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Original Article

# Linear and non-linear electrical behaviors in graphene ribbon based devices

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## ABSTRACT

We experimentally investigate the carrier transport in back-gated graphene ribbons. The ribbons are monolayer graphene formed by the chemical vapor deposition process and transferred on the $SiO_2/Si$ substrate. Electrical measurements show that two categories of electrical behavior are distinguished, respectively, linear and nonlinear. The *in-situ* Raman characterization along the ribbons area highlights interesting results for the 2D peaks shift. The Raman shift variation corresponding to the position of the 2D peaks between all measured spectra extends from 2697 $cm^{-1}$ to 2700 $cm^{-1}$ for devices exhibiting a linear behavior. While, for the devices exhibiting a nonlinear behavior, the variation range is more important, from 2686 $cm^{-1}$ to 2704 $cm^{-1}$. These results reveal that the carrier density is non-uniform and localized in term of concentration over the ribbon area, and the electrical behavior appears strongly related to the graphene local carrier density.

## 1. Introduction

From the isolation of real two-dimensional carbon sheet in 2004 [1], the discovery of graphene has enabled intense fundamental and applied research activities in this novel two-dimensional carbon based electronic system. The huge scientific and technological interest in graphene has been largely driven by its physical properties, that make graphene as material with interesting low-dimensional physics and potential applications in electronics [2–5]. From electronic device point of view, graphene is a promising material for future smaller and faster electronics, it has been suggested as a channel material for the next generation of field effect transistors (FETs), and as a semi/conductive sheet upon which nanometer scale devices may be patterned to create single electron or few electron transistors [6].

The physical properties of graphene are the most explored ones for the new fundamental scientific perspectives [7]. Several studies used Raman spectroscopy to analyze the carrier density over large area of the samples [8–11]. This nondestructive characterization technique can be used as a support to explain the carrier density influence on electron transport.

Nonlinear electrical behavior was already reported for monolayer graphene ribbons at critical cryogenic temperature [12]. The nonlinear electrical behavior at the cryogenic temperature in the current–voltage characteristics (or $I_{ds}$–$V_{ds}$ curves) is attributed to the presence of an energy gap in graphene monolayer acting as a potential barrier for the carriers. Shin et al. [13] reported that the nonlinear electrical behavior in graphene ribbons was caused by doping in the ribbons. This conclusion was drawn after making measurements in two steps: first measurements were nonlinear, after performing a thermal treatment generated by a high current annealing on their devices, the nonlinear behavior were never been observed with more than 20 devices and the curves had a linear shape. They concluded that the nonlinear phenomenon is strongly correlated to electrochemical reactions caused by active radicals which are attached and detached to the graphene channel from air.

For the graphene ribbon based devices, many papers investigate the electrical behavior of the metal/graphene contact [7,14–16] since of its importance for the graphene FET applications. Experimental investigation [15] reported that the doped monolayer graphene beyond ~$10^{13}$ $cm^{-2}$ produces an ohmic behavior in contacting metal. In addition, in terms of theory and modeling of

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the graphene devices [17–21], it is important to get an ohmic graphene/metal contact in order to study the electronic behavior of the graphene as an active material in FET devices. In this emergent field of research, previous study of Vicarelli et al. [22] reported the importance of the graphene quality and the graphene defects on the optimization of the electrical properties of graphene devices.

In our study, hundreds of devices have been fabricated and measured. We observed two typical electrical behaviors: linear and non-linear output characteristics.

The objective of this work is the highlighting of the non-uniform carrier concentration impact on graphene ribbons electrical behavior. First, the scanning electron microscopy (SEM) characterizations show the studied devices. We will in parallel expose outlines of the devices fabrication process and the experimental setup for electrical measurements. Second, we present the typical electrical behaviors for hundreds measured devices. Then, the Raman characterization is used to evaluate the carrier's concentration in the graphene ribbon, leading to original conclusion.

## 2. Experiments and devices description

Two-terminal back-gated monolayer graphene ribbon devices are fabricated on conventional silicon (Si) substrate covered by a 90 nm-thick thermal silicon dioxide ($SiO_2$). Chemical vapor deposition (CVD) process is used for single-layer graphene deposition on Copper in CVD furnace, then the graphene layer is transferred on the $SiO_2$/Si substrate. The quality of graphene is checked with optical microscopy, SEM, Raman spectroscopy and Hall measurements. The large area Hall measurements reveal initial doping concentration of $1.9 \times 10^{13}$ $cm^{-2}$ and a mobility of 410 $cm^2$/V. For the devices fabrication, optical lithography is used for electrode patterning through a mask, an ohmic Ti/Au (10 nm/100 nm) metallic contacts are deposited by thermal evaporation and defined with lift-off technique.

