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# Dependability assessment of Transfer Length Method to extract the metal–graphene contact resistance

Francesco Driussi*, Stefano Venica*, Amit Gahoi†, Satender Kataria†, Max C. Lemme†‡, Pierpaolo Palestri*

***Abstract*—The measurement of the contact resistance ($R_C$) in semiconductor devices relies on the well–established Transfer Length Method (TLM). However, an in–depth investigation on its applicability to characterize the metal–graphene contacts is still missing. In this work, a dependability analysis on the $R_C$ values extracted from several metal–graphene stacks is performed, also devising strategies to limit the large observed statistical errors and to obtain dependable results. In particular, artifacts due to an incorrect application of TLM, e.g. negative resistance values, can be eliminated. Finally, a simulation study is proposed to quantify the contribution to $R_C$ of the so–called junction resistance at the edge of the contact, that some authors in the literature invoke to explain the observed artifacts.**

***Index Terms*—Graphene, contact resistance, Transfer Lenght Method, measurement reliability, junction resistance, modeling.**

## I. Introduction

TWO–dimentional (2D) materials are largely investigated as possible boosters/enablers for "more than Moore" technologies [1]. As an example, the high mobility and electron velocity in graphene make graphene–FETs (GFETs) promising for high performance RF analog circuits [2]. Indeed, nowadays GFET cut–off frequencies are comparable with those of state–of–the–art RF transistors [3]. Furthermore, graphene is excellent for many other applications such as fast photodetectors [4], NEMS/MEMS and sensors [5], terahertz modulators [6], supercapacitors [7] and displays [8].

However, the performance of all these devices is largely hampered by the large Metal–Graphene (M–G) contact resistance ($R_C$) [9]. For instance, it strongly limits the maximum oscillation frequency of GFETs and also of alternative device concepts based on 2D materials [2], [10]–[12].

Despite the efforts spent to improve the quality of the M–G contacts [13], a further breakthrough in the engineering of the M–G junction to lower $R_C$ is mandatory to boost graphene technology. However, this cannot be achieved without an in–depth understanding of the physics behind the conduction mechanism across the M–G stack and this is possible only through reliable experimental techniques allowing the assessment of the M–G stack nature [14], [15].

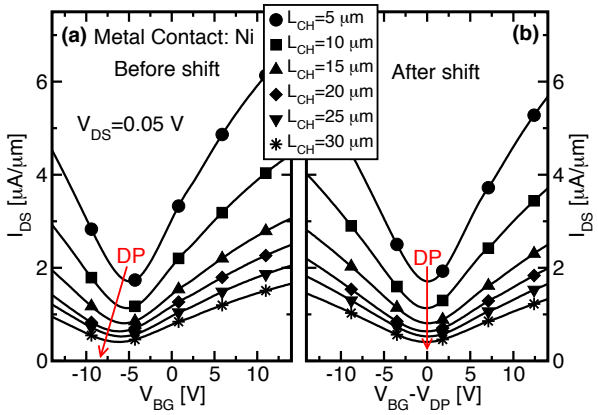



Fig. 1. (a) Typical current vs. $V_{BG}$ curves of GFETs of a TLM structure with $W = 20$ $\mu$m and Ni contacts. All GFETs show a DP at $V_{DP}<0$, with a value slightly depending on $L_{CH}$. (b) Transfer characteristics are shifted to align the DP positions.

In semiconductor technology, the Transfer Length Method (TLM) has been routinely used to measure $R_C$ between metals and semiconductor materials [14]. However, the applicability of TLM to graphene devices and the correctness of the obtained $R_C$ values have not been deeply investigated yet. Indeed, the $R_C$ data for M–G contacts reported in the literature are characterized by large error bars [15] and, in several cases, by negative $R_C$ values [16]–[20]. Often the authors impute these negative $R_C$ values to the metal–induced doping of the graphene underneath or in proximity of the contacts, that translates in the so–called junction resistance ($R_{JUN}$) at the edge between the metal contact and the GFET channel. $R_{JUN}$ is due to different graphene charge densities in the channel and underneath the contact region [21].

