Contact resistance and mobility in back-gate graphene transistors

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Keywords: graphene, contact resistance, mobility, temperature dependence, TLM structures, Y-function method, field effect transistors

Abstract

The metal–graphene contact resistance is one of the major limiting factors toward the technological exploitation of graphene in electronic devices and sensors. High contact resistance can be detrimental to device performance and spoil the intrinsic great properties of graphene. In this paper, we fabricate back-gate graphene field-effect transistors with different geometries to study the contact and channel resistance as well as the carrier mobility as a function of gate voltage and temperature. We apply the transfer length method and the y-function method showing that the two approaches can complement each other to evaluate the contact resistance and prevent artifacts in the estimation of carrier mobility dependence on the gate-voltage. We find that the gate voltage modulates both the contact and the channel resistance in a similar way but does not change the carrier mobility. We also show that raising the temperature lowers the carrier mobility, has a negligible effect on the contact resistance, and can induce a transition from a semiconducting to a metallic behavior of the graphene sheet resistance, depending on the applied gate voltage. Finally, we show that eliminating the detrimental effects of the contact resistance on the transistor channel current almost doubles the carrier field-effect mobility and that a competitive contact resistance as low as 700 $\Omega \cdot \mu$m can be achieved by the zig-zag shaping of the Ni contact.

1. Introduction

The isolation of graphene [1–3] in 2004 and, later on, of h-BN [4], phosphorene [5], MoS 2 [6–14], WSe 2 [15–17], PdSe 2 [18, 19], PtSe 2 [20, 21] etc., has strongly attracted the interest of the material science community to the world of two-dimensional (2D) materials.

Graphene, the two-dimensional layer of carbon atoms arranged in a honeycomb lattice, is still one of the most studied 2D systems for the unmatched electron mobility, the remarkable current capability and thermal conduction, the relatively high optical absorption coefficient, the mechanical strength as well as the easy and low cost fabrication [22–27].

Graphene is commonly produced by exfoliation from graphite [28, 29], epitaxial growth on SiC [30] or chemical vapor deposition (CVD) [31, 32]. In particular, CVD produces uniform and large-scale graphene flakes of high-quality and is compatible with the silicon technology; therefore, it has been largely exploited to realize new electronic devices such as diodes [33–36], transistors [37–39], field emitters [40, 41], chemical–biological sensors [42, 43], optoelectronic systems [44], photodetectors [45–50] and solar cells [51].

Due to its gapless band-structure, with the valence and conduction bands touching each other at the so-called Dirac points, graphene originates ambipolar field-effect transistors with V-shaped transfer characteristics, dominated by a p-branch at negative and n-type conduction at positive gate voltage [52]. The ambipolar conduction can be an important feature for complementary logic applications; however, the limited on/off ratio...
caused by the absence of intrinsic bandgap is a significant obstacle and requires delicate material engineering for real applications [53–55].

Despite the several doping techniques available to tune the graphene conductivity and boost the performance of graphene transistors, a major problem remains the suppression of device on-current caused by the graphene/contact resistance [36]. Indeed, ohmic and low resistance contacts are important figures of merit for high frequency devices and the realization of stable and low-resistance contacts is still under intensive study [57–61]. The variation of the contact resistance, $R_C$, is attributed to many different causes, related to graphene growth and number of layers, metal type and deposition process, quality of the metal graphene/interface, measurement conditions, etc.

Conventional ohmic contacts between graphene and various metals exhibit rather large contact resistance ranging from few hundreds to thousands $\Omega \cdot \mu$m. Studies have been conducted on various types of metal/graphene interfaces showing that the best contact resistances can be achieved with Ni and Cu contacts yielding $R_C$ as low as $\sim 300 \Omega$ [62–65]. Although the choice of the metal type is an important ingredient for good quality contacts, recent researches have developed special techniques for the reduction of the contact resistance. The most successful strategies have been the modification of the contact area to increase charge injection through the graphene edges and the graphene etching under the contacts to favor the formation of dangling carbon-to-metal bonds. Contact resistances down to $100 \Omega \cdot \mu$m have been obtained in this way [63, 65–67]. Anzi et al [67] report that the under-contact graphene etching reduces the contact resistance both for Au and Ni/Au contacts. Smith et al [63] demonstrate a contact resistance dependence on the number of graphene cuts under the contacts. Similarly, Lisker et al [57] optimize the metal/graphene interface by incrementing the contact perimeter. A low contact resistance enables the study of intrinsic graphene properties and increases the performance of graphene devices. As the matter of fact, the contact resistance can be tuned by the application of a gate voltage ($V_g$), which modulates the carrier concentration of the graphene channel. In this scenario, the contact resistance becomes larger in correspondence of the Dirac points, where the graphene conductivity is suppressed [68, 69].

The temperature dependence of $R_C$ in graphene devices is still a controversial topic. A conspicuous number of studies report discrepant results evidencing either a negligible dependence of $R_C$ on $T$ or strong changes of contact resistance with temperature [70–72].

