Nanoscale Diodes Without *p-n* Junctions

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Abstract. The *p-n* junction cannot be implemented at the nanoscale because the doping is very often a detrimental effect. The doping could change dramatically the properties of a nanomaterial such as graphene or single-walled carbon nanotubes. Therefore, we will present two graphene diodes without a *p-n* junction. The first is based on the dissimilar metals having workfunction below and above the graphene workfunction and playing the role of a Schottky diode. The second diode is a ballistic graphene diode having a trapezoidal-shape where the rectification is achieved only by the geometry of the device.

1. Graphene Schottky Diodes Based on Graphene

The Schottky diode is the second electronic device as importance after transistors. The Schottky diodes due to their abrupt nonlinear *I-V* characteristics are used in any electronic circuit where nonlinearities are needed *i.e.* in multipliers, mixers, detectors. Schottky diodes are well-known in semiconductors where metal such as Mo, Pt, or Au or metallic alloys and a semiconductor (*e.g.* Si, GaAs), are producing a Schottky barrier [1]. When new nanomaterials have attained a certain degree of maturity new Schottky diodes were developed using nanoparticles, nanowires, and nanotubes. Also geometrical diode via carving parallel channels in 2 DEG devices are used to detect THz waves at room temperature [2].

In principle, the CNT Schottky diodes are implemented with the help of asymmetric contacts [3] and this principle is used even to diodes operating at THz frequencies[4]. However, the impedance of a single CNT is greater than 6.5 kΩ which is a huge mismatch since 50 Ω is used for RF instrumentation. This is a problem for all nanomaterials enumerated above and there are not straightway methods to solve this. In the case of CNTs, many parallel CNTs could reach 50 Ω, but the process is not fully reproducible.

The aim of this first part of the paper is to use the metal contact asymmetry for a Schottky diode based on a graphene monolayer. The wok is motivated by the previous work on Schottky diodes graphene displaying poor performances *i.e.* the current does not exceed more than 100–200 μA and poor high frequency performances.[5], [6].

Our graphene diode is fabricated using a coplanar line (CPW), where the central conductor is the central conductor and the outer electrodes are grounds.

The Schottky diodes formed by dissimilar electrodes were deposited on a graphene monolayer which is deposited on Si/SiO_2. We have used a high-resistivity Si substrate, with resistivity greater than 8 kΩ, which has on the top a 300 nm of SiO_2 thermally deposited. Outside Schottky diode area , RF pads were patterned on SiO_2. Fig. 1 is a SEM of our Schottky diode:

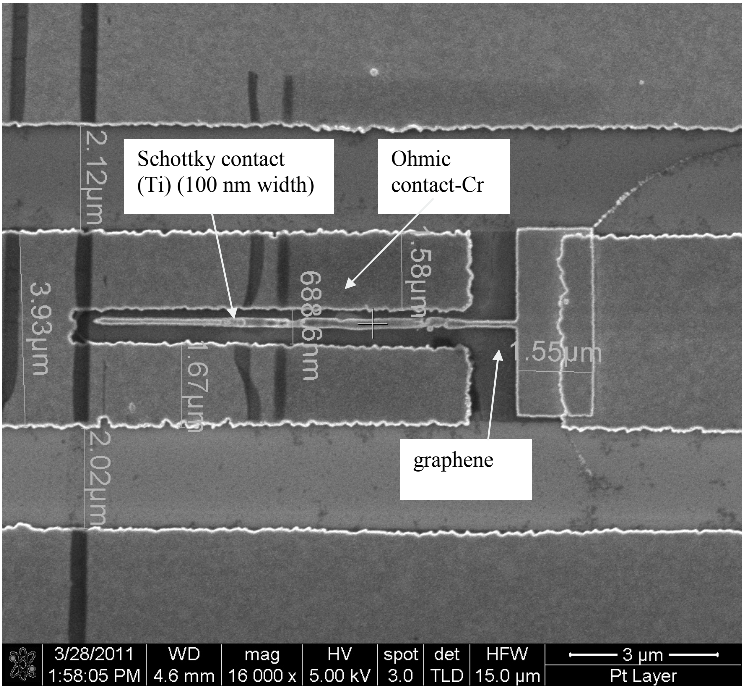

Fig. 1. The Schottky diode (from [7]).

We see that thet the central conductor is formed by the two dissimilar electrodes on graphene. The fabrication which implies the utilization of e-beam lithography several times to define in PMMA first the Cr electrodes and then the Ti electrodes, is described in [7]. However, a typical technological flow scheme of fabricating graphene device is depicted in Fig. 2 In the case of the above diode the technological flow scheme is repeated two times for each metal.