In this paper, an in–depth assessment of $R_C$ extracted through TLM is presented and strategies to limit the observed errors are proposed, thus leading to dependable M–G contact resistance values. Furthermore, the work of [22] is extended by using semi–classical Monte–Carlo (MC) simulations to evaluate the effect of the metal–induced doping of graphene and the contribution of $R_{JUN}$ to $R_C$, with the aim to solve the open question concerning the origin of the negative $R_C$ values reported in the literature.

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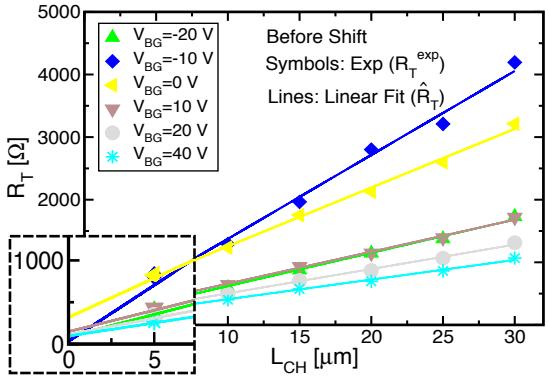



Fig. 2. Total resistance $R_T^{exp}$ (symbols) versus $L_{CH}$ obtained from the data in Fig. 1(a) at different $V_{BG}$. Linear regression (lines) allows to extract $R_{SH}$ and $R_C$. The zoom near the origin of the axis highlights the intercept value ($2R_C$).

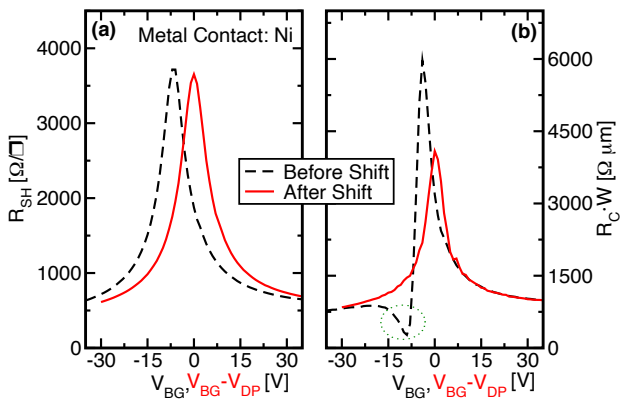



Fig. 3. Sheet resistance (a) and contact resistance (b) versus $V_{BG}$ (dashed lines) extracted from the linear fittings in Fig. 2. Near the DP, $R_C$ shows an evident drop (highlighted area). The shifted transfer charateristics in Fig. 1(b) lead to a very different $R_C$ behavior and the dip disappears.

## II. Fabricated TLM structures and experimental procedure

The measured TLM test structures consist of a series of back–gated GFETs with different width ($W$) and a channel length ($L_{CH}$) that ranges from 5 to 50 $\mu$m. Boron–doped ($p$–type) silicon substrates have been thermally oxidized to obtain an 85 nm $SiO_2$ back oxide, on top of which a monolayer CVD graphene is tranferred. To make the contacts, nickel (Ni), copper (Cu) or gold (Au) were used. The complete fabrication process flow of the TLM structures can be found in [23].

The samples were characterized in DC at 300 K in a Lake Shore Cryotronics probestation to ensure ultra–high vacuum conditions ($< 10^6$ mbar). The source–drain currents ($I_{DS}$) of the GFETs with different $L_{CH}$ are routinely measured as a function of the applied back–gate bias ($V_{BG}$). Fig. 1(a) reports the typical results for a TLM sample with Ni contacts. The Dirac Point (DP), i.e. the minimum conduction point, is clearly visible and, for this sample, it is located at negative back–gate voltages ($V_{DP} < 0$ V). Furthermore, $V_{DP}$ slightly depends on $L_{CH}$ and this can be due to some unintentional graphene doping/interfacial impurities and/or to residual air/humidity that shift the DP position with respect to zero [24].

