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Quantum coherence in quantum dot - Aharonov-Bohm ring hybrid systems

S. Katsumoto*, K. Kobayashi, H. Aikawa, A. Sano, Y. Iye

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

Abstract

We investigate coherent transport through hybrid systems of quantum dots and Aharonov-Bohm (AB) rings. Strong coherence over the entire system leads to the Fano effect, which originates from the interference and the phase shift caused by the discrete states in the dots. The high controllability of the system parameters reveals that the Fano effect in mesoscopic transport can be a powerful tool for detecting the phase shift of electrons. We apply it to detect electrostatic phase modulation and the phase shift in a quantum wire with a side-coupled dot. Finally, we provide an experimental answer to the problem of "neighboring in-phase Coulomb peaks".

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1. Introduction

An Aharonov-Bohm (AB) ring and a quantum dot (QD) are typical mesoscopic systems that continually attract attention [1, 2]. Yacoby *et al.* [3] performed a pioneering experiment on a combination of these complementary systems, although the phase of AB oscillation shows "lapses" at Coulomb peaks [4] due to the two-terminal nature of the device used, manifesting the difficulty of "phase measurement"[5]. In four-terminal measurements, it was found that the QD acts as a Breit-Wigner-type scatterer in that the phase of an electron smoothly changes by π at resonances [6]. At the same time, however, the phase shift θ at Coulomb peaks is in-phase (*i.e.*, if θ changes from 0 to π at a peak, it also changes from 0 to π at the next peak) and phase lapse occurs in the middle of the Coulomb valley. This problem of "in-phase peaks" has long been discussed [7, 8, 9, 10], although a clear solution has not been reached.

Another aspect of such systems is a resonator with a discrete energy level, which leads to the emergence of the Fano effect[11, 12]. In this article, we show that the Fano effect can be

*Correspoinding author.
E-mail : kats@issp.u-tokyo.ac.jp

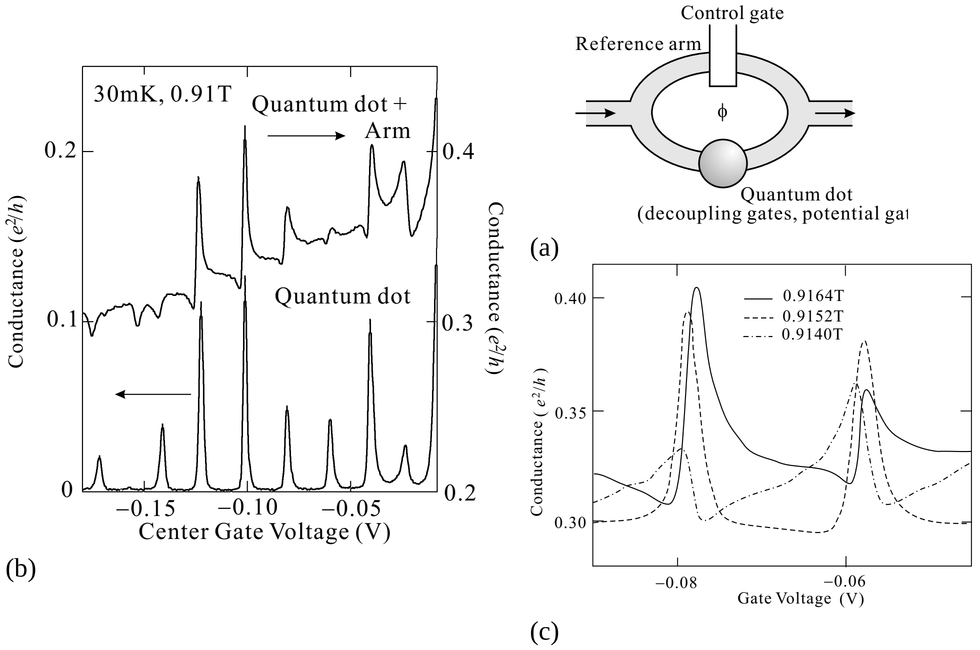

Fig. 1: (a) Schematic of a sample. (b) Coulomb oscillations with (upper) and without (lower) parallel conduction of reference arm. Clear Fano distortion is observed in the data with reference conduction. (c) Transformation of the Fano line shape with variation in flux piercing the ring. Broken line: $-\phi_0/4 \equiv -(h/e)/4$. Dotted line: $-\phi_0/2$.

used as a powerful tool for investigating the electron phase in mesoscopic transport and even leads to the solution of the above problem of "in-phase peaks".

