The Kondo resonance in a single InAs quantum dot probed by nanogap electrodes

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Abstract. We fabricated a pair of nano-gap electrodes to contact an uncapped single self-assembled InAs quantum dot and studied the single-electron transport properties. We observed clear signatures of the Kondo effect as the temperature was lowered, such as lifting of a Coulomb valley corresponding to an odd number of electrons in the dot and zero-bias anomaly in the differential conductance in the Coulomb valley. From the temperature dependence of these features, we estimated the Kondo temperature of about 2 K.

For the last decades intensive studies have been performed on the optical properties of self-assembled quantum dots (SAQDs) and their applications to optical devices, because distinct optical processes can be expected for electrons and holes both strongly confined in the QDs by abrupt heterojunction barriers. By contrast, there are only a limited number of studies reported on the electronic properties to date. For example, atom-like shell structure in the energy spectrum was studied by capacitance spectroscopy method [1]. These experiments, however, suffered from inhomogeneous broadening due to the ensemble averaged means of SAQDs. To investigate the electronic structure in SAQDs precisely, it is necessary to probe just a single SAQD. As a consequence, various devices and techniques, such as point contact devices including one or two SAQDs in the conducting channel [2], gated sub-micron mesa devices containing just a few SAQDs [3], noncontact AFM probes [4], and nanogap electrode contacts [5], were developed and used to measure the transport properties of individual single and coupled QDs. These efforts enabled observations of well resolved features of shell structure [6], spin pairing [7] and molecular phase [8], all reflecting the strong confinement of SAQDs. Also associated with the strong confinement effect, it has recently been demonstrated that electronic spin is a more robust quantum number in SAQDs than in standard QDs made in a two-dimensional electron gas, because of the reduced phonon scattering [9]. This feature can lead to new insights in spin-related physics in SAQD as well as spin-based solid-state quantum information processing. Spin coherence is a key concept in this context, and has recently been studied for various kinds of QDs. The Kondo effect is a typical example, and can only appear in QDs when spin coherence extends over the tunnel junction between the QD and contact leads. Observation of the
Kondo effect has been reported for various QD devices including semiconductor lateral and vertical QDs [10-12], carbon nanotubes [13] and individual molecules [14,15] but not yet for SAQDs. In this paper, we investigate the electron transport properties of a single uncapped self-assembled InAs QD and observe the Kondo effect. This is the first observation for SAQDs to our knowledge. The electrical contacts, which are tunnel-coupled to a single QD, were made by placing a pair of metallic electrodes with a ~20 nm gap on the QD (Figure 1). Previously we used this same technique for smaller InAs QDs to study the energy spectrum, and observed a shell structure [16]. The device in the former study had a relatively weak tunnel coupling between the contacts and the QD. In this work, we adopted a QD of larger size. The tunnel coupling strength largely depends on the contact area between the electrode metal and the QD, i.e., larger area gives a smaller tunnel resistance. The small tunnel resistance is necessary to observe the Kondo effect. Therefore, we used a relatively large QD that is strongly coupled to the contact leads.

The wafer we used was grown by molecular beam epitaxy. The epitaxial layer sequence consists of an InAs wetting layer, a 200-nm thick undoped GaAs buffer layer, and a 100-nm thick AlGaAs barrier layer on n+-GaAs (100) substrate. InAs QDs are formed on the wetting layer and left uncapped on the surface. The lateral contact leads were prepared using electron beam lithography, metal (10-nm thick Ti/10-nm thick Au) evaporation, and lift-off. The n-type substrate was used as a back gate. Figure 1 shows the SEM image of the device used in this study. The inset schematically shows the cross-sectional view of the device. A pair of contact leads with a ~20 nm gap is placed on a large QD whose diameter is ~90 nm. We measured the conductance between the paired contacts in the linear and nonlinear responses, using a standard AC lock-in technique. The device was mounted in a dilution refrigerator with base temperature of 30 mK.