## III. Experimental M–G contact resistance

The measured transfer characteristics have been used to calculate the total resistance $R_T^{exp}$ of each GFET. It is generally assumed that $R_T^{exp}$ is contributed by the channel resistance, the M–G contact resistance $R_C$ and the resistance of the metallic electrode (this latter is typically neglected) [14]. If the sheet resistance $R_{SH}$ of the graphene layer is uniform in the whole TLM structure, $R_T^{exp}$ linearly depends on $L_{CH}$, as:

$$R_T^{exp} = \frac{V_{DS}}{I_{DS}} = \frac{R_{SH}}{W} L_{CH} + 2R_C. \quad (1)$$

$R_T^{exp}$ is calculated for the data in Fig. 1(a), obtaining the $R_T^{exp}$ versus $L_{CH}$ curves of Fig. 2 (symbols). According to Eq. 1, $R_{SH}$ and $R_C$ are extracted from the slope and the intercept with the $y$–axes of the linear regression (lines), respectively. The zoomed area near the origin of the axis highlights the $2R_C$ value, that appears to be non–monotonic with $|V_{BG}|$ and rapidly drops for $V_{BG} = -10$ V (blue line).

The $R_{SH}$ and $R_C$ versus $V_{BG}$ values extracted from Fig. 2 are reported in Fig. 3 (dashed lines). $R_{SH}$ (a) shows the typical bell–shape behavior of graphene channels (large resistivity near the DP). Instead, the extracted $R_C$ (b) shows a clear dip at $V_{BG} \simeq -10$ V similar to those previously reported in the literature [15]–[17].

### A. Statistical errors in the extracted $R_C$

In order to assess the correctness of the data in Fig. 3 (dashed lines), the statistical errors related to the $R_{SH}$ and $R_C$ extraction are calculated. In particular, the regression coefficient ($r^2$) and the errors ($\varepsilon$) caused by the linear regression in Fig. 2 are [25]:

$$r^2 = 1 - \frac{\sum_i^N (R_T^{exp} - \widehat{R}_{T_i})^2}{\sum_i^N (R_T^{exp} - \overline{R}_T)^2} \quad (2)$$

$$\varepsilon(R_{SH}) = \pm\, W \sqrt{\frac{\sigma^2}{S_{xx}}} \quad (3)$$

$$\varepsilon(R_C) = \pm\, \frac{1}{2} \sqrt{\sigma^2 \left[ \frac{1}{N} + \frac{\overline{L_{CH}}}{S_{xx}} \right]}, \quad (4)$$

where:

$$\sigma^2 = \frac{\sum_i^N (R_{T_i}^{exp} - \widehat{R}_{T_i})}{N-2} \quad (5)$$

$$S_{xx} = \sum_i^N (L_{CH_i} - \overline{L_{CH}})^2 \quad (6)$$

$$\widehat{R}_{T_i} = \frac{R_{SH}}{W} L_{CH_i} + 2R_C. \quad (7)$$

The calculated $r^2$ is very close to one ($r^2 > 0.987$), although it reduces near the DP (see [22]). Also the $R_{SH}$ error reported in Fig. 4(a, dashed line) is quite small, supporting the correctness of the extracted $R_{SH}$ data.

Instead, the relative error for $R_C$ reported in Fig. 4(b, dashed line) is very huge, especially in correspondence of

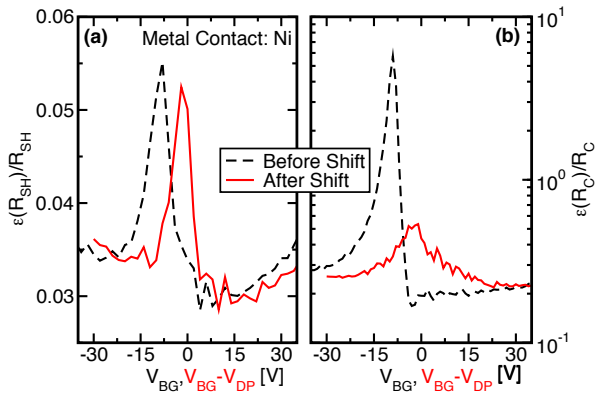



Fig. 4. Relative error on $R_{SH}$ (a) and on $R_C$ (b) versus $V_{BG}$ calculated applying Eqs. 3–7 to the data in Fig. 2. The error is small for $R_{SH}$, while it is huge for $R_C$ at $V_{BG} \approx -10$ V. The transfer characteristics versus $(V_{BG}-V_{DP})$ in Fig. 1(b) lead to much smaller errors (solid lines), especially near the DP.

