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Citation: Appl. Phys. Lett. 101, 213103 (2012); doi: 10.1063/1.4768690

View online: http://dx.doi.org/10.1063/1.4768690
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Direct extraction of carrier mobility in graphene field-effect transistor using current-voltage and capacitance-voltage measurements

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(Received 21 September 2012; accepted 8 November 2012; published online 21 November 2012)

Top gated graphene field-effect transistors were fabricated using yttrium oxide film as high-κ gate dielectric, and the gate voltage dependent drain current and gate capacitance characteristics were both measured on one graphene device. Based on the two kinds of data sets, we developed a method to extract the carrier mobility of graphene field-effect transistors, along with some other parameters, such as series resistance and residual carrier density. Prior to previous method, this method could well fit the transfer curve of graphene field-effect transistor with high gate oxide capacitance since its carrier concentration is directly obtained from the experimental data rather than from analytic equation. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4768690]

Recently, graphene field-effect transistor (G-FET) has attracted much attention especially for radio-frequency applications owing to ultra-high carrier mobility and saturation velocity. Top gated G-FETs with large transconductance and high speed have been fabricated by many groups through improving the quality of graphene and gate insulator. To characterize and then optimize the quality of graphene surrounded by substrate and gate insulator, it is important to extract the effective carrier mobility of graphene from the experimental data of electrical measurement. Generally, there are two methods to retrieve mobility according to the kind of experimental data, i.e., from Hall measurement or field-effect measurement. For a top-gated G-FET, it is not easy to measure Hall effect, and then extracting mobility from field-effect characteristic is conventional and reasonable choice. To retrieve carrier mobility exactly, the effect of contact resistances should be decoupled from field-effect conductance of G-FET. A widely used method for extracting carrier mobility of G-FET was developed to fit the transfer properties of G-FET, and then obtain mobility, contact resistances, and residual carrier density. However, the gate capacitance of G-FET was not precisely given since the quantum capacitance of graphene cannot be rightly expressed through the simple analytic equation (2) in Ref. 11. It is obvious that the imprecise gate capacitance value should result in inaccuracy of extracted carrier mobility since both of the gate capacitance and carrier mobility co-determine channel conductance. Therefore, obtaining the precise value of gate capacitance is the precondition to retrieve accurate carrier mobility from transfer characteristics of G-FET.

In this letter, gate voltage dependent gate capacitance of G-FET was directly measured rather than given by theoretical equation. Based on combined information of gate voltage dependent current and gate capacitance, a method is developed to precisely extract carrier mobility in G-FET, along with other key parameters, such as serial resistance and residual carrier density.

Graphene was deposited by mechanical exfoliation of Kish graphite on n-doped silicon substrate covered with 287 nm thick SiO2. Single layer graphene samples were identified by optical contrast and Raman spectroscopy. The graphene was first tailored to a rectangle by electron beam lithography (EBL) and reactive ion etching. The gate oxide window was patterned by EBL and then a thin uniform yttrium (Y) film was deposited by electron beam evaporation. The Y film was oxidized at 180°C in air and a uniform yttrium oxide film was then formed on graphene and followed by a lift-off process. Source, drain, and gate electrodes were then formed through EBL, electron beam evaporation of Ti/Au film with thickness of 5/45 nm, and a lift-off process. The schematic and scanning electron microscopy images of the fabricated graphene field-effect transistor are shown in Figures 1(a) and 1(b), in which the gate length (LTG) and width (WTG) are 7 μm and 4.5 μm, respectively. All electrical measurements reported in this work were carried out by a probe station (Lakeshore TTP-4) in vacuum and at room temperature. DC transport measurements were carried out using Keithley 4200 semiconductor analyzer, while C-V measurements by Agilent 1500 B with a small AC modulation (30 mV and 50 kHz). The transfer curves IGS-VTG of a typical G-FET under different back gate voltages (VBG = 0 V, −60 V and 60 V) are shown in Fig. 1(c), and its gate voltage dependent gate capacitance (CTG-VTG) per area is shown in Fig. 1(d).

