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Weak localization and universal conductance fluctuations in multi-layer graphene

Chiashain Chuang [a,b], Tak-Pong Woo [a,*], Akram M. Mahjoub [b], Takahiro Ouchi [b], Chang-Shun Hsu [c], Chia-Pei Chin [d], Nobuyuki Aoki [b], Li-Hung Lin [e], Yuichi Ochiai [b], Chi-Te Liang [a,f,*]

[a] Department of Physics, National Taiwan University, Taipei 106, Taiwan, ROC
[b] Graduate School of Advanced Integration Science, Chiba University, Chiba 263-8522, Japan
[c] Graduate Institute of Applied Physics, National Taiwan University, Taipei 106, Taiwan, ROC
[d] Department of Physics, National Chung Cheng University, Chiayi 621, Taiwan, ROC
[e] Department of Electrophysics, National Chiayi University, Chiayi 600, Taiwan, ROC
[f] School of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon 440-746, Republic of Korea

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ABSTRACT

We have performed magneto transport measurements on a multi-layer graphene device fabricated by conventional mechanical exfoliation. Suppression of weak localization (WL) as evidenced by the negative magnetoresistance (NMR) centered at zero field, and reproducible universal conductance fluctuations (UCFs) are observed. Interestingly, it is found that the phase coherence lengths calculated by fitting the observed NMR to conventional WL theory are longer than those determined from fitting the amplitudes of the UCFs to theory in the low temperature regime ($T \leq 8$ K). In the high temperature regime ($T > 8$ K), the phase coherence lengths calculated by fitting the observed NMR to conventional WL theory are shorter than those determined from fitting the amplitudes of the UCFs to theory. Our new results therefore indicate a difference in the electron phase-breaking process between the two models of WL and UCFs in graphene. We speculate that the presence of the capping and bottom graphene layers, which leads the enhancement of disorder in-between, improves the localization condition for WL effect during carrier transportation in the low temperature regime. With increasing temperature, the localization condition for WL in multi-layer graphene becomes much weaker due to strong thermal damping. Therefore, the phase coherence lengths calculated by fitting the observed NMR to conventional WL theory are shorter than those determined from fitting the amplitudes of the UCFs to theory at high temperatures.

1. Introduction

Graphene, a single-layer of carbon atoms forming sp^2 bonding in a hexagonal lattice, exhibits quantum interference phenomena, such as Berry's phase [1,2], weak localization (WL) [3–6] and universal conductance fluctuations (UCFs) [7–15]. Combining the extraordinary electrical property, graphene could find applications in nano-electronic device, such as interference-based electronic switches due to the wave properties of carriers [7]. Coherent quantum transport depends strongly on scattering by the lattice disorder of graphene, because the total conductance can be changed by the interference of carrier waves traveling along different paths. The mechanism of WL is created by the coherent backscattering of carrier waves from a disordered potential as shown in Fig. 1(a), and the mechanism of UCFs is produced by the interference of carrier waves traveling along all achievable paths as illustrated in Fig. 1(b). The definition of the phase coherence length $\sim L_\varphi$ is that the set of paths which interfere from carriers is restricted by the diffusive length [5]. Highly disordered graphene such as hydrogenated graphene [16–19], reduced graphene oxide [20] and fluorinated graphene [21,22], are not ideal for one to observe the WL and UCFs effect due to the strongly insulating transport behavior from carbon sp^3 bonding atoms. Very recently, we proposed that multi-layer graphene could provide suitable disorder without changing the sp^2 π bonding so as to enhance the localization effect [23] since monolayer pristine graphene does not show the insulator-quantum Hall transition. Compared with

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* Corresponding authors. Department of Physics, National Taiwan University, Taipei 106, Taiwan, ROC.
E-mail addresses: bonwood@gmail.com (T.-P. Woo), chiteliang@gmail.com, ctliang@phys.ntu.edu.tw (C.-T. Liang).

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single-layer graphene, the WL and UCFs effect in multi-layer graphene could be different from those in single-layer graphene due to the enhancement of disorder.

In this paper, we report low-temperature magneto transport measurements on a multi-layer graphene device. We observe negative magnetoresistance centered at zero field and conductance fluctuations at different temperatures, which can be ascribed to the WL and UCFs effect. By appropriate analysis for the phase coherence length, the phase coherence lengths determined from the WL effect are longer than those calculated from the UCFs in the low temperature regime. In contrast, in the high temperature regime, the phase coherence length in WL effect is shorter than that in UCFs effect. We suggest the enhancement of disorder improves the localization condition so as to increase the phase coherence length in WL effects in the low temperature regime. With increasing temperature, the localization condition for WL in multi-layer graphene becomes much weaker owing to strong thermal damping. Therefore, the phase coherence lengths calculated by fitting the observed NMR to conventional WL theory are shorter than those determined from fitting the amplitudes of the UCFs to theory at high temperatures. We suggest that further studies are required for understanding the differences in the calculated phase coherence lengths using both WL and UCFs in mechanically exfoliated multi-layer graphene.

