Quasi-Periodic Nanoripples in Graphene Grown by Chemical Vapor Deposition and Its Impact on Charge Transport

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Graphene1 is a promising material for many novel device applications such as ultrafast nanoelectronics, optoelectronics, and flexible transparent electronics.2–5 Cu-based CVD methods have now made wafer-scale graphene synthesis and transfer feasible both for single-layer graphene6,7 (SLG) and bilayer graphene (BLG).8 This not only brings the commercial applications of graphene within reach but also provides great advantages in introducing new substrates to enhance and engineer its electronic properties by tuning the substrate-induced screening9–12 and substrate-induced strain.13,14 Unlike CVD graphene growth on Ni,15,16 Cu–CVD graphene growth has a rather weak interaction with the underlying Cu substrate, allowing CVD graphene to grow continuously crossing atomically flat terraces, step edges, and vertices without introducing significant defects.17 Thus, by controlling pregrowth annealing7 and fine-tuning growth parameters,18,19 it is now possible to synthesize CVD graphene with submillimeter grain size. However, pregrowth annealing and CVD growth typically require high temperatures very close to the melting point of Cu at 1083 °C. This leads to Cu surface reconstruction and local surface melting17,20 during graphene growth, making high density Cu single-crystal terraces and step edges ubiquitous surface features. Taking into account the negative thermal expansion coefficient of graphene, this leads to new surface corrugations in CVD graphene during the cool down process.21 Previously, grain boundaries have been identified as one of the limiting factors to degrade graphene quality.22 While the heptagon and pentagon network22,23 at grain boundaries does disrupt the sp² delocalization of π electrons in graphene, it remains to be seen whether this is indeed the charge scattering source most relevant for device applications. In this paper, we show that Cu single-crystal step edges lead to the formation of quasi-periodic nanoripple arrays (NRAs). Electron-flexural phonon scattering in such partially suspended graphene devices introduces anisotropic charge transport and sets limits to both the highest possible charge mobility and lowest possible sheet resistance values. Our findings provide guidance for further improving the CVD graphene growth and transfer process.

KEYWORDS: CVD graphene · quasi-periodic nanoripple arrays · anisotropic · charge transport · flexural phonon scattering · transparent electrodes · sheet resistance

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corrugations suspend up to 20% of graphene and give rise to flexural phonon scattering. In particular, at room temperature and density levels of the order of $10^{12}/\text{cm}^2$, this leads to a strong anisotropy in the room temperature (RT) conductivity depending on the relative orientation between NRAs and current flow direction. More importantly, flexural phonon scattering within the nanoripples sets a lower bound on the sheet resistance and upper bound on the charge carrier mobility even in the absence of grain boundaries.

**RESULTS AND DISCUSSION**

We first compare the RT resistivity versus gate voltage ($\rho$ vs $V_{BG}$) characteristics in four graphene field-effect transistors (GFETs) of very different dimensions, ranging from the micrometer scale to the millimeter scale. The resistivities of these devices, fabricated from the same batch of CVD graphene, are presented in Figure 1f. Surprisingly, except introducing stronger charge inhomogeneity, increasing the device channel area by 6 orders of magnitude does not significantly alter the charge carrier mobility; RT mobilities vary generally speaking independent of samples size for $\mu \sim 4000$–$6000$ cm$^2$/V-s. This excludes grain boundaries (10–20 per mm; see Figure 1a) as the main limiting factor for $\mu$ in our CVD graphene and strongly suggests that the main scatterers are identical to the ones in exfoliated graphene: adatoms and/or charged impurities. Similar conclusions have recently been reached also by ref 12.

However, high-resolution contact mode atomic force microscopy (AFM) of CVD graphene on Si/SiO$_2$ with ultrasharp tips reveals a new type of surface corrugations (Figure 2), whose influence on charge transport is not known. Distinct from the well-known low-density strain-induced wrinkles ($\sim 1$ per 5 $\mu$m), we observe nanoripples of $\sim 3$–10 $\mu$m in height of much higher density ($\sim 10$ per 5 $\mu$m), which are typically arranged in a quasi-periodic fashion (Figure 2b). Each nanoripple location contains multiple peaks of 10–50 nm width (see Figure 2e and Supporting Information), thus making it possible that overall a section of up to $\sim 100$ nm, that is, up to 20% of the graphene sheet, becomes effectively suspended.

