Electronic States and Transport Properties in Semiconductor Quantum Dots —from Coulomb Blockade to Kondo Effect—

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We review the electronic states and transport properties in quantum dots fabricated on semiconductors, from a theoretical point of view.

Coulomb blockade: In quantum dots the charging energy can be larger than the thermal energy, which significantly influences the transport properties through the quantum dots. The electric current is suppressed unless the "resonant" condition of $E(N) = E(N-1) + \mu$ is fulfilled, where $E(N)$ is the energy of N-electron state and μ is the Fermi energy of the external leads connected to the dots by the tunnel junctions. This is called Coulomb blockade. When the gate voltage is applied to change the electrostatic potential in the dots, a large current flows at the resonance. In consequence, the conductance shows a quasi-periodic peak structure as a function of the gate voltage (Coulomb oscillation; solid line in Fig. 1(a)). Between the current peaks is the Coulomb blockade region where the number of electrons in the dot, N, is almost fixed to an integer value. N is changed one by one with increasing the gate voltage [1].

Cotunneling and Kondo effect: The conductance is usually very small in the Coulomb blockade region at low temperatures. Then the transport properties are dominated by the higher-order tunneling processes, so-called cotunneling [2, 3].

The Kondo effect can significantly enhance the cotunneling conductance, to a value of the order of $2e^2/h$ below the Kondo temperature, T_K. Generally the Kondo effect takes place when a localized spin is brought in contact with electron Fermi sea. It gives rise to a new many-body ground state that has a lesser spin, which influences the transport properties of conduction electrons. In quantum dots coupled to external leads through tunneling barriers, the localized spin is formed by the electrons confined in the dots. The Kondo effect is usually observed for an odd number of electrons in a quantum dot with spin $S = 1/2$, whereas it is not relevant for an even number of electrons with spin-singlet ($S = 0$).

