Two electrostatically coupled quantum dot systems as a new realization of the Anderson impurity model

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In the last decade, quantum dots weakly coupled to leads – denoted in the following as quantum dot systems – have been the subject of many studies in electrical transport. Due to the electron-electron interaction on the quantum dot site, Coulomb blockade and single-electron charging effects are observed. Due to their in situ tunability – for instance, the electron number on the quantum dot and tunnel coupling to the leads – quantum dot systems are considered as model systems which mimic also basic properties of single atoms or molecules between leads. In the more recent years, it has been experimentally demonstrated, that such systems show under certain conditions Kondo physics as it was already predicted in 1988 by mapping the Anderson impurity model [Anderson, Physical Review **124**, 41 (1961)] on a single quantum dot system (see review by Kouwenhoven and Glazman [Physics World, 33, January 2001]). The presence of a spin-degeneracy on the quantum dot site induces at low temperature correlated electron tunneling between the quantum dot and the leads, forming overall a spin-singlet state. A highly conductive channel of transport is opened between the leads via the quantum dot, which even reaches the conductance $2e^2/h$ in the case of symmetric tunnel couplings to the leads – the value also found for a spin-degenerate one-dimensional channel. Increasing the temperature breaks the correlations, the Kondo effect is destroyed, and the Coulomb blockade effect is recovered.

The Anderson impurity model describes a spin-degenerate energy level at an impurity or quantum dot site which is coupled via tunneling to a Fermi sea containing electrons of both spin orientations. In other words, it describes two separate electron subsystems labelled by a two-valued index which is usually identified with the spin quantum number (Fig. 35(a)). The two spin electron systems interact only on the impurity site through Coulomb interaction which suppresses double occupancy of the impurity. As we proposed [Wilhelm *et al.*, Physica E **9**, 625 (2001)], one may interpret the 'spin' index of the Anderson impurity model differently which