Systematic AFM studies on centimeter size samples further confirm that quasi-periodic nanoripple arrays (NRAs) are a general feature of the CVD graphene-on-SiO$_2$ surface morphology (see Supporting Information). To find out the origin of these NRAs, we carefully examined the single-crystal surface of Cu substrates. As shown in Figure 2a, thermally annealed Cu has a characteristically high density of single-crystal terraces and
step edges. The terrace structure is typically a few hundred nanometers in width, separated by step edges of \( \sim 100 \) nm in width. These parameters agree very well with the dimensions of NRAs. The patterning of Au alignment mark arrays on Cu right after graphene growth allows the direct correlation of the local Cu step edge pattern, density, and orientation with the surface morphology of graphene after it is transferred to a substrate. This comparison of graphene transferred from different Cu grains clearly demonstrates that NRAs originate from Cu step edges and, thus, rules out any other factors during the transfer and fabrication process (see Supporting Information). Previous studies\(^6,7\) proposed that the wrinkle formation (i.e., out-of-plane mechanical deformations in graphene sheets on Cu) is sufficient to release strain arising from the difference in thermal expansion coefficients between graphene and Cu. The observation of high-density NRAs suggests that strain is, in fact, mainly released by high-density Cu step edges. Below we will show that at RT these NRAs ultimately also set a lower bound on the sheet resistance, \( R_0 \), and an upper bound for the charge mobility, \( \mu \), even if all other extrinsic scatterings are eliminated.

We now focus on \( T \)-dependent electrical transport measurements. In micrometer size devices, the QHE is well-developed for both SLG and BLG, as shown in Figure 3a,b, respectively. From an application point of view, the zero field measurements of \( \sigma \) versus \( n \) are more relevant. They show a pronounced sublinear behavior, not only in CVD SLG but also in CVD BLG devices. The sublinearity is strongest at RT and diminishes gradually with decreasing temperature, as shown in Figure 3c,d, respectively. This is best studied by plotting the \( T \)-dependent part of the resistivity instead and represents the key finding of our experiments. Our data reveal a superlinear \( T \)-dependent resistivity for \( T > 50 \) K. Remarkably, such a metallic behavior is observed in both SLG and BLG (Figure 3e). Previous studies on supported exfoliated samples only reported such a \( T \)-dependent resistivity in SLG, while BLG samples did not show any \( T \) dependence away from the charge neutrality point (CNP).\(^24\) Such behavior for BLG is expected only for suspended samples, where the \( T \)-dependent contribution to \( \rho (n, T) \) scales as \( T^2/n \) and is generally associated with electron-flexural phonon (FP) scattering.\(^25\) Indeed, the high-density NRAs effectively decouple up to 20\% of CVD graphene sheets from the substrate, activating low-energy FP excitations in both SLG and BLG even when the samples are overall supported.

For CVD BLG, this clearly demonstrates that at RT NRAs will limit both \( R_0 \) and \( \mu \) due to FP scattering. However, the CVD SLG case is more ambiguous. Its resistivity has additional \( T \)-dependent contributions due to scattering from remote interfacial phonons (RIP) of the SiO\(_2\) substrate\(^26,27\) and possibly high-energy FPs arising from quenched 10 nm wide nanoripples.\(^28,29\) On SiO\(_2\) substrates, both the FP and RIP scattering mechanisms lead to a very similar \( T \)- and \( n \)-dependent behavior over 50–350 K and \( \sim 10^{12}/\text{cm}^2 \) ranges (Figure 3e).\(^27\)

To explicitly measure the influence of NRAs on CVD SLG’s resistivity, we have fabricated GFETs where the orientation of the electrodes is such that the current is either perpendicular (\( \perp \)) or parallel (\( \parallel \)) to the NRAs (Figure 4a,b). In total, four sets of devices have been characterized. Here we discuss representative data for...
two sets (namely, S1 and S2). We analyzed the corresponding transport data by assuming a resistivity $\rho$ of the form

$$\rho(n, T) = \rho_0(n, T) + \alpha T + \rho_1(n, T)$$ (1)

where $\rho_0(n)$ is the $T$-independent residual resistivity, $\alpha T$ is the acoustic phonon (AP)-induced resistivity ($\alpha = 0.1 \Omega \cdot K^{-1}$), and $\rho_1(n, T)$ is the superlinear part of the resistivity. In Figure 4c,e, we directly compare $\rho_1(n, T)$ for the $\perp$ and $\parallel$ devices by computing the increase in resistivity between 100 K and $T$ at fixed density $n$, namely, $\Delta \rho_1(n, T) = \rho_1(n, 100 K) - \rho_1(n, T) = \alpha(T - 100 K) = \rho_{\parallel}(n, T) - \rho_{\parallel}(n, 100 K)$ and $\Delta \rho_1(n, T) = \rho_1(n, T) - \rho_0(n, 100 K) = \rho_{\perp}(n, T) - \rho_{\perp}(n, 100 K)$. Strikingly, in both samples, $\Delta \rho_1$ remains always significantly greater than $\Delta \rho_0$. In other words, the RT CVD graphene resistivity is anisotropic. This is in sharp contrast with the isotropic resistivity of exfoliated samples and clearly shows that the phonon scattering rate is higher in the devices with the $\perp$ configuration. Since FPs are the only phonons which are activated upon suspension, this demonstrates that NRAs contribute also in CVD SLG importantly to the $T$ dependence of $\rho$.

