Linewidth roughness in nanowire-mask-based graphene nanoribbons

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We present the analysis of linewidth roughness (LWR) in nanowire-mask-based graphene nanoribbons (GNRs) and evaluate its impact on the device performance. The data show that the LWR amplitude decreases with the GNR width, possibly due to the etching undercut near the edge of a nanowire-mask. We further discuss the large variation in GNR devices in the presence of LWR by analyzing the measured transport properties and on/off ratios. © *2011 American Institute of Physics*. [doi:10.1063/1.3599596]

In the past decades, the aggressive scaling of silicon-based technology has reached to the regime where intrinsic variation sources exert large impact on the device performance.[1,2] Among them, linewidth roughness (LWR) reflects the drastic process variation inherent from the channel materials, thus posing an intrinsic limit in nanoscale silicon-based devices.[3,4] Graphene shows its potential in broad applications such as wafer-scale production of high-speed transistors.[5,6] Graphene with a nanometer-sized width, graphene nanoribbon (GNR), features a transport-gap that favors device functionalities with the ease of switching on/off devices.[7,8] However, LWR is usually unavoidable in reported GNRs due to the imperfection in fabrication processes.[7,9,10] Theoretical works suggest that LWR can increasingly affect the device performance as the GNR width (W) narrows down.[11–14] It is thus both of fundamental interest and practical concern to explore the W-dependence of LWR in GNRs, and furthermore, evaluate its impact on the device variation. In this perspective, Yang and Murali[15] have reported the W-dependence of carrier mobilities in GNRs and suggested its origin from LWR. An experimental study with a direct analysis of LWR in GNRs is yet still lacking.

In this work, we present an experimental study of the LWR in GNRs fabricated by a nanowire-mask-based method.[16,17] Unlike a lithography-based process which leads to a constant LWR of the linewidth,[3] here the LWR amplitude decreases with W, whose value can be less than 5 nm for W ~ 30 nm. This W-dependence of LWR can relate to the etching undercut due to the circular cross-section of the nanowire-mask. We further discuss the large variation in GNR devices in the presence of LWR, through an analysis of the measured transport properties and on/off ratios. The large variation in as-made GNR devices can relate to LWR, however, other possible reasons can coexist due to the complexity of the edge defects in GNRs and their sensitivity to the environment (e.g., substrate).

GNR devices are prepared by a similar nanowire-based method as before[16] [see Fig. 1(a)]: single-layer and bilayer GNRs (i.e., SLRs and BLRs, which are identified by Raman spectroscopy) were fabricated by etching graphene sheets using O_2 plasma with a mask defined by a Si nanowire. For all samples, the plasma power and duration is maintained at 40 W and 25–30 s, respectively. GNRs are then scanned by atomic force microscopy (AFM) to measure the averaged length/width (i.e., L/W) values (a typical error is ΔW

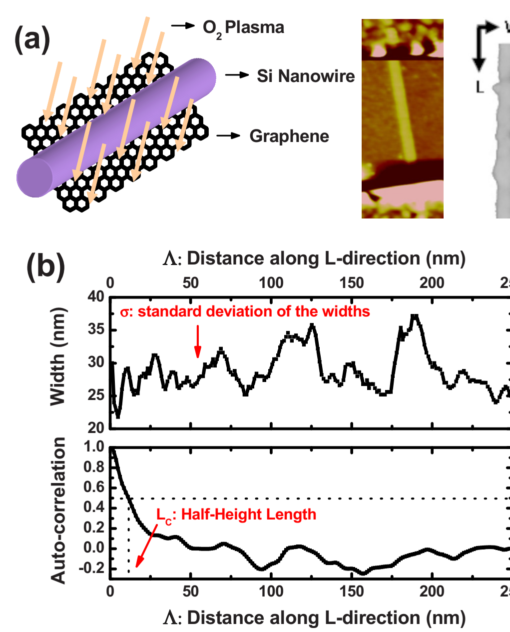

FIG. 1. (Color online) LWR analysis for nanowire-mask-based GNRs. (a) The left panel shows the schematics of the nanowire-mask-based patterning method; the middle panel shows the AFM image of a fabricated GNR on top of 300 nm SiO_2 layer; the right panel shows the extracted edge-profile image for LWR analysis. (b) The top panel shows a typical width sampling (smoothened) along the L-direction of a SLR vs the distance along the L-direction (Λ). The LWR amplitude, σ, is defined as the standard deviation of the sampled width values. The bottom panel shows the autocorrelation function (τ) of the sampled widths vs Λ. The correlation length, L_c, is defined as the half-height length of the autocorrelation function [i.e., $\tau(L_c)=0.5$].