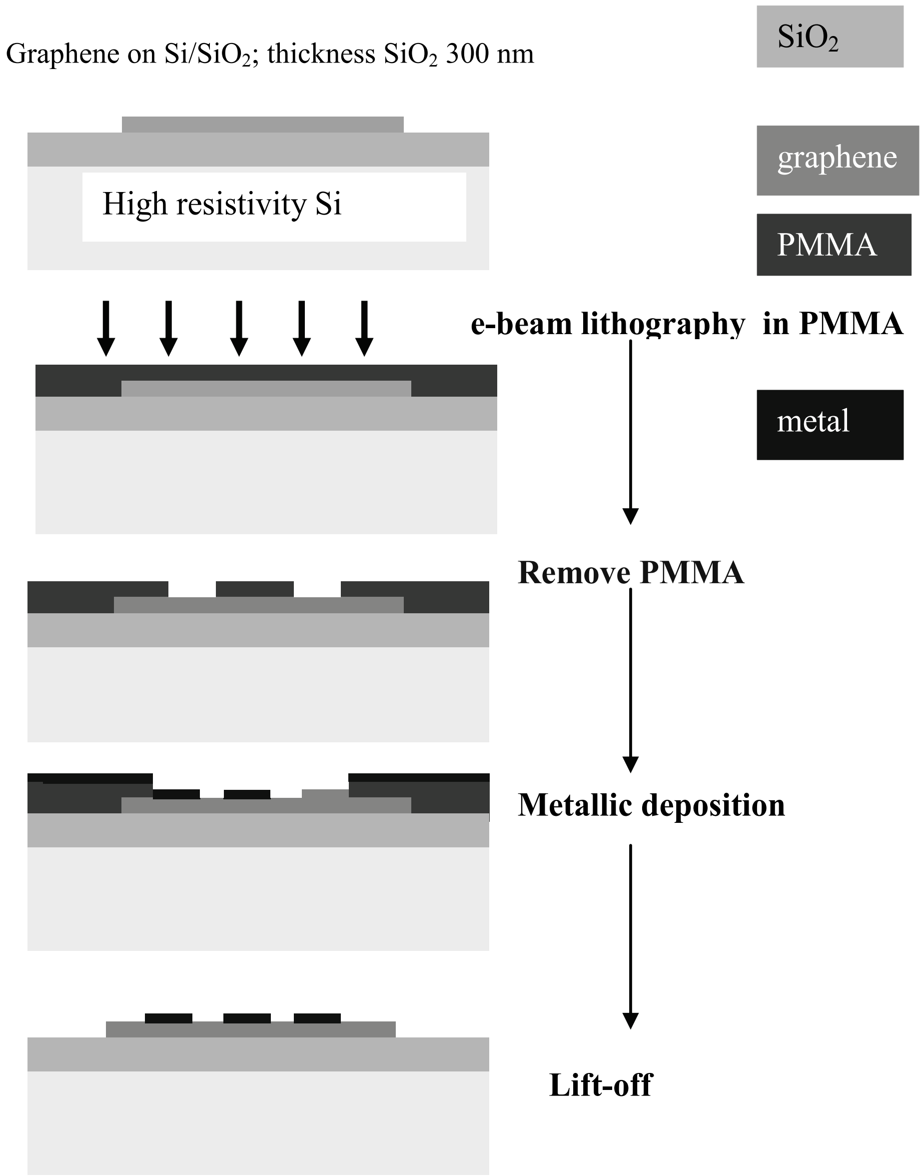

Fig. 2. The typical technological scheme for fabrication RF graphene devices.

In the following table we show the metals which are resistive or make a Schottky contact on graphene taking into account that the graphene workfunction is around -4.5 eV.

Table 1.

Schottky contact:

Metal	Work function (eV)
Al	-4.27 eV
Ti	**-4..3 3 eV**

Ohmic contact:

Metal	Work function (eV)
Pd	-5. 12 eV
Cr	**-4.5 eV**

This Ti/Cr Schottky diode on graphene based on dissimilar metallic contact has an I-V dependence represented in Fig. 3.

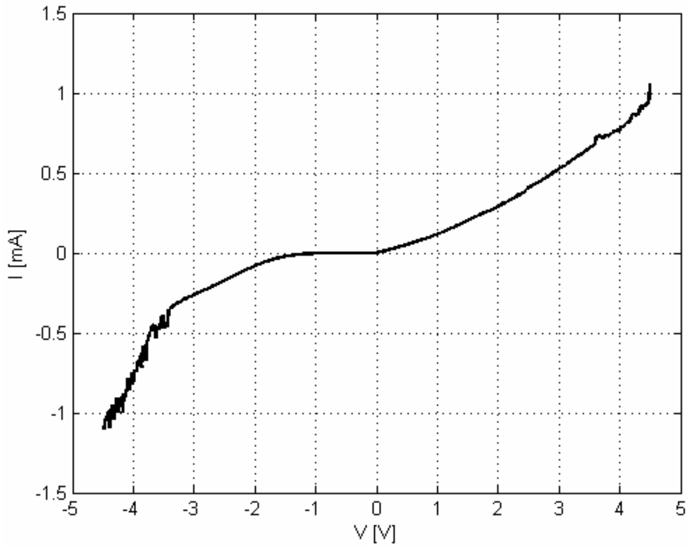

Fig. 3. The I-V dependence of graphene Schottky [7].