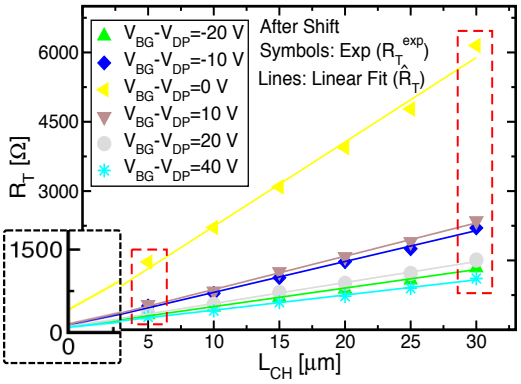



Fig. 5. Experimental $R_T^{exp}$ (symbols) as a function of $L_{CH}$ at different $(V_{BG}-V_{DP})$ obtained from the curves reported in Fig. 1(b). The shortest and longest devices (5 and 30 $\mu m$) are potentially responsible for the errors in the DP proximity seen in Fig. 4(b).

the dip in the $R_C$ curve of Fig. 3(b) (close to the DP). This extremely large error can be due to the small $L_{CH}$ dependence of the DP position in the curves of Fig. 1(a). To verify this, the currents of each GFET as a function of $(V_{BG}-V_{DP})$ are re–plotted in Fig. 1(b), thus compensating the slightly different $V_{DP}$ in the measured devices. In this way, $R_T^{exp}$ of the different GFETs is compared at the same charge carrier concentration in the graphene channels. The $R_{SH}$ and $R_C$ are now extracted from the shifted $I_{DS}$ curves of Fig. 1(b).

Figure 5 shows $R_T^{exp}$ versus $L_{CH}$ curves obtained at given $(V_{BG}-V_{DP})$ values. Differently from Fig. 2, by looking at the zoomed area, the intercept of the linear regression is now monotonic with $|V_{BG}-V_{DP}|$. Furthermore, Fig. 3 compares the newly extracted $R_{SH}$ and $R_C$ values (red solid lines) with those (black dashed lines) extracted from the initial $I_{DS}$–$V_{BG}$ curves. $R_{SH}$ is pretty similar, as it is similar the $R_{SH}$ statistical error made by using both the original and shifted IV curves [Fig. 4(a)].

Instead, $R_C$ is very different from the previous extraction and the dip near the DP disappears. Furthermore, these new $R_C$ values are characterized by a much smaller relative error [Fig. 4(b), solid line], making the extracted $R_C$ values much more robust.

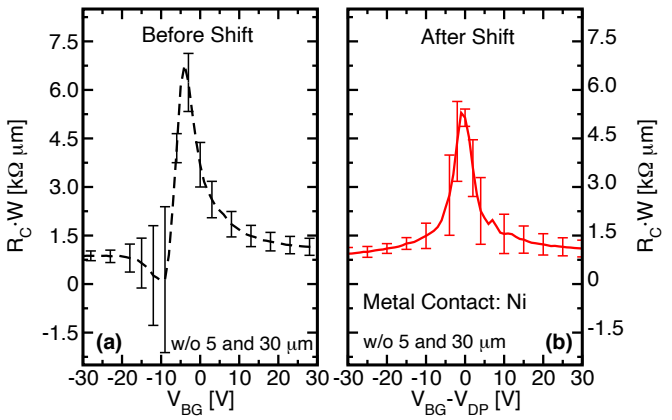



Fig. 6. $R_C$ characteristics with the corresponding error bars $[\pm\varepsilon(R_C)]$ obtained excluding the outliers. Data are extracted considering the original (a) and the shifted transfer characteristics (b). The latter can be considered as the most dependable result.

By carefully observing the $R_T^{exp}$ vs. $L_{CH}$ curves in Fig. 5, it is also possible to note that some points slightly deviate from the linear behavior ($L_{CH} = 5$; 30 $\mu$m, red dashed box). In [22], it has been verified that the exclusion of these outliers from the linear regression indeed improves $r^2$ and the $R_C$ error related to the extraction procedure. However, it has been also demonstrated that the huge error in Fig. 4(b) (dashed line, especially at $V_{BG} \approx V_{DP}$) is mainly due to the DP variation between the GFETs in the TLM structure (see Fig. 6). Hence, the compensation of the $V_{DP}$ variability among the $I_{DS}$ characteristics is mandatory to obtain dependable $R_C$ and it is much more important than the identification of possible outliers. Anyway, to further improve the dependability of the $R_C$ results, the extraction procedure is run also by excluding the GFETs with $L_{CH} = 5$ $\mu$m and 30 $\mu$m of the investigated TLM structure with Ni–graphene contacts and Fig. 6(b) shows the obtained $R_C$ with the corresponding error bars. Even by considering these error bars, the calculated $R_C$ is always positive.

### *B. Contact resistance for different metal materials*

The validity of the developed extraction procedure has been verified also on TLM structures with different metal contacts. Indeed, the issue related to the $V_{DP}$ position varying along the TLM structure is observed also in the samples with Au and Cu contacts, as also reported in [22]. As a reference, the $R_C$ values are first extracted by using the raw $I_{DS}$–$V_{BG}$ curves measured in the samples [Fig. 7(a)]. All the curves peak at the DP position ($V_{DP} < 0$ for Ni and Au; $V_{DP} > 0$ for Cu, see Fig. 12 of [22]), but they show different and somewhat distorted shapes with dips and also negative $R_C$ values for the Au sample.

In this respect, the relative $R_C$ error is unacceptably large for all the metals, with values up to 600% for Ni and Au [see Fig. 7(b)]. In general, the error is very large in correspondence of distortions and dips in the $R_C$ curves and, in particular, when $R_C$ becomes negative in the Au sample.

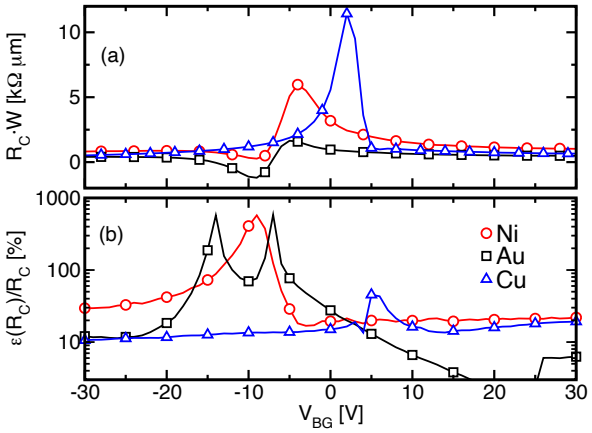



Fig. 7. (a) $R_C$ obtained from TLM structures with different metal contacts by using the raw $I_{DS}$–$V_{BG}$ characteristics. The curves show artifacts and distortions, such as negative $R_C$ values for the Au contact. (b) For all the metal materials, the statistical error related to the $R_C$ extraction is huge and unacceptable.

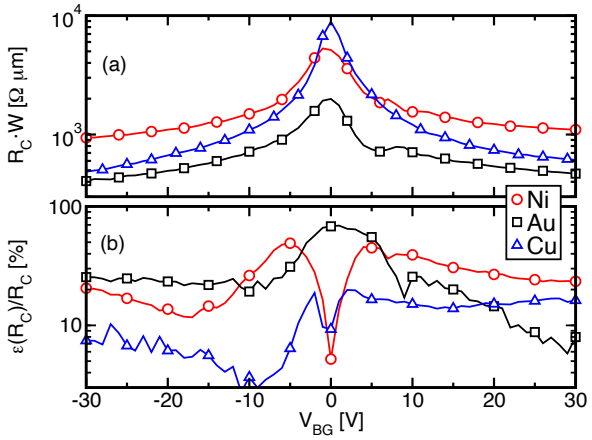



Fig. 8. (a) $R_C$ obtained from TLM structures with different metal contacts by using the developed procedure, namely by compensating the $V_{DP}$ variability and excluding the outliers. The $R_C$ curves show the typical bell–shape. (b) For all the metals, now the $R_C$ statistical error is much smaller than before.