After the fabrication step, it was necessary to evaluate the quality to select the best wafer for the measurements. For that, Raman spectroscopy was performed on the different samples. Even though SEM imaging provides a more precise view of the graphene, this technique was used only on few devices because it is known to induce a contamination of the graphene surface. During these steps the rest of the devices were kept in a nitrogen atmosphere enclosure.

In order to study the electrical behavior in the graphene ribbons, we performed measurements in the vacuum on hundreds of devices. The devices are 10 μm-long by 16 μm-wide supported by the $SiO_2$/Si substrate. In Fig. 1, one of the measured devices is illustrated. The three dimensional (3D) view of the device structure is shown in Fig. 1a. The graphene ribbon between the source and drain metallic contacts can be distinguished on SEM image in Fig. 1b. The typical Raman spectrum of the graphene on $SiO_2$ is shown in Fig. 1c. The 2D peak is fitted by one single Lorentzian component indicating that the graphene ribbon is monolayer. Complementary information about the Raman measurements is given in Section 3.2.

The electrical measurements of the graphene ribbons at room temperature were tested using a micro probe station (CPX Cryogenic 6 probes system) under vacuum with chamber pressure below $10^{-5}$ mTorr, reached with a turbo vacuum pump. The samples were kept under vacuum for 6 h for the test, and one day before the measurements, to minimize any effect resulting from any adsorbed or desorbed particles or radicals on the surface of graphene. The current–voltage data were collected thereafter by an Agilent K4200-SCS semiconductor analyzer. The 3D schematic view of the measurement setup is shown in Fig. 2g.

## 3. Results and discussion

### 3.1. Electrical characterization

From all the measured devices, we distinguish two typical electrical behaviors that can illustrate all the devices. First, we note the nonlinear (NL) device: the measurements presenting a NL behavior, second, the linear (L) device: the measurements presenting a L behavior, as shown in Fig. 2. As reported previously [13], we also make measurements on our devices before and after a high current annealing in order to generate a thermal heating in the graphene ribbons. None difference was observed in the measurements with respect to those presented in Fig. 2.

From Fig. 2a and b, while the gate voltage is varied from 0 V to 40 V, the resistance of the device increases monotonically, this evolution indicates that the ribbons are of p-type. In Fig. 2c–f, we compare the room temperature output characteristics for each gate voltage value. The comparison between the two behaviors for a constant back gate voltage shows that there is a difference in current transport behavior in the ribbon for both NL and L devices.

We can easily differentiate two slopes from the NL output characteristics. A first slope at low drain voltage, for $V_{ds} < 0.8$ V, defining a linear low voltage regime. The second slope have a larger tilt, for $V_{ds} > 0.8$ V, shows a kink effect, defining a high voltage regime.

In Fig. 3a, the drain current decreases with increasing back gate voltage down to reach a minimum value corresponding to the charge neutrality point (CNP) at $V_{gs} = 39$ V. From these data, we can define the minimum carrier concentration $n_{min} = 4 \times 10^{12}$ $cm^{-2}$ and the mobility $\mu = 560$ $cm^2$/V of the graphene. This result demonstrates the influence of the gate voltage on the graphene ambipolar behavior.

From the L device measurements shown in Fig. 3b, it is clear that the CNP is situated beyond 60 V. The ribbon cannot resist to such voltage range, so, we cannot define the CNP with accuracy. However, the comparison of these measurements with those in Fig. 3a reveals that the L device is more doped than NL device. Consequently, these results suggest that the difference in both electrical behaviors is directly related to the position of the CNP, i.e., related to the graphene carrier's concentration. For more accuracy, we used Raman analysis to evaluate the carrier's concentrations over the graphene ribbons.

Otherwise, in term of experimental measurements, all devices having a CNP > 60 V exhibit a linear behavior, while, all devices exhibiting a nonlinear behavior have a CNP in a range from 39 V to 55 V.

### 3.2. Raman characterization

In this part, we aim to identify how the Raman shift changes through the ribbon area. We investigate the NL and L ribbons with Raman spectroscopy with 514.5 nm laser excitation wavelength and 1% power filter in order to do not damage the graphene. The Raman spectra are collected with a ×100 objective, the spectrometer with 2400 line/mm grating and the Raman resolution is 0.2 $cm^{-1}$. Changes in the bands position are reported.

As shown in Fig. 2, the nonlinear behavior is independent of the back gate voltage, so, the Raman measurements were performed without any bias.

The influence of the graphene carrier's concentration on Raman spectra was already studied, it was demonstrated that Raman spectroscopy is an excellent method to estimate the carrier's concentration in graphene [8–11]. According to Ferrari et al. [8], the 2D peak is independent of the defects, thus, it is always present. Moreover, the shape of the 2D peak is the most effective way to

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