Contact resistance in graphene-based devices

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We report a systematic study of the contact resistance present at the interface between a metal (Ti) and graphene layers of different, known thickness. By comparing devices fabricated on 11 graphene flakes we demonstrate that the contact resistance is quantitatively the same for single-, bi-, and tri-layer graphene (\(\sim 800 \pm 200 \Omega \mu m\)), and is in all cases independent of gate voltage and temperature. We argue that the observed behavior is due to charge transfer from the metal, causing the Fermi level in the graphene region under the contacts to shift far away from the charge neutrality point.

The versatility of graphene-based materials is illustrated by the large variety of novel electronic phenomena that have been recently discovered in these systems. Examples are provided by Klein tunneling in single layers and the opening of a gate tunable band gap in bilayers\textsuperscript{2,3,4,5,6,7,8,9,10,11,12,13}. This versatility, together with the surprisingly high values of carrier mobility\textsuperscript{8,11}—which exceed by far those of technologically relevant semiconductors such as Silicon—make graphene-based materials promising candidates for possible electronic device applications\textsuperscript{8,11}.

Whereas considerable work has focused on the electronic properties of bulk graphene, virtually no experiments have addressed the properties of metal/graphene interfaces\textsuperscript{2,10,11,12,13}. This is somewhat surprising, since these interfaces will unavoidably be present in future electronic device, and may crucially affect their performance. In recently demonstrated single-molecule sensors, for instance, graphene trilayers have been claimed to be better suited than single-layers because of a lower contact resistance, leading to a higher device sensitivity (the measurements of the values of contact resistance, however, were not discussed in any detail—see Ref. \textsuperscript{4} and related online supporting material).

Not only in the realm of electronic applications, but also for many transport experiments of fundamental interest, the quality of graphene/metal contacts is of crucial importance. For example, the simplest shot-noise measurements require the use of a two terminal configuration, and it was recently argued\textsuperscript{14} that properly taking into account the quality of the contacts is essential to interpret the experimental data correctly.

In order to better understand the influence of the contacts we have performed a series of measurements of the contact resistance (\(R_C\)) present at the interface between Ti/Au electrodes and graphene layers of different thickness (single, double and triple layer). The Ti/Au bilayer was chosen because, together with Cr/Au, it is most commonly used as electrode. In addition, in contrast to the Cr interlayer, Ti/graphene interface gives highly transmissive contacts, as demonstrated by the large probability for Andreev reflection reproducibly observed in Josephson junctions with Ti/Au\textsuperscript{15}.

Our work is based on transport measurements performed on graphene flakes of different thickness (11 in total: three single layers, six bilayers, and two trilayers), on which different kinds of devices were fabricated. Using these devices we succeeded in extracting the value of contact resistance as a function of gate voltage, using three different methods: through scaling as a function of device length, of device width, and by comparing the resistance values measured in a two and four terminal device configuration. We find that, irrespective of the method used to extract the contact resistance, \(R_C \approx 800 \Omega \mu m\), independent of thickness of the graphene layer, gate voltage, and temperature.

The graphene flakes utilized in the device fabrication were obtained by mechanical exfoliation of natural graphite, and subsequently transferred onto an highly doped Si substrate (acting as a back gate), coated with a 285nm SiO\textsubscript{2} layer. Metallic contacts were defined by conventional electron-beam lithography, electron-gun evaporation of Ti/Au (10/25nm thick), and lift-off. The thickness of the graphene layers was identified by determining the shift in intensity in the RGB green channel relative to the substrate\textsuperscript{7,16,17,18}, analyzing images taken with a digital camera under an optical microscope. For a number of flakes the thickness determination was also confirmed by means of transport measurements (quantum Hall effect, resistance dependence on a perpendicular electric field, etc.). Different contact configurations were employed, with two and four contacts, to enable the quantitative determination of the contact resistance by both scaling experiments and multi-terminal measurements. To this end, conducting channel with width \(W\) ranging from 0.8\(\mu m\) to 3.5\(\mu m\), and contact separation \(L\) ranging from 1.2\(\mu m\) to 8.8\(\mu m\) were fabricated. The use and the comparison of these different configurations was instrumental to insure the uniformity of the graphene layers and of the current injected from the contact, which are both essential for
a reliable quantitative determination of the contact resistance. All measurements were taken using a lock-in technique (excitation frequency: 19.3 Hz), in the linear transport regime, at temperatures ranging from 50 mK to 300 K, depending on the specific device.

The inset of Fig. 1 shows measurements of $R_{2p}(V_{bg})$ performed on devices fabricated on a bilayer graphene flake, with different contacts separations ($L$ ranging from 1.4 µm to 8.8 µm) and fixed conductive channel width ($W = 5.5$ µm). As it appears from the main graph in Fig. 1b, at each fixed value of $V_{bg}$ the total device resistance scales linearly with $L$. The deviations from such a linear dependence are small, indicating that the contact resistance for the different electrodes is approximately the same. From the linear extrapolation of $R_{2p}$ we determine the intercept at $L = 0$ as a function of $V_{bg}$. It appears that $R_C$ is only weakly dependent on $V_{bg}$ even in the charge neutrality region (see Fig. 1b), in contrast to the resistance of bilayer graphene, which exhibits a pronounced peak.