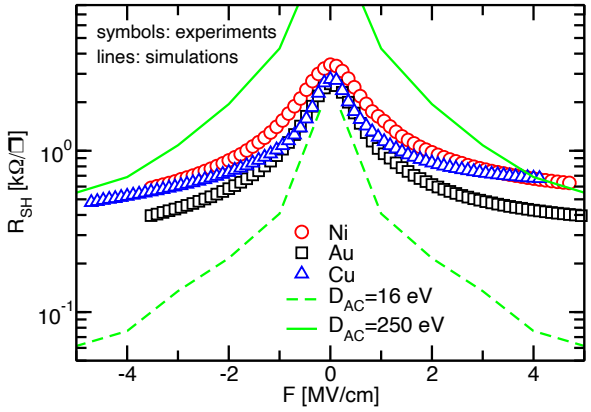



Fig. 9. $R_{SH}$ vs. the back–oxide electric field $F$ extracted from TLM structures by using the developed procedure (symbols). The curves show the typical bell–shape of graphene channels. The samples with different metal contacts show similar graphene quality. For comparison, MC simulations assuming two values of the deformation potential of acoustic phonons ($D_{AC}$) are also reported (lines).

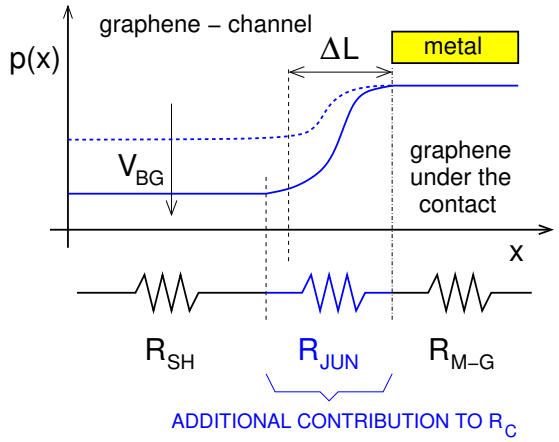



Fig. 10. Sketch of the hole density profile in the graphene layer along the transport direction in proximity of the Au contact. The step between the channel and the region under the metal (higher at large $V_{BG}$) leads to a $p$–$p+$ junction. The associated junction resistance $R_{JUN}$ adds to the resistance $R_{M-G}$ due to the sole M–G stack.

To reduce the $R_C$ extraction error, the $V_{DP}$ variation is compensated among the IV curves of GFETs in the same TLM structure and the outliers from the linear regression of $R_T$ versus $L_{CH}$ data are excluded. The $R_C$ results in Fig. 8(a) are obtained following this procedure and they are characterized by much lower errors than before [although not very small close to the DP, see Fig. 8(b)]. So now the extracted $R_C$ can be considered dependable and all curves show the bell–shape behavior typical of graphene channels. It is worth noticing that Ni contacts exhibit the highest $R_C$ (except at the DP position), while Au contacts show the lowest $R_C$ values [9].

Figure 9 (symbols) finally reports the extracted $R_{SH}$ values as a function of the back–oxide electric field $F$ for the TLM samples with the different metals, demonstrating the similar quality of the graphene in the measured samples.

## IV. MC SIMULATIONS OF THE JUNCTION RESISTANCE

As mentioned in Sec. I, the negative $R_C$ reported in the literature is often ascribed to the metal–induced doping of the graphene underneath or in proximity of the contact [16]–[20]. Indeed, metals electrostatically dope graphene [9], inducing different charge concentrations between the graphene channel and the region underneath the contact and possibly forming a pseudojunction [21]. As an example, graphene is $p$–doped by Au contacts [9] and $p$–$p+$ or $n$–$p+$ junctions may appear near the contact edge, depending on the applied $V_{BG}$ value (it drives the graphene channel charge, see Fig. 10).

This pseudojunction has a twofold effect: 1) it leads to a *junction* resistance ($R_{JUN}$) that depends on $V_{BG}$ and contributes to the series resistance in the GFETs; 2) it extends into the channel ($\Delta L$, Fig. 10) and shortens the portion of graphene with uniform charge density and characterized by $R_{SH}$. Hence, Eq. 1 must be re–written as:

$$R_T^{exp} = \frac{R_{SH}}{W}(L_{CH} - 2\Delta L) + 2(R_{JUN} + R_{M-G}), \quad (8)$$