The data sets of IGS-VTG and CTG-VTG are then used to extract some key electrical parameters of the devices, especially including the carrier mobility.

For a long channel G-FET in which carriers transport can be described by drift-diffusive model, the total resistance of device can be given by

$$R_{\text{Total}} = R_s + \frac{L_{\text{TG}}}{W_{\text{TG}}} \frac{1}{q \mu n (V_{\text{TG}})^3},$$

where $R_s$ is serial resistance, $\mu$ and $n$ are mobility and concentration of carrier (electron or hole), respectively, and $q$ is element charge. The serial resistance $R_s$ includes contact resistances between S/D and graphene and access resistances...
originated from the part of graphene channel which is un-gated by top gate, and the second term on the right hand of Eq. (1) is the resistance of graphene controlled by top gate. Since the conductance of graphene channel is the product of carrier density $n$ and mobility $\mu$, the main difficulty to retrieve $\mu$ locates at how to obtain the value of $n$. Generally, $n$ is calculated through analytic equation, and its accuracy is strongly dependent on gate capacitance which consists of oxide capacitance and quantum capacitance of graphene in series. Since the quantum capacitance is not easy to express just through any simple analytic expression, it is impossible to give the exact value of $n$. Especially, in G-FET with ultra-thin gate insulator, the effect of quantum capacitance is significant, and then the analytic equation of gate capacitance should not be more valid. Compared with the analytic calculation, a more effective and accurate method to obtain gate capacitance is to measure it directly. Here, the carrier concentration $n$ can be obtained directly from $C_{TG}$-$VTG$ data through

$$n(V_{TG}) = \frac{1}{q} \int_{V_{Dirac}}^{V_{TG} - V_{D}} C_{TG} dV.$$  \hspace{1cm} (2)$$

Integrating the measured $C_{TG}$-$VTG$ data, we can obtain the value of $n$ through Eq. (2) directly. Equation (1) means that the total resistance of G-FET, i.e., $R_{total}(V_{TG})$, is proportional to $\frac{1}{n(V_{TG})}$, then indicates a method to retrieve carrier mobility from measured $C_{TG}$-$VTG$ and $I_{ds}$-$VTG$ data of G-FET, including the following steps:

1. Calculate $n$ from $C_{TG}$-$VTG$ data as shown in Fig. 1(d) through Eq. (2) and then plot the curve of $1/n$ vs. $V_{TG}$ as shown in Fig. 2(a).

2. Calculate $V_{TG}$ dependent $R_{total}$, i.e., $V_{ds}$/$I_{ds}(V_{TG})$, from $I_{ds}$-$VTG$ data in Fig. 1(e), and then plot the curve of $R_{total}$ vs. $V_{TG}$ as shown in Fig. 2(b).

3. Plot $R_{total}$ vs. $1/n$ curve through combining two sets of data (in Figs. 2(a) and 2(b)) as shown in Fig. 2(c) or 2(d). The n-branch (Fig. 2(c)) and p-branch (Fig. 2(d)) are separately handled here. If the $R_{total}$ vs. $1/n$ curve becomes linear, its slope will reflect the mobility $\mu$ and the intercept at $R_{total}$ axis is equal to the series resistance $R_s$ according to Eq. (1).

It should be noted that the $R_{total}$ vs. $1/n$ curve in Fig. 2(c) or 2(d) is actually not always linear because Eq. (2) is not available at all gate voltage ranges. It is well known that the total carrier concentration of G-FET contains two parts, i.e., carrier concentration $n_{TG}$ caused by gate potential and residue concentration $n_0$ induced by charged impurities, while Eq. (2) only comprises $n_{TG}$. The total carrier concentration is
codetermined by \( n_{TG} \) and \( n_0 \) at low concentration (i.e., around the Dirac voltage), but dominated by \( n_{TG} \) at high gate voltage (high carrier concentration). Therefore, \( R_{total} \) vs. \( 1/n \) curve is becoming more and more linear as \( n \) goes up (or \( 1/n \) goes down) as shown in Figs. 2(c) and 2(d). When \( n \) is larger than \( 1 \times 10^{12}/\text{cm}^2 \), the \( R_{total} \) vs. \( 1/n \) curve is almost linear, which means that the effect of residual carrier concentration \( n_0 \) is negligible. Then slope of the linear region can be obtained through linear fitting, and is about \( 7.31 \times 10^{15} \) \( \Omega \) \( \text{cm}^2 \) for \( n \)-branch and \( 7.21 \times 10^{15} \) \( \Omega \) \( \text{cm}^2 \) for \( p \)-branch. According to Eq. (1), the slope can be expressed as