In this work, we investigate the effect of back-gate voltage and temperature on the contact and channel resistance and on the carrier mobility in graphene field-effect transistors with Ni contacts. We fabricate back-gate devices with multiple leads which we analyze by both the transfer length method (TLM) [73–77] and the Y-function method [78–80]. The complementary application of the two methods leads to a more robust estimation of the contact resistance and of the gate-voltage dependence of the carrier mobility. We show that the gate voltage modulates the contact and the channel resistance in a similar way but has negligible effect on the carrier mobility. We also find that the field effect mobility decreases with raising the temperature, which does not affect the contact resistance, but can induce a transition from a semiconductor to a metallic behavior in the channel resistance, depending on the gate voltage. Finally, we show that eliminating the detrimental effect of the contact resistance can result in more than 80% increase of the field effect mobility.

2. Materials and methods

Graphene synthesis has been performed on 200 mm Ge/Si substrates using Aixtron’s Black Magic BM300T CVD tool. The synthesis was carried out at the deposition temperatures of 885 °C using CH$_4$ as source of carbon and Ar/H$_2$ mixture as carrier gas, at 700 mbar for 60 min Raman and micro-Raman mapping confirmed that the optimized fabrication process led to high quality, defect-free, and uniform graphene film over the whole wafer [57, 81]. The so-obtained graphene was then transferred on p-type doped Si (5 $\sim$ 20 $\Omega \cdot $ cm) capped with 100 nm SiO$_2$ layer, patterned in long stripes by electron beam lithography (EBL) and dry etching, and finally covered by PMMA to prevent damages. Ni metal contacts were sputtered using a 50 W low-power process after annealing in 1:2 mixture of hydrogen and argon at 580 °C for 30 min was applied to further reduce the specific contact resistivity. The devices consist of patterned graphene stripes contacted with several parallel leads, at gradually increasing distances ($d$). Structures with diverse combinations of the contact size, distance and/or shape, were fabricated and analyzed as well, with an example reported in figures 1(a), (b).

Measurements at different temperatures were performed using a Janis probe station equipped with four metallic nanotips connected to the source-measurement units of a Keithley 4200 SCS (Tektronix Inc.), at pressure of $\sim$0.8 mbar. The metal contacts were used as the drain and source electrodes while the Si/SiO$_2$ substrate as the back gate and the gate dielectric, respectively.
The schematic of figure 1(d) shows that the total resistance, $R_T$, obtained from the $I_{ds}$-$V_{ds}$ (drain-to-source current versus drain-to-source voltage) curves measured in a two-probe configuration between two given contacts, includes the contributions of the metal resistance, $R_m$, the contact resistance, $R_C$, i.e. the resistance at the 3D-metal/2D-graphene interface, and the channel resistance, $R_{channel}$:

$$R_T = R_{channel} + 2R_m + 2R_C$$  \hspace{1cm} (1)

The channel resistance can be written as

$$R_{channel} = R_{sheet} \frac{d}{W}$$  \hspace{1cm} (2)

where $R_{sheet}$ is the graphene sheet resistance in $\Omega$/sq ($sq = \text{square}$), $W$ the width of the graphene stripe and $d$ the distance between the two chosen contacts. We can express the contact resistance in terms of the transfer length, $L_T$, that represents the distance over which most of the current $(1 - 1/e)$ flows between the contact and the channel:

$$R_C = R_{sheet} \frac{d}{W}$$  \hspace{1cm} [82]

Therefore, neglecting $R_m$ (order of magnitude lower than $R_C$ and $R_{channel}$), it results

$$R_T = R_{sheet} \frac{d}{W} + 2R_C = \frac{R_{sheet}}{W}(d + 2L_T)$$  \hspace{1cm} (3)

Equation (3) is used to estimate $R_{sheet}$ and $R_C$ from the straight-line fitting of a $R_T$ vs $d$ plot (TLM plot). The intercept of the straight-line with the horizontal axis ($-2L_T$) provides the transfer length. If $L_T$ is small compared to the size $D$ of the contact, the current flows mostly through the edge of the contact (current crowding effect) and only the contact edge influences the carrier injection and the conduction in the graphene channel. In this scenario, there are only two possibilities to reduce the contact resistance: etching the graphene under the contact to increase the contact edges or increasing the perimeter of the edge, for instance using zig-zag shaped edges.

For two-probe configuration measurements, an alternative approach to estimate the contact resistance is the so-called Y-function method (YFM). The method includes the contact resistance in the expression of the transistor current $I_{ds}$ as a function of $V_{ds}$ and $V_{gs}$ (the gate-to-source voltage) [79, 83]:

$$I_{ds} = \frac{W}{L} \mu C_{ox} V_{ds}(V_{gs} - V_{th}) \frac{1}{1 + \frac{W}{L} \mu C_{ox} R_C(V_{gs} - V_{th})}$$  \hspace{1cm} (4)
where \( C_{\text{ox}} \) is the SiO\(_2\) capacitance (\( C_{\text{ox}} = 33\ \text{nF/cm}^2 \) for 100 nm SiO\(_2\)), \( \mu \) is the field-effect mobility and \( V_{\text{Dirac}} \) is the gate voltage corresponding to the Dirac point, i.e. to the minimum of the \( I_d - V_g \) characteristic of the graphene transistor.

The \( V_g \) derivative of equation (4) represents the transconductance

\[
\begin{align*}
g_m &= \frac{dI_d}{dV_g} = \frac{W}{L} \mu C_{\text{ox}} \frac{V_g}{V_{\text{Dirac}}} \left[ 1 + \frac{W}{L} \mu C_{\text{ox}} R_C (V_g - V_{\text{Dirac}}) \right]^{-2}
\end{align*}
\]

and the ratio

\[
\frac{I_d}{\sqrt{g_m}} = \sqrt{\frac{W}{L}} \mu C_{\text{ox}} \frac{V_g}{V_{\text{Dirac}}} (V_g - V_{\text{Dirac}}) = Y
\]

is the so-called Y-function. \( Y \) results independent of \( R_C \), while \( g_m^{-1/2} \) depends linearly on \( (V_g - V_{\text{Dirac}}) \) with angular coefficient proportional to the contact resistance. Thus, the plots of \( I_d g_m^{-1/2} \) and \( g_m^{-1/2} \) versus \( (V_g - V_{\text{Dirac}}) \) can be exploited to obtain the mobility \( \mu \) (which is not affected by the contact resistance) and the contact resistance \( R_C \), respectively.

Finally, taking the derivative of the Y-function in equation (6) with respect to \( V_g - V_{\text{Dirac}} \), we obtain the mobility unaffected by the contact resistance, which should be independent of \( V_g - V_{\text{Dirac}} \):

\[
\mu = \left[ \frac{-dY}{d(V_g - V_{\text{Dirac}})} \right]^2 \frac{L}{WC_{\text{ox}} V_d}
\]

### 3. Results and discussion

A two-probe configuration is adopted to measure the transfer \( (I_d - V_g) \) curve at given \( V_g \) and output \( (I_d - V_d) \) curves at selected \( V_g \) characteristics for different contact combinations. In figure 2, we report an example of such measurements for the 2 \( \mu \text{m} \) wide and 1 \( \mu \text{m} \) long graphene channel contacted with Ni leads of size \( D \sim 3 \mu \text{m} \) and zig-zag shaped edges (see figures 1(a), (b) and the schematic of the device figure 1(c)).

The transfer characteristic (figure 2(a)) displays an asymmetric ambipolar behavior with a dominant hole branch and a current minimum (Dirac point) slightly above \( V_g = 0 \) V. The different slope of the two branches corresponds to the hole mobility (\( \sim 150 \text{cm}^2\text{V}^{-1}\text{s}^{-1} \)) higher than the electron one (\( \sim 100 \text{cm}^2\text{V}^{-1}\text{s}^{-1} \)), while the slight shift of the Dirac point to positive \( V_g \) indicates a low p-type carrier concentration due to adsorbates and process residues such as PMMA, not removed by the 1 mbar vacuum and 400 K annealing [59, 84]. The hole-electron asymmetry is due to both unbalanced carrier injection from metal contacts and graphene interaction with the SiO\(_2\) dielectric [84–89]. The interaction with SiO\(_2\) is also the main cause of the hysteresis which appears when the gate voltage is swept back and forth [88–90]. The low mobility is also attributed to the fabrication process which needs further optimization. Figure 2(b) shows a linear \( I_d - V_d \) behavior confirming the ohmic nature of the Ni/graphene contacts in the investigated voltage range. We intentionally limited the analysis to the triode region, as the achievement of a saturation regime would require operating the transistor at high drain bias and power dissipation, which would make the local temperature out of control.

Figure 3(a) shows the total resistance \( R_T \) measured between multiple couples of leads of the TLM structure, at room temperature and under different gate biases, ranging from \(-40 \) V to 40 V. The TLM curves display the linear behavior predicted by equation (3) and are used to extract \( R_C \) and \( R_{\text{sheet}} \) as a function of the gate voltage \( V_g \) (figure 3(b)). Both parameters exhibit a non-monotonic trend with maximum values (\( R_C \sim 2.5 \text{k}\Omega \) and \( R_{\text{sheet}} \sim 14 \text{k}\Omega/\text{sq} \)) corresponding to the Dirac point (\( V_{\text{Dirac}} \sim 0 \) V), and a decrease when the back-gate dopes the graphene by attracting electrons or holes in the channel. We highlight that figure 3(b) demonstrates how the gate voltage affects the graphene layer not only in the channel region but also under the contacts, as previously reported [91].

\( L_T \) extracted from the \( R_T \) versus \( d \) plot ranges between 300 nm and 500 nm, smaller the 3 \( \mu \text{m} \) contact size, thereby confirming that the device works under the aforementioned current crowding regime.