We have also checked the scaling as a function of contact width but fixed channel length, by comparing two devices fabricated on the same flake. In this case $R_C$ is given by $(R_{2p}^{Dev1} - \rho_G(V_{bg})L^{Dev1}/W^{Dev1})/2$, with $\rho_G(V_{bg}) = (R_{2p}^{Dev1} - R_{2p}^{Dev2})(L^{Dev1}/W^{Dev1} - L^{Dev2}/W^{Dev2})^{-1}$. In Fig. 2a-d we show the results of these experiments for layers of different thickness, with the light grey lines representing values obtained for $R_C$ as a function of $V_{bg}$. Consistently with the previous results, also these experiments show that $R_C$ is a gate independent quantity over the full back gate range ($\sim R_C \sim 800 \Omega$) and that its value ($\sim 800 \Omega \mu m$) does not depend on the thickness of graphene layer.

Finally, we have extracted the value of $R_C$ by comparing directly two and four probe resistance measurements. In a four-probe configuration only the resistance of the graphene channel is measured, i.e. $R_G(V_{bg}) = R_{4p}$. From the value of $R_{4p}$ and the known device geometry we obtain the resistivity of graphene, and use it to extract the contact resistance from resistance measured in a two-terminal configuration $R_{2p}$. In Fig. 2e we plot $R_{2p}$ and $R_{4p}$ versus $V_{bg}$, together with the extracted $R_C$. Once again we find that $R_C \sim 800 \Omega \mu m$ and gate voltage independent. The fact that all these three independent transport methods (scaling of $L$, $W$, and comparison of two- and four-probe measurements) give quantitatively consistent results confirms the validity of our analysis.

Note also that measurements performed at different temperature give the same result, indicating that contact resistance is temperature independent (or only very weakly temperature dependent) up to room temperature.

![FIG. 1: a) The inset shows the total device resistance $R_{2p}$ measured at $T = 250$ mK in a bilayer graphene with Ti/Au contacts for fixed device width ($W = 5.5$ µm) and several different contact separations (from high to low resistance $L = 1.4, 1.7, 3.5, 6$ and 8.8 µm, respectively). The main panel shows the scaling of the device resistance vs. $L$, for different values of fixed $V_{bg}$. ](image)

One of the methods most commonly used to determine the contribution of the resistance present at an interface between two different materials is by means of a scaling analysis of the resistance, measured in a two probe configuration in devices with different contact separations. Specifically, the two-probe resistance of a graphene device reads $R_{2p}(V_{bg}) = 2R_C(V_{bg}) + R_G(V_{bg})$, where $R_G = \rho_G(V_{bg})L/W$ is the contribution of graphene to the resistance ($\rho_G(V_{bg})$ graphene resistivity) and $R_C(V_{bg})$ is the (contact) resistance of one metal/graphene interface. Experimentally, $R_C(V_{bg})$ is obtained by measuring the resistance of devices having different lengths $L$, and extrapolating the data to $L = 0$ (while keeping fixed $W$).
FIG. 2: Gate-voltage dependence of $R_C$ (light gray curve) extracted from the scaling with device width of $R_{2p}$, on single layers in (a) (with $L = 2.75\mu m$, $W = 0.8$ and $2.4\mu m$ respectively for the continuous and dashed line measurements), on double layers in (b) ($L = 1.26\mu m$, $W = 1.05$ and $1.8\mu m$ respectively for the continuous and dashed line measurements), and on trilayers in (c,d) (in (c) $L = 1.2\mu m$, $W = 1.62$ and $1.94\mu m$ respectively for the continuous and dashed line, in (d) $L = 1.25\mu m$, $W = 1.66$ and $2.12\mu m$ respectively for the continuous and dashed line measurement).e) Gate-voltage dependence of $R_C$ obtained from the comparison of two and four probe measurements, as described in the text, for a double layer device ($W = 3.3\mu m, L = 1.96\mu m$).

and tri-layer are markedly different, the independence of $R_C$ from layer thickness suggests that a substantial charge transfer from the metal contact to the graphene shifts the Fermi level far from the degeneracy point. This same argument may also explain why $R_C$ is independent on $V_{bg}$, since the density of charge transferred from the metal contact can easily be much larger than the typical modulation induced by the back gate voltage. Indeed, it has been predicted theoretically that a large transfer of charge should occur between many different metals and graphene. For Ti, however, no calculations have been yet performed.

In conclusion we have conducted a systematic study in transport experiments of the contact resistance at graphene-metal (Ti/Au) interface, using single, double and triple layer graphene. Employing three independent methods we have established that $R_C$ is $\sim 800 \pm 200\Omega \mu m$, independent of back gate voltage, of temperature and of layer thickness. A significant charge transfer at the graphene-metal interface, which shifts the Fermi level of the few-layer graphene far away from degeneracy point, is the likely explanation for this unexpected result.

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