Fano resonance in crossed carbon nanotubes

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We report the observation of the resonant transport in multiwall carbon nanotubes in a crossed geometry. The resonant transport is manifested by an asymmetric peak in the differential conductance curve. The observed asymmetric conductance peak is well explained by Fano resonance originating from the scattering at the contact region of the two nanotubes. The conductance peak depends sensitively on the external magnetic field and exhibits Aharonov-Bohm-type oscillation.

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Being a good conductor [1], metallic carbon nanotube (CNT) is considered to be an ideal system to study various quantum transport phenomena in low dimension, such as single electron tunneling effect [2,3], Luttinger liquid behavior [4–6], Kondo effect [7], etc. Also expected but yet to be observed is the Fano resonance [8] which is a general phenomenon that can be observed whenever resonant and non-resonant scattering interfere. Recently it has been observed in the transport through a single electron transistor (SET) [9], which proved the phase-coherent transport in the SET structure.

In this paper, we report the observation of the Fano-like resonance in transport through two multiwall CNTs in a crossed geometry, demonstrating coherent and quasi-ballistic nature of the electronic transport in the CNTs. The resonance is manifested by a sharp asymmetric peak in the differential conductance curve. The asymmetric conductance peak, after subtracting background power-law behavior due to the Luttinger liquid effect, is well fitted to the Fano formula. Such Fano-like resonance is attributed to the interference of resonant and non-resonant scattering in the contact region of the two CNTs. Also observed is a quasi-periodic oscillation of the Fano-like resonance with the magnetic field. The evolution of the conductance peak with the magnetic field exhibits characteristic oscillation of the peak position and shape, which can be explained by the Aharonov-Bohm oscillation of the Fano resonance.

The multiwall CNTs were synthesized by arc discharge method. We have dispersed ultrasonically the CNTs in chloroform for about half an hour and then dropped a droplet of the dispersed solution on the Si substrate with 500 nm-thick thermally-grown SiO2 layer. The multiwall CNTs in a crossed form were searched by scanning electron microscope (SEM). The patterns for electrical leads were generated using e-beam lithography technique onto the selected CNTs and then 20 nm of Ti and 50 nm of Au were deposited successively on the contact area by thermal evaporation. Shown in the inset of Fig. 1(b) is the SEM photograph of the measured sample which consists of two multiwall CNTs in a crossed geometry. The atomic force microscope study showed that the diameter of the CNTs were in the range of 25 - 30 nm. In order to form a low-ohmic contact between the CNT and the Ti/Au electrode, we performed a rapid thermal annealing at 600-800 °C for 30 s [10,11]. The contact resistances were in the range of 5 kΩ - 18 kΩ at room temperature and became 10 kΩ - 60 kΩ at 4.2 K. The cross junction had a junction resistance of 5.4 kΩ at room temperature and of 16.8 kΩ at 4.2 K. The four-terminal resistance of each CNT increased monotonically with lowering temperature and depended sensitively on the bias current level, implying non-ohmic current-voltage characteristics of the CNTs.

Figure 1(a) shows the temperature dependent differential conductance (dI/dV) curves for the horizontally placed nanotube (hereafter named CNT-1). We have adopted the four-probe measurement configuration, with the current leads 1, 4 and the voltage leads 2, 3. At low temperatures the differential conductance curve of CNT-1 displays a pseudogap structure near zero bias. It has been shown that such suppressed conductance can be fitted to the power-law, \( G = dI/dV \sim V^\alpha \), and was attributed to the Luttinger-liquid behavior [4–6]. The Luttinger-liquid behavior of the CNTs in our sample was carefully analyzed before [6], and it was found that the contact between the two nanotubes plays a crucial role.

In addition to the pseudogap structure, there appears a sharp peak in the differential conductance curve at temperatures below 1 K. The peak appears at non-zero bias voltage and its shape is not symmetric with respect to its center. We have redrawn in Fig. 1(b) the differential conductance curve after subtracting background pseudogap structure. Then the asymmetric feature of the conductance peak becomes more apparent. The differential conductance curve clearly shows that there are two dis-
distinct energy scales. One energy scale, of the order of 0.1 meV, is related to the pseudogap structure in the conductance curve and is attributed to the Luttinger liquid behavior [6]. The other energy scale, of the order of 0.02 meV, corresponds to the width of the conductance peak which we address in the following.

