Kondo physics in electrical transport through a quantum dot system

During the last decade, worldwide experimental investigations on electronic transport through small conducting grains (denoted in the following as ‘islands’) which are coupled to a source and a drain contact by weak tunnel barriers have shown phenomena like Coulomb blockade, single–electron charging and single–electron tunneling. These effects are caused by the Coulomb interaction of the electrons on the island leading to an energy barrier for adding an electron to the island and to an energy barrier for taking off an electron. Due to this, at low temperature thermally induced fluctuations in the number of electrons on the island are suppressed causing a suppression of electron transport through this island for small drain–source voltage values V_{DS} (Coulomb blockade effect). By applying a positive voltage V_G to a nearby gate electrode, the electrostatic potential of the electrons on the island is lowered reducing the energy barrier for adding an electron to the island. Whenever it is energetically almost equivalent of having N or $N+1$ electrons on the island, the number of electrons on the island strongly fluctuates between N and $N+1$, and for small $|V_{DS}|$ a net electron transport is measured between source and drain contact. Since the current is carried by electrons passing one after the other through the island, this is denoted as single–electron tunneling. With increasing the gate voltage, energy barriers for recharging the island appear again, but now with one electron more on the island being stable. Therefore, with increasing V_G, electrons are accumulated one by one on the island (single–electron charging) and for small $|V_{DS}|$ only at certain gate voltage values, where the number of electrons on the island fluctuates, conductance is measured between source and drain.

In the limit of weak tunnel coupling and at low but finite temperature, the dynamics of this electron transport can be described by rate equations revealing the basic features of Coulomb blockade and single–electron tunneling. By this approach, only processes involving a single tunneling event of an electron through one of the barriers are taken into account. This does not work in the case of strong tunnel coupling.

Besides thermally induced fluctuations in the number of electrons on the island, quantum fluctuations occur and become stronger with increasing the tunnel coupling to the source and/or drain electrodes. A simple example for this are so–called co–tunneling events: An electron from one of the contact electrode occupies the island while *at the same time* another electron leaves the island to one of the contact electrodes. Since the charge on the island is not changed by this coupled tunneling event of two electrons, no Coulomb charging energy has to be paid. Even in the Coulomb blockade regime this leads to a net current flow from source to drain for $|V_{DS}| > 0$. Instead of having two electrons involved, it is also possible that the electron entering the island *immediately* leaves the island. The island is only virtually occupied by this electron. This can also be described by an effective broading of the electronic levels on the island due to the short dwell time of the electron on the island. Again, for a small $|V_{DS}|$, a net current is measured in the Coulomb blockade regime. In the regime of strong coupling and where the phase coherence between tunneling events is not destroyed by temperature, the description becomes even more sophisticated. Glazman *et al.* [JETP Lett. **47**, 452 (1988)] pointed out that electrical transport through a spin–degenerate localized state (impurity) embedded between two electron reservoirs should show Kondo physics if the temperature is low enough. They concluded this in analogy to Anderson's impurity model [Phys. Rev. **124**, 41 (1961)]. The electronic state of the island hybridize with the electronic states of the contact electrodes: Although the energy level of this localized state is deep below the Fermi level of the reservoirs, the tunnel coupling to the reservoirs creates an effective density of state on the site of the impurity pinned to the Fermi level of the reservoirs. Electron transport is possible around $V_{DS} = 0$. The weaker the tunnel coupling and the deeper the impurity level, the lower the temperture has to be to observe this Kondo effect.

To study such physics in experiment we choose a quantum dot, i.e. an island with a discrete energy spectrum, with in–situ tunable tunneling barriers. In Fig. 56a our experimental setup is shown. On top of an AlGaAs/GaAs heterostructure which contains a two–dimensional electron system (2DES) at a GaAs/AlGaAs interface 50 nm below the surface, six metallic gates are deposited (the opening between the fingers is 180 nm in diameter). By applying a negative voltage to these fingers, the electrons in the 2DES below the gates are depleted dividing the 2DES into a small region (island) between the fingers and two parts acting as source and drain electrodes. By the voltage applied to the outer pairs of gate fingers, the tunnel coupling is tuned.