We see that in Fig. 3 all the characteristics of a Schottky diode *i.e.*(i) a rectifying region where the current is very low and two conduction regions. In the positive bias region we see that the current is increasing very fast and at 4.5 V we have 1 mA. We have measured the all the S parameters of the diode in the range 0.04–65 GHz. Based on them we have elaborated an equivalent circuit represented in Fig. 4.

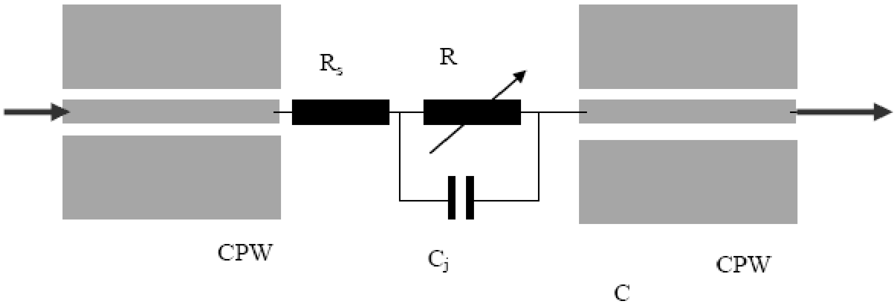

Fig. 4. Equivalent circuit model.

Based on DC and microwave measurement we have extracted the parameters of the diode *i.e.* the series resistance R*s* and the junction capacitance, *Cj* and having the following values:

Table 2.

Bias voltage (V)	RS [Ω]	CJ [fF]
0V	60	3.5
1V	60	3.5
2V	60	3.5
3V	60	3.5
4V	60	3.5

These values allow us to calculate the conversion loss of a graphene mixer with two antiparallel Schottky diodes (see Fig. 5):

$$CL(\mathrm{dB}) = 3.9 + 1.7 f / f_C + 9 R_S / Z_0$$

At 10 GHz and $Z_0 = 100\ \Omega$ we have a CL of 9.2 dB.

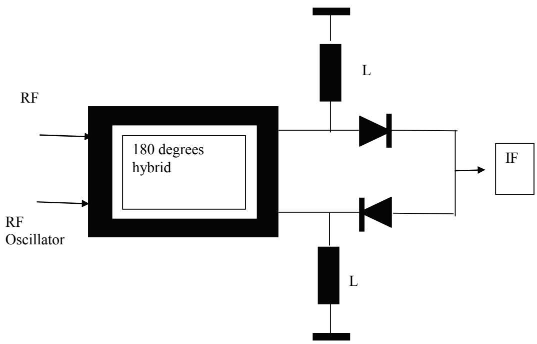

Fig. 5. A graphene Schottky mixer.

This approach has emerged after various works based on graphene FET resistive mixers. Here the drain-source resistance ratio Rds(max)/Rds (Vg = 0) must be greater than 10 which is difficult to be obtained even when nanoidentations are done in the graphene channel.[8]. The reason is that graphene monolayers have no bandgap. Moreover, these nanoidentations mean a lot of work using e-beam nanolithography and the results are hardly reproducible, So, a graphene bilayer will be more suitable, but here very high dc fields are applied to open the gap which could destroy the entire transistor.

2. A ballistic Graphene Diode on Graphene

A geometric diode is a diode which rectifies signals only due its shape. Such a diode is represented in Fig. 6.

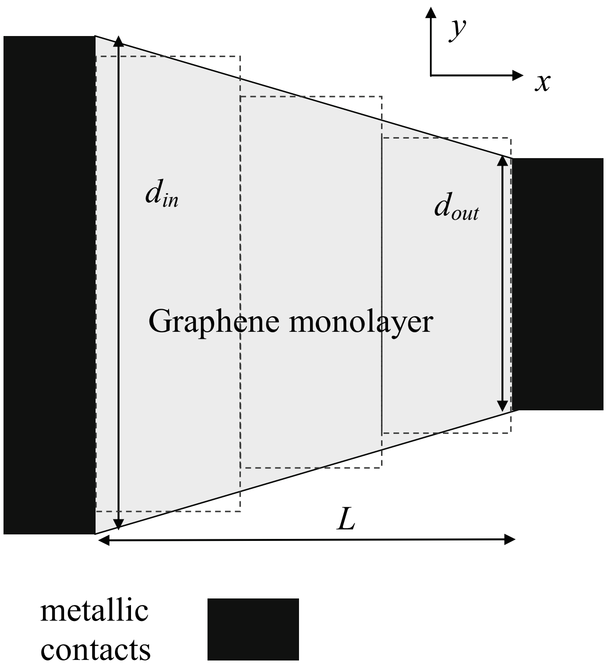

Fig. 6. A geometric diode on graphene.