We interpret this asymmetric conductance peak in terms of the resonant scattering of the electrons at the contact region of the two nanotubes. It is well known that, in the presence of non-resonant background contribution as well as the resonant scattering, interference between the two components leads to the asymmetric conductance peak, known as the Fano resonance. For our sample, the existence of the cross junction is essential for the resonant scattering and thus for the observation of the Fano resonance, based on the following three facts: (1) We have never observed the present resonant behavior in many (more than 20) single nanotubes without cross-contact we have studied, (2) we have observed Fano-like behavior in another sample with the cross-contact geometry, though not in all the samples with cross-junction, and (3) that both nanotubes (CNT1, CNT2) of the present sample show the Fano-resonance behavior which implies that it is very unlikely that the resonances originate from some accidental impurities or defects.

We also point out that highly nonlocal characteristics of the transport in the CNT [12] can explain the occurrence of a conductance peak in the measurement configuration where the voltage is measured within one side of the CNT, not across the cross junction.

As shown in Fig. 1(b), the conductance peak, after subtracting the background power-law contribution, can be well fitted to the Fano line shape of the form

\[ \frac{dI}{dV} = G(V) \propto \frac{|e + Q|^2}{e^2 + 1}, \]

where \( \epsilon = (V - V_0)/\Gamma/2 \). The Fano factor \( Q \) is a complex number determined by the relative values of the magnitude and the phase difference between the resonant and the non-resonant transmission amplitude. Note that the imaginary component of \( Q \) is directly related to decoherence and/or breaking of the time reversal symmetry [13,14]. The best fit gives \( \Gamma = 9.0 \mu eV \), \( \text{Re}(Q) = -7.1 \), and \( \text{Im}(Q) = 0.22 \) at \( T = 13 \text{mK} \). The imaginary part of the Fano factor is small compared to the real part and is not affected much with increasing temperature. This is consistent with the observation that aside from the peak height and width the the asymmetry of the resonance is almost unaffected with the temperature. This implies that the coherence of the electron transmission is preserved at the measured temperature range \( T \lesssim 1 \text{ K} \). Since the peak structure vanishes for \( T > 1 \text{ K} \) mainly due to thermal smearing, decoherence in transport could not be investigated at higher temperatures. Shown in Fig. 2 are the width and the height of the conductance peak as a function of the temperature. The resonance width increases linearly with the temperature as \( \Gamma \approx 6.63 + 0.2k_B T(\mu eV) \), aside from the saturation at the very low temperature. From the Fermi-Dirac distribution, the resonance width is expected to exhibit a linear temperature dependence with the temperature coefficient of 3.5, i.e., \( \Gamma = 3.5k_B T \). We believe that deviation from such ideal behavior comes from the four terminal configuration of our measurement.

As shown in Fig. 2(b), the peak height seems to exhibit \( 1/T \)-law dependence expected from the Fermi-Dirac distribution. However, with the short range of the temperature, we cannot conclude that it follows the \( 1/T \)-law. Actually, logarithmic law provides equally reasonable fit for this temperature range, which might indicate the existence of the strong electronic correlation such as the Kondo effect, for example. However, it seems that the Kondo effect can be ruled out because the peak position locates at non-zero bias. Further, the fact that the anomaly exists at relatively high magnetic field (up to \( 6T \)) indicates that the conventional Kondo effect should not be present.

The vertically placed CNT (CNT-2) also shows asymmetric conductance peak. For the CNT-2, however, the pseudogap structure in the differential conductance curve is not so apparent as in the CNT-1. We have measured the magnetic field dependence of the differential conductance of the CNT-2. With the application of the magnetic field, the shape of conductance peak changes significantly. Fig. 3 (a) shows the evolution of the differential conductance curve with the magnetic field in the range of \( 3.5 \text{ T} \leq H \leq 5.7 \text{ T} \). For \( H = 3.5 \text{ T} \), the peak position is located at a negative bias voltage. With the increase of the magnetic field, the peak position shifts to the positive bias. Further increase of the magnetic field (\( H \sim 5.7 \text{ T} \)) results in the return of the peak position and shape similar to those for \( H \sim 3.5 \text{ T} \).

