Millimeterwave Schottky diode on grapene monolayer via asymmetric metal contacts

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The paper presents the experiments regarding a Schottky diode fabricated on a graphene monolayer using asymmetric metallic contacts. The current is in the mA range, which is with orders of magnitude higher than for reported Schottky diodes prepared on graphene bilayers or related graphene materials. Moreover, this device exhibits a DC controllable phase shift of more than 20 degrees in the range 40–65 GHz. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4759347]

I. INTRODUCTION

The Schottky diode is a key component in many circuits, such as multipliers, mixers, and detectors, due to its strong nonlinear current-voltage (*I-V*) characteristic. Taking into account the very broad spectrum of applications of the Schottky diode, we could claim that this device is the most important electronic component after the transistor. Conventional Schottky diodes consist of a contact between a metal (Mo, Pt, Cr, W) and a semiconductor (Si, GaAs, SiC or GaN), which creates a Schottky barrier. More recently, Schottky nanodiodes based on nanomaterials, such as nanoparticles,[1] nanowires,[2] and nanotubes[3] have appeared. Furthermore, the symmetry breaking in tailored semiconductor short channels[4] has been shown to display a Schottky-like behavior.[4] The quest for new Schottky nanodiodes is powered by the longstanding expectation that significantly higher performances could be achieved compared to its semiconductor counterpart and thus signal processing at high frequencies could be achieved. Very recently, THz fields were detected at room temperature[5] using a unipolar nanodiode based on symmetry breaking in a nanochannel (see Ref. 5). We also show below that a millimeter-wave phase shifter controllable by an applied DC voltage can be fabricated using a graphene monolayer and metallic asymmetric contacts.

In the last years, carbon nanotubes (CNTs) and graphene were used to obtain Schottky diodes at the nanoscale. The Schottky diodes based on CNTs are implemented using asymmetric metal contacts.[6,7] Rectifying signals are obtained up to 40 GHz.[8] The main issue with Schottky diodes based on CNTs is the impedance of a single CNT, which is greater than 6.5 kΩ. This produces a very large impedance mismatch compared to the typically used 50 Ω. Therefore, CNT horizontal arrays formed by hundreds of CNT in parallel are used to alleviate this thorny issue. Impedance mismatch, however, is not present in the case of graphene. In fact, it was shown that graphene embedded in a coplanar waveguide (CPW) can exhibit 50 Ω impedance. Moreover, the impedance of graphene is tunable in a wide range of frequencies well beyond 100 GHz.[9]

However, since graphene has no bandgap, no high-frequency Schottky diode on graphene has been reported so far. The few Schottky diodes on graphene reported up to now work only at low frequencies and exhibit poor performances. Another alternative is to fabricate a Schottky diode on a graphene bilayer, which exhibits a bandgap around the Dirac point, the bandgap being tunable with the gate voltage. Such a Schottky diode was recently fabricated by depositing an exfoliated bilayer graphene on doped Si.[10] The measured barrier was of 0.4 eV and the current did not exceed 0.2 mA. This is the graphene-based Schottky diode with the best performance so far. In addition, Schottky diodes based on graphene oxides, e.g., Ref. 11, exhibit poor performances with currents that did not exceed few nA.

II. THE FABRICATION OF THE SCHOTTKY-LIKE GRAPHENE DIODE

In this section, we present a Schottky-like diode able to withstand currents at mA level and to operate at millimeter wave frequencies, at which no graphene-based Schottky diode has been reported so far. To achieve this performance level, we have used a graphene monolayer with asymmetric metallic contacts deposited on a high-resistivity Si substrate, with resistivity greater than 8 kΩ, on which 300 nm of SiO_2 were thermally grown. The graphene monolