Interference Effect in Multi-level Transport through a Quantum Dot

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We present experimental results and a model to solve the problem of "in-phase Coulomb peaks" ubiquitously observed in transport through a quantum dot. In a marginal region between Coulomb-blockade and open-dot, we observed Fano-type interference through two energy levels inside the dot, which manifest itself as two widely different kinds of Coulomb-diamond-like structures in the excitation spectrum. One of the two levels is strongly coupled to the leads and the phase of traversing electrons is locked. We have detected the phase change at the vertices and the centers of the larger diamonds through the sign of the Fano's asymmetric parameters supporting the above deduction.

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A particle scattering experiment gives us information of the scatterer through the scattering cross section and the phase shift. Electric conduction through a quantum dot (QD) can be viewed as scattering process and the phase shift and the transmission amplitude furnish with useful pieces of information on the electronic states in the QD. One of the ways to extract the phase shift is a double-slit experiment. Such an experiment was first carried out by Yacoby *et al.* using an Aharonov-Bohm (AB) ring with a QD [1]. In their experiment, the phase shift was found to jump by π just at every Coulomb peak. This was pointed out to be due to the two-terminal configuration [2] of the sample and a subsequent experiment adopting four-terminal configuration [3] demonstrated Breit-Wigner-type gradual phase change up to π as a Coulomb peak was traversed. A surprising finding in that experiment, however, was that there appeared additional phase shift by π between adjacent peaks hence the phase was brought back to the original value after a single cycle of Coulomb oscillation. The same phenomenon has been observed in the case of Fano resonance peaks with the same sign of Fano's asymmetric parameter [4].

A number of theoretical models have been put forward to explain this "in-phase peaks" problem [2, 5–11]. All of them seem to reproduce the main features of the existing experiments, and it is a task of further experiments to find out which of them or other mechanism is appropriate to the real systems. We have experimentally proven in a previous work [12] that such in-phase Coulomb peaks appear in a quantum wire with a side-coupled QD, which rules out a certain class of models that base themselves on the specific geometry of the AB resonator.

Recently Nakanishi *et al.* performed numerical simulation on a realistic model for a QD plus AB ring system based on two-dimensional electron gas (2DEG) [13]. Introduction of small disorder into the QD results in a sequence of in-phase resonance peaks. In a crude approximation, their result is interpreted as follows. Quantum states inside a clean rectangular QD elongated along the x-axis can be labeled by the wave number $\boldsymbol{k}_{ln} = (\frac{2\pi}{L_x}l, \frac{2\pi}{L_y}n)$ $(L_x > L_y)$. Here we take the indices l and n as positive integers that are proportional to the x and y components of $\boldsymbol{k}$, respectively. Consider a situation that two quantum wires (leads) are attached to the QD through tunnel barriers along the x-direction. In the transport through the QD, the single-electron levels indexed by (l, n) appear as Coulomb peaks. For a given l, the $(l, 1)$ state among the series (l, n) most strongly couples with the leads because the kinetic energy of the motion along the x-direction is highest, which makes the effective barrier height lowest. Hence a peak broader than the neighboring ones appears in the Coulomb oscillation when the lead Fermi energy E_{F} matches a level with $n = 1$. We can thus classify the QD states into small number of strong coupling states (SCSs) and large number of weak coupling states (WCSs).

In the presence of weak disorder, the motion along the x and y directions are intermixed. From the viewpoint of transport through the QD, mixing between a WCS and an SCS is important. The wave function of a WCS after the mixing is thus approximated as

$$\psi_j \approx \psi_j^0 + \psi_N \frac{\langle \psi_j^0 | V | \psi_N \rangle}{E_j^0 - E_N}. \quad (1)$$

Here N is the index of SCS closest to the energy level E_j^0 of the unperturbed state ψ_j^0, and V is the perturbation due to the disorder. Because ψ_N has much stronger coupling with the lead states, the transport property is dominated by the second term. This leads to trains of in-phase Coulomb peaks and the phase change occurs only when the closest SCS takes over due to the energy denominator in Eq. (1).

Because an SCS has a large level-broadning due to the strong coupling, the one closest to E_{F} gives "background" conduction to the transmission through the WCS level in question. Thus there appear parallel conducting channels through a QD [16], resulting in the Fano interference [17–19]. We have demonstrated that Fano effect can be utilized for the detection of phase shift without AB geometry [12, 20]. Therefore investigation of the single-dot Fano effect should be the touchstone of the above theory.