Assuming a simple resistor-in-series and resistor-in-parallel model (see Supporting Information), we estimate the impact of NRAs on key figures of merit such as $\mu$ and $R_{\parallel}$ (Figure 4d). Note that in our model $\rho_1(n, T)$ arises from both electron-FP scattering (in the nanoripples) and electron-RIP scattering events (between the nanoripples) independent of the NRA orientation. With this, we write $\rho_{\perp} = \rho_{\parallel} + (1 - \gamma)\rho_{FP} + \gamma\rho_{RIP}$ and $\rho_{\parallel} = \rho_{\parallel} + (1 - \gamma)\rho_{FP} + \gamma\rho_{RIP}$, where $\gamma$ is the ratio of the typical ripple width $w$ and the mean inter-ripple spacing $a$. Besides, we assume $\rho_{FP}$ is of the form $\rho_{FP} = A\gamma T^2/n_e$, and $\rho_{RIP}$ can be written as $B\gamma T^{-1}n_e$, where $A = 3.2 \text{ meV}$ and $B = 8.7 \text{ meV}$ are the respective coupling strengths of the SiO$_2$ RIP modes of energies $E_1 = 63 \text{ meV}$ and $E_2 = 149 \text{ meV}$. We can now estimate the two free parameters $A$ and $B$ setting the magnitude of $\rho_{FP}$ and $\rho_{RIP}$ by fitting the curves of Figure 4c,e (see Supporting Information). This leads to $A \approx 3 \times 10^{-17} \text{ K}\Omega/(\text{eV} \cdot \text{cm})^2$, in reasonable agreement with refs 26 and 27, and $B \approx 6 \times 10^{-6} \text{ V} \cdot \text{s}/(\text{mK})^2$. Interestingly, these extracted values of $\gamma$ match well the experimental $\gamma$ values recently obtained for fully suspended graphene samples.

With this, it is now possible to predict FP-induced limits on CVD SLG’s $\mu$ and $R_{\parallel}$. Figure 4d shows the calculated RT mobility as a function of the helium-$T$ mobility $\mu_0$ for CVD graphene with $f = 20\%$ both in $\perp$ and $\parallel$ orientations. As $\mu_0$ is unaffected by phonons, this is a convenient variable to gauge the influence of FPs. Including AP scattering NRAs limits the RT mobility to $\sim 40,000 \text{ cm}^2/(\text{V} \cdot \text{s})$ in $\perp$ orientation and $\sim 80,000 \text{ cm}^2/(\text{V} \cdot \text{s})$ in $\parallel$ orientation, independent of the choice of substrate. In contrast, RT mobilities greater than $100,000 \text{ cm}^2/(\text{V} \cdot \text{s})$ have already been achieved for exfoliated graphene encapsulated in h-BN.