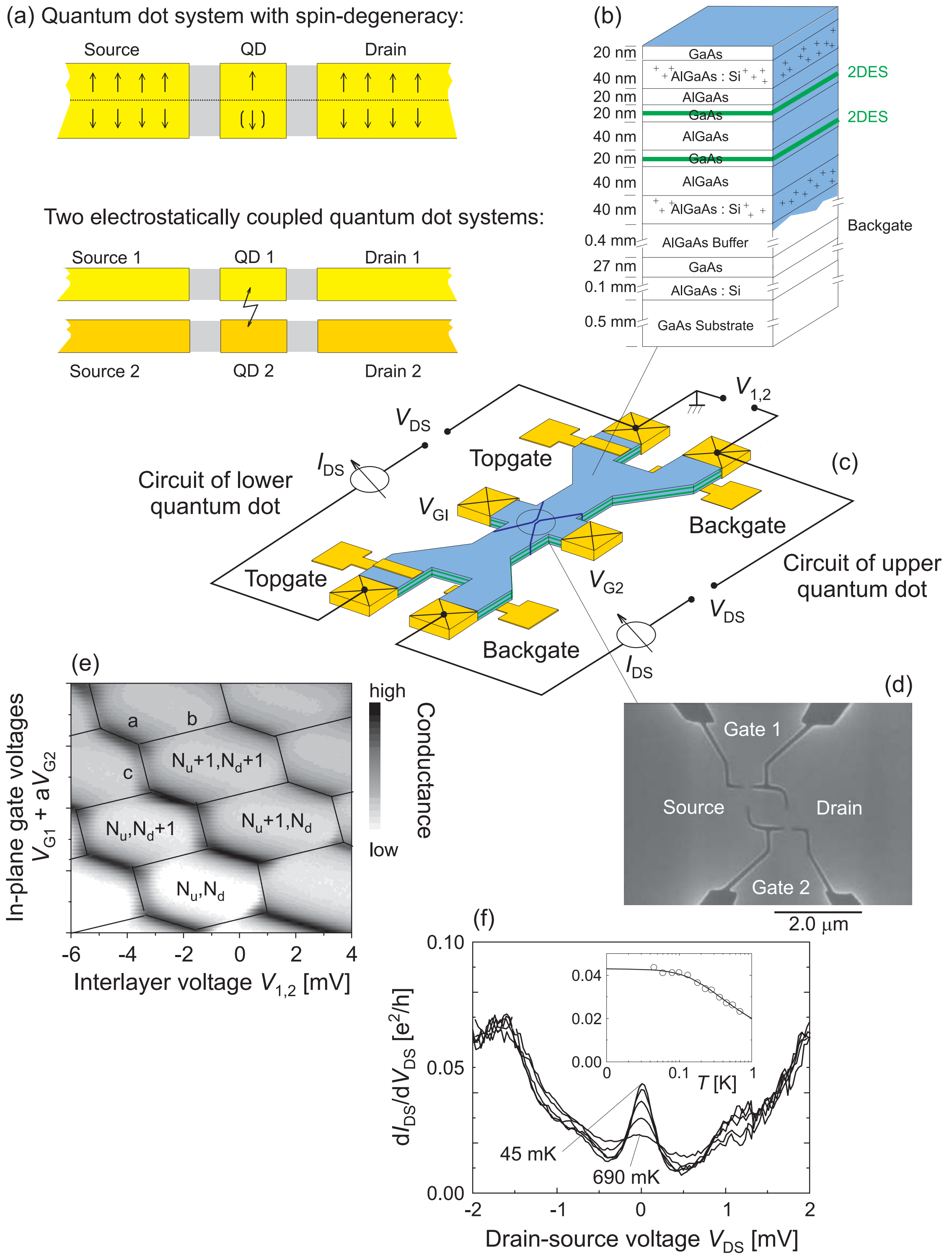

Figure 35: (a) Possible realizations of the Anderson impurity model: Single quantum dot system with spin-degeneracy or two electrostatically coupled quantum dot systems without spin-degeneracy. (b) GaAs/AlGaAs heterostructure used for the sample. (c) Sketch of the experimental setup. (d) Scanning electron microscope image of the etched heterostructure surface. (e) Conductance through upper quantum dot as a function of the in-plane gate voltages V_{G1} and V_{G2}, and the interlayer voltage $V_{1,2}$. (f) Differential conductance dI_{DS}/dV_{DS} versus drain-source voltage V_{DS} on a point on the line ‘c’ marked in (e) for different temperatures ($T = 45, 80, 180, 360, 690$ mK). Inset: temperature dependence of the peak height at $V_{DS} = 0$.

gives a new realization of the Anderson impurity model: the label marks two electrostatically coupled quantum dots with separate leads to each quantum dot (Fig. 35(a)). This mapping is valid if (1) an energetical degeneracy is present in occupying either the upper or the lower quantum dot, (2) the ground state of each quantum dot is not degenerated and excited states are energetically well separated. Our goal has been to verify this idea experimentally.

Base for the sample is a $GaAs/Al_xGa_{1-x}As$ heterostructure ($x = 0.33$), grown by Molecular Beam Epitaxy in the MBE group of the Institute. The heterostructure contains two quantum wells with a two-dimensional electron system (2DES) in each well, separated by an insulating 40 nm thick AlGaAs barrier. The full layer sequence is shown in Fig. 35(b). In a further step, the two quantum dot systems are defined on top of each other by reactive ion etching through the two quantum wells. A scanning electron microscope image of the etch pattern at the heterostructure surface is shown in Fig. 35(d). The two-dimensional electron system in each quantum well is divided by the etched grooves and the electrostatic depletion around them into the quantum dot region, the source and drain regions, and in addition into two regions usually denoted as in-plane gates. At low temperature, the electron systems confined in quantum dots have an extension of about 0.3 μm in diameter weakly coupled by respective tunnel barriers to the source and drain regions. The electron systems in the two quantum dots are strongly electrostatically interacting through the 40 nm thick AlGaAs layer which, however, prevents due to its thickness any tunnel current between both quantum dot systems. The quantum dot systems are separately contacted by alloying metal and by using top and back gates for locally depleting the upper or lower 2DES (Fig. 35(c)). The properties of the quantum dots are tuned by voltages applied to the two in-plane gates and the voltage $V_{1,2}$ applied between the 2DESs of the two quantum wells. All the measurements presented here were performed in a ^{3}He–^{4}He dilution refrigerator at base temperature $T = 45$ mK. To measure the differential conductance dI_{DS}/dV_{DS}, a lock-in modulation technique is used with an applied rms amplitude of 2.5 μV added to the dc drain-source voltage V_{DS}.