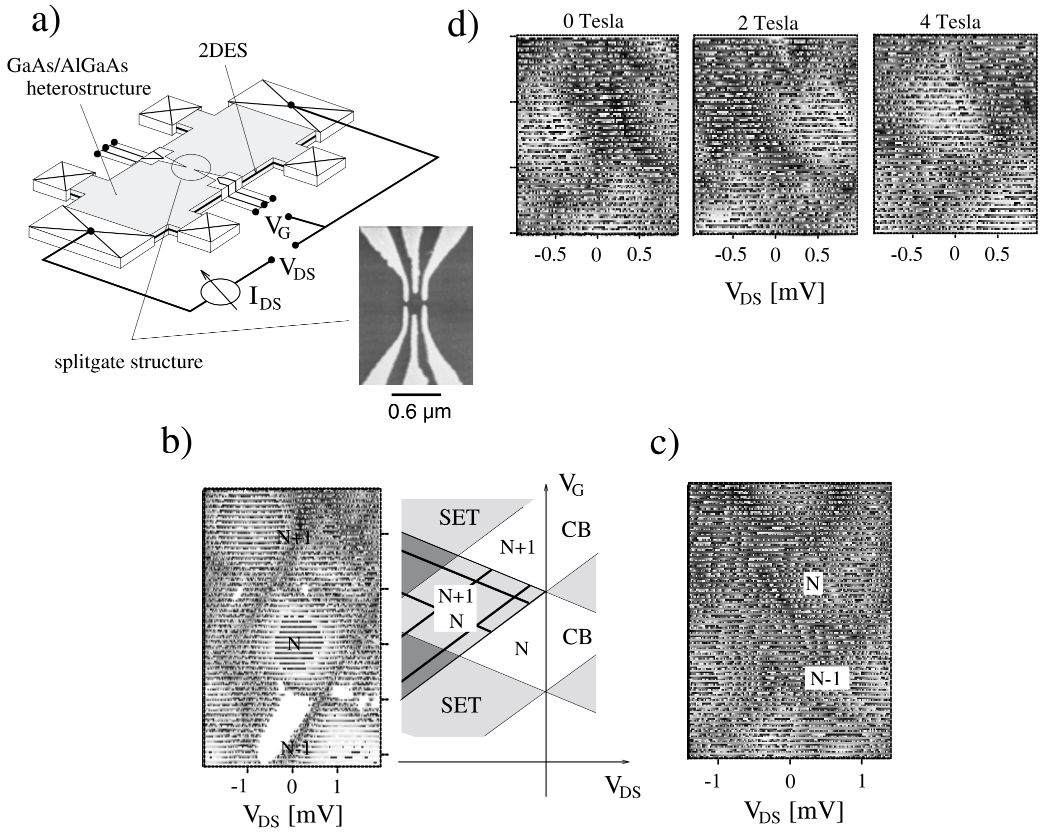

Figure 56: *a) Experimental setup: A splitgate structure is deposited on top of a Hall bar which has been etched into a GaAs/AlGaAs heterostructure containing a two-dimensional electron system. Alloyed ohmic contacts give electrical connection to the 2DES. By applying a negative voltage to the six gate fingers, a quantum dot is defined which couples to source and drain by tunnel barriers. b) The measured differential conductance,* dI_{DS}/dV_{DS}*, shown in greyscale as a function of a gate voltage and the drain-source voltage (temperature* $T < 0.1$ *K) (black means high differential conductance, white zero). The regimes of Coulomb blockade (CB) and single-electron tunneling (SET) (see sketch on the right) are clearly resolved in the data. c) Same as b), but for the case of strong tunnel coupling. A peak appears in the regime of Coulomb blockade at* $V_{DS} = 0$*, which behaves like a Kondo resonance. With one electron less in the quantum dot, an unexpected resonance appears in the regime of CB. d) Same as c), but for an externally applied magnetic field of 0, 2 and 4 Tesla. The zero-bias anomaly splits with twice the Zeeman energy.*

Figure 56b shows the differential conductance, $\mathrm{dI_{DS}/dV_{DS}}$, through our quantum dot measured as a function of the drain–source voltage, $\mathrm{V_{DS}}$ and a gate voltage, $\mathrm{V_G}$, for the case of weak tunnel coupling to both source and drain contact. By changing the gate voltage, the electronic levels of the quantum dot are shifted and start to contribute to the conductance through the quantum dot if they are aligned with the Fermi level of source, respectively drain (peak in the differential conductance for these $(\mathrm{V_{DS}}, \mathrm{V_G})$ values). The regimes of Coulomb blockade and single–electron tunneling are clearly visible. In the regime of single–electron tunneling, additional resonances in the differential conductance occur reflecting the discrete energy spectrum of the quantum dot system [Weis *et al.*, Phys. Rev. Lett. **71**, 4019 (1993)].

Figure 56c shows the result obtained for the case of strong tunnel coupling to the reservoirs. The regimes of Coulomb blockade are no longer well–defined, but the remarkable feature is the appearance of a peak in the differential conductance at $V_{DS} = 0$ over the whole Coulomb blockade regime of N electrons. This zero–bias anomaly remains unaffected by V_G, although the electronic states of the dot are shifted by V_G. It becomes stronger with increasing the tunnel coupling and disappears with increasing the temperature. These properties are expected for Kondo resonances. By applying an external magnetic field in the plane of the 2DES, the electronic states, if they are spin–degenerated, should split. As shown in Fig. 56d, the zero–bias anomaly splits to higher $|V_{DS}|$ with twice the Zeeman energy as expected [Meir *et al.*, Phys. Rev. Lett. **70**, 2601 (1993); König *et al.*, Phys. Rev. **B54**, 16820 (1996)]. Although the data discussed up to now confirm qualitatively the theoretical predictions about Kondo resonances, and they are consistent with data recently presented [Goldhaber–Gordon *et al.*, Nature **391**, 156 (1998); Cronenwett *et al.*, Science **281**, 540 (1998)], we cannot confirm that with changing the parity in the number of electrons in the quantum dot, we get for odd number this zero–bias anomaly and for even number not. The simple picture that the energy spectrum of the dot is independent of the number of electrons ('constant interaction model') and by adding electrons to the quantum dot, the spin–degenerated electronic states are just filled, seems not to work in our system. In the Coulomb blockade regime with one electron less (Fig. 56c), we observed a similar resonance, but which slightly shifts with gate voltage to finite drain–source voltage values and shows a strange magnetic field dependence (not shown). Further experiments are required to understand its origin and the influence of excited states of the quantum dot system.

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