\[
slope = \frac{L_{TG}}{W_{TG}q\mu}.
\]

Therefore, carrier mobility of G-FET can be obtained through Eq. (3), and is \( 1332 \) \( \text{cm}^2/\text{Vs} \) for electron and \( 1348 \) \( \text{cm}^2/\text{Vs} \) for hole. We can also extend the linear region of \( R_{total} \) vs. \( 1/n \) curve to left hand, and the intercept with \( R_{total} \) axis can be considered as series resistance \( R_s \), which is about \( 3.56 \) \( \text{k}\Omega \) for \( n \)-branch and \( 3.50 \) \( \text{k}\Omega \) for \( p \)-branch. Besides carrier mobility and series resistance, residual carrier concentration \( n_0 \) is also a concerned parameter in G-FET, since it reflects the degree of charge impurity scattering.\textsuperscript{11,16–19} Here, we can also estimate \( n_0 \) through this model. At first, we should presume carrier mobility is a constant value independent of \( V_{TG} \), and \( R_{total} \) vs. \( 1/n \) then satisfy linear relation strictly throughout all \( 1/n \) range. Therefore, the linear region of \( R_{total} \) vs. \( 1/n \) curve can be extended right to intercept with the maximum resistance line (red dotted line in Fig. 2(c) or 2(d)). The value of \( n \) at intercept point can be considered as \( n_0 \), which is about \( 8.2 \times 10^{11}/\text{cm}^2 \) for \( n \)-branch and \( 8.0 \times 10^{11}/\text{cm}^2 \) for \( p \)-branch, respectively. In fact, the carrier mobility of graphene should increase near Dirac point rather than keeping constant,\textsuperscript{20,21} and then the actual value of \( n_0 \) is slightly smaller than the extracted value through the model.

If constant carrier mobility is still presumed, the total carrier concentration \( n \) can be obtained through the linear dotted curve of \( R_{total} \) vs. \( 1/n \) ([in Fig. 2(c) or 2(d)]) and is plotted as the function of \( V_{TG} \) as shown in Fig. 2(e). This gate voltage dependent carrier concentration contains the effects from gate induced part and charged impurity induced part simultaneously, and varies from \( 8.2 \times 10^{11}/\text{cm}^2 \) at the Dirac point to about \( 4.5 \times 10^{12}/\text{cm}^2 \) at a net gate voltage of 0.6 V. To further verify validity of the model and extracted parameters, we substitute these parameters retrieved above, including constant \( \mu, R_s, V_{TG} \), and \( V_0 \) dependent \( n \) as shown in Fig. 2(d), into Eq. (1), and the fitted \( R_{total} \) vs. \( V_{TG} \) curve is shown in Fig. 2(f) (solid line). The well coincidence between fitted data and experimental data indicates that this model and the retrieved parameters are self-consistent. As a direct contrast, the same experimental data are fitted through the widely used conventional model developed in Ref. 11,\textsuperscript{11} and the fitted results were shown in Figs. 2(g) and 2(h). It is obvious that the conventional model cannot well fit the transfer properties of G-FET especially near Dirac point. The main reason is that the analytic equation for calculating quantum capacitance cannot describe the real quantum capacitance value of graphene.\textsuperscript{7,12–14} For G-FET with small gate capacitance,\textsuperscript{11} the contribution of quantum capacitance for total gate capacitance is very small, and then the analytic equation is still valid. But, for G-FET with high gate capacitance, the contribution of quantum capacitance for total gate capacitance is significant and becomes more significant near Dirac point.\textsuperscript{7,13,14} Therefore, the analytic equation for calculating gate capacitance is completely invalid, and the fitting is failed near Dirac point. Moreover, the extracted parameters are strongly dependent on the chosen value of Fermi velocity \( v_f \) since the gate capacitance is \( v_f \) dependent. According to the published experimental results,\textsuperscript{7,13,18} \( v_f \) can at least vary from \( 1 \times 10^6/\text{m/s} \) to \( 1.2 \times 10^7/\text{m/s} \), then we fitted the transfer curve in Fig. 2(b) by setting \( v_f \) as \( 1 \times 10^6/\text{m/s} \) and \( 1.2 \times 10^7/\text{m/s} \), as shown in Figs. 2(g) and 2(h), respectively. The retrieved carrier mobility varies from \( 1614\text{ cm}/\text{V} \text{s} \) to \( 1994\text{ cm}/\text{V} \text{s} \) as \( v_f \) varies from \( 1 \times 10^6/\text{m/s} \) to \( 1.2 \times 10^7/\text{m/s} \). An approximate 25% variation is originated from the chosen value of Fermi velocity which, in fact, varies in different devices. However, in our method, the gate capacitance is obtained directly from the experimental data, and then it is not dependent on the value of Fermi velocity. Therefore, this method is more effective and accurate than the conventional one, in principle.