Remarkably, comparison with a similar device contacted by straight contacts, i.e. no zig-zag edges, measured in the same conditions, exhibits \( \sim 400\% \) higher contact resistance (\( \sim 3.5 \text{k}\Omega \cdot \mu \text{m} \) versus \( \sim 700 \Omega \cdot \mu \text{m} \) at \( V_g = -40 \) V), confirming the importance of increasing the length of the contact perimeter.
Similar measurements were performed as a function of the temperature, T, in the range 90 K to 400 K. The linear behavior of the $R_d$ vs $T$ curves is preserved when the temperature is changed (figure 3(c)) but their slope decreases with increasing $T$. Figure 3(d) reports the temperature dependence of $R_C$ and $R_{\text{sheet}}$ evaluated at $V_{gs} = 0$ V. $R_C$ remains constant over the 90–400 K temperature range while the graphene sheet resistance decreases, changing linearly from $\sim 22 \, k\Omega/\text{sq}$ at 90 K to $\sim 12 \, k\Omega/\text{sq}$ at 400 K with slope $dR_{\text{sheet}}/dT \sim -15 \, \Omega/\text{K}$. The independence of $R_C$ on the temperature is confirmed also when $R_C$ is evaluated at $V_{gs} = -40$ V, as shown in the inset of figure 3(d). Conversely, a new feature appears in the temperature behavior of $R_{\text{sheet}}$ at $V_{gs} = -40$ V: the sheet resistance decreases until the temperature reaches $\sim 200$ K and raises for $T > 200$ K up to $\sim 4.8 \, \Omega/\text{sq}$ at $T = 400$ K. Otherwise stated, a transition from a semiconducting to a metallic behavior occurs in graphene around $T \sim 200$ K, consistently with what has been observed before [92–95]. Similar TLM analyses have been conducted on devices of the same chip with graphene channel 2 $\mu$m or 10 $\mu$m wide or with different layout. The estimated contact resistance, normalized by the channel width, $R_{\text{C}}^* = R_C W$, and sheet resistances are summarized in figure 4, showing a mean $R_{\text{C}}^*$ value of $\sim 2 \, k\Omega \cdot \mu$m and

![Figure 2](image-url) (a) Transfer and (b) output characteristics of a graphene transistor with 2 $\mu$m channel width and 1 $\mu$m channel length.

![Figure 3](image-url) (a) TLM plot and (b) $R_C$ and $R_{\text{sheet}}$ as function of the gate voltage. (c) TLM curves and (d) $R_C$ and $R_{\text{sheet}}$ at $V_{gs} = 0$ V and $-40$ V (inset) as function of the temperature.
We note that, owed to the zig-zag geometry, the TZ structure in figure 4 (which is the previously analyzed one), shows a normalized contact resistance as low as $R_{C} \approx 700 \Omega \cdot \mu m$ at $V_{gs} = -40 V$ within the range of the good quality contacts typically reported in the literature [63, 65–67]. Considering that the device-to-device fluctuations across the wafer are less than 30% [54], the improvement of the zig-zag geometry is highly significant. The differences in the sheet resistance shown in figure 4(b) can be attributed to local variations of the transferred graphene foil and different damage induced by the fabrication process.

We further exploited the TLM measurements to study the dependence of the field-effect mobility, $\mu$, on the channel length $d$ and the temperature. The mobility was estimated from the slope $\frac{dI}{dV_{gs}}$ of the linear part of the

\begin{equation}
R_{\text{sheet}} \approx 4 \ \text{k}\Omega/\text{sq}
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transfer characteristics as

\[ \mu = \frac{d}{W C_{\text{ox}} V_{\text{gs}} d V_{\text{gs}}} \]  

Figure 5(a) shows the hole mobility as function of channel length, an increase of \( \mu \) with \( d \) appears for small \( d \) with a further saturation at larger channel lengths. Such a behavior can be expressed as \( \mu = \mu_0 \frac{d}{\lambda} \), where \( \mu_0 \) is the saturated mobility and \( \lambda \) the mean free path [96]. From the fit of the experimental data, we obtain \( \lambda \approx 1 \mu m \) and \( \mu_0 \approx 175 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1} \). The saturation at channel length \( d \gg \lambda \) corresponds to the establishment of a diffusive transport regime, while the mobility degradation at lower \( d \) (\( d \ll \lambda \)) is an artifact due to the application of equation (8) in a regime where the transport becomes quasi-ballistic or ballistic [96, 97]. The influence of the temperature on the mobility, for the chosen device with \( d = 110 \mu m \), is shown in figure 5(b), which indicates that most of the mobility degradation occurs for \( T > 250 \text{ K} \) (\( \approx 15\% \) from its value at \( 90 \text{ K} \), \( \mu_{90K} \approx 195 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1} \)). This behavior can be understood considering that phonon scattering in graphene becomes relevant only at higher temperatures [98–100].

The electron/hole mobilities evaluated from the numerical derivative of the \( I_{ds} - V_{gs} \) curves according to equation (8), are plotted in figure 5(c) as function of \( V_{gs} - V_{\text{Dirac}} \) (gate overdrive) for two channel lengths (1 and 10 \( \mu m \), respectively). The mobilities show a minimum at the Dirac point, reach a maximum for increasing overdrive and decrease smoothly for \( |V_{gs} - V_{\text{Dirac}}| > 10 \text{ V} \). The contact resistance, whose effect on the mobility is not eliminated in this type of analysis, could cause this decrease of \( \mu \) with gate overdrive. To confirm such a hypothesis and obtain a more accurate \( \mu \) versus \( V_{gs} \) behavior, we considered the Y-function method as complementary approach to the TLM analysis.