2. Fano effect

We adopt the so-called wrap gate structure to define quantum dots and wires in two-dimensional electron gas (2DEG) formed in a GaAs/AlGaAs heterostructure (sheet carrier density $3.8 \times 10^{15}\ \mathrm{m}^{-2}$; mobility, 80 m^2/Vs). Quantum wire circuits are defined by using electron beam lithography and wet etching. The fine patterns of the metallic gates fabricated on the circuits form tunneling barriers, which define the quantum dots and control the parameters. A schematic of a sample is shown in Fig. 1(a). The conductance of the "reference arm", *i.e.*, the quantum wire for parallel transport, can be modified by the control gate. The samples are cooled in a dilution refrigerator down to 30 mK. The conductance is measured by a standard lock-in technique in a two-terminal setup.

Figure 1(b) shows Coulomb oscillations with and without the conduction of the reference arm. The line shapes of the Coulomb peaks against the gate voltage V_g show a clear Fano distortion described as

$$G(V_\mathrm{g}) \propto \frac{(\epsilon + q)^2}{\epsilon^2 + 1}, \tag{1}$$

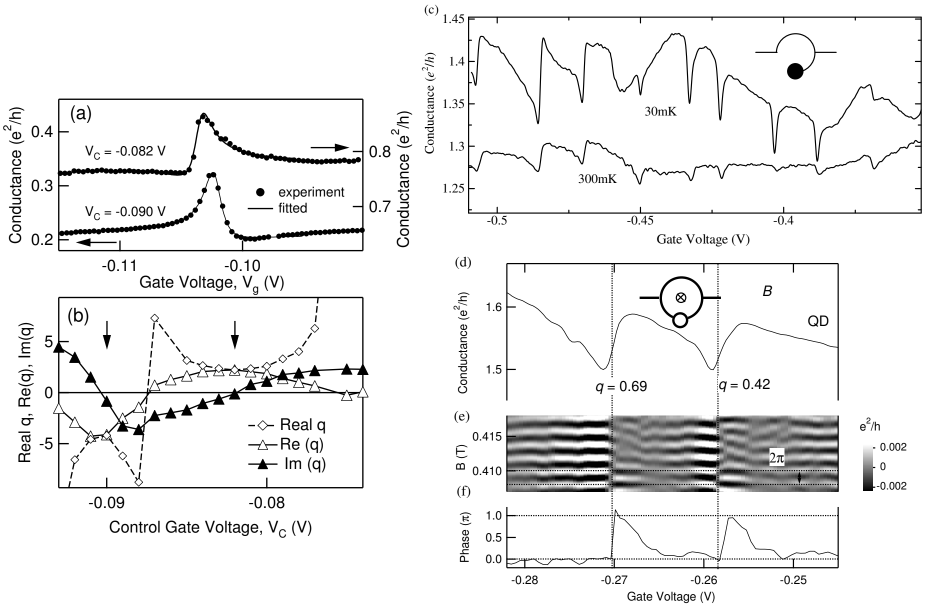

Fig. 2: (a) Transformation of Fano line shape by a change in control gate voltage on the reference arm. (b) Fitted values of real q and complex q in (1) as a function of $V_{\rm C}$. (c) Temperature dependent Coulomb "dips" in conductance of a quantum wire with a side-coupled dot versus $V_{\rm g}$. (d) Two Coulomb dips with Fano line shapes showing the same sign of q. (e) AB oscillation observed around the peaks in (d). (f) Phase shift of the AB effect in (e).

where $\epsilon = \alpha(V_{\rm g} - V_{\rm res})/(\Gamma/2)$, α is a conversion factor, $V_{\rm res}$, the peak position, Γ, the width of resonance, and q, Fano's asymmetric parameter.

The Fano effect originates from the interference between the path through the continuum and that with scattering caused by localized discrete states. Thus, the information of the phase shift in the scattering is contained in q. In Fig. 1(b), a series of peaks with the same direction of distortion are observed; that is, the signs of q for the peaks in a series are the same. This is the reproduction of the problem of successive in-phase peaks observed through the Fano effect.

