Enhanced intervalley scattering in artificially stacked double-layer graphene

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Abstract
We fabricated artificially stacked double-layer graphene by sequentially transferring graphene grown by chemical vapor deposition. The double-layer graphene was characterized by Raman spectroscopy and transport measurements. A weak localization effect was observed for different charge carrier densities and temperatures. The obtained intervalley scattering rate was unusually high compared to normal Bernal-stacked bilayer or single-layer graphene. The sharp point defects, local deformation, or bending of graphene plane required for intervalley scattering from one Dirac cone to another seemed to be enhanced by the artificially stacked graphene layers.

Keywords: graphene, double-layer, weak localization, intervalley scattering

1. Introduction

Graphene, a two-dimensional (2D) sp\textsuperscript{2}-hybridized network of carbon atoms, has received remarkable attention because of its linear dispersion relation together with unique electronic properties such as ambipolar transport, Dirac particle quantum Hall effect including anomalous
integer quantum Hall effect and quantized opacity [1–6]. In addition, it also shows intriguing electron phase coherent phenomena such as weak localization and antilocalization (WL/WAL) effects. In particular, the WL/WAL phenomena have been used as a commanding tool to probe carrier transport such as scattering processes and disorder in graphene [7–9]. Because of its long electronic phase coherence, graphene is considered a promising material for quantum interference devices as well as high-performance spin valley electronic devices [10, 11]. However, the experiments regarding WL/WAL phenomena were mostly performed with graphene obtained by mechanical exfoliation, which is not a scalable method for controlling the number of layers and wafer-size production. One of the methods for large-area production of graphene is epitaxial growth on a SiC substrate, but this is a relatively expensive way for growth and this process requires very high temperature. However, a relatively low-cost and feasible approach is chemical vapor deposition (CVD) on metal (Cu, Ni) substrate for large-scale growth of graphene [12]. Although a few experiments have been performed on CVD-grown or epitaxially grown graphene [13–15], the WL effect is a mesoscopic quantum transport phenomenon that is still a fascinating result from the phase coherence of charge carriers. The interference of electron waves that are scattered by disorder and form closed trajectories leads to an enhancement in resistivity, resulting in the localization of electrons [7–9, 16–19]. This phenomenon can be observed when constructive interference occurs between two phase-coherent time-reversed electron paths with increment in elastic backscattering [8, 16, 20]. The application of a low magnetic field perpendicular to the plane where charge carriers are confined can cause a phase difference and annihilate the WL effect [7]. In graphene, the isospins of oppositely momentum-directed electrons can have reversed directions depending on the specific Dirac cone. Hence, the backscattering of charge carriers is suppressed because of the conservation of isospin in scattering processes, resulting in a reduction of the resistance of graphene [7–9]. This characteristic quantum phenomenon becomes more intriguing in a graphene field effect transistor where the charge carrier type and density are controlled by the gate voltage [16, 21, 22]. The nature of WAL in graphene, i.e. a positive magnetoresistance, was initially predicted to be distinguishable from normal metals because of the existence of the Berry phase [1]. However, elastic intervalley scatterings that break chirality can evidently validate the observable facts of WL [17], i.e., the negative magnetoresistance. The sharp point defects, local deformation, or bending of graphene plane in graphene play an important role in the enhancement of intervalley scattering and reversal of valley isospin, which involves a large momentum transfer between two Dirac cones [23–25]. These intriguing characteristics provide an opportunity to use valley isospin for so-called valleytronics devices [10, 26].

Noticeably, it is already known that the linear dispersion becomes parabolic by adding a second layer of graphene. However, so far no magnetotransport experiments on the WL effect on artificially stacked double-layer graphene from large-scale CVD growth have been performed. In principle, it would be interesting to observe the WL effect in a new system made by breaking the Bernal stacking symmetry of two graphene layers. Here, we present evidence of the WL effect on two artificially stacked graphene layers. The characteristics of double-layer graphene, i.e., two artificially stacked graphene layers, were studied by Raman spectroscopy and transport measurements. Phase coherent, inter- and intravalley scattering lengths were obtained by WL magnetoresistance fitted to a theoretically predicted formula at different charge carrier densities. The effect of temperature was examined on the phase coherent, intervalley, and the combined inter- and intravalley scattering lengths. Finally, these results were
corroborated by comparison with magnetotransport measurements of single-layer graphene (SLG).