Figure 35(e) shows the conductance (differential conductance at $V_{DS} = 0$) in greyscale through the upper quantum dot as a function of a linear combination of the in-plane gate voltage V_{G1} and V_{G2}, and the interlayer voltage $V_{1,2}$.* Dark regions indicate high conductance, light regions low conductance. A honeycomb-like pattern is visible which is expected for two strongly electrostatically coupled single-electron transistors. Within each honeycomb cell, a certain configuration of the electron numbers of the two quantum dots is found, for instance (N_u, N_d). Crossing a borderline between two adjacent cells, at least in one quantum dot the number of electrons is changed by one. Along the borderlines labelled by ‘a’, single-electron tunneling occurs through the upper quantum dot due to the electrostatic degeneracy between the charge states characterized by a change only in the upper quantum dot, for instance from (N_u, N_d) to $(N_u + 1, N_d)$. Along the borderlines labelled by ‘b’, single-electron transport is possible through the lower quantum dot, while the upper quantum dot is in the Coulomb blockade regime. Along the lines labelled by ‘c’, finite conductance through the upper quantum dot is detected although this is not expected in the picture of single-electron tunneling. However, due to the electrostatic degeneracy, it is possible to have there a surplus electron *either* on the upper *or* lower quantum dot, i.e., for instance, the charge states $(N_u, N_d + 1)$ and $(N_u + 1, N_d)$ are energetically equivalent.

*In this parameter regime, the lower quantum dot was only connected by tunneling to one lead so that no conductance could be measured. However, this does not affect the conclusions presented in the following, but leaves signature at larger drain-source bias [Wilhelm *et al.*, Physica E **14**, 385 (2002)].

This allows for so-called 'co-tunneling' – an electron leaves one dot while another electron enters the other dot. This is the lowest order of correlated electron tunneling switching the charge state of both quantum dots at the same time by quantum mechanical correlation.

However, due to the analogy to the Anderson impurity model along the borderline 'c', we expect that it is not enough to treat correlated electron tunneling in perturbation theory: a Kondo-correlated state should form at low temperature leading to high conductance through both quantum dots at the same time. To prove this, the differential conductance is measured at points on the borderline 'c' as a function of drain-source voltage V_{DS}, and indeed – as shown in Fig. 35(f) – a peak is found at $V_{DS} = 0$ which disappears in a logarithmic way with increasing temperature. A semi-empirical fit of the experimental data gives a Kondo temperature $T_K = 850$ mK and a zero-temperature conductance $G_0 = 0.043\, e^2/h$ (inset of Fig. 35(f)). We checked that Kondo resonances due to a spin-degeneracy in the single quantum dot do not occur in the neighboring honeycomb cells for this parameter range. Therefore, the behavior observed is induced by the charge degeneracy due to the electrostatic coupling between the two quantum dots. However, the measured Kondo temperature is surprisingly high. But an enhancement of the Kondo temperature is expected in the *combination* of a spin-degeneracy for each quantum dot and the electrostatic degeneracy between both quantum dots. In our experiment the spin-Kondo effect alone might not be visible in the neighboring honeycomb regions because our working temperature is too high and therefore these correlations are destroyed. To prove the hypothesis of an enhanced Kondo temperature, the spin-degree of freedom can be frozen out by applying a high magnetic field so that only the electrostatic degeneracy remains. Such experiments will be performed in the near future to clarify the unusual high Kondo temperature.