Quantum fluctuations in the low temperature magneto-resistance of bi-layer graphene

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Abstract. We report here the observation of quasi-periodic conductance fluctuations in the low temperature magneto-resistance of gated bi-layer (BL) field-effect transistors (FETs). Both correlation field analysis and conductance fluctuation behaviour suggests that the quantum transport in the BL-FETs closely resembles that in conventional semiconductor open quantum dots.

1. Introduction
There is considerable interest in the details of electrical transport in graphene because of its linear energy dispersion, and the chirality of its charge carriers [1, 2]. Indeed, there is exceptional promise of epitaxial graphene (on SiC) for integrated circuit applications. There have been many recent quantum transport studies of one or two-layer graphene structures. It has been reported that a considerably longer coherent length exists in the graphene samples [3] and the coherent nature can be discussed in comparison to the case of semiconductor quantum dots. The quantum transport in such systems has been tentatively analyzed in terms of Fabry-Perot interference and conductance fluctuations in quantum billiards, Aharonov Bohm (AB) interference in electron AB rings, and Coulomb oscillations and Fractal behavior in quasi-ballistic quantum dots [4-8]. We report here the observation of conductance fluctuations in the low temperature magneto-resistance (MR) of gated bi-layer (BL) graphene field effect transistors (FETs). We see no fractal behavior as discussed in our previous study of a sub-micron size BL graphene [8]. However, the correlation field analysis and conductance fluctuation behavior can be understood based on the corresponding behavior found for conventional open quantum dots.

2. Experiments
The BL-FET was fabricated by micromechanical cleavage of HOPG (SPI Grade-2) on a heavily doped Si/SiO₂ wafer. The graphene thickness was determined by AFM and Raman spectroscopy. Electrical contact was realized by forming 3 nm/30 nm Pt/Au electrodes whose pattern was defined by electron beam lithography. The dot size was approximately 5 μm × 5 μm, two orders of magnitude larger than our previous sub-micron size BL-FET [9]. We observe ripples and defects on the BL device, which is believed to decrease the carrier mobility [10]. Our previous estimates for BL graphene film [9] suggest a carrier concentration of 1.4 × 10¹² cm⁻² and a mobility of 2.0 × 10³ cm²V⁻¹s⁻¹. We did not perform in-situ heating and thermal annealng, which would be expected to improve the homogeneity and the carrier mobility in the FETs. The MR of the devices was measured using lock-in detection
with small excitation voltage (< 100 μV @ 17 Hz) in a He-3 cryostat refrigerator in applied normal magnetic fields up to 8 T.

3. Results
Typical MR of the graphene is shown in Fig. 1. The large variation of the MR might originate from the $\sigma_{xy}$-component of the quantum hall effect, as similar dependences were observed in the previous study of BL graphene samples [9]. The gate voltage dependence of the MR arises from the quantum coherent nature of the BL graphene. Therefore, subtraction of the rapid varying MR component has been performed and the quantum fluctuating part is shown in Fig. 2. It is clear that the quantum nature has been kept because of the existence of the magneto-fingerprint of the MR. The correlation field $B_c$ of the fluctuations has been determined by the correlation function method based on the fluctuating MR as shown in Fig. 3, where the gate voltage dependence of $B_c$ can be plotted as in Fig. 4. We determine the mean value of the MR height in the conductance fluctuations (CF) from the original MR data in Fig. 2, which is discussed below to show the quantum coherent nature. From the gate voltage dependence of the MR at 4.2 K, we summarize the dependences of the $B_c$ and mean-fluctuations together with the resistance value at zero magnetic field in Fig. 4. The maximum of the resistance probably corresponds to the Dirac point and the other two parameters shows a clear change near zero gate voltage, but the fact that this is located at a slightly negative bias may suggest a hole nature.

![Figure 1](image1.png)

**Figure 1.** The magneto-resistance (MR) of the BL graphene at $V_g = 0$ V at 4.2 K. The solid line shows the original MR data while the dotted line shows the averaged MR obtained by smoothing. The inset shows an AFM image and of the BL graphene with the two-terminal Ti/Au electrode schematically illustrated.

4. Discussions
In our larger size BL-FET, we have not clearly observed fractal behavior in the transport. The coherence length is one third shorter than that in the smaller dot [9], so that the transport seems to belong in quasi-ballistic region. Scanning tunnelling spectroscopy indicated that the transport properties in an epitaxial graphene should be significantly influenced by atomic defects within the graphene lattice [11]. Also, a pronounced dielectric-screening effect has been observed in mono-layer graphene [12]. Here, comparing with previous study, we determine a slightly larger $B_c$ and observe a
smaller magneto-finger print of the MR. Discussing the above differences in terms of the quantum nature of the low temperature MR, they indicate that the fluctuations must originate from changes in many regular trapped orbits arising from the pointer states [13].

We observe a very interesting behavior of $B_c$, and the mean-fluctuations in the CF, as the back-gate voltage is varied. As shown in Fig. 4, near the Dirac point, the strength of the mean-fluctuations indicates a decrease of quantum coherency of the transport in the graphene because the decrease usually shows a slowdown of the degree of quantum nature and reduction of the coherent length in the graphene. However, also near the Dirac point, $B_c$ decreases. As a simple and naive explanation, there seems to exist a contradiction in the relation between $B_c$ and the mean-fluctuations in our present results. We need other evidence in order to fully explain these results.

![Figure 2](image2.png)  
**Figure 2.** After subtraction from the MR data in the Fig. 1 are shown. In case of the CF, the magneto-finger print can clearly be observed.

![Figure 3](image3.png)  
**Figure 3.** Auto correlation function calculated from the data in Fig. 2.

5. Summery  
We have observed quasi-periodic conductance fluctuations in the low temperature MR of a BL graphene FET. Both of correlation field analysis and CF behavior suggests that the quantum transport in the BL-FET closely resembles that in conventional semiconductor open quantum dots. However, since there is a contradiction between $B_c$ and CF, new explanation or evidence of the nano-scale transport in the graphene is needed.
Figure 4. Correlation field $B_c$, mean-fluctuation of the MR and the zero-field resistance at 4.2 K are plotted in the same figure.

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