2. Experimental details

Graphene film was grown on 25 μm thick copper foils from Alfa Aesar (99.8% pure) via thermal CVD. A mechanically polished and electropolished copper foil was inserted into the CVD furnace. The furnace was evacuated to ~10^{-4} Torr, and the temperature rose to 1010 °C with H₂ gas flow (~10^{-2} Torr). After the temperature stabilized at 1010 °C, CH₄ and H₂ (20 and 5 standard cubic centimeters per minute, respectively) were injected into the furnace to synthesize the graphene for 8 min, after which the sample was cooled at a rate of 50 °C min⁻¹ to room temperature [12]. The graphene film grown on Cu foil was transferred to a Si substrate by the wet transfer method. The Cu foil was spin-coated (850 rpm for 10 s, 2500 rpm for 30 s) with a thin layer of polymethylmethacrylate (PMMA). Then, the bottom Cu foil was removed by etching in a 1 M solution of ammonium persulfate (APS, (NH₄)₂S₂O₈), and the PMMA membrane was washed with deionized water. Next, the graphene film with the PMMA membrane was transferred to the p-doped Si substrate having a top 300 nm thick layer of SiO₂. The graphene layers transferred onto the Si/SiO₂ substrate were heated at 80 °C for 10 min to dry and then put in acetone for one day to completely dissolve the PMMA layer. An artificial double-layer graphene was formed by subsequent transfer of another layer onto the first layer of graphene. Half of the first layer of graphene in the Hall bar was removed with a combination of electron-beam lithography and oxygen plasma treatment. Therefore, we were also able to examine the characteristics of SLG. Raman spectra were measured with a Renishaw microspectrometer over a wavenumber range from 1100 to 3200 cm⁻¹, with a laser wavelength of 514.5 nm. The spot size was 1 μm and the power was kept at 1.0 mW to avoid local heating. Atomic force microscope (AFM) is used to analyze the surface morphology of single- and double-layer graphene. The typical Hall bar patterns were fabricated by photolithography and Cr/Au (5/30 nm) contacts were coated by using a thermal evaporation system. The magnetotransport measurements were performed by using the standard lock-in technique at low temperature (down to 0.35 K) in a cryostat.

3. Results and discussion

The Raman spectrum of the artificially stacked double-layer graphene grown by the CVD method is shown in figure 1(a). The G peak in the Raman spectrum corresponds to the in-plane bond stretching of C atoms with E₂g symmetry optical phonon at the Brillouin zone center [27]. The 2D peak is the second order of the D peak, which originates from a process where momentum conservation is satisfied by two phonons with opposite wave vectors. The 2D/G peak intensity ratio (I₂D/I_G) value is ~2.7 in figure 1(a). The D peak is attributed to A₁g phonons near the K-zone boundary [27]. The low value of the D/G peak intensity ratio (I_D/I_G < 0.14) is indicative of the existence of a high quality CVD-grown graphene. To check that the quality of graphene was uniform, we performed Raman spectroscopy at different locations on the artificially stacked double-layer graphene device fabricated in this experiment. The I₂D/I_G ratio at different points in the graphene device is shown in figure 1(b) and positions G and 2D peaks at different points are shown in figure 1(c). The I₂D/I_G ratio of ~2.7 is distinct from that of the
Bernal-stacked bilayer graphene, whereas it is comparable to that of SLG. However, the $I_{2D}/I_G$ ratio of twisted bilayer graphene was reported to be closely correlated with twisted angle. When twisted angle increased from 5.4° to 27.2°, the Raman intensity ratio of $I_{2D}/I_G$ increased from $\sim 1$ to $\sim 3$ [28]. Since the $I_{2D}/I_G$ ratios show uniform values around 2.7, artificially stacked double-layer in this experiment has a uniform twisted angle rather than random rotational disorder. There were intriguing reports that stacking disorder in multilayer graphene can induce a low-energy linear dispersion as in SLG. Magnetotransport and far-infrared magneto-transmission investigations revealed the Dirac-type SLG-like characteristics of electronic states for multilayer epitaxial graphene grown on SiC substrate [29, 30]. The electronic structure of SLG preserved even in multilayer epitaxial graphene was attributed to a high degree of rotational disorder in the multilayer epitaxial graphene.