Figure 3. (a,b) QHE of CVD SLG and BLG grapheme on Si/SiO$_2$ substrate, respectively. SLG shows the anomalous quantization plateaus of $\pm 4e^2/h(N = 1/2)$, while BLG has the typical $\pm 4e^2/h$ quantization signatures. (c) $T$-dependent sublinear behavior of a SLG. Inset: Insulating behavior with $n < 5 \times 10^{12}/\text{cm}^2$. (d) $T$-dependent sublinear behavior of a BLG. Inset: AFM image of a flower-shaped CVD BLG; quasi-periodic NRAs are clearly seen in both SLG and BLG; the scale bar is 1 $\mu$m. (e) $\rho(T)$ for SLG at $T = 0.5 \times 10^{12}/\text{cm}^2$ and for BLG at $T = 0.5 \times 10^{12}/\text{cm}^2$ and $n = 3.8 \times 10^{12}/\text{cm}^2$. Dashed lines correspond to a two-parameter fit to the data using $\rho = \rho_0 + 0.1T + \gamma T/n_e$ and serve as guide to the eyes. (f) RT superlinear contribution $\rho_1$ to the total resistivity $\rho$ as a function of charge density $n$ for CVD SLG FET (black squares) and CVD BLG FET (white squares). The solid red and blue curves correspond to fits of the form $\rho_{\parallel} = \alpha n$, where $\rho_{\parallel}$ arises from both FPs and RPs. We used $\alpha = 1.57 \times 10^{12}$ and $2.87 \times 10^{12} \Omega/\text{m}^2$ for SLG and BLG, respectively.
Figure 4. (a,b) T-dependent sublinear conductivity for both \( \perp \) and \( \parallel \) NRA orientations. The scale bar is 1 \( \mu m \). (c) Anisotropic resistivity results obtained with sample set \( S1 \) at \( n = 2 \times 10^{12} \text{cm}^{-2} \) for data obtained at higher carrier density, see Supporting Information); the blue and red data points correspond to the \( \perp \) and \( \parallel \) NRA configurations, respectively. They are fitted with \( \Delta \rho_{\perp}(n,T) = \rho_{\perp}(n,100 \text{ K}) - \rho_{\perp}(n,100 \text{ K}) \) (solid red) and \( \Delta \rho_{\parallel}(n,T) = \rho_{\parallel}(n,100 \text{ K}) - \rho_{\parallel}(n,100 \text{ K}) \) (solid black). The black points correspond to \( \Delta \rho_{\text{int}} \), and are extracted from \( \Delta \rho_{\perp} \) and \( \Delta \rho_{\parallel} \) following the method described in the Supporting Information; \( \Delta \rho_{\text{int}} \) is fitted with \( \rho_{\text{int}}(A_n,T) = \rho_{\text{int}}(A_n,100 \text{ K}) \) with \( A = 3 \times 10^{-17} \text{ K}^2/\text{eV} \cdot \text{cm}^2 \) (black solid curve). The inset shows the optical image of the device set. The scale bar is 10 \( \mu m \). (d) Estimate of the NRA impact on CVD SLG \( \rho_{\perp} \), and \( \mu \) at \( n = 2 \times 10^{12} \text{cm}^{-2} \). The solid red and black curves represent the RT mobility \( \mu \) against liquid helium temperature \( T \), and are fitted with \( \Delta \rho_{\parallel}(A_n,T) = \rho_{\parallel}(A_n,100 \text{ K}) \) with \( A = 3 \times 10^{-17} \text{ K}^2/\text{eV} \cdot \text{cm}^2 \) (black solid curve). The inset shows the optical image of the device set. The scale bar is 2 \( \mu m \). (e) Value of \( \Delta \rho_{\perp}(T) \) obtained from a second set of devices \( S2 \) for different charge densities ranging from \( 2.0 \times 10^{12} \text{cm}^{-2} \) to \( 3.4 \times 10^{12} \text{cm}^{-2} \). The data points and fitting curves have the same definitions as described in (c).

CONCLUSIONS

For large-scale transparent electrodes and display applications at RT, \( \rho_{\parallel} \) is a more relevant number. Here, electron-FP scattering introduced by NRAs increases \( \rho_{\parallel} \) unacceptably, given the industry requirement of \( \rho_{\parallel} \ll 100 \text{ \Omega} \). At a technologically relevant carrier density of \( 1 \times 10^{12} \text{cm}^{-2} \), the FP-induced increase in sheet resistance \( \Delta \rho_{\parallel} \) alone is approximately 80 \( \Omega \) independent of the AP and RIP scattering induced contributions to the sheet resistance \( \rho_{\text{int}} \) (Figure 4d). Various approaches may be employed to overcome this issue. One may either try to reduce the effect of NRAs by inducing high charge carrier densities (\( \Delta \rho_{\parallel} \sim T_f^2/n e \sim 2 \text{ \Omega} \) at \( n = 5 \times 10^{12} \text{cm}^{-2} \)) and/or straining engineering or eliminating the NRAs altogether by transferring graphene under strain or using wet transfer processes which do not require any polymer coating. The rippling in CVD graphene can most likely never be fully avoided, but engineering Cu substrates properly may significantly reduce their presence (see Supporting Information).

