Fano-Kondo interplay in a side-coupled double quantum dot

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(Dated: December 10, 2009)

We investigate low-temperature transport characteristics of a side-coupled double quantum dot where only one of the dots is directly connected to the leads. We observe Fano resonances, which arise from interference between discrete levels in one dot and the Kondo effect, or cotunneling in general, in the other dot, playing the role of a continuum. The Kondo resonance is partially suppressed by destructive Fano interference, reflecting novel Fano-Kondo competition. We also present a theoretical calculation based on the tight-binding model with slave boson mean field approximation, which qualitatively reproduces the experimental findings.

Large tunability of electronic states in semiconductor quantum dot (QD) systems has unveiled rich quantum transport phenomena in recent years. In particular, the Kondo effect has been extensively investigated as archetypical many-body physics, and its interplay with Fano interference is of great interest from the viewpoint of tuning spin correlation by quantum coherence. A QD having an odd number of electrons with spin \( S = 1/2 \) displays the Kondo effect at temperature lower than \( T_K \) (the Kondo temperature) as a result of spin singlet formation between the localized magnetic moment in the QD and the delocalized electrons in the reservoirs. Then, the conductance is enhanced at Coulomb blockade regions and a zero-bias peak appears. The Kondo resonance is partially suppressed by destructive Fano interference, reflecting novel Fano-Kondo competition. We also present a theoretical calculation based on the tight-binding model with slave boson mean field approximation, which qualitatively reproduces the experimental findings.

When a second QD (QD2) is tunnel-coupled to the side of the first QD (QD1) exhibiting the Kondo effect, the competition with the inter-dot spin singlet formation, and the influence by the Fano interference are expected, such as the two-stage Kondo effect, the competition with the inter-dot spin singlet formation, and the influence by the Fano interference. In contrast to the large number of theoretical studies in the literature, very few experiments have been reported on such a side-coupled double quantum dot (DQD).

In this Letter, we report low-temperature transport properties of a side-coupled DQD. At charge state transitions on QD2, we observe Fano resonances arising from interference between discrete levels in QD2 and the cotunneling process in QD1, which serves as a continuum. In agreement with the Fano formalism, the asymmetric resonance line shape is found to evolve systematically with the magnitude of the non-resonant channel transmission, i.e., cotunneling conductance, which can be changed by the gate voltage or magnetic field. On the other hand, unlike the standard Fano interference, the magnitude of the resonance is reduced due to the competition with the Kondo effect. We also present a tight binding calculation incorporating slave boson mean field approximation, which is in qualitative agreement with the experiment.

The DQD device is fabricated from a GaAs/Al\(_x\)Ga\(_{1-x}\)As heterostructure with two-dimensional electron gas (2DEG) located 90 nm from the surface. Several Schottky gate electrodes are deposited on the wafer to form parallel QD’s. Direct connection between QD2 and 2DEG reservoir is lost by applying sufficiently negative gate biases, \( V_L \) and \( V_U \). Then, the device operates as a side-coupled DQD with the only current path through QD1. In this geometry, complications arising from multiple current paths can be avoided, and even when QD2 has a local magnetic moment, it is not screened by the external leads due to the Kondo effect. Therefore, the influence of QD2 on QD1 transport, or correlated transport of the coheren-
nonresonant channel conductance, 
across resonance

FIG. 2: (a) The observed mid-valley conductance profile
across resonance

ent DQD system as a whole, is expected to be more
straightforwardly investigated than in a serial or parallel
DQD. Transport measurement is performed with a
standard lock-in technique at temperatures down to
T ∼ 40 mK in a dilution refrigerator. The source-drain
bias Vsd = Vdc + Vac, where Vdc is a DC offset and AC
excitation (about 13 Hz) Vac = 5 μV.

Figure 1 shows a color-scale plot of the linear conduc-
tance as functions of the plunger gate voltages, V1 and
V2. Three strong Coulomb peaks are observed when the
electron number in QD1, N1, changes by one. Inter-dot
and dot-lead tunnel barriers are tuned in the strong
coupling regime in excess of ∼ 200 μeV for the parameter
range of interest. Inter-dot Coulomb interaction is re-
vealed as jumps in the Coulomb peak positions whenever
the electron number in QD2, N2, changes by one, forming
a well-known honeycomb stability diagram. We find
such jumps disappear at sufficiently negative V2, indicat-
ing that N2 = 0 there. N2 values determined this way
are shown in Fig. 1. Conductance in the lower Coulomb
blockade valley (marked with a triangle) is much larger
than in the upper one, and a zero-bias peak is observed
in the Vdc dependence of the differential conductance.
The Kondo effect is responsible for these features with
T_K ∼ 750 mK as estimated from the half width of the
zero-bias peak.