The consistent characteristics in the Raman spectroscopy indicate that the layer-by-layer transfer of the CVD-grown graphene made a uniform quality of graphene with relatively low defects for the large area of the device in this experiment. Figure 1(d) is AFM image of the single layer graphene showing a uniform surface of graphene, whereas a few wrinkles are observed in the figure 1(e), which is AFM image of the double-layer graphene. Surface

![Figure 1](image.png)

**Figure 1.** (a) Raman spectrum of artificially stacked double-layer graphene. (b) The G and 2D Raman peak position at different locations in the transport measurement area. (c) The ratio of 2D/G peak intensity ratio ($I_{2D}/I_G$) values at different locations in the transport properties measurement area. (d) Atomic force microscope (AFM) image of single layer graphene region and (e) AFM image of double-layer graphene region of the device.
uniformity and wrinkles were reported to affect the characteristic lengths of transport properties in the epitaxial graphene grown on SiC substrate [25, 31, 32].

The artificially stacked double-layer graphene was further characterized by electrical transport measurements. The resistivity of graphene devices was measured as a function of the back-gate voltage ($V_g$). The longitudinal resistivity showed a clear Dirac point ($V_{\text{Dirac}}$) at +10 V at 0.35 K and 300 K (see figure 2(a)). The field effect hole mobility values of the double-layer graphene device were found to be around 2150 and 2410 \( \text{cm}^2\text{V}^{-1}\text{s} \) at temperature of 300 K and 0.35 K, respectively. The charge carrier density ($n$) as a function of $V_g$ is shown in figure 2(b). The $n$ controlled by $V_g$ was obtained from the Hall measurement. The black solid line shown in figure 2(b) represents a linear fit of the relation $n = C_g (V_g - V_{\text{Dirac}})/e$, where $C_g$ is the capacitance of the 300 nm-thick SiO$_2$ layer. The estimated magnitude of $C_g$ was 124 aF $\mu$m$^{-2}$, which is consistent with previous reports [33].

The WL magnetoresistance properties were measured by sweeping a magnetic field ($B$) perpendicular to the graphene plane. The electron scattering resulting from disorder can form a closed trajectory that interferes with the time-reversed path. If the phase coherence length is longer than the elastic scattering length, the quantum corrections to the resistance because of constructive interference of the time-reversed path lead to an enhanced resistance at zero magnetic field. For a detailed analysis of this phenomenon, the measured relative change in magnetoresistivity ($\Delta \rho/\rho$) versus the $B$ field are fitted by the following equation [17]:

![Figure 2.](image-url)

(a) Resistivity as a function of back-gate voltage of artificially stacked double-layer graphene at 0.35 K and 300 K. Inset: Hall bar pattern of a single- and artificially stacked double-layer graphene device with Au electrodes. (b) Charge carrier density as a function of back-gate voltage.
Here $\psi(x)$ is the digamma function, $\tau_\phi$ is the dephasing rate because of inelastic scattering, $\tau_i$ is the elastic intervalley scattering time, and $\tau_r$ is the relaxation time, which is a combination of the three other main scattering terms: $\tau_z$, the elastic intravalley chirality breaking scattering term, which originates from defects or dislocation; $\tau_w$, the elastic intravalley trigonal warping scattering term, and $\tau_i$. The resultant rate, $\tau_*^{-1}$, forms the relation of $\tau_*^{-1} = \tau_z^{-1} + \tau_w^{-1} + \tau_i^{-1}$. The elastic intervalley scattering time $\tau_i$ comes from atomically sharp scatterers and scattering from the edges of the device. The relative change in magnetoresistivity ($\Delta \rho / \rho$) versus $B$ for different $V_g$ values was shown in figure 3(a) and the solid red lines are the fits of equation (1). All solid lines fitted well with the experimental data, whereas $\tau_\phi$, $\tau_i$, and $\tau_r$ were obtained as fitting parameters. These curves show the same WL trend at various $V_g$ values in figure 3(a). However, the WL effect near the Dirac point ($V_g=+10 \, V$) region deserved special consideration, where we observe that the resistivity started increasing significantly when the magnitude of magnetic field was higher than $\pm 0.25 \, T$ (see figure 3(b)). The increase in resistance with magnetic field indicates a signature of the WAL effect in this regime. This prominent effect may be caused by enhancement of inelastic scattering near the Dirac point.

