The Nonlinear Electronic Transport in Multilayer Graphene on Silicon-on-Insulator Substrates *

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(Received 17 February 2017)

We conduct a study on the superlinear transport of multilayer graphene channels that partially or completely locate on silicon which is pre-etched by inductively coupled plasma (ICP). By fabricating a multilayer-graphene field-effect transistor on a Si/SiO_2 substrate, we obtain that the superlinearity results from the interaction between the multilayer graphene sheet and the ICP-etched silicon. In addition, the observed superlinear transport of the device is found to be consistent with the prediction of Schwinger's mechanism. In the high bias regime, the values of α increase dramatically from 1.02 to 1.40. The strength of the electric field corresponding to the on-start of electron–hole pair production is calculated to be 5×10^4 V/m. Our work provides an experimental observation of the nonlinear transport of the multilayer graphene.

PACS: *72.80.Vp*, *72.20.Ht* DOI: 10.1088/0256-307X/34/6/067201

Graphene, one of the most-renowned two-dimensional materials in the van der Waals family, has been intensively investigated since its first realization.[1–4] Due to the linear dispersion relationship of graphene,[5] the behavior of the quasiparticles in graphene is described by the Dirac equation instead of the Schrodinger equation,[6] resulting in a variety of interesting phenomena such as the Klein tunneling effect in p–n junctions[5,7] and the minimum conductivity value close to the Dirac point.[8] Consequently, a number of fundamental research interests have been focused on the electronic transport properties of graphene.[5,9–11] For example, by studying the suspended graphene sheets, Bolotin *et al.* demonstrated that the substrates supporting the graphene sheets play an important role in the electric transport of graphene.[11] In addition, theoretical studies predict superlinear transport of graphene caused by the Zener tunneling effect and Schwinger's mechanism.[12–14] However, few works have reported the experimental evidence of this predicted superlinear behavior so far.

In this Letter, we fabricate multi-layer graphene (MLG) channels on inductively coupled plasma (ICP)-etched silicon-on-insulator (SOI) substrate. An obvious superlinear transport behavior is observed. We attribute this nonlinearity to the interaction between MLG and ICP-etched SOI substrate. Furthermore, we analyze the mechanism of the nonlinearity by the Schottky contact model, Schwinger's mechanism and the Zener tunneling effect.

The substrate of the device was a commercially available SOI substrate with 340-nm intrinsic top silicon. We then selectively etched 200-nm silicon via ICP etching. The multi-layer graphene (MLG) sample was mechanically exfoliated on a silicon substrate with 300-nm-thick thermal oxide. Then a transfer process with a precision of sub-micrometer was performed to transfer MLG microsheet to the SOI substrate. The electrodes were fabricated by a standard electron-beam lithography followed by electron-beam evaporation of 20-nm Ti and 70-nm Au.

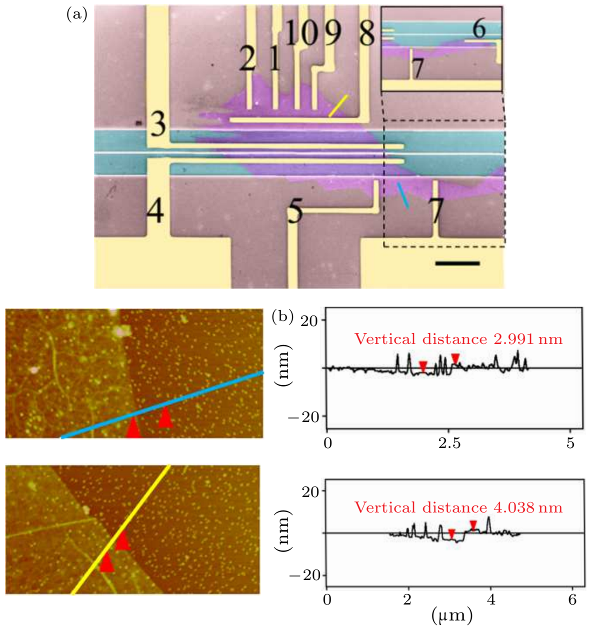

Fig. 1. (a) A top-view false-color SEM image of the device, showing MLG (purple), etched region (green), and metal electrodes (yellow). The scale bar is 10 μm. (b) AFM height profiles measured along the blue (upper panel) and yellow (lower panel) lines shown in (a).