Figure 2(a) shows the conductance vs. gate voltage $V_g$, or Coulomb oscillations, measured for various temperatures $T$. We observed Coulomb peaks corresponding to the one-by-one electron filling of the QD, starting from $N = 0$. The QD was empty at $V_g = 0$ V, and only filled by application of positive voltage to the gate. The Coulomb valley holding an odd number of electrons, i.e. $N = 3$ and 5 QD grows as the temperature decreases, although the dependence is not very strong for the $N = 5$ Coulomb valley. In contrast no such temperature dependence was observed for the Coulomb valleys holding even numbers of electrons.

Figure 3 shows the differential conductance $dI/dV_{sd}$ in the $V_{sd} - V_g$ plane (a) and the $dI/dV_{sd}$ vs. $V_{sd}$ measured in the center of the Coulomb valley for $N = 3$ ($V_g = 0.37$ V) and $N = 5$ ($V_g = 0.56$ V), respectively (b). In (a) and (b) we see a zero-bias peak or Kondo anomaly in the $N=3$ and 5 Coulomb valleys. Both features shown in Figs. 2 and 3 indicate the Kondo effect associated with a spin-half state in the QD. Figure 2(b) shows the temperature dependence of the linear conductance in the middle of the $N = 3$ Coulomb valley. As the temperature is decreased, the conductance increases logarithmically and becomes finally saturated below 100 mK as expected from theory [17]. The solid
Figure 2. (a) Conductance oscillations with gate voltage with $V_{sd} \approx 0$ V at various temperatures ranging from 30 to 800 mK. The Coulomb valley holding $N = 3$ and 5 grows with decreasing temperature. (b) Temperature dependence of the conductance in the middle of the $N = 3$ Coulomb valley. Solid line denotes the fit of the empirical function (given in the text) to the data.

Figure 3. (a) Differential conductance as a function of $V_g$ and $V_{sd}$. Vertical lines at $V_{sd} = 0$ V in the Coulomb blockade with $N = 3$ and 5 shows the conductance induced by the Kondo effect. (b) Zero-bias anomaly measured in the center of the $N = 3$ and 5 Coulomb valley, respectively.

Line is a fit to the data assuming an empirical function: $G(T) = G_0/[1+(2^{1/2}-1)(T/T_K)^2]^{s}$, where $s = 0.22$ for a spin-1/2 state and $G_0$ is the maximum conductance in the low $T$ limit. The good fit was obtained assuming $G_0 \approx 0.076e^2/h$, $s \approx 0.15$ and Kondo temperature $T_K \approx 1.9$ K. The estimated $T_K$ is consistent with that estimated from the full width at half maximum of the zero-bias $dI/dV$ peak.

The estimated $G_0$ is much smaller than the unitary limit ($= 2e^2/h$), probably because of the asymmetry in the QD tunneling rate between the source and drain contacts. Note the conductance $G_K$ due to the Kondo state is approximated by: $G_K \approx (2e^2/h) 4\Gamma_S \Gamma_D (\Gamma_S + \Gamma_D)^2$ for $T \ll T_K$, where $\Gamma_S$ and $\Gamma_D$ is the tunneling rate between the source (drain) contact and the QD [18,19]. Although the tunneling rate is large enough to favor the Kondo effect, $\Gamma_S$ and $\Gamma_D$ can be different in our device. We did not observe the Kondo effect for the $N = 1$ Coulomb valley, probably because as the gate voltage is made more negative, the tunneling rates $\Gamma_S$ and $\Gamma_D$ become so small that the Kondo temperature is too low for our measurement.

In conclusion, we used a pair of nano-gap electrodes to contact an uncapped single InAs SAQD with a pair of nano-gap electrode contacts to study the single-electron transport properties. We clearly observed the Kondo effect for Coulomb valleys holding three and five electrons. We evaluated the Kondo temperature of about 2 K from the temperature dependence of the Kondo conductance.
Part of this work is financially supported by the DARPA grant no. DAAD19-01-1-0659 of the QuIST program, the Grant-in-Aid for Scientific Research A (No. 40302799), SORST Interacting Carrier Electronics, JST, and Focused Research and Development Project for the Realization of the World's Most Advanced IT Nation, IT Program, MEXT.

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