2. Experiment

A multi-layer graphene flake, mechanically exfoliated from natural graphite, was deposited onto a 300-nm-thick SiO_2/Si substrate [24]. Optical microscopy was used to locate the graphene flakes, and the thickness of multi-layer graphene is 3.5 nm, checked by atomic force microscopy. Therefore, the layer number of our graphene device is around ten according to the 3.4 Å graphene inter-layer distance [24,25]. Two-terminal Ti/Au contacts were deposited on multi-layer graphene flake by optical lithography and lift-off process. In order to enhance the mesoscopic phase coherence, the circumscription of multi-layer graphene was made into a longitudinal shape and the source and drain distance is 10 μm by oxygen plasma etching process [26]. Similar to the work done using disordered graphene, our graphene flakes did not undergo a post-exfoliation annealing treatment [13,14,23]. The magnetoresistance of the graphene device was measured using standard AC lock-in technique at 17 Hz with a constant current $I = 20$ nA in a He^3 cryostat equipped with a superconducting magnet.

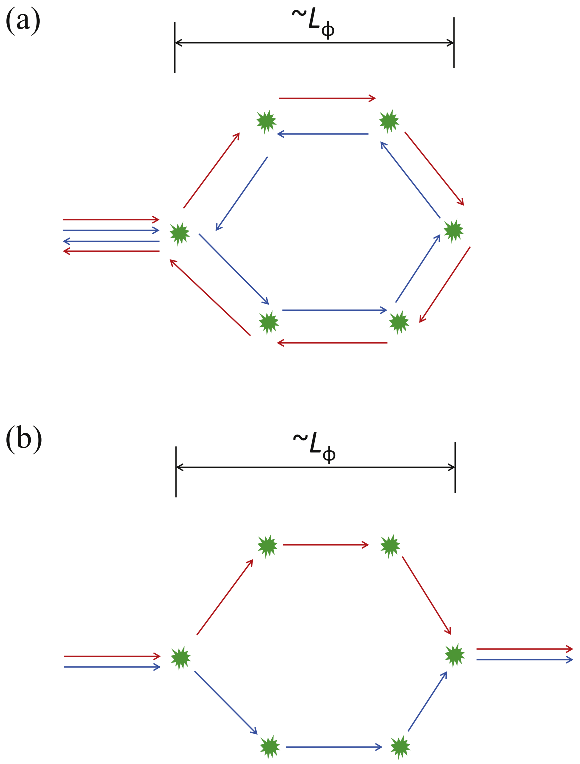

Fig. 1. (a) Schematic diagram showing time-reversed backscattered trajectories with a serious of elastic collisions from the origin point, which interfere to create WL. (b) The forward scattering trajectories with a series of elastic collisions, whose interference to present UCFs.

3. Results and discussion

The temperature dependence of magnetoresistance, $R(B)$, measured under magnetic fields from −2.3 to 2.3 T is shown in Fig. 2. Negative magnetoresistance is observed at low field region, which indicates the weak localization (WL) effect [3–6]. In addition, there are small conductance fluctuations which are reproducible at different temperatures. This is a signature of UCF [7–15]. These two quantum transport effects both come from the carrier interference. The phase coherence length from WL and UCFs effect is a considerable indication for the interference of electron waves [5]. For comparison from these effects in the multi-layer graphene system, we calculate the phase coherence lengths by adopting suitable theoretical models [4,27].

With increasing the temperature, the measured height of WL peak gradually reduces due to the decrease of phase coherence length [6,28]. Furthermore, for $T \leq 55$ K, the temperature dependence of resistance at $B = 0$ T shows a logarithmic dependence of T as shown in the inset of Fig. 2, consistent with the weak localization effect [7,29,30]. As shown in Fig. 2, the suppression of WL and positive magnetoresistances at high field regime are shown due to the chiral nature of carriers in graphene system [3,4,28,31]. The phase coherence length can be extracted by fitting the following equation [4–6]:

$$\Delta\rho(B) = -\frac{e^2\rho^2}{\pi h}\left[\mathrm{F}\left(\frac{B}{B_\varphi}\right) - \mathrm{F}\left(\frac{B}{B_\varphi + 2B_i}\right) - 2\mathrm{F}\left(\frac{B}{B_\varphi + B_*}\right)\right], \tag{1}$$

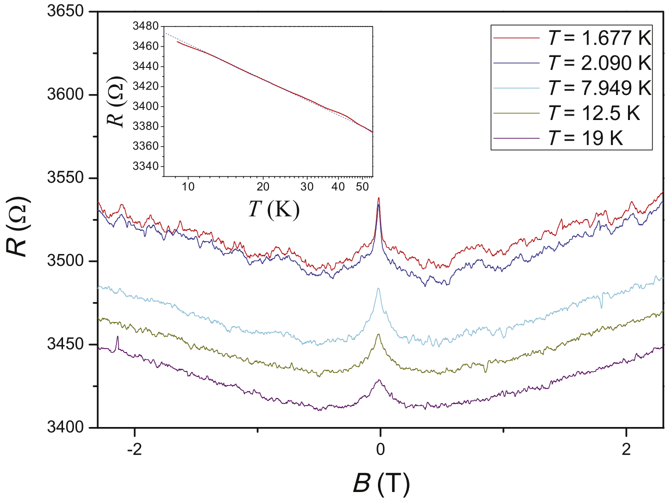

Fig. 2. Resistance R (B) as a function of magnetic field at various temperatures T. Inset shows the multi-layer graphene device resistance R (T) as a function of temperature in semi-logarithmic scale for $B = 0$.