In this Letter, we report systematic experiments on the single-dot Fano interference in a multi-level transport regime. We have observed clear trace of SCSs and changes of sign of the Fano parameter in accordance with the inference. The present result provides a simple explanation for the long-standing "in-phase peaks" puzzle.

We prepared a QD from 2DEG formed at GaAs/AlGaAs hetero-structure (sheet carrier density $n_s = 3.8 \times 10^{15}$ m^{-2}, mobility $\mu = 80$ m^2/Vs) by using electron beam lithography followed by deposition of metallic gates and wet chemical etching. The inset of Fig. 1(a) shows the gate configuration. The sample was cooled in the dilution refrigerator with a base temperature of 30 mK and was measured by standard lock-in techniques in a two-terminal setup. In order to enhance the interference effect, we chose the side gate (SG1 and SG2) voltages to keep the total conductance around e^2/h where the QD is at the border between the Coulomb blockade regime and the open-dot regime.

Figure 1(a) shows the conductance G of the QD as a function of the gate voltage V_g. A fine oscillation is superposed on a slow background oscillation (BO). It appears as a sequence of sharp dips at the lowest temperature, which is the sign of reversed Coulomb oscillation. Such anti-resonance type Coulomb oscillation naturally occurs in side-coupled-dot configurations [12]. In the present case, the influence of SCSs is so large as to change the effective configuration to side-coupled type, where the conductance of WCSs enhances the reflection rather than the transmission of the system. In Fig. 1(b), we show a gray-scale plot of G on the plane of V_g and V_{sd}. The Coulomb diamonds are reversed in the conductance as expected (also shown in Fig. 2(b)), though their width along the V_{sd} axis is strongly modulated by V_g; they are small (large) around the peaks (valleys) of the BO. As a result, there appears larger diamond structures in Fig. 1(b), one of which is indicated by dashed lines.

The above observation suggests that the slow BO is due to the conduction through SCSs. Since they are spatially extended, the Coulomb peaks of SCSs themselves are smeared in the present condition. The modulation of small Coulomb diamonds by V_g, *i.e.*, the appearance of larger diamonds thus can be understood from Eq. (1). Around the peaks of the BO, quantum mixing of the corresponding SCS to the WCSs is large due to small energy denominator, resulting in large spatial size and large effective capacitance $C_{\rm eff}$ of the corresponding QD states, hence the diamonds are small. In the valleys of the BO, the conditions are opposite and larger diamonds are observed. It should be noted that the period of the fine oscillation is smaller for smaller negative V_g besides the oscillating variation due to the mixing of SCSs. This is because the effective QD size (and hence $C_{\rm eff}$) is reduced by increasing the negative gate voltage.

Figure 2 shows a magnification of a part of Fig. 1. Clear Fano distortion is observed and each dip can be

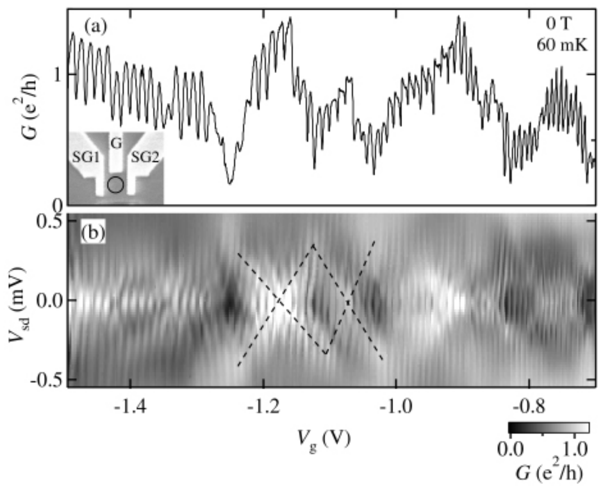

FIG. 1: (a) QD conductance G vs gate voltage V_g in the multi-level transport regime. Rapid oscillations that originate from the WCSs are superimposed on the slow background oscillation. The inset shows a scanning electron micrograph of the sample. The white regions are metallic gates that define a QD as illustarted by the black circle (200 nm diameter). The side gates (indicated as SG1, SG2) determine the coupling to the leads and the center gate G mainly modifies the electrostatic potential of the QD. The lower region is etched off (not well resolved in this picture). (b) Gray-scale plot of G as a function of bias voltage V_{sd} and V_g. Fine stripe-like features are Coulomb diamonds of WCS. On top of these fine structures, high conductance (white) regions show systematic change, leading to the large Coulomb-diamond-like structure (dashed lines).

fitted by Fano's asymmetric line shape [21],

$$G(V_g) = A\frac{(\epsilon + q)^2}{\epsilon^2 + 1} \qquad (2)$$

where $\epsilon = \alpha(V_g - V_{res})/(\Gamma/2)$, A is the amplitude, α, gate voltage-energy conversion factor, V_{res}, resonance position, Γ, width of the resonance, and q, Fano's asymmetric parameter. Note that Eq. (2) can be applied to both resonance and anti-resonance, where the latter is the case here. This confirms that the two-level transport model is a good approximation for the present case.