From figure 6(a), we obtained a field effect mobility \( \mu \approx 160 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1} \), which together with the data in figure 6(b) yields \( R_C = 310 \Omega \) (or \( R_C^* = 700 \Omega \cdot \mu m \)). These values are consistent with the results from the TLM analysis.

The plots of the mobility versus \( V_{gs} - V_{\text{Dirac}} \) (figures 6(c) and (d) for 1 \( \mu m \) and 10 \( \mu m \) channel lengths, respectively) show that \( \mu \) is unaffected by \( R_C \) and is independent of the gate overdrive. The elimination of the contact resistance effect by the YFM confirms that gate dependence of the field-effect mobility is only an artifact of the TLM method.
We also note from figures 6(c) and (d) that removing $R_C$ results in significantly higher mobility, with over 80% increase.

4. Conclusions

In conclusion, we have fabricated and analyzed Ni-contacted graphene FETs and studied the back-gate and temperature dependence of the contact and channel resistance. We have measured devices with different geometrical structures and achieved competitive contact resistances using zig-zag shaped Ni contacts, also confirming the importance of contact geometry in the metal/graphene contact resistance.

We have found that the gate voltage modulates the contact and the channel resistance in a similar way but does not change the carrier mobility. We have also shown that raising the temperature decreases the carrier mobility, has a negligible effect on the contact resistance and can change the initial semiconducting behavior of the channel resistance into a metallic one, depending on the gate voltage. We used two complementary methods, namely the TLM and the YFM, to show that, eliminating the detrimental effect of the contact resistance, can almost double the carrier field-effect mobility.