where $R_{M-G}$ is the actual contact resistance of the sole M–G

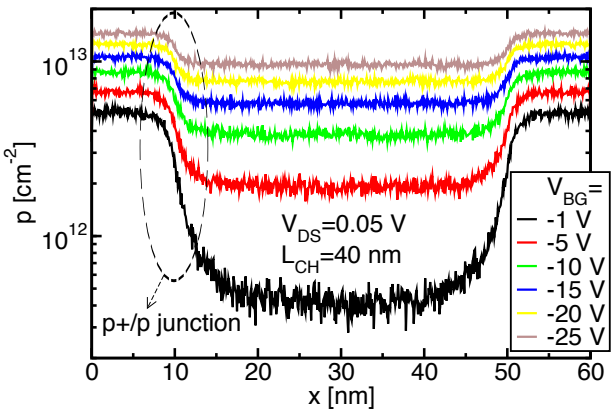



Fig. 11. Hole density along the GFET for different $V_{BG}$ values calculated with the MC simulator. Near the contact edge, the $p$–$p+$ junction is higlighted.

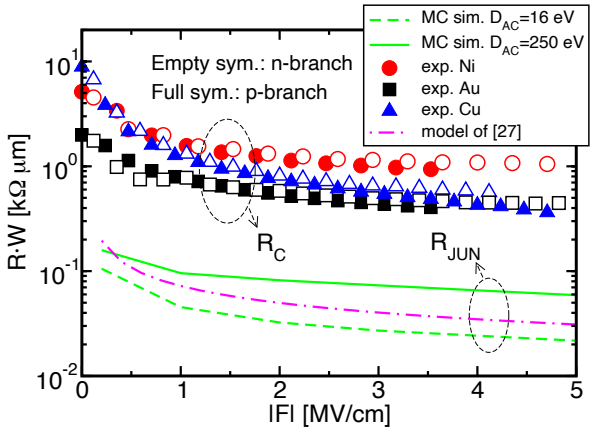



Fig. 12. Experimental $R_C$ (symbols) compared with $R_{JUN}$ simulated with the MC model (green lines) for two $D_{AC}$ values. As a reference, the $R_{JUN}$ is calculated also with the ballistic model of [27], namely $R_{JUN} = \frac{\pi^2\hbar^2 v_F}{2q^2(E_F - E_{DP})}$, where $v_F$, $E_F$ and $E_{DP}$ are, respectively, the Fermi velocity, the Fermi level and the DP energy level in the graphene channel, since this latter is the bottleneck for the carrier transport in the pseudojunction at the contact edge.

stack (Fig. 10). $R_T^{exp}$ is still proportional to $L_{CH}$ and $R_C$ is extrapolated at $L_{CH} = 0$, leading to:

$$R_C = -\frac{R_{SH}}{W}\Delta L + R_{JUN} + R_{M-G}. \quad (9)$$

Close to $V_{DP}$, the charge density in the channel is rather low and, by assuming that the metal is anyway inducing a large graphene doping under the contact, this high charge step may lead to large $R_{JUN}$ and $\Delta L$ and, thus, to a $R_C$ value very different from the actual $R_{M-G}$. This assumption has been used in the literature to justify the reported negative $R_C$ values near the DP. Indeed, the first term in Eq. 9 can produce, in some cases, negative $R_C$, depending on the $R_{JUN}$, $\Delta L$ and $R_{M-G}$ values. To investigate on this point and to evaluate the $R_{JUN}$ contribution to $R_T$ of GFETs, Monte-Carlo (MC) simulations of the charge density profile along the GFET have been performed.

The MC simulator couples self–consistently the Boltzamnn transport equation for electrons and holes in the graphene channel to the non–linear Poisson equation [26]. For graphene, it considers a gapless energy dispersion relationship, scattering with acoustic and optical phonons and band-to-band tunneling. Remote phonon scattering in the top–oxide and back–oxide is also considered. Concerning source/drain regions, the simulator can model either chemical or electrostatic doping. The latter relates to the M–G interactions [9] and the tool calculates the metal–induced displacement with respect to DP of the Fermi level in the graphene underneath the contact. Furthermore, the model also accounts for the voltage drop across $R_{M-G}$ and its impact on the GFET current. More details on the MC model can be found in [26].