**Figure 3.** (a) Relative magnetoresistivity ($\Delta \rho / \rho$) as a function of magnetic field ($B$) of artificially stacked double-layer graphene at varying back-gate voltage at $T=4.2 \, K$. The solid red lines are the fits of equation (1). (b) ($\Delta \rho / \rho$) as a function $B$ near Dirac point.

\[
\frac{\Delta \rho}{\rho} = -\frac{e^2 \rho}{\pi \hbar} \left[ F \left( \frac{B}{B_\phi} \right) - F \left( \frac{B}{B_\phi + 2B_i} \right) - 2F \left( \frac{B}{B_\phi + 2B_*} \right) \right],
\]

$$F(z) = \ln(z) + \psi\left(\frac{1}{2} + \frac{1}{z}\right),$$

$$B_{\phi,i,*} = \frac{\hbar}{4De} \frac{1}{\tau_{\phi,i,*}}.$$  

(1)
region caused by electron-hole puddles. The observed WAL effect may be associated with the low-energy quasiparticles of double-layer graphene which exhibit a similar chirality as that of single layer graphene. Fittings to the magnetoresistivity curves with carrier densities from $-5.41 \times 10^{12} \text{ cm}^{-2}$ ($V_g = -60 \text{ V}$) to $3.77 \times 10^{12} \text{ cm}^{-2}$ ($V_g = +60 \text{ V}$) (see figure 3) allowed us to extract the scattering times with best-fit values for the parameters using equation (1) and these were later converted into scattering lengths. The ratio of $\tau_{\phi}/\tau_*$ as a function of $\tau_*/\tau_i$ is shown in figure 4(a), and indicates the existence of favorable conditions for the observation of both the WL and WAL phenomena. The large values of these ratios correspond to a regime where the WL effect is dominant, whereas near the Dirac point region these ratios have lower values, which is evidence for the existence of the WAL effect [19].

The most striking result of this paper is the large difference between the intervalley scattering rates for stacked layers compared to the single layers. This central result permits a more detailed discussion using theoretical study of Kechedzhi et al [34]. The scattering rates are $\tau_i^{-1} = 4\tau_{\perp \perp}^{-1} + 2\tau_{\perp \parallel}^{-1}$, $\tau_z^{-1} = 2\tau_{\perp \parallel}^{-1} + \tau_{zz}^{-1}$ and $\tau_*^{-1} = \tau_z^{-1} + \tau_i^{-1}$ up to the warping term which is small close to the Dirac point. So a small intervalley rate means that $\tau_{\perp \perp} \ll \tau_{\perp \parallel}$, $\tau_{\perp \parallel} \ll \tau_{zz}^{-1}$. The rate $\tau_{zz}^{-1}$ arises from the scattering potential $u_{zz}$, which describes an asymmetry in the potential felt at the A and B site in graphene. The other potentials like $u_{\perp \parallel}$ involve some form of bond stretching. This can be a local deformation of the hexagon, or a bending of the graphene plane. An interesting relation is found between scattering rates $1/\tau_*$ and $1/\tau_i$ in figure 4(a). The linear fit of $\tau_*^{-1} = 2\tau_i^{-1}$ is obtained regardless of carrier density except for the Dirac point region. Since the relation of $\tau_*^{-1} = \tau_i^{-1} + \tau_{\perp \parallel}^{-1}$ holds for small trigonal warping scattering rate, a relation of $\tau_i^{-1} = \tau_z^{-1}$ is obtained. Therefore, the intervalley scattering rate is same as the elastic intravalley chirality breaking scattering rate due to defects and dislocations.

Figure 4. (a) The $\tau_{\phi}/\tau_*$ versus $\tau_{\phi}/\tau_i$ plot of artificially stacked double-layer graphene. The scattering times are obtained from the magnetoresistivity curve fit to equation (1). (b) The characteristics lengths as a function of charge carrier density at $T = 4.2 \text{ K}$. The uncertainty in the scattering lengths are shown as a function of carrier density are shown with error bars.
The scattering lengths as a function of n are shown in figure 4(b). The phase coherence length \( (L_\varphi) \), the elastic intervalley scattering length \( (L_i) \) and the combination of inter- and intravalley scattering length \( (L_\varphi) \) were obtained by the relation \( L_{\varphi,i,*} = \sqrt{D\tau_{\varphi,i,*}} \). Here \( D = \frac{1}{2}v_F^2 \tau_F = v_F^2 \tau_0 \) is the diffusion constant of the graphene sheet having momentum relaxation time \( (\tau_0) \) deduced from the relation \( \tau_0 = \frac{\hbar}{\sqrt{n}F_0(e^2v_F)} \) with the Fermi velocity \( v_F \approx 1 \times 10^6 \, \text{m} \, \text{s}^{-1} \). The transport scattering time \( (\tau_\varphi) \) is twice that of the momentum relaxation time in graphene because of chiral transport properties. The characteristics of WL usually become prominent when both the intra- and the inter valley scatterings are large. The observed phase coherence length is greater than the intervalley scattering length, i.e. \( L_\varphi > L_i \), whereas the difference between \( L_i \) and \( L_\sigma \) is relatively small, as shown in figure 4(b). This is in contrast to the previous studies on a mechanically exfoliated bilayer graphene by Gorbachev et al and Liao et al, where \( L_\varphi \), \( L_i \), and \( L_\sigma \) are all of comparable magnitudes [7, 21].