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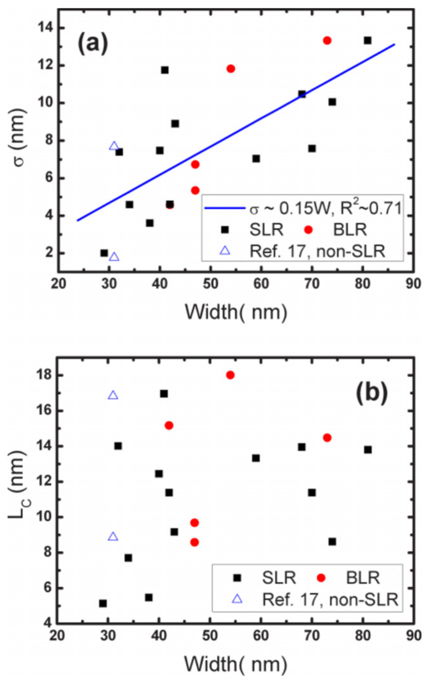

FIG. 2. (Color online) Width-dependence of LWR data in nanowire-mask-based GNRs. (a) σ-W curve in GNRs with different number of layers (SLR: single-layer GNR, BLR: bilayer GNR). GNRs in Ref. 17 are typically not SLRs (i.e., non-SLR). The linear fit (all data included) shows $\sigma \sim 0.15W$ with $R^2 \sim 0.71$. The smallest σ is less than 5 nm in SLRs with W $\sim$30 nm. (b) L_c-W curve in GNRs with different number of layers. The L_c stays around 10–20 nm for W from 30 to 80 nm.

<3 nm and $\Delta L < 10$ nm from multiple measurements).[17] Our LWR analysis is described as follows [steps (A)–(D)]: (A) AFM images were used to extract the edge profile of GNRs by an image-processing algorithm in MATLAB environment.[18,19] A typical image resolution is below 1 nm for W ~ 30–50 nm and 1–2 nm for W ~ 50–80 nm. (B) We sample the width values (~200–400 points) along the L-direction of GNR from the edge-profile image,[18] and smooth the data by averaging the nearest neighbors along the L-direction to reduce the image noise[19] [see the top panel in Fig. 1(b)]. (C) A normalized autocorrelation function, $\tau(\Lambda) \sim \Sigma_i W(l_i) \cdot W(l_i + \Lambda)$ with Λ as the distance along the L-direction (l_i is the location along the L-direction), is used to describe how the W values along the L-direction correlate with each other[3] [see the bottom panel in Fig. 1(b)]. (D) We define two parameters to quantify the LWR: (1) σ is the standard deviation of the sampled width values, which represents the root-mean-square LWR amplitude; (2) L_c is the half-height length [i.e., $\tau(L_c) = 0.5$] of the autocorrelation function, which describes the extent of correlation of the W values along the L-direction.[20] We repeat the LWR analysis for multiple images from the same GNR, having $\Delta\sigma/\sigma < 0.24$ and $\Delta L_c / L_c < 0.16$, respectively (see Fig. S1 in Ref. 21). In addition, our LWR data [see Figs. 2(a) and 2(b)] are consistent with those in the GNRs reported by Bai *et al.*[17] (also employed a nanowire-based method), suggesting the robustness of our analysis. Based on the LWR data from 13 SLRs and 5 BLRs, the smallest σ can be less than 5 nm near W ~ 30 nm for SLRs [see Fig. 2(a)].

