines in (a).

This clear change in the zero bias anomaly splitting when both QDs are tuned into the Kondo regime is another hint for the presence of the RKKY exchange interaction between the two QDs.

When the polarity of magnetic field is changed and QD2 is "upstream", a similar effect can be seen as function of the bias on drain 2.

Note that the observed splitting at -4.83 T is a factor of 2 larger than the expected Zeeman splitting for bulk GaAs ($|g^*| = 0.44$) of about 130 μeV at 5 T.

5. Conclusion

We have shown the chiral coupling of two QDs in a perpendicular magnetic field. The RKKY exchange interaction between the magnetic moments of the QD can be probed by using the Kondo effect as a spectroscopic tool. By analysing the Kondo temperature a change in the ground state of the system can be confirmed which is present regardless of chirality. In bias dependent measurements a splitting of the zero bias anomaly of QD1 can be observed, when only one QD shows the Kondo effect. It is strongly suppressed, when both QDs exhibit Kondo transport and the RKKY interaction is present.

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