Figure 11 shows the hole density along the GFET length calculated with the MC simulator. In this plot, Au contacts with a workfunction of 5.2 eV has been assumed, so that they $p$–dope the underneath graphene [9]. Lowering $V_{BG}$, more holes are accumulated in the graphene channel and the step in hole concentration at the contact edge is reduced. Note that the extension of the $p$–$p+$ junction is rather limited, resulting in $\Delta L < 10$ nm for all the simulated $V_{BG}$ values [27]–[30]. This is in agreement with the fact that the metal–induced doping vanishes within a few nanometers [9], [31]. It is worth mentioning that we consider these simulations as a worst case, since Ni and Cu have workfunctions (5 eV and 4.7 eV, respectively) that are lower than Au and closer to the graphene electron affinity (4.6 eV), so smaller charge density steps are expected for the Ni and Cu cases.

To calculate the $R_{JUN}$ values, GFETs with different $L_{CH}$ are simulated by imposing $R_{M-G} = 0$ in the MC model (see Eq. 9). Then the simulated $R_{SH}$ and $R_{JUN}$ are extracted again via the linear fitting of the GFET resistance vs. $L_{CH}$ curves. Figure 9 (lines) directly reports the MC results for $R_{SH}$. By assuming standard graphene scattering parameters (dashed line), the simulated $R_{SH}$ is smaller than in the experiments, especially at large magnitudes of the vertical electric field $|F|$. This may reflect a non ideal graphene quality, with increased scattering. To the sole purpose of reproducing the experiments with the model, the deformation potential $D_{AC}$ of the acoustic phonons is empirically increased (solid line). Now simulations are much closer to the measurements for large $|F|$ values, although the simulated $R_{SH}$ is larger close to the DP (at $F = 0$). By assuming the two $D_{AC}$ values in Fig. 9, the $R_{JUN}$ curves in Fig. 12 (green lines) are obtained, that are rather consistent with the data of the ballistic model for pseudojunctions in graphene of [27] (dot–dashed line).

$R_{JUN}$ is in the order of 100 $\Omega \cdot \mu$m or less, hence it is much smaller than the measured $R_C$ (symbols). In the worst case ($D_{AC} = 250$ eV), $R_{JUN}$ is about one tenth of $R_C$. These simulations allow us to estimate the relative error in the experimental $R_C$ due to the impact of the pseudojunction at the edge contact, that is obtained from Eq. 9 as

$$\varepsilon_r = \frac{R_C - R_{M-G}}{R_C} = -\frac{R_{SH}}{R_C W}\Delta L + \frac{R_{JUN}}{R_C}. \quad (10)$$

In the first term of Eq. 10, $\frac{R_{SH}}{R_C W}$ is in the order of 1 $\mu$m$^{-1}$ (see Figs. 8 and 9) and $\Delta L < 10$ nm, making impossible to obtain negative $R_C$ values. Furthermore, from Fig. 12 it can be seen that $\frac{R_{JUN}}{R_C} < 0.1$, indicating that the error related to

$R_{JUN}$ is anyway limited, at least in our study. In particular, neglecting $R_{JUN}$, the error made is less that 10%, a value that is below the average error due to the $R_C$ extraction procedure with TLM, as reported in Fig. 8(b).

## V. Conclusions

It has been shown how the use of TLM to extract the M–G contact resistance may lead to artifacts, like negative $R_C$ values. This is due to the small variation of the $V_{DP}$ value among the GFETs in the same TLM array, that hampers to have the same charge density in the channel of the different GFETs used to extract $R_C$.

It is possible to suppress this effect by shifting the $I_{DS}$–$V_{DS}$ characteristics, thus compensating the DP position differences. This largely reduces the errors related to the extracted values. It is also possible to exclude the outliers from the linear regression of $R_T$ data; this further improves the dependability of the extracted $R_C$, but it has been also demonstrated that the largest source of $R_C$ errors is the above mentioned $V_{DP}$ variability. Furthermore, MC simulations have shown that the metal–induced doping and thus the pseudojunction at the contact edge cannot be the main origin of the negative $R_C$ values reported in the literature.

The developed procedure represents a guideline to extract dependable M–G contact resistance values through TLM structures, thus avoiding negative $R_C$ values. This has been verified also by presenting results for different metal contacts. Concluding, this study helps to assess the techniques to characterize the contact resistance of metal–2D materials stacks, also shading new light on the different contributions to the M–G contact resistance and promoting the better understanding of the physics governing the conduction through the M–G stack.

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