We find that σ nearly linearly decreases as the averaged W decreases [$\sigma \sim 0.15W$, see Fig. 2(a)], whereas L_c (typically 10–20 nm) does not show a clear trend with W [see Fig. 2(b)]; both facts do not depend on the number of GNR layers. This W-dependence of σ in GNRs is in sharp contrast with that in traditional lithography-based technology, where σ is a constant of the linewidth.[3] Given the lack of existing theories on the LWR formation mechanism in GNRs, we propose that this σ-W relation can relate to the etching undercut due to the circular cross-section of the nanowire-mask [see Fig. 1(a)]. In nanowire-based method, the plasma-etching step unavoidably involves an etching undercut near the edge of the nanowire [see the left panel in Fig. 1(a)]. This fact is supported by a generally narrower as-made GNR than the nanowire-mask.[17] To generate a wider GNR, we usually use a wider nanowire-mask, leaving more space where the nanowire is not fully in contact with the graphene; this space can cause a larger etching undercut, thus resulting in a larger LWR amplitude (σ). We find that our Si nanowires generally have $\sigma < 0.6$ nm (much less than those in GNRs), while σ values have no clear dependence on the nanowire width (see Fig. S2 in Ref. 21); these facts suggest that the LWR of GNRs may not directly relate to the LWR of nanowires. On the other hand, the difference between the W-dependence of σ and L_c in GNRs [see Figs. 2(a) and 2(b)] suggests different etching rates along the W-direction (more related to σ) and L-direction (more related to L_c), respectively.[3,4,19] The physics is not clear to us for now, though we suspect that it might be related to the anisotropic edge bonds near the GNR edge.[22] As a simplified case, if the edge profile of GNRs can be seen as a sum of multiple spatial sine functions along the L-direction (see Fig. S3 in Ref. 21), then our data support the following picture: as W decreases, the edge profile decreases its amplitude (σ), but on average maintains a constant period (thus having a similar L_c) along the L-direction.

To evaluate the device performance in the presence of LWR, we measured the G-V_g curves of SLRs with different LWR values (Ref. 16) [shifted by V_{Dirac}, which is the gate bias (V_g) with the minimum conductance in the G-V_g curve]. Here G is the dc conductance measured in the linear region by a four-terminal setup. To reduce the size-dependence, we chose the SLRs with a similar L value, and divided the measured conductance by W. The experiments were made on multiple devices and the data in Fig. 3(a) come from two typical SLRs (see Fig. S4 in Ref. 21).

Although some conductance plateaus appear at 77 K [not at 300 K (Ref. 16)], Fig. 3(a) shows that the G/W value has overall weak T-dependence, possibly due to the weak phonon scattering in SLRs. We find that the G/W value is typically lower in the SLR with a larger σ, which may relate to enhanced carrier scatterings by LWR (Ref. 11) (i.e., smaller transmission coefficients[23]). Due to the complexity of the edge defects in GNRs and their sensitivity to the environment,[24–26] however, we cannot rule out other possible reasons that may affect the G/W values. For instance, the LWR in our GNRs has a typical scale of the order of 10^0–10^1 nm; this size is much larger than other types of edge defects with an atomic scale (e.g., vacancies, adatoms, dislocations),[24,25] which can also significantly affect the GNR transport[27] (i.e., these edge defects can also lead to the difference in the G/W values). Future work with well-controlled edge/substrate engineering is needed to further clarify the LWR effect on the GNR transport.[9,28]

We next present the on/off ratio of GNRs versus the averaged W at T = 300 K [see Fig. 3(b)].[29] The on/off ratio is calculated as the ratio of the measured G at both on- and