In the original theoretical model by Fano [11], a point scatterer is assumed; hence, the interference cannot be modified by a magnetic field. However in the present case, a finite flux can pierce between the two interfering paths, and the time-reversal symmetry can be broken. In such a case, (1) can still be applicable by treating q as a complex number [12, 13].

This is clearly evident in the magnetic response of distortion shown in Fig. 1(c). If we fit (1) to the results with a real q, it should diverge for $\Delta\phi = -\phi_0/4$ ($\phi_0 \equiv h/e$) while complex q almost remains on a circle of $|q|$ = const [14]. A magnetic field is also relevant to the visibility of Fano distortion. This has two possible origins. The field provides chirality to the electron orbital, reducing the rate of back scattering. It also reduces inter channel mixing, which should be more crucial for the visibility.

3. Application to electrostatic phase modulation

Here, we discuss the application of the Fano effect to the detection of electrostatic phase modulation. The phase difference $\Delta\theta$ introduced by the control gate voltage V_C is,

$$\Delta\theta(V_\mathrm{C}) = 2\pi(W/\lambda_\mathrm{F})\left(1 - \sqrt{1 - (V_\mathrm{C}/V_\mathrm{dep})}\right), \tag{2}$$

where W and V_dep are the width of the gate and the pinch-off voltage of the corresponding conduction channel, respectively.

However, there are many difficulties in the detection [15]. The phase shift π by V_C indicates the increment/decrement of a single conducting channel beneath the control gate. Hence, the conductance modification caused by the channel variance is usually much larger (order of e^2/h) than that caused by the change in the interference. Furthermore, as can easily be seen in (2), $\Delta\theta$ is dependent on the channels. Thus, in conventional multichannel transport, the resultant modification of the interference is incoherent and difficult to be detected.

In the detection by the Fano effect all the above problems can be avoided[14]. The coherent transport through the dot is mainly dominated by a single conducting channel because the dot works as a filter of the wave vector, and the single channel is responsible for the Fano distortion. The variation in V_g only changes the conductance of this channel. We can safely subtract the background contribution.

Figure 2(a) shows the variation in line shape versus V_g with V_C. A clear inversion of the direction in distortion is observed. The fitted values of real q and complex q (two components) versus V_C are shown in Fig. 2. Complex q follows deformed sinusoidal patterns and real q changes its sign in accordance with the real part of complex q with divergence. The clear detection of electrostatic phase modulation manifests that the Fano effect can be a powerful tool for investigating the quantum phase in the transport.

4. Fano effect in side-coupled structure

In the transport through a quantum wire with a side-coupled quantum dot, the effect of the dot appears in the nonlocal part of conductance, *i.e.*, through quantum interference. Hence, the Fano effect inevitably appears at the resonances. By pinching off one of the decoupling gates, we can bring the sample in Fig. 1(a) into such a side-coupled region.

Figure 2(c) shows the Coulomb oscillation of the side-coupled dot in the reflection mode, in which conductance dips appear instead of peaks. That is, the enhancement of conductance between the wire and the dot results in the enhancement of reflection at the T-shaped junction. This also appears in the temperature dependence, in that the dips themselves disappear with increasing temperature and dephasing due to thermal broadening and other decoherence factors.

Every dip reveals a clear Fano distortion. The dips (peaks) with the same sign of Fano parameters indicates that they are in-phase. In order to confirm this, we make the pinched connection slightly conductive and observe AB oscillation. The results are shown in Fig. 2(d). Here, the two peaks have the same sign of q and the phase shift also changes by π to the same direction. This again supports the above inference.