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References

[1] Novoselov K S 2004 Electric field effect in atomically thin carbon films Science 306 666–9
[2] Novoselov K S, Geim A K, Morozov S V, Jiang D, Katsnelson M I, Grigorieva I V, Dubonos S V and Firsov A A 2005 Two-dimensional gas of massless dirac fermions in graphene Nature 438 197–200
[3] Geim A K and Novoselov K S 2007 The rise of graphene Nature Mater 6 183–91
[4] Xu M, Liang T, Shi M and Chen H 2013 Graphene-like two-dimensional materials Chem. Rev. 113 3766–98
[5] Carvalho A, Wang M, Zhu X, Rodin A S, Su H and Castro Neto A H 2016 Phosphorene: from theory to applications Nat Rev Mater 1 16061
[6] Urban F et al 2019 Gas dependent hysteresis in MoS2 field effect transistors 2D Mater. 6 045049
[7] Giubileo F, Grillo A, Passacantando M, Urban F, Iemmo L, Luongo G, Pelella A, Loveridge M, Lozzi L and Di Bartolomeo A 2019 Field emission characterization of MoS2 nanoflowers Nanomaterials 9 717
[8] Ahn J-H, Parkin W M, Naylor C H, Johnson A T C and Drndić M 2017 Ambient effects on electrical characteristics of CVD-grown monolayer MoS2 field-effect transistors Sci. Rep. 7 4075
[9] Grillo A, Giubileo F, Iemmo L, Luongo G, Urban F and Di Bartolomeo A 2019 Space charge limited current and photocative effect in few-layer MoS2 J. Phys.: Conf. Ser. 1226012013
[10] Bai A, Valsaraj A, Movva H C P, Roy A, Tuttu E, Register L F and Banerjee S K 2015 Interfacial-oxygen-vacancy mediated doping of MoS2 by high-v. dielectrics Proc. of the 2015 73rd Annual Device Research Conf. (DRC) pp 189–90
[11] Di Bartolomeo A et al Asymmetric Schottky contacts in bilayer MoS2 field effect transistors Adv. Funct. Mater. 28 1800657
[12] Das S, Chen H Y, Penumatcha A V and Appenzeller J 2013 High performance multilayer MoS2 transistors with scandium contacts Nano Lett. 13 100–5
[13] Urban F, Passacantando M, Giubileo F, Iemmo L and Di Bartolomeo A 2018 Transport and field emission properties of MoS2 bilayers Nanomaterials 8 151
[14] Iemmo L, Urban F, Giubileo F, Passacantando M and Di Bartolomeo A 2020 Nanotip contacts for electric transport and field emission characterization of ultrathin MoS2 flakes Nanomaterials 10 106
[15] Feng C, Xiang J, Liu P and Xiang B 2017 The growth study of bilayer and monolayer WSe2 Mater. Res. Express 4 095703
[16] Urban F, Martucciello N, Peters L, McEvoy N and Di Bartolomeo A 2018 Environmental effects on the electrical characteristics of back-gated WSe2 field-effect transistors Nanomaterials 8 901
[17] Di Bartolomeo A, Urban F, Passacantando M, McEvoy N, Peters L, Iemmo L, Luongo G, Romeo F and Giubileo F 2019 A WSe2 vertical field emission transistor Nanoscale 11 1538
[18] Di Bartolomeo A, Pelella A, Liu X, Miao F, Passacantando M, Giubileo F, Grillo A, Iemmo L, Urban F and Liang S-J 2019 Pressure-tunable ambipolar conduction and hysteresis in thin palladium diselenide field effect transistors Adv. Funct. Mater. 29 1902483
[19] Long C, Liang Y, Jin H, Huang B and Dai Y 2019 PdSe2: flexible two-dimensional transition metal dichalcogenides monolayer for water splitting photocatalyst with extremely low recombination rate ACS Appl. Energy Mater. 2 513–20
[20] Yim C, Passi V, Lemme M C, Duesberg G S, Ô Coileáin C, Pallecchi E, Fadil D and McEvoy N 2018 Electrical devices from top-down structured platinum diselenide films Npj 2D Mater Appl 2 5
[21] Ansari L et al 2019 Quantum confinement-induced semimetal-to-semiconductor evolution in large-area ultra-thin PtSe2 films grown at 400 °C Npj 2D Mater Appl 3 33
[22] Schwierz F 2010 Graphene transistors Nat. Nanotechnol. 5 487
[23] Meric I, Dean C R, Young A F, Balikciayka N, Tremblay N J, Nuckolls C, Kim P and Shepard K L 2011 Channel length scaling in graphene field-effect transistors studied with pulsed current—voltage Measurements Nano Lett. 11 1093–7
[24] Castro Neto A H, Guinea F, Peres N M R, Novoselov K S and Geim A K 2009 The electronic properties of graphene Rev. Mod. Phys. 81 109–62
[25] Ghosh S, Calizo I, Teweldebrhan D, Pokatilov EP, Nika D L, Balandin A A, Bao W, Miao F and Lau C N 2008 Extremely high thermal conductivity of graphene: prospects for thermal management applications in nanoelectronic circuits Appl. Phys. Lett. 92 151911
[26] Nagashio K, Nishimura T, Kita K and Toriumi A 2009 Mobility variations in mono- and multi-layer graphene films Appl. Phys. Express 2 025003
Riazimehr S, Bablich A, Schneider D, Kataria S, Passi V, Yim C, Duesberg G S and Lemme M C 2016 Spectral sensitivity of graphene
Xia F, Mueller T, Lin Y, Valdes-Garcia A and Avouris P 2009 Ultrafast graphene photodetector
Shivananju B N, Yu W, Liu Y, Zhang Y, Lin B, Li S and Bao Q 2017 The roadmap of graphene-based optical biochemical sensors
Di Bartolomeo A, Giubileo F, Iemmo L, Romeo F, Santandrea S and Gambardella U 2013 Transfer characteristics and contact
Vaziri S, Lupina G, Henkel C, Smith A D, Östling M, Dabrowski J, Lippert G, Mehr W and Lemme M C 2013 A graphene-based hot
Luongo G, Di Bartolomeo A, Giubileo F, Luongo G, Passacantando M, Niu G, Hatami F, Skibitzki O and Schroeder T 2017 Graphene enhanced field emission from InP nanocrystals Nanotechnology 28 495705