In summary, we show that the current growth and transfer methods of CVD graphene leads to quasi-periodic nanoripple arrays in graphene. Such high-density NRAs partially suspend graphene, giving rise to flexural phonon scattering. This not only causes anisotropy in charge transport but also sets limits on both the sheet resistance and the charge mobility even in the absence of grain boundaries. At room temperature, NRAs are likely to play a limiting role also for the mobility of ultraclean samples, in particular, when the graphene sheets are transferred onto ultraflat BN substrates.\(^{11,12}\) On the other hand, the controlled rippling of graphene (Supporting Information) may be useful for graphene-based sensor applications as the ripples are more prone to adsorptions than flat graphene.\(^{34}\) Controlled rippling may also be instrumental for spin-based device applications requiring surface modifications.\(^{35}\)

METHODS

CVD Graphene Synthesis. The synthesis and transfer of large-scale CVD graphene are the same as in ref 7. Electron backscattering diffraction reveals that the annealed Cu(001) substrates have single-crystal patches of Cu(111) and Cu(101), indicating local surface melting and recrystallization during growth (see Supporting Information). The grain size of our CVD graphene is \( \sim 50-100 \mu m \), as determined by scanning electron microscopy (SEM) of submonolayer graphene on Cu foil (Figure 1a). We can synthesize CVD graphene with a high
BLG coverage up to 40% (Figure 1b) or SLG-dominant samples (>95%).

18 Raman spectra (Figure 1c) show insignificant defect peaks demonstrating the high quality of both SLG and A–B stacked BLG. Except for areas with optically visible wrinkles, Raman imaging with micrometer resolution also shows that on this scale strain is negligible (Figure 1c and Supporting Information). Furthermore, scanning Kelvin probe microscopy is used to confirm energy favorable A–B stacking structure26 in CVD BLG (see Supporting Information).

AFM Measurements. Both high-resolution contact mode and tapping mode AFM technique have been utilized to characterize graphene morphology on top of copper and on top of the Si/SiO2 substrate. For contact mode AFM, ultrasharp tips with radii as small as 10 nm were used, limiting the error to ~10% error when measuring the 100 nm nanorippled area in Figure 2 and SFigure 4. However, the contact mode AFM tips are more vulnerable to surface contaminations. Thus, for large-scale characterization, tapping mode AFM was used.

Raman Spectroscopy. Raman spectroscopy/imaging was carried out with a WITEC CRM200 Raman system with 532 nm (2.33 eV) excitation and laser power at sample below 0.1 mW to avoid laser-induced heating. A 100× objective lens with a NA of 0.95 was used in the Raman experiments. To obtain the Raman images (see Supporting Information), a piezo stage was used to move the sample with step size of 200 nm, and Raman spectrum was recorded at every point. The stage movement and data acquisition were controlled using ScanCtrl Spectroscopy Plus software from WITec GmbH, Germany. Data analysis was done using WITec Project software.

Graphene FET Device Fabrication. Graphene field-effect transistor (GFET) Hall bars and four-terminal devices ranging in size from 1.2 × 0.8 to 100 × 10 mm2 were patterned by e-beam lithography (EBL) for metal contacts (5 nm Cr/30 nm Au) and O2 plasma etching. Very large-scale GFETs of 1.2 × 1.2 mm2 were etched into van der Pauw geometry by EBL followed by metal contact evaporation using shadow masks. To precisely define four contacts either perpendicular or parallel with the NRAs, Au alignment mask arrays were prepatterned using standard EBL processes followed by systematic noncontact mode atomic force microscopy (AFM) scanning. The devices were finally thermally annealed at 400 K in high vacuum level (10−5 mbar) for 2 h to clean the graphene working channel.

Transport Measurements. Electrical transport measurements were done in vacuum in a four-contact configuration using a lock-in amplifier with an excitation current of 100 nA. T-dependent measurements were done from 350 to 2 K in variable temperature insert (VTI) using standard four-contact lock-in techniques. In total, eight SLG devices and three BLG devices have been measured. Here we discuss five (two) representative SLG (BLG) devices in more detail.

Conflict of Interest: The authors declare no competing financial interest.

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Supporting Information Available: (1) Ultragrate copper grain size by pregrowth annealing, (2) SKPM of CVD-grown graphene on Cu, (3) correlation of structure of Cu and CVD graphene after wet transfer, (4) CVD graphene transferred on Si/SiO2 substrate without any other support, (5) how to avoid nanoparticle arrays, (6) T-dependent sublinear conductivity for CVD BLG FETs, (7) Raman spectroscopy 2-D mapping of CVD SLG device, (8) modeling of the anisotropic resistivity, (9) method used to extract A and γ for µpp and µsp, (10) anisotropic resistivity as a function of charge density for sample set S1. This material is available free of charge via the Internet at http://pubs.acs.org.

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32. In our estimate, we assumed no electron-RIP scattering for CVD graphene at RT since it can, in principle, be suppressed by choosing a proper substrate.