Figure 1(a) gives a top-view false-color scanning electron microscope image of the device. The electrodes are designated counter-clockwise. The inset of Fig. 1(a) shows the location of electrode 6. The AFM height profiles along the blue and yellow lines (shown

*Supported by the National Key Research and Development Program of China under Grant No 2016YFB0402404, the High-Tech Research and Development Program of China under Grant Nos 2013AA031401, 2015AA016902 and 2015AA016904, and the National Natural Science Foundation of China under Grant Nos 61674136, 61176053, 61274069 and 61435002.

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in Fig. 1(a)) are shown in Fig. 1(b), respectively. The thickness of the MLG layer is 3–4 nm. Given the existence of the absorbed water molecule layer between the MLG and the substrate and the theoretical thickness of single layer graphene (~0.34 nm), the number of layers of MLG is estimated to be 6–12.

Two-terminal current–voltage (I–V) curves between different pairs of the electrodes are measured, as shown in Figs. 2. Interestingly, we find that the I–V curves exhibit two distinct characteristics. In Fig. 2(a), I is linear with V for the MLG channels that completely locate on an un-etched silicon region. However in Fig. 2(b), the I–V curves exhibit superlinearity for the MLG channels that completely or partially locate on ICP-etched silicon region. To manifest this superlinearity, we calculate the differential resistance dV/dI, as shown in Fig. 2(c). The differential resistances have a sharp peak around zero bias while gradually diminish with increasing the bias voltage for the nonlinear transport group. Taking into account that all the MLG channels shown in Fig. 1(a) are fabricated in one device, we obtain that the superlinearity results from the interaction between MLG and the ICP-etched SOI substrate.

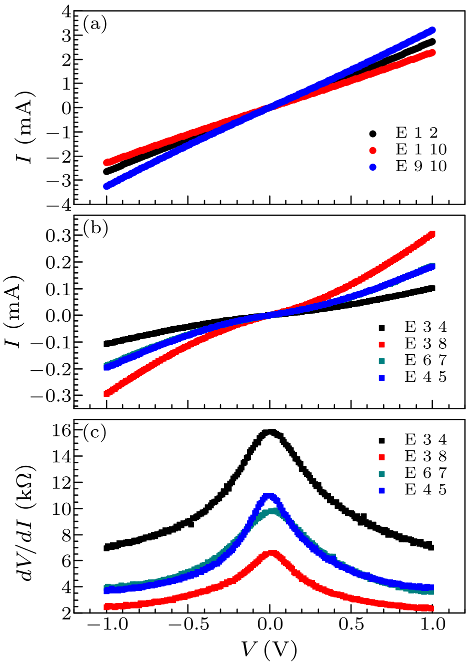

Fig. 2. (a) The linear I–V curves for the MLG channels which completely locate on un-etched silicon. The numbers in the legend refer to the numbers of the electrodes from which the I–V measurements are carried out. (b) The superlinear I–V curves for the MLG channels which completely or partially locate on ICP-etched silicon. (c) Differential resistances as a function of the bias voltage.

To explain the mechanism of the superlinearity, firstly we examine the influence caused by the transfer process and the fabrication technique. We fabricate an MLG field-effect transistor on a Si/SiO_2 substrate with 300-nm top thermal oxide, as shown in Fig. 3(a). Using buffered oxide etchant (BOE), 150-nm silica was selectively etched. Then an MLG sheet is transferred onto the substrate. Part of the MLG sheet is invisible in the microscope image and is outlined by the white dashed line. Following the same fabrication process, metal electrodes were patterned and evaporated. A typical I–V curve at zero gate bias is shown in Fig. 3(b). The red line refers to the linear fitting. The linear I–V curve indicates that the transfer process and the fabrication technique have negligible contribution to the superlinearity.