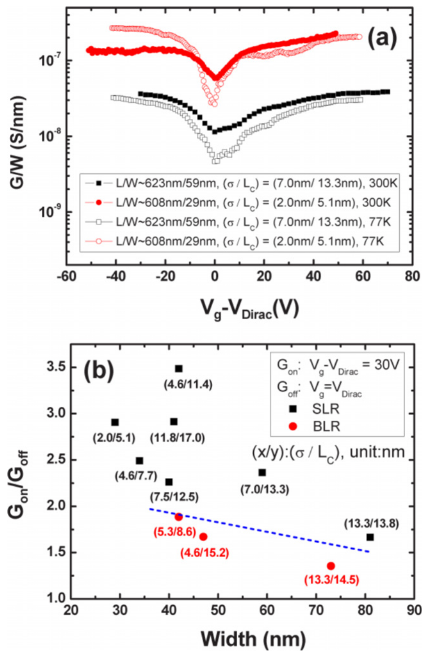

FIG. 3. (Color online) Transport properties and on/off ratios of nanowire-mask-based GNR devices in the presence of LWR. (a) Four-terminal G-V_g curves (shifted by V_{Dirac}) of two typical SLRs at both T=300 and 77 K. To reduce the dimension effect, samples are chosen with a similar L value and the conductance is normalized by W. (b) The on/off ratios (G_{on}/G_{off}) of as-made GNRs (both SLRs and BLRs, T=300 K) vs the averaged width (W). Here the low-bias conductance (G_{on}/G_{off}) at both on- and off-states are measured at $V_g-V_{Dirac}=30$ V and $V_g=V_{Dirac}$, respectively. The values of σ and L_c are labeled as (x/y): (σ/L_c) (unit: nm). The guide to the eyes shows that the on/off ratios are generally lower in BLRs than those in SLRs.

off-states (G_{on}/G_{off}), defined at $|V_g-V_{Dirac}|=30$ V and $V_g=V_{Dirac}$, respectively. Here we only present the data from the electron-conduction side ($V_g-V_{Dirac}=30$ V) since the data from the hole-conduction side ($V_g-V_{Dirac}=-30$ V) give similar results. Figure 3(b) shows that the G_{on}/G_{off} values in BLRs are overall lower than those in SLRs, possibly due to the screening effect and interlayer coupling in BLRs.[30] Moreover, we find a large variation in the W-dependence of G_{on}/G_{off} in SLRs with $W\sim30-80$ nm. For instance, the G_{on}/G_{off} value in SLRs can vary from 2.2 to 3.5 near W ~40 nm with no clear dependence on their σ and L_c values. This large variation in on/off ratios in GNRs in the presence of LWR is consistent with previous works;[11,12,14] however, it may not be fully attributed to LWR. In fact, a large variation is suggested to exist even in GNRs with the same probability of having the roughness along the edge (i.e., similar LWR);[11,12] this fact can relate to the existence of atomic-scale edge defects as discussed above.[24,25] Hence, although LWR is one factor that can degrade the device performance (e.g., by lowering the G_{on}/G_{off} ratio[11,12]), we cannot rule out other possible effects on the large variation in on/off ratios.

In summary, we present an experimental study of the LWR in GNRs fabricated by nanowire-mask-based method. In contrast to lithography-based silicon technology with a constant LWR of the linewidth, the LWR amplitude (σ) in GNRs is found to generally decrease with W, with values as low as 5 nm in SLRs for $W\sim30$ nm. This W-dependence of LWR can relate to the etching undercut due to the circular cross-section of the nanowire-mask. We further discuss the large variation in GNR devices in the presence of LWR, through an analysis of the measured on/off ratios and transport properties. The large variations in SLRs can relate to LWR, however, other possible reasons can coexist due to the complexity of the edge defects in GNRs and their sensitivity to the environment. This work may help understand the LWR properties in as-made GNRs and attract further work to evaluate its impact on device performance, both of which can provide insight on scalable graphene electronics.