Figure 2(b) shows a an expanded view of Fig. 1(b). Outside the borders of clear inverted Coulomb diamonds, parallel lines which originate from excitation to higher level, are observed around $V_g = -0.95$ V. The Fano distortion is observed only around $V_{sd} = 0$ again in accordance with the previous result [4] though finer structures are also observed as described afterwards.

Figure 3(a) displays the temperature dependence of the zero-bias conductance oscillation. The asymmetric line shapes of the Fano interference are smeared out at around 500 mK. We have already discussed the temperature dependence of such line shape of a side-coupled QD in detail in Ref. [12], where it is quantitatively deduced

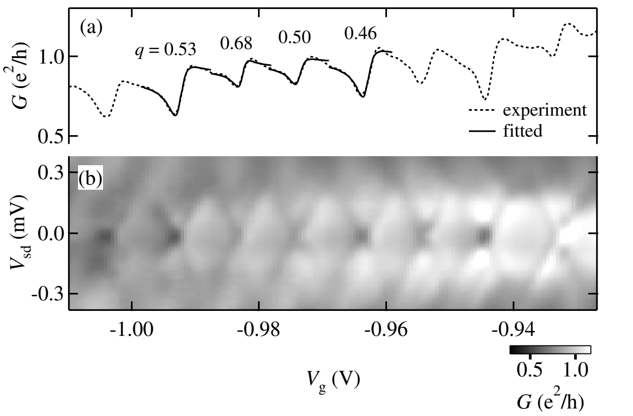

FIG. 2: Enlarged view of Fig. 1. (a) Line shapes of the Coulomb oscillation are distorted by the Fano interference. Fitting results to Eq. (2) (solid lines) and the obtained values of q are also shown. Constant background is assumed for the fitting process. (b) Conductance as a function of both V_{g} and V_{sd}. The shapes of the diamonds are formed by lower conductance borders.

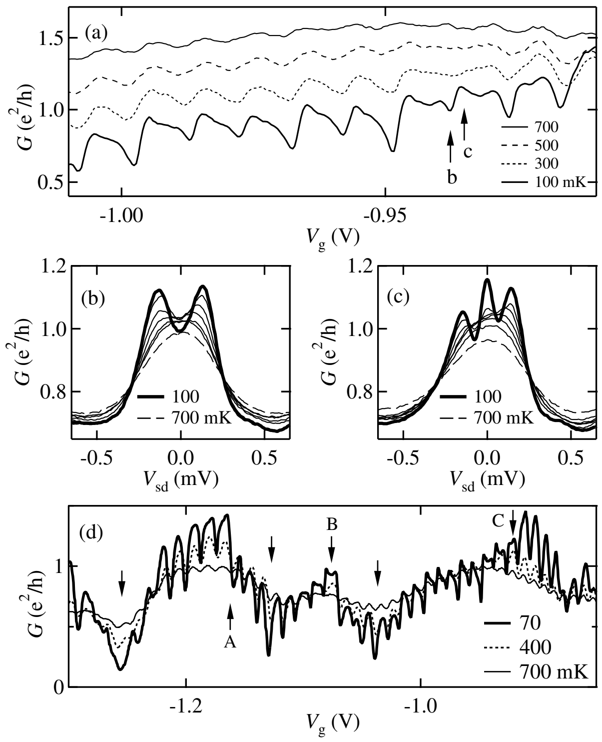

FIG. 3: (a) Temperature dependence of the Fano interference displayed with offset for clarity. (b) and (c) show V_{sd} measurement at fixed V_{g} indicated by arrows in (a) corresponding to destructive (constructive) interference, respectively. (d) Temperature dependence of the SCSs. Arrows indicate where the sign of q changes (see text).

that the thermal broadening of electron energy distribution as well as quantum decoherence result in the smearing of the interference. Essentially the same discussion is applicable to the present case.