The temperature dependence of the WL effect at \( V_g = 0 \, \text{V} \) in the range from 0.35 to 10 K is shown in figure 5(a). The red lines represent the fitting of equation (1) for different temperatures. Figure 5(b) shows the temperature dependence of the phase coherence scattering time \( (\tau_\varphi) \), which is obtained from the fits of the WL corrections and follows the \( \sim T^{-2/3} \) law above 4.2 K. As electron–electron interaction is enhanced with increasing temperature, \( \tau_\varphi \) decreases at high temperature [35]. The inelastic interactions due to electron–electron scattering were found to be the dominant mechanism in the case of graphene, limiting the coherence of quasiparticles at low temperature [35–37]. The extracted scattering lengths from the fitting parameters are plotted in figure 5(c). The value of \( L_\varphi \) increased at lower temperature and saturated below 2 K, the red dashed line is a guide to the eye. On the other hand \( L_i \) and \( L_\sigma \) are independent of temperature in the range of this experiment. The \( L_i \) and \( L_\sigma \) are replotted as a function of temperature in the figure 5(d) for clarity. Since the variations of \( L_i \) and \( L_\sigma \) with temperature are within the error bar, one can see that \( L_i \) and \( L_\sigma \) are independent of temperature. The value of \( L_i \) for the artificially stacked double-layer graphene was much smaller than for the Bernal-stacked bilayer graphene. As our sample was rather wide (\( \sim 10 \, \mu \text{m} \)), the edge scatterings were apparently negligible. The elastic intervalley scattering is thought to be enhanced by the presence of C atoms in the top graphene layer that work as sharp point defects, or local deformation and bending by the top graphene layer.

We have intentionally left one half of the device uncovered in the etching process to investigate the WL effect on single-layer CVD-grown graphene. In inset of figure 2(a) the upper part corresponds to artificially stacked double-layer graphene, whereas the lower part corresponds to SLG. This helped in the comparison with the artificially stacked double-layer graphene. The same magnetotransport measurements were performed for the single-layer CVD-grown graphene. The longitudinal resistivity of the graphene device as a function of back-gate voltage showed \( V_{\text{Dirac}} = +2 \, \text{V} \) at the temperature of 4.2 K (figure 6(a)). The hole mobility of the SLG region was around 2400 cm\(^2\) V\(^{-1}\) s\(^{-1}\). Shown in figure 6(b) is the relative change in magnetoresistivity \( \Delta \rho/\rho \) versus B for different \( V_g \) and the solid lines (red color) represent fits to equation (1). From the fitted curves we obtained the scattering length parameters \( L_\varphi \), \( L_i \), and \( L_\sigma \), shown in figure 6(c) for different charge carrier density. For clarity, \( L_i \) and \( L_\sigma \) are redrawn in figure 6(d) as a function of charge carrier density. We found that \( L_\varphi \), \( L_i \), and \( L_\sigma \) are in line with previous reports for SLG [14, 15]. The value of \( L_i \) (=150 ~ 210 nm) of the SLG is much larger than that of the artificially stacked double-layer graphene. As shown in figure 4(b), \( L_i \) is much smaller (\( \lesssim 50 \, \text{nm} \)) for the case of artificially stacked double-layer graphene. These results support the finding that the top graphene layer in the artificially stacked double-layer graphene.

The value of \( L_\varphi \) deduced from the relation \( \tau_\varphi = \frac{\hbar}{\sqrt{n}F_0(e^2v_F)} \) with the Fermi velocity \( v_F \approx 1 \times 10^6 \, \text{m} \, \text{s}^{-1} \). The transport scattering time \( (\tau_\varphi) \) is twice that of the momentum relaxation time in graphene because of chiral transport properties. The characteristics of WL usually become prominent when both the intra- and the inter valley scatterings are large. The observed phase coherence length is greater than the intervalley scattering length, i.e. \( L_\varphi > L_i \), whereas the difference between \( L_i \) and \( L_\sigma \) is relatively small, as shown in figure 4(b). This is in contrast to the previous studies on a mechanically exfoliated bilayer graphene by Gorbachev et al and Liao et al, where \( L_\varphi \), \( L_i \), and \( L_\sigma \) are all of comparable magnitudes [7, 21].