At the boundaries between different N2 ground states
where the Coulomb peaks jump, conductance in the
coulomb blockade region shows maxima (minima) at
the upper (lower) valley. Conductance profiles extracted
along dashed lines in the middle of the QD1 Coulomb
blockade valleys across QD2 resonances α and β (see Fig. 1)
are plotted in Fig. 2(a) and (b), respectively. We inter-
pret these conductance modulations in terms of Fano in-
terference between the indirect transmission via
discrete levels in QD2, and the Kondo effect (cotunnel-
ing process) in QD1 playing the role of a continuum. Data
points of conductance G are fitted with the Fano formula
(solid line)

\[ G(\varepsilon) = G_0 \left( \frac{\varepsilon + \eta}{(\varepsilon^2 + 1)} \right) + G_1. \]

Here, \( \varepsilon \equiv 2(E - E_0)/\Gamma \) is a normalized detuning with
E the energy of an electron, E0 the energy of the res-
onance, and \( \Gamma \) the level broadening. \( G_0 \) is conductance
via a nonresonant transmission channel, and \( G_1 \) is an
offset which is normally ascribed to an incoherent trans-
mission component. The dimensionless parameter \( q \) is
known as Fano’s asymmetric parameter and character-
izes the shape of the resonance line. Fano interference
occurs between transmissions via a nonresonant chan-
nel (continuum channel) and a resonant one, and their
relative amplitude determines \( q \). When the former dom-
ninates, the resonance at \( E = E_0 \) appears as a dip with
\( q \approx 0 \). On the contrary, when the latter dominates, the
resonance appears as a peak similar to a normal Coulomb
blockade peak with \(|q| \gg 1 \). We define \( G_N^R \equiv G_0 + G_1 \)
(i = α, β etc.) as the conductance (including the back-
ground) ascribed to the nonresonant channel, i.e. cotun-
neling conductance far from the \( N_2 \) transitions. We also
define resonant channel conductance \( G_N^R \equiv (1 + q^2)G_0 \).
When \( q = 0 \) (|q| = ∞), \( G_R^N \) is the magnitude of the res-
onance dip (peak) measured with respect to \( G_N^R \). Since
cotunneling conductance is relatively small \( (G_N^R \approx 10μS) \)
near the resonance \( \alpha \) in the non-Kondo valley, a large
resonance peak is observed with \( q = 22 \). On the other
hand, a resonance dip is observed at \( \beta \) in the Kondo val-
ley with \( q = 0.17 \) and \( G_N^R \approx 29 \mu S \). A value of \( q = 1.4 \)
is obtained with a large asymmetry in the line shape
(not shown) at another resonance \( γ \) in the non-Kondo
valley having an intermediate value of \( G_N^R \approx 25 \mu S \).
This trend of smaller \( q \) for larger \( G_N^R \) is consistent with the
Fano formalism because \( G_N^R \) reflects the transmission
amplitude via a nonresonant channel. Fano resonances
have been extensively investigated recently in mesoscopic
systems involving QD’s where the nonresonant channel
arises from a quantum wire.\textsuperscript{16,17,18,19} Fano resonances
are also observed in a semi-open single QD without an
obvious continuum channel.\textsuperscript{20,21,22} Although cotun-
neling has been suggested as a nonresonant channel in Ref.\textsuperscript{20},
particular orbital states strongly coupled with the leads
seem to be more likely sources of nonresonant channels.\textsuperscript{22}
In the present DQD system, cotunneling through QD1
unambiguously serves as a nonresonant channel, which is
corroborated by the device geometry.

The behavior captured in Fig. 2(b) clearly demon-
strates suppression of the Kondo effect by Fano destructive interference. However, the Kondo zero-bias peak is not completely suppressed even at the dip region $(V_2 \approx -0.08 \text{ V})$. The amount of this partial suppression of the Kondo peak gives the dip magnitude, $G^2_R \approx 7 \mu \text{S}$, while the remaining peak increases the background conductance to $G_1 \approx 22 \mu \text{S}$ over a true incoherent background of $\approx 10 \mu \text{S}$. This point is discussed again in the later section dealing with the magnetic field dependence.

Figure 2(c) shows temperature dependence of $G_{N}^{0}$, $G_{R}^{0}$, and $G_{R}^{\beta}$, $G_{R}^{\alpha}$ is the normal Kondo conductance showing a linear log$T$ behavior as expected. $G_{R}^{\beta}$ and $G_{R}^{\alpha}$ seem to change in a linear log$T$ manner as well, which may suggest their relevance to the Kondo physics. The same $G_{R}^{\beta}$ and $G_{R}^{\alpha}$ data are plotted as a function of inverse temperature in Fig. 2(d). The high temperature part of the resonant channel conductance decreases linearly with temperature, which suggests thermal broadening of the electron distribution in the leads, as known for normal Coulomb blockade peaks.