Such oscillatory evolution of the conductance peak can be explained by the Aharonov-Bohm oscillation of the Fano resonance. In the presence of a magnetic field, the time reversal symmetry of the system is broken and the resonant and the nonresonant components of the transmission amplitude may have arbitrary phase difference \( \psi \), determined by the magnetic field. Ignoring the decoherence, this phase difference leads to the the Fano factor \( Q \) given by [15,16]

\[ Q = Q_R \cos \psi + i Q_I \sin \psi. \]

Assuming an effective area \( A \) associated with the resonant level at the cross junction, \( \psi \) can be written as \( \psi = \psi_0 + 2\pi AH/\Psi_0 \) where \( \psi_0 \) is an offset and \( \Psi_0 = h/e \) is the magnetic flux quantum of the electron. Here it is assumed that the magnetic field affects only the phase difference of the two different transmission amplitudes originating from the resonant and the non-resonant component. We have shown in Fig. 3(b) the evolution of
the Fano resonance with the phase factor, determined by Eqs (1,2). The oscillation amplitudes of the real and the imaginary parts of the Fano factor are chosen as $Q_R = -2.0$ and $Q_I = 0.5$, which provides reasonable agreement with the experimental result of Fig. 3(a). Note that the Fano resonance for $\psi = \pi$ is a mirror image of that for $\psi = 0$. Such characteristic feature is consistent with the experimental observation, supporting strong evidence of the Fano resonance in the crossed CNTs.

Following Eq.(2), the shape of the Fano resonance changes continuously with the phase factor in a oscillatory manner with the period of $\Delta \psi = 2\pi$ or $\Delta H = \Psi_0/A$. We call such oscillatory evolution of the Fano resonance as a Aharonov-Bohm (AB) oscillation of the Fano resonance. For our sample, such oscillatory evolution of the differential conductance curve was clearly seen in the field range of $3.5 \ T \leq H \leq 5.7 \ T$ as shown in Fig. 3(a). The AB oscillation of the Fano resonance is also expected to give magnetoresistance (MR) oscillation. We have shown in Fig. 3(c) the bias-dependent MR curves of the CNT-2. The measured MR curve exhibits small quasi-periodic fluctuation embedded in a large oscillation with the period of about 3.5 T. The large MR oscillation in the range of $3.5 \ T \leq H \leq 5.7 \ T$ reflects the evolution of the Fano resonance with the magnetic field. The MR curve depends strongly on the bias current due to the highly nonlinear current-voltage characteristics. One can identify the occurrence of the second MR peak near 8 T. Leaving aside the complex structure near zero field, MR oscillation with the period of 3.5 T can be clarified by the AB oscillation of the Fano resonance. Assuming that the phase factor is acquired at the cross junction, the MR oscillation period of 3.5 T corresponds to the effective area $A$ of about (33 nm)$^2$. This is comparable to the estimated diameter of the CNTs, 25-30 nm.

Here it should be noted that our model (Eq.(2)) is also relevant to the system of an AB interferometer containing a quantum dot in one of the two reference arms [14,17]. The oscillatory behavior of the Fano resonance as a function of the magnetic field has been observed and analyzed [14], but its origin was not properly explained. Our model explains clearly the behavior of the AB oscillations of the Fano resonance, including the sign change of the real part of the Fano factor.

The conductance curve changed in shape with the application of magnetic field also for the CNT-1. But such dramatic evolution as shown in Fig. 3(a) was not observed. The peak height decreases with the increase of the magnetic field for the CNT-1. Such difference in the evolution of the conductance peak was attributed to the structural difference of the CNTs. The two CNTs are considered to be metallic but may have different chirality and diameters. It is well known that tiny difference in diameter or chirality leads a noticeable difference in the transport properties of CNT, though the microscopic origin of the difference cannot be clarified in our study.

In summary, we have observed Fano resonance of electronic transport in two cross-contact carbon nanotubes. The observed asymmetric conductance peak could be explained in terms of the Fano resonance originating from the scattering at the contact region. Further, by applying external magnetic field peculiar Aharonov-Bohm oscillation of the Fano resonance has been found and analyzed.

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FIG. 1. (a) The temperature-dependent differential conductance curves of the CNT-1. (b) The measured differential conductance data at the temperature of 13 mK with subtracting background power-law behavior (solid circle) and the best fit to the Fano formula (line). Inset shows the SEM image of the sample.

FIG. 2. The temperature dependence of (a) peak width and (b) peak height of the CNT-1.
FIG. 3. (a) The evolution of the differential conductance curve of the CNT-2 with the magnetic field. The direction of the field is perpendicular to the substrate. (b) The evolution of the differential conductance curves with the phase factor calculated by using Eq. (2) with the parameters given by $Q_R = -2.0$ and $Q_I = 0.5$. (c) The bias-dependent magnetoresistance curves.
\[ T \text{ (µeV)} \]

\[ \Delta G \text{ (µS)} \]

\[ 1/T \text{ (K}^{-1}) \]
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