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[1]H.-S. P. Wong, D. J. Frank, P. M. Solomon, C. H. J. Wann, and J. J. Welser, Proc. IEEE **87**, 537 (1999).
[2]D. J. Frank, R. H. Dennard, E. Nowak, P. M. Solomon, Y. Taur, and H.-S. P. Wong, Proc. IEEE **89**, 259 (2001).
[3]A. Asenov, S. Kaya, and A. R. Brown, IEEE Trans. Electron Devices **50**, 1254 (2003).
[4]K. Patel, T.-J. K. Liu, and C. J. Spanos, IEEE Trans. Electron Devices **56**, 3055 (2009).
[5]A. K. Geim, Science **324**, 1530 (2009).
[6]Y. M. Lin, C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, and P. Avouris, Science **327**, 662 (2010).
[7]M. Y. Han, B. Özyilmaz, Y. Zhang, and P. Kim, Phys. Rev. Lett. **98**, 206805 (2007).
[8]M. Sprinkle, M. Ruan, Y. Hu, J. Hankinson, M. Rubio-Roy, B. Zhang, X. Wu, C. Berger, and W. A. de Heer, Nat. Nanotechnol. **5**, 727 (2010).
[9]L. Jiao, X. Wang, G. Diankov, H. Wang, and H. Dai, Nat. Nanotechnol. **5**, 321 (2010).
[10]C. Lian, K. Tahy, T. Fang, G. Li, H. G. Xing, and D. Jena, Appl. Phys. Lett. **96**, 103109 (2010).
[11]Y. Yoon and J. Guo, Appl. Phys. Lett. **91**, 073103 (2007).
[12]D. Basu, M. J. Gilbert, L. F. Register, S. K. Banerjee, and A. H. MacDonald, Appl. Phys. Lett. **92**, 042114 (2008).
[13]T. Fang, A. Konar, H. Xing, and D. Jena, Phys. Rev. B **78**, 205403 (2008).
[14]M. Luisier and G. Kimeck, Appl. Phys. Lett. **94**, 223505 (2009).
[15]Y. Yang and R. Murali, IEEE Electron Device Lett. **31**, 237 (2010).
[16]G. Xu, J. Bai, C. M. Torres, Jr., E. B. Song, J. Tang, Y. Zhou, X. Duan, Y. Zhang, and K. L. Wang, Appl. Phys. Lett. **97**, 073107 (2010).
[17]J. Bai, X. Duan, and Y. Huang, Nano Lett. **9**, 2083 (2009).
[18]G. P. Patsis, V. Constantoudis, A. Tserepi, E. Gogolides, and G. Grozev, J. Vac. Sci. Technol. B **21**, 1008 (2003).
[19]T. Yu, R. Wang, R. Huang, J. Chen, J. Zhuge, and Y. Wang, IEEE Trans. Electron Devices **57**, 2864 (2010).
[20]The L_c can be defined differently according to Refs. 3 and 18, while all definitions reflect how closely the neighboring edge widths correlate with each other. At this stage, the statistics of $\tau(\Lambda)$ in the LWR of GNRs is not fully clear; we thus generally define the L_c as $\tau(L_c)=0.5$.
[21]See supplementary material at http://dx.doi.org/10.1063/1.3599596 for additional schematics and experimental data.
[22]R. Faccio, P. A. Denis, H. Pardo, C. Goyenola, and A. W. Mombrú, J. Phys.: Condens. Matter **21**, 285304 (2009).
[23]Y. M. Lin, V. Perebeinos, Z. Chen, and P. Avouris, Phys. Rev. B **78**, 161409(R) (2008).
[24]X. Jia, J. Campos-Delgado, M. Terrones, V. Meuniere, and M. S. Dresshaus, Nanoscale **3**, 86 (2011).
[25]P. Koskinen, S. Malola, and H. Häkkinen, Phys. Rev. B **80**, 073401 (2009).
[26]S. Adam, E. H. Hwang, E. Rossi, and S. D. Sarma, Solid State Commun. **149**, 1072 (2009).
[27]M. Evaldsson, I. V. Zozoulenko, H. Xu, and T. Heinzel, Phys. Rev. B **78**, 161407(R) (2008).
[28]P. Gallagher, K. Todd, and D. Goldhaber-Gordon, Phys. Rev. B **81**, 115409 (2010).
[29]The data in Fig. 3(a) are collected from GNRs with different lengths (L). At T=300 K, we observe no (or weak) L-dependence on the on/off ratio in GNRs with a similar W.
[30]Y. Sui and J. Appenzeller, Nano Lett. **9**, 2973 (2009).