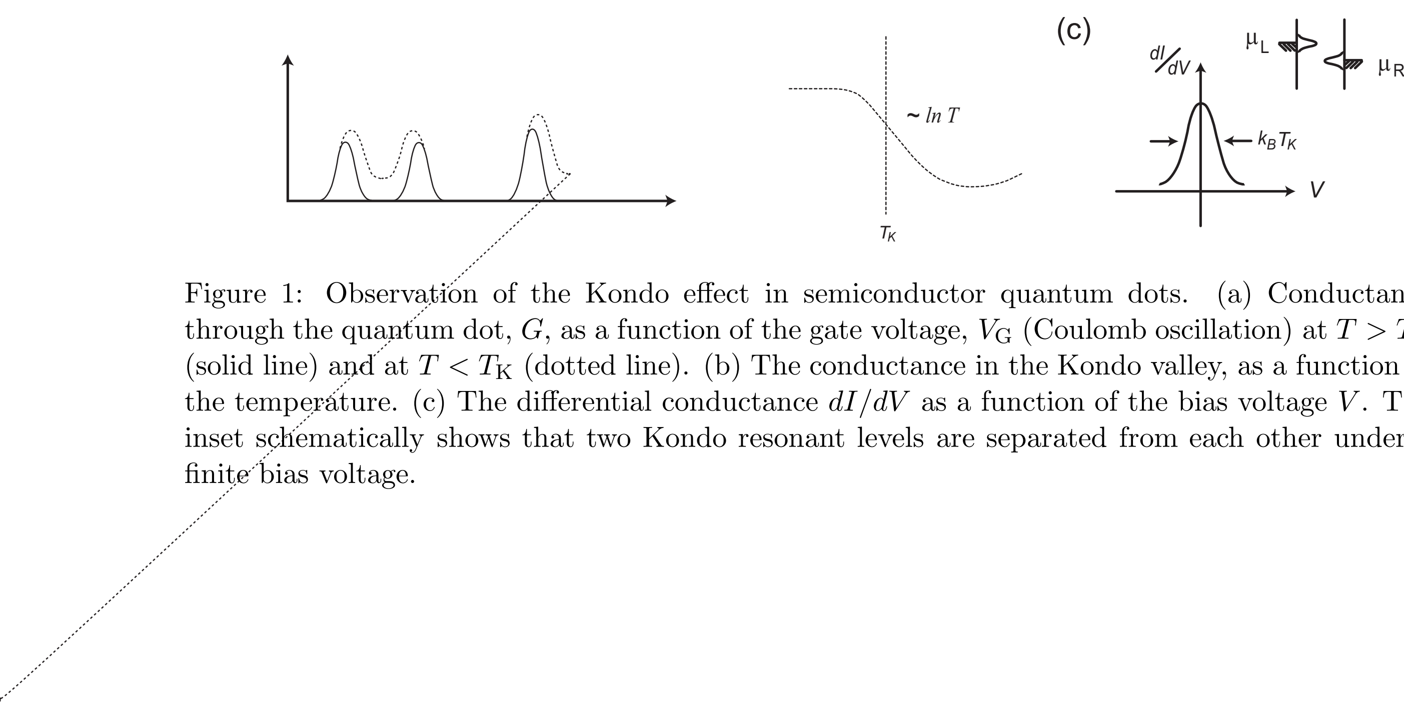

Figure 1: Observation of the Kondo effect in semiconductor quantum dots. (a) Conductance through the quantum dot, G, as a function of the gate voltage, V_G (Coulomb oscillation) at $T > T_\mathrm{K}$ (solid line) and at $T < T_\mathrm{K}$ (dotted line). (b) The conductance in the Kondo valley, as a function of the temperature. (c) The differential conductance dI/dV as a function of the bias voltage V. The inset schematically shows that two Kondo resonant levels are separated from each other under a finite bias voltage.

There are several ways to observe the Kondo effect in quantum dots. First, the conductance G increases with decreasing temperature in the Coulomb blockade regions with an odd number of electrons (dotted line in Fig. 1(a)). Second, in the Kondo valley, G shows a logarithmic T dependence between $\sim 0.1T_{\rm K}$ and $10T_{\rm K}$ (Fig. 1(b)). G becomes as large as $\sim 2e^2/h$ at $T \ll T_{\rm K}$. This is called unitary limit. Third, under finite bias voltages, V, the Kondo resonant level on one lead is off that on the other lead. As a result, the differential conductance dI/dV has a sharp peak at $V = 0$. The width of the peak is of the order of $T_{\rm K}$ (Fig. 1(c)) since the Kondo resonance has a width of $\sim T_{\rm K}$.

Singlet-triplet Kondo effect: The Kondo effect with an even N has been reported in "vertical" quantum dots [4]. In vertical dots, the strength of the electron-electron Coulomb interaction is comparable with the spacing of discrete levels, and this may give rise to a complicated ground state [5]. If two electrons are put into nearly degenerate levels, the exchange interaction favors a spin-triplet state. This state can be changed to a spin-singlet by applying a magnetic field since the magnetic field increases the level spacing [3, 5]. Hence the energy difference between the spin-singlet and -triplet states, Δ, can be tuned experimentally. Sasaki *et al.* has found a large Kondo effect when the spin states are nearly degenerate ($\Delta \approx 0$). Tuning of the energy difference between the spin states is hardly possible in traditional Kondo systems of dilute magnetic impurities in metal and thus this situation is quite unique to the quantum dot systems.

We examine the Kondo effect in quantum dots with an even N, in the vicinity of the degeneracy between spin-singlet and -triplet states [6]. By the scaling method, we evaluate $T_{\rm K}$ as a function of the energy difference between the states, $\Delta = E_{S=0} - E_{S=1}$. We find that (i) $T_{\rm K}(\Delta)$ is maximal around $\Delta = 0$, (ii) for positive Δ, $T_{\rm K}(\Delta)$ decreases with increasing Δ obeying a power law, $T_{\rm K}(\Delta) \propto 1/\Delta^\gamma$, and (iii) for negative Δ, the Kondo effect is not relevant when $|\Delta| \gg T_{\rm K}(0)$. Our calculated results indicate an enhancement of the Kondo effect by the competition between the spin states, which is in accordance with the experimental results by Sasaki *et al.* Recently the power law of $T_{\rm K}(\Delta)$ has been observed experimentally [7].

For qualitative discussion, we study the "singlet-triplet Kondo effect" by the mean-field method [8]. In the mean-field theory of the Kondo effect, the spin couplings between the dot states (pseudo-fermion operator $f^\dagger_{SM}$ to create state $|SM\rangle$) and conduction electrons ($c^\dagger_{k,\sigma}$ to create state $|k,\sigma\rangle$) are taken into account by the mean field, $\langle f^\dagger_{SM} c_{k,\sigma}\rangle$. This results in the resonant state at the Fermi level μ with the width of the Kondo temperature $T_{\rm K}$. The unitary limit of the conductance, $G \sim 2e^2/h$, can be understood in terms of the resonant tunneling through the state at μ. In the singlet-triplet Kondo effect, the overlap between the resonant states of $S = 1$ and $S = 0$ in the quantum dot enhances the Kondo effect. The mean-field calculations yield a power-law dependence of $T_{\rm K}$ on Δ, in accordance with the scaling calculations.

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