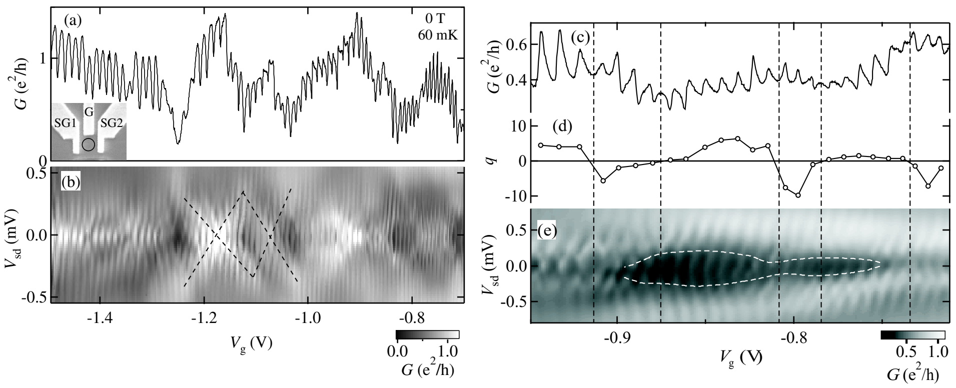

Fig. 3: (a) Dot conductance G is plotted versus gate voltage V_{g}. The inset shows a scanning electron micrograph of the sample. The lower region is etched off (hard to see). (b) Gray scale plot of the dot conductance as a function of bias voltage V_{sd} and gate voltage V_{g}. One of the "larger" diamonds is indicated by a broken line. (c) Coulomb oscillation under a lower conductance condition. Eq.(1) is fitted to each peak to obtain the values of q plotted in (d). Vertical broken lines indicate zero-crossing points. (e) Gray scale plot of G versus V_{g} and V_{sd}. The white broken line indicates the boundary of Coulomb diamonds.

5. Solution to the problem of "in-phase Coulomb peaks"

Utilizing the above results, we attempt to find an answer to the problem of trains of "in-phase Coulomb peaks". Nakanishi *et al.* have performed a realistic numerical simulation [16] and found the Fano effect even without the conductance through the reference arm and trains of peaks with the same sign of q. The result is interpreted as follows.

In the simplest rectangular quantization, electronic states in quantum dots are classified into states with strong coupling to the leads (strong coupling states, SCSs) and those with weak coupling (WCSs). The existence of such SCSs has been pointed out by Silvestrov and Imry[17]. Let ψ_j^0 a WCS with the energy E_j^0, and ψ_N an SCS with the energy E_N closest to the WCS. The introduction of disorder in the dot causes a quantum hybridization, which is described in the first-order perturbation as

$$\psi_j \approx \psi_j^0 + \psi_N \frac{\langle \psi_j^0 | V | \psi_N \rangle}{E_j^0 - E_N}, \tag{3}$$

where ψ_j is the perturbed wavefunction, V is the disorder potential. Many other contributions from WCSs can be ignored from the viewpoint of transport. It is easy to see that the conductance peak corresponding to (3) reflects the phase of ψ_N rather than that of ψ_j^0; hence, the phase is locked to ψ_N. This can be the origin of trains of in-phase Coulomb peaks.

Around the Coulomb peak corresponding to ψ_j, there also exists a conduction through ψ_N because of the strong coupling. This works as a "reference" conduction, resulting in the Fano effect in the transport through a simple quantum dot structure.

For the examination of the above inference, we have prepared a simple quantum dot shown in the inset of Fig. 3(a), but the decoupling gate voltages are determined so as to keep the conductance averaged over $V_{\rm g}$ around e^2/h in order to enhance the Fano effect of the above mechanism. Figure 3 (a) shows the Coulomb oscillation, which is a series of sharp dips similar to the side-coupled dot in the previous section [18]. This is due to the comparatively large background conduction of SCSs. The background also has a large but slow oscillation, which is the result of the variation in energy denominator and the change in the nearest SCS. This clearly appears in the gray scale plot of conductance G versus $V_{\rm sd}$ and $V_{\rm g}$ (Fig. 3(b)), which shows an overlap of fine Coulomb diamonds and larger ones. We observe that the sign of real q obtained by fitting (1) to fine dips changes its sign at around the vertices of larger diamonds.

In order to see this more clearly, we plot the dot conductance for a weaker coupling condition in Fig. 3(c) in a narrower region of $V_{\rm g}$. As the SCSs shrink, the dips change to ordinal peaks. The direction of the Fano distortion changes at the peaks and the valleys of the background oscillation, supporting the above inference. To be more quantitative, vertical broken lines are drawn to indicate the zero-crossing point of q (Fig. 3(d)) and in the gray scale plot of G in Fig. 3(e), the vertical lines meet the vertices of larger diamonds. These observations, as a whole, constitute the evidence that the trains of in-phase Coulomb peaks originate from the quantum mixture of SCSs.

In summary, we have studied the Fano effect in the transport through quantum dots. It is proven that the Fano effect can be a powerful tool for investigating the electron phase in a mesoscopic conductor. For an example, we show a solution to the problem of the “in-phase” series of Coulomb peaks in quantum dots.

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