In Figs. 3(b) and (c), we present the V_{sd} dependence of G taken at fixed V_{g} as indicated by the arrows b and c in Fig. 3(a), where the interference is destructive and constructive respectively. In the destructive case (Fig. 3(b)), a simple resonance dip appears at zero-bias while in the constructive case (Fig. 3(c)), side peaks appear at low temperatures in addition to the zero-bias peak. The interference with an SCS with higher energy may be responsible for the side peaks though at present we have no concrete idea for them. Figure 3(d) shows the temperature dependence of the BO, the amplitude of which simply diminishes with increasing temperature as expected.

So far we have investigated how multi-level transport appears in the conductance. Now we examine the phase shifts at the Coulomb peaks. The previous works [4, 12, 20] have established that information on the phase shift at a QD can be obtained from the sign of q. What we expect here are the following. i) An SCS dominates the perturbations over a range of WCSs, of which the Coulomb peaks are in-phase; ii) The sign of q of a Coulomb peak reflects the phase, provided that the reference (or the continuum) phase is unchanged. The turnover of the dominant SCS occurs at the valleys of the BO. From i), therefore, the Coulomb peaks are in-phase between two adjacent valleys of the BO. However in the present case, the reference of the Fano interference is the SCS itself, whose phase changes by π at the corresponding peak of the BO. As a result, q should change its sign both at the peaks and the valleys of the BO. In the numerical simulation in Ref.[13], this behavior is clearly observed.

We can see the expected behavior in Fig. 3(d) where the zero-crossing points of q are indicated by the arrows. They are placed at the peaks and the valleys of the BO. Especially the changes of the sign at the peaks (labeled as A, B, and C) are clear while those at the valleys are rather obscure because the absolute values of q are close to zero there.

In order to detect the crossing points, we adjusted the coupling strength by the side-gate voltages so as to make $|q| > 1$. This adjustment makes the sign change of q clearer, while it sacrifices the clarity of the diamond-like structure in the BO because the SCSs are shrunk and the modulation of C_{eff} becomes weaker.

Figure 4(a) shows the Coulomb oscillation at the weaker coupling conditions (the average conductance $\sim 0.5\ e^2/h$). The peaks show clear Fano distortion and have large enough $|q|$ for their sign to be distinguished. In Fig. 4(b), q is plotted as a function of V_{g} obtained by the fitting. The V_{g} positions where the sign of q changes are indicated by the vertical dotted and dashed lines, and they are again placed at the peaks and the valleys of the

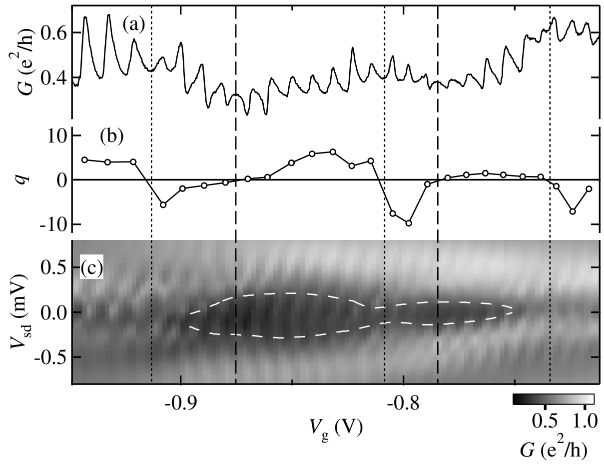

FIG. 4: (a) Coulomb oscillation under lower conductance condition. Each asymmetric line shape in (a) is fitted to obtain q as displayed in (b). Vertical broken lines indicate where the sign of q changes. (c) Gray scale plot of G versus V_g and V_{sd}. The small Coulomb diamonds are modulated by the SCSs as presented by the white broken line.

BO, respectively. In Fig. 4(c), we show a gray-scale plot of G as a function of both V_g and V_{sd}. Though larger diamonds are not so clear as in Fig. 1(c), the modulation of widths of the small Coulomb diamonds is still noticeable. In order to see the modulation clearer, we connect the edges of black regions that are distorted from the diamond shape due to the Fano effect with the white broken line. The vertical broken lines where the sign changes go through the narrowest points and broadest points of the region enclosed by the white line. This adds a further support to the above discussion. We believe that the present observations and the model discussed above constitute a solution to the problem of in-phase Coulomb peaks.

In summary, we observed Fano interference arising from the transmission through two energy levels inside a QD. One of the levels has stronger coupling to the leads and dominates the phase at the Coulomb peak, which was confirmed from the V_{sd} dependence and the analysis of the Fano resonance. These results provide a solution to the long-standing puzzle of the in-phase Coulomb peaks.

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