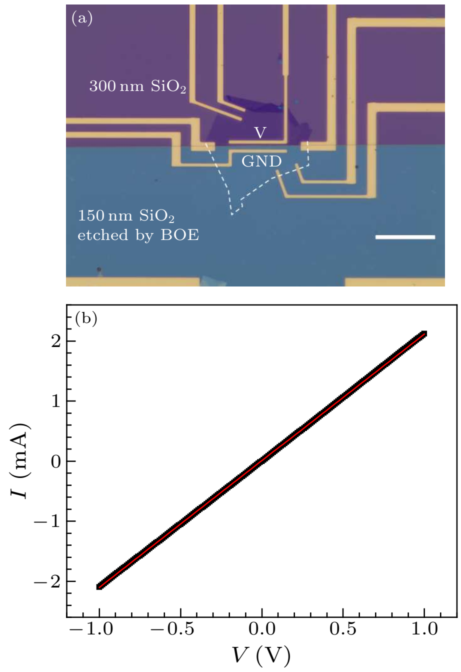

Fig. 3. (a) MLG FET fabricated on a Si/SiO_2 which is selectively etched 150 nm by BOE. The scale bar is 20 µm. (b) Linear I–V curve of the device. Red line refers to the linear fitting.

A recent study indicates that MLG can be considered as a narrow-gapband (~0.2 eV) semiconductor.[15] In this scenario, the contact between MLG and the metal electrode can be regarded as a Schottky contact. Using the Schottky contact model,[16] the current is determined by

$$I = I_{\rm TE}\Big[\exp\Big(\frac{eV}{\eta kT}\Big) - 1\Big], \qquad (1)$$

where $I_{\rm TE}$ is the saturation current, e is the electron charge, η is the ideal factor, k is the Boltzmann constant, and T=300 K is the room temperature. Although the measured data is perfectly fitted by Eq. (1) as shown in Fig. 4, the ideal factor η, which is generally close to 1, is extracted to be 43.3, which is rather unpractical. Therefore, we reasonably believe that the Schottky contact model is not responsible for the superlinearity in the device.

One theory that may explain the superlinear transport is Schwinger's mechanism, which originally refers to the production of particle–antiparticle in the presence of a strong electric field.[13,14,17] As for the matter of graphene, a large amount of electron–hole pairs are created, producing the superlinear effect. Recently, Dora *et al.* theoretically predicted that I is proportional to V^{α} with α being equal to 1.5 in the high bias regime.[13] The hallmark of this mechanism is that there is a crossover region from linear to superlinear behavior, where α increases rapidly from 1.0 up to 1.5 when the strength of the electric field is higher than a critical value.[13,18,19] Using the Landau–Zener model, the critical electric field E_c is determined by

$$E_c = \hbar / v_F e \tau^2, \tag{2}$$

where $\hbar$ is the Plank constant, v_F is the Fermi velocity, and τ is the shortest of the additional restricting timescales. In ballistic transport, τ ranges from 0.1 to 1 ps, giving $E_c \sim 10^3$–10^5 V/m.[13,18]

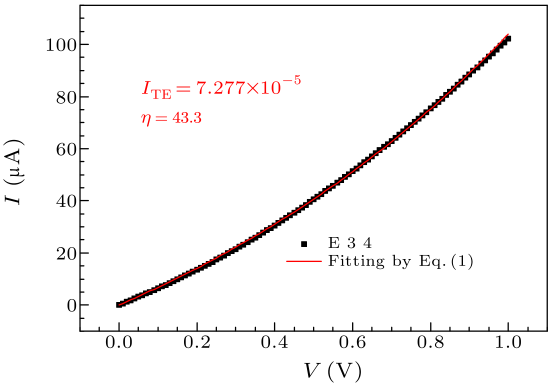

Fig. 4. Numerical fitting using the Schottky contact model. Black dots are the I–V curve measured between electrodes 3 and 4. Red line refers to the fitting using Eq. (1).