Giubileo F, Di Bartolomeo A, Iemmo L, Luongo G and Urban F 2018 Field emission from carbon nanostructures Applied Sciences 8 526
Kim H-Y, Lee K, McEvoy N, Yim C and Duesberg G S 2013 Chemically modulated graphene diodes Nano Lett. 13 2128–8
Shivananju B N, Yu W, Liu Y, Zhang Y, Lin B, Li S and Bao Q 2017 The roadmap of graphene-based optical biochemical sensors Adv. Funct. Mater. 27 1603918
Di Bartolomeo A, Giubileo F, Luongo G, Iemmo L, Martucciello N, Niu G, Fraschke M, Skibitzki O, Schroeder T and Lupina G 2016 Tunable Schottky barrier and high responsivity in graphene/Si-nanotip optoelectronic devices 2D Mater. 4 015024
Xia F, Mueller T, Lin Y, Valdes-Garcia A and Avouris P 2009 Ultrafast graphene photodetector Nat. Nanotechnol. 4 839–43
Riazimehr S, Bablich A, Schneider D, Kataria S, Passi V, Yim C, Duesberg G S and Lemme M C 2016 Spectral sensitivity of graphene/ silicon heterojunction photodetectors Solid-State Electronics 115 207–12
Luongo G, Giubileo F, Genovese L, Iemmo L, Martucciello N and Di Bartolomeo A 2017 I-V and C-V Characterization of a high- responsivity graphene/silicon photodiode with embedded MOS capacitor Nanomaterials 7 158
Riazimehr S, Kataria S, Bornemann R, Haring Bolivar P, Ruiz F J G, Engstroem O, Godoy A and Lemme M C 2017 High photocurrent in gated graphene–silicon hybrid photodiodes ACS Photonics 4 1506–14
Di Bartolomeo A, Luongo G, Giubileo F, Funicello N, Niu G, Schroeder T, Lisker M and Lupina G 2017 Hybrid graphene/silicon Schottky photodiode with intrinsic gating effect 2D Mater. 4 025075
Luo F, Zhu M, Tan Y, Sun H, Luo W, Peng G, Zhu Z, Zhang X-A and Qin S 2018 High responsivity graphene photodetectors from visible to near-infrared by photogating effect AIP Adv. 8 115106
Mahmoudi T, Wang Y and Hahn Y-B 2018 Graphene and its derivatives for solar cells application Nano Energy 47 31–65
Mina A N, Awadallah A A, Phillips A H and Ahmed R R 2012 Simulation of the band structure of graphene and carbon nanotube J. Phys.: Condens. Matter 24 343303
Yankowitz M, Jung J, Laksono E, Leconte N, Chittari B L, Watanabe K, Taniguchi T, Adam S, Graf D and Dean C R 2018 Dynamic band-structure tuning of graphene moiré superlattices with pressure Nature 557 404–8
Nag A, Kumar J and Sassri O S K S 2015 Electronic properties of graphene and effect of doping on the same. AIP Conf. Proc. 1661 080202
Sahu S and Rout G C 2017 Band gap opening in graphene: a short theoretical study Int Nano Lett 7 81–9
Schwierz F 2013 Graphene transistors: status, prospects, and problems Proc. IEEE 101 1567–84
Lisker M, Lukiosus M, Kitzmann J, Fraschke M, Wolansky D, Schulze S, Lupina G and Mai A 2018 Contacting graphene in a 200 mm wafer silicon technology environment Solid-State Electronics 144 17–21
Gahoi A, Wagner S, Bablich A, Kataria S, Passi V and Lemme M C 2016 Contact resistance study of various metal electrodes with CVD graphene Solid-State Electronics 125 234–9
Di Bartolomeo A, Giubileo F, Iemmo L, Romeo F, Santandrea S and Gambardella U 2013 Transfer characteristics and contact resistance in Ni- and Ti-contacted graphene-based field-effect transistors J. Phys. Condens. Matter 25 155303
Nagashio K, Nishimura T, Kita K and Toriumi A 2010 Systematic investigation of the intrinsic channel properties and contact resistance of monolayer and multilayer graphene field-effect transistor Jpn. J. Appl. Phys. 49 051304
Xia F, Perebeinos V, Lin Y, Wu Y and Avouris P 2011 The origins and limits of metal–graphene junction resistance Nature Nanotech 6 179–84
Watanabe E, Conwill A, Tsuya D and Koide Y 2012 Low contact resistance metals for graphene based devices Nanoscale 4 2171–4
Smith J T, Franklin A D, Farmer D B and Dimitrakopoulos C D 2013 Reducing contact resistance in graphene devices through contact area patterning ACS Nano 7 3661–7
Min Song S, Yong Kim T, Jae Sul O, Cheol Shin W and Jin Cho B 2014 Improvement of graphene–metal contact resistance by introducing edge contacts at graphene under metal Appl. Phys. Lett. 104 183506
Park H-Y et al 2016 Extremely low contact resistance on graphene through n-type doping and edge contact design Adv. Mater. 28 664–79
Wang L et al 2013 One-dimensional electrical contact to a two-dimensional material Science 342 614–7
Anzi L et al 2018 Ultra-low contact resistance in graphene devices at the Dirac point 2D Mater. 5 025014
[68] Venugopal A, Colombo L and Vogel E M 2010 Contact resistance in few and multilayer graphene devices Appl. Phys. Lett. 96 013512
[69] Song S M 2013 조병철 Contact resistance in graphene channel transistors Carbon letters 14 162–70
[70] Gahoi A, Kataria S and Lemmle M C 2017 Temperature dependence of contact resistance for gold–graphene contacts Proc. of the 2017 47th European Solid-State Device Research Conf. (ESSDERC); IEEE: Leuven, Belgium pp 110–3
[71] Zhu M, Wu J, Du Z, Tsang S and Teo E H T 2018 Gate voltage and temperature dependent Ti-graphene junction resistance toward straightforward p-n junction formation J. Appl. Phys. 124 215302