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device enhances the intervalley scattering. The temperature dependence of the WL effect at $V_g = 0$ V ranging from 0.35 to 10 K for SLG is given in figure 7(a). The red lines represent the fitting of equation (1) for different temperatures. The temperature dependence of the phase coherence time is obtained from the fits of the WL corrections, which follows the $\sim T^{-1}$ law above 4.2 K. (c) The characteristics lengths at $V_g = 0$ V as a function of temperature. The red dashed lines are a guide to the eye. (d) The scattering lengths, $L_i$ and $L_\ast$ as a function of temperature. The uncertainty in the $L_i$ and $L_\ast$ with temperature are expressed by the error bars.

Figure 5. (a) Relative magnetoresistivity ($\Delta \rho/\rho$) as a function of magnetic field (B) of artificially stacked double-layer graphene at various temperatures from 0.35 to 10 K. The solid red lines are the fits of equation (1). (b) Temperature dependence of the phase coherence scattering time is obtained from the fits of the WL corrections, which follows the $\sim T^{-2/3}$ law above 4.2 K. (c) The characteristics lengths at $V_g = 0$ V as a function of temperature. The red dashed lines are a guide to the eye. (d) The scatterings lengths, $L_i$ and $L_\ast$ as a function of temperature. The uncertainty in the $L_i$ and $L_\ast$ with temperature are expressed by the error bars.
Figure 6. (a) Resistivity as a function of back-gate voltage of single-layer graphene device at 4.2 K. (b) Relative magnetoresistivity ($\Delta \rho / \rho$) as a function of magnetic field (B) at various back-gate voltage at $T=4.2$ K, the solid red lines are the fits of equation (1). (c) The characteristic lengths as a function of charge carrier density at $T=4.2$ K. (d) The $L_i$ and $L_*$ as a function of charge carrier density are plotted with error bars.
Figure 7. (a) Relative magnetoresistivity ($\Delta \rho / \rho$) as a function of magnetic field (B) of the single-layer graphene device at various temperatures from 0.35 to 10 K. The solid red lines are the fits of equation (1). (b) Temperature dependence of the phase coherence time is obtained from the fits of the WL corrections, which follows the $\sim T^{-1}$ law above 4.2 K. (c) The characteristics phase coherence length at $V_g = 0$ V as a function of temperature. The red dashed line is a guide to the eye. (d) The $L_i$ and $L_*$ as a function of temperature are plotted with error bars.
above 4.2 K. This is inline with previous reported results for single layer graphene [32]. The extracted phase coherence length from the fitting parameters are plotted in figure 7(c). The value of $L_{\phi}$ increased as the temperature was lowered and saturated below 4.2 K. The red dashed line is a guide to the eye. The $L_i$ and $L_*$ are plotted as a function of temperature in the figure 7(d). However, $L_i$ and $L_*$ is independent of temperature in the range of this experiment. The $L_i$ and $L_*$ are plotted as a function of temperature with error bars in the figure 7(d).

4. Conclusion

We fabricated artificially stacked double-layer graphene by sequentially transferring CVD-grown graphene. Raman spectroscopy showed that the two transferred layers of graphene were of uniform quality and longitudinal resistivity measurements as function of $V_g$ showed considerably high mobility. The WL effect was observed at different charge carrier densities and temperatures, whereas the clear signature of the WAL effect was manifested near the Dirac point region. The large values of $\tau_\phi/\tau_*$ and $\tau_\phi/\tau_i$ ratios also demonstrated the existence of favorable conditions for the WL effect, whereas the small values corresponded to a dominant WAL-effect regime. The intervalley scattering rate of the artificially stacked double-layer graphene was much higher than that of Bernal-stacked bilayer graphene or that of SLG. The large momentum transfer required for intervalley scattering from one Dirac cone to another seemed to be enhanced and the sharp point defects, local deformation, or a bending of graphene plane are provided by the artificially stacked graphene layers. The observed phenomena can provide an idea on how to manipulate intervalley scattering in some attractive future applications such as valleytronics devices.

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