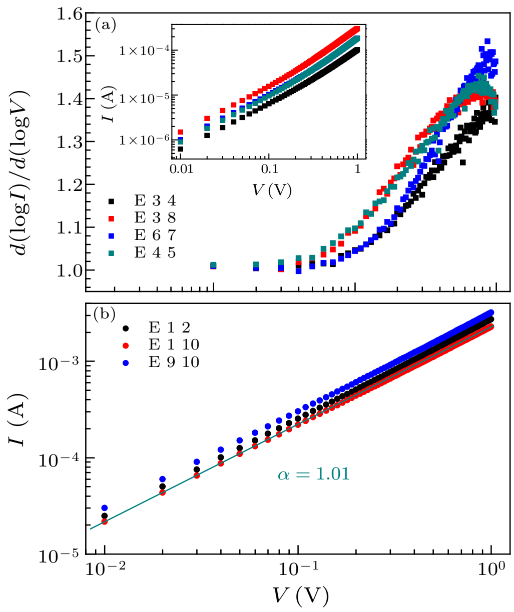

Fig. 5. (a) The calculated $d(\log I)/d(\log V)$ as a function of the bias voltage. Inset reprints the I–V curves shown in Fig. 2(b) in logarithmic scale. (b) Reproduction of the linear I–V curves in logarithmic scale. The exponents α are fitted to be 1.01.

The inset of Fig. 5(a) reprints the superlinear I–V curves in logarithmic scale. As can be seen, the slopes of the curves, which are equal to the exponent α, gradually increase when the bias voltage is higher than 0.1 V. To evaluate the change in α, we calculate the value of $d(\log I)/d(\log V)$ and the results are presented in the main panel of Fig. 5(a). Here $d(\log I)/d(\log V)$ rapidly increases from 1.03 to 1.40 in the high bias regime. Such an evident increase of α as a function of electric field is consistent with Ref. [13] and such a high value of α (close to 1.5) is consistent with the prediction of Schwinger's mechanism.[13,14,18,19] For the MLG channel between electrodes 3 and 4, using the parallel capacitor model, the strength of the electric field that corresponds to the on-start of the increase of α is calculated to be 5×10^4 V/m, also consistent with the theoretical prediction.[13,19]

It is worth mentioning that in the low bias regime ($V < 0.1$ V), the device exhibits feeble nonlinearity as well. The exponents α in the superlinear transport group range from 1.00 to 1.10 (Fig. 5(a)). In comparison, the exponents α in the linear transport group are all equal to 1.01 (Fig. 5(b)). One explanation for this moderate elevation in α is that the device witnesses electron–hole pair production in the low bias regime, at a low rate though. Another reason is the Zener–Klein tunneling effect, where carriers tunnel from the valence band to the conduction band through interband transition at low bias owing to the linear dispersion relationship of graphene and the absence of energy gap band.[19]

In summary, we have obtained that MLG channels that partially or completely locate on ICP-etched silicon exhibit superlinear transport behavior. By fabricating MLG channels on SOI and Si/SiO_2 substrates, we obtain that this superlinearity results from the interaction between the MLG sheet and the ICP-etched silicon rather than the transfer process or the fabrication technique. In addition, the mechanism of the superlinear transport of the device is investigated and is found to be consistent with the prediction of Schwinger's mechanism. The exponent α increases dramatically from 1.02 to 1.40 in the high bias regime. The strength of the electric field corresponding to the on-start of electron–hole pair production is calculated to be 5×10^4 V/m, consistent with the theoretical prediction. Our work provides an experimental observation of the nonlinear transport behavior of the multilayer graphene.

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