[72] Zhong H, Zhang Z, Chen B, Xu H, Yu D, Huang L and Peng L 2015 Realization of low contact resistance close to theoretical limit in graphene transistors Nano Res. 8 1669–79
[73] Anteronein J, Kim W, Stadius K, Rijkenen J, Lipsanen H and Rynnamen J 2012 Extraction of graphene–titanium contact resistances using transfer length measurement and a curve–fit method
[74] Schroeder D K 2006 Semiconductor Material and Device Characterization (New York: Wiley) pp 156
[75] Russo S, Craciun M F, Yamamoto M, Morpurgo A F and Tarucha S 2010 Contact resistance in graphene-based devices Physica E 42 677–9
[76] Giannazzo F, Fisichella G, Piazza A, Di Franco S, Greco G, Agnello S and Roccaforte F 2017 Impact of contact resistance on the electrical properties of MoS2 transistors at practical operating temperatures Beilstein J. Nanotechnol. 8 254–63
[77] Wang S, Mao D, Jin Z, Peng S, Zhang D, Shi J and Wang X 2015 A more reliable measurement method for metal/graphene contact resistance Nanotechnology 26 405706
[78] Ghibaudo G 1988 New method for the extraction of MOSFET parameters Electron. Lett. 24 543
[79] Henry J B, Raffay Q, Cros A and Ghibaudo G 2016 New Y–function based MOSFET parameter extraction method from weak to strong inversion range Solid-State Electronics 123 84–8
[80] Lai S, Cosseddu P and Bonfiglio A 2017 A method for direct contact resistance evaluation in low voltage coplanar organic field-effect transistors Appl. Phys. Lett. 110 153504
[81] Lukosius M et al 2016 Metal-free CVD graphene synthesis on 200 mm Ge/Si(001) substrates ACS Appl. Mater. Interfaces 8 33786–93
[82] Giubileo F and Di Bartolomeo A 2017 The role of contact resistance in graphene field-effect devices Prog. Surf. Sci. 92 143–75
[83] Diod C, Cros A, Monfray S, Mitard J, Rossa J, Gloria D and Ghibaudo G 2013 ‘Y function’ method applied to saturation regime: Apparent saturation mobility and saturation velocity extraction Solid-State Electronics 85 12–4
[84] Bartolomeo A D, Giubileo F, Romeo F, Sabatino P, Carapella G, Lemo L, Schroeder T and Lupina G 2015 Graphene field effect transistors with niobium contacts and asymmetric transfer characteristics Nanotechnology 26 475202
[85] Farmer D B, Golizadeh-Mojadar R, Perebeinos V, Lin Y-M, Tulevski G S, Tsang J C and Avouris P 2009 Chemical doping and electron–hole conduction asymmetry in graphene devices Nano Lett. 9 388–92
[86] Barraza-Lopez S, Vanevic M, Kindermann M and Chou M Y 2010 Effects of metallic contacts on electron transport through graphene Phys. Rev. Lett. 104 076807
[87] Toral-Lopez A, Marin E G, Pasadas F, Gonzalez-Medina J M, Ruiz F G, Jiménez D and Godoy A 2019 GFET asymmetric transfer response analysis through access region resistances Nanomaterials 9 1027
[88] Bartolomeo A D, Giubileo F, Santandrea S, Romeo F, Cito R, Schroeder T and Lupina G 2011 Charge transfer and partial pinning at the contacts as a result of a double dip in the transfer characteristics of graphene-based field-effect transistors Nanotechnology 22 275702
[89] Wei J, Liang B, Cao Q, Ren H, Zheng Y and Ye X 2020 Understanding asymmetric transfer characteristics and hysteresis behaviors in graphene devices under different chemical atmospheres Carbon 156 67–76
[90] di Bartolomeo A, Yang Y, Rinza M B M, Boyd A K and Barbara P 2010 Record endurance for single-walled carbon nanotube–based memory cell Nanoscale Res. Lett. 5 1382
[91] di Bartolomeo A, Santandrea S, Giubileo F, Romeo F, Petrosino M, Cito R, Barbara P and Lupina G 2013 Effect of back-gate on contact resistance and on channel conductance in graphene-based field-effect transistors Diam. Relat. Mater. 38 19–23
[92] Mogera U, Walia S, Bannur B, Gedda M and Kulkarni G U 2017 Intrinsic nature of graphene revealed in temperature–dependent transport of twisted multilayer graphene J. Phys. Chem. C 121 13958–43
[93] Mayvorov A S, Elias D C, Mukhin I S, Morozov S V, Ponomarenko L A, Novoselov K S, Geim A K and Gorbachev R V 2012 How close can one approach the dirac point in graphene experimentally? Nano Lett. 12 4629–34
[94] Das Sarma S and Hwang E H 2013 Density-dependent electrical conductivity in suspended graphene: approaching the dirac point in transport Phys. Rev. B 87 035415
[95] Bolotin K I, Sikes K J, Hone J, Stormer H L and Kim P 2008 Temperature-dependent transport in suspended graphene Phys. Rev. Lett. 101 096802
[96] Lundstrom M and Jeong C 2013 Near–equilibrium transport: fundamentals and applications Lessons from Nanoscience (Singapore: World Scientific)
[97] Chen Z and Appenzeller J 2008 Mobility extraction and quantum capacitance impact in high performance graphene field-effect transistors Proc. of the 2008 IEEE Int. Electron Devices Meeting IEEE, San Francisco, CA, USA pp 1–4
[98] Chen J-H, Jiang C, Xiao S, Ishigami M and Fuhrer M S 2008 Intrinsic and extrinsic performance limits of graphene devices on SiO2 Nat. Nanotechnol. 3 206
[99] Zhu W, Perebeinos V, Freitag M and Avouris P 2009 Carrier scattering, mobilities, and electrostatic potential in monolayer, bilayer, and trilayer graphene Phys. Rev. B 80 235402
[100] Dorgan V E, Bae M-H and Pop E 2010 Mobility and saturation velocity in graphene on SiO2 Appl. Phys. Lett. 97 082112