Since graphene channel of G-FET is co-modulated by top-gate and back-gate together, top gate transfer curve of G-FET should vary under different back gate voltages, which is also demonstrated by the experimental results as shown in Fig. 1(c). As a contrast, transfer curves of the same G-FET under back gate voltage \( V_{BG} = -60 \) V and \( +60 \) V are also handled through our method, respectively. \( R_{total} \) vs. \( V_{BG} \) curves under \( V_{BG} = -60 \) V and \( 60 \) V are plotted as shown in Figs. 3(a) and 3(c), respectively, which can be used to retrieve the corresponding key parameters under different back gate voltages. It should be mentioned that only one branch of the conduction curve is used, i.e., \( p \)-branch is used under \( V_{BG} = -60 \) V, while

\[ n_0 = \frac{R_{ps}}{C_0}., \]

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n-branch is used under $V_{BG} = 60$ V, since data of the other branch are not enough to retrieve parameters exactly owing to large shift of top gate Dirac voltage under large $V_{BG}$. In order to facilitate comparison, the retrieved parameters under three different back voltages are listed together in Table I. Under negative back gate voltage, hole concentration in graphene is improved especially at the part under S/D contact and the un-negative back gate voltage, hole concentration in graphene is improved as well.

<table>
<thead>
<tr>
<th>$V_{BG}$ (V)</th>
<th>$n_0$ (cm$^{-2}$)</th>
<th>$R_s$ (kΩ)</th>
<th>Mobility of electron (cm$^2$/V·s)</th>
<th>Mobility of hole (cm$^2$/V·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$8.2 \times 10^{11}$</td>
<td>3.56</td>
<td>1332</td>
<td>1348</td>
</tr>
<tr>
<td>-60</td>
<td>$9.8 \times 10^{11}$</td>
<td>1.83</td>
<td>Null</td>
<td>1099</td>
</tr>
<tr>
<td>60</td>
<td>$1.04 \times 10^{12}$</td>
<td>2.36</td>
<td>1099</td>
<td>Null</td>
</tr>
</tbody>
</table>

In conclusion, a method is proposed to precisely extract carrier mobility in G-FET, based on experimental gate voltage dependent carrier concentration, and then the mean value of $n$ is also larger than that under $V_{BG} = 0$. Therefore, it is reasonable that the extracted carrier mobility under $V_{BG} = \pm 60$ V is slightly smaller than that without applying $V_{BG}$.

This work was supported by the Ministry of Science and Technology of China (Grant Nos. 2011CB933001 and 2011CB933002), and National Science Foundation of China (Grant No. 61071013).