Next, we present a theoretical calculation of the conductance for the side-coupled DQD at $T = 0$ K. We employ the tight-binding model to incorporate relevant parameters in the present DQD geometry as schematically shown in Fig. 3(a). QD1 (QD2) is assumed to have single-particle energy $\varepsilon_1$ ($\varepsilon_2$) and the on-site Coulomb energy $U_1$ ($U_2$). Inter-dot Coulomb interaction is not taken into account. An analytical expression for the conductance equivalent to eq. (1) is obtained for $U_1 = U_2 = 0$ [134]. For $U_1 \neq 0$, the Coulomb interaction in QD1 is taken into account by the slave-boson mean field approximation. We assume $U_2 = 0$ to avoid calculational complexity, believing that the essential physics for an individual Fano resonance can be still captured. The conductance is calculated from the transmission probability obtained by the S-matrix formalism.

Figure 3(b) shows the calculated conductance as functions of single-particle levels $\varepsilon_1$ and $\varepsilon_2$ with respect to the Fermi energy, $E_F$, for $U_1 = 4$, $t_1 = 0.45$, and $t_d = 0.14$ in units of $t_0$. When $\varepsilon_2$ is away from the Fermi level, the conductance shows an ordinary Kondo-enhanced conductance within the QD1 Coulomb blockade valley between $E_F - \varepsilon_1 = 0$ and 4. As $\varepsilon_2$ approaches $E_F$, Fano resonance involving the QD2 discrete level suppresses the Kondo-enhanced conductance in QD1 to zero. As shown in Fig. 3(d), a symmetric conductance profile with a dip, similar to Fig. 2(b), is obtained in the middle of the QD1 Coulomb blockade valley ($\beta$) at $E_F - \varepsilon_1 = 2$ corresponding to $q = 0$. On the other hand, an asymmetric peak similar to Fig. 2(a) is obtained outside the QD1 Coulomb blockade valley ($\alpha$). The conductance profile at $E_F - \varepsilon_1 = 6$ is shown in Fig. 3(c) corresponding to $q \approx 5$. These results are in qualitative agreement with our experimental results. The calculated line shape in Fig. 3(d) is slightly different from the one obtained by putting $q = 0$ in eq. (1) because of the Kondo correlation. This will be discussed in more detail in a separate publication.

We finally present experimental results on the magnetic field dependence of the Fano resonances. When perpendicular magnetic field is applied to a lateral QD, level crossings occur between different orbital states. Then, the “Kondo chessboard” is observed as a result of electron redistribution within a QD between an inner orbital and an outer one, the latter coupling more strongly to the leads. This means that a non-Kondo valley at zero field can change to a Kondo valley when its outer orbital holds an odd number of electrons even though its total electron number is even. In fact, the upper non-Kondo valley changes to the Kondo valley at $B = 150 \text{T}$, as shown in Fig. 4(b). Here, the intensity of the Coulomb valley conductance is swapped between the upper and lower valleys, and a Kondo zero bias peak is confirmed in the upper valley, and not in the lower one. The expected Zeeman energy $\approx 4 \mu \text{eV}$ at $B = 150 \text{T}$ is much smaller than the half width of the Kondo zero-bias peak $\approx 85 \mu \text{eV}$ (Fig. 4(d)) giving $T_K \approx 1 \text{ K}$. Therefore, suppression of the Kondo effect by magnetic field is negligible.
given by $G_1$ in eq. (1), increases with magnetic field, resulting in the reduction of the resonance amplitude, $G_{ Kerr}$. This might seem strange at first because the increase of conductance due to the Kondo effect, undoubtedly a coherent transport process, results in the increase of $G_1$, which is normally regarded as an incoherent background. As shown in Fig. 4(d), where $V_{dc}$ dependence of differential conductance is plotted for $B = 0.15$ T near the resonance minima, the Kondo zero bias peak is only partially suppressed and the actual incoherent background $\simeq 10 \mu S$ inferred at finite $V_{dc}$ is much smaller than $G_1 \simeq 26 \mu S$. The remaining Kondo peak, which can be regarded as coherent background, accounts for the increase of $G_1$ over the true incoherent background and, in its turn, suppresses the Fano resonance amplitude $G_{ Fano}$. The same situation occurs at $B = 0$ T shown in Fig. 2(b). This mutual suppression demonstrates a novel competition between the Kondo effect and the Fano interference.

To summarize, we have investigated transport characteristics of the side-coupled DQD both experimentally and theoretically. Suppression (enhancement) of the conductance is observed in the Kondo (non-Kondo) valley of QD1 when charge state transitions occur on QD2. We demonstrate that these features are Fano resonances where the Kondo effect (cotunneling) in QD1 plays the role of a continuum. It is found that the Fano destructive interference partially suppresses the Kondo resonance, revealing a novel Fano-Kondo interplay. We have also presented a theoretical calculation based on the tight-binding model and obtained qualitative agreement with the experimental results.

Acknowledgments

The authors thank T. Kubo and Y. Tokura for valuable discussions. This work was partially supported by SCOPE from the Ministry of Internal Affairs and Communications of Japan, and by the Next Generation Super Computing Project, Nanoscience Program, MEXT, Japan.