The graphene diode is designed to have a ballistic transport. The theory of this diode is explained in [9], while in [10] it is described the fabrication on a graphene monolayer wafer. The length of the diode is 100 nm while the graphen monolayer has a mean-free-path at room temperature of 300–400 nm. The diode shoulder is also 100 nm while its neck is only 30 nm. The diode is represented in Fig. 7.

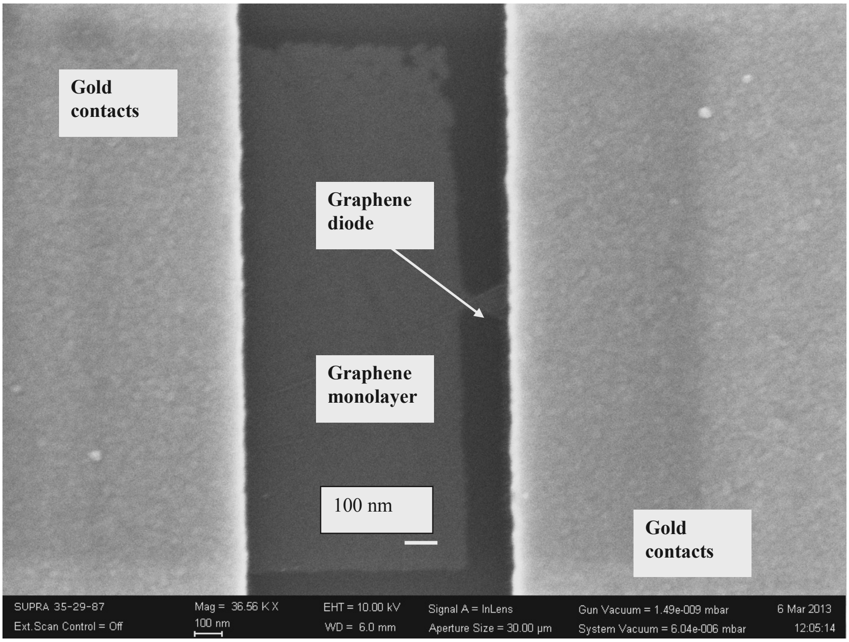

Fig. 7. The graphene geometric diode (SEM) [10].

The I-V characteristics of the diode is represented in Fig. 8

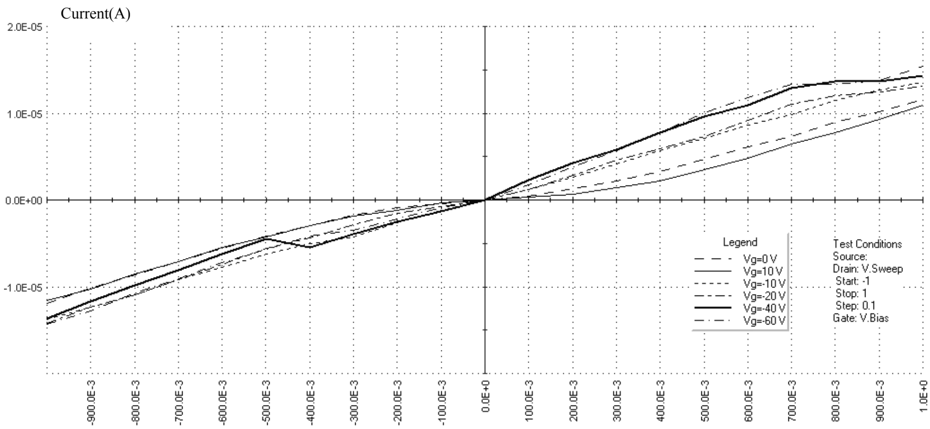

Fig. 8. The I-V dependence of the geometric diode.

The diode was measured using a Keithley 4200 SCS we can see that at small back -gate voltages (-10 – -30 V), a zero current region of about 0.7 V is present However, at the high back-gate voltages of -60 V, there are too many electrons and the ballistic transport is lost. Therefore. the zero current region is vanishing and we see a linear dependence of I-V followed by a current saturation. The cutoff frequency of these diode is about 15 THz.

3. Conclusions

We have reported two different types of graphene diodes which are junctionless. Both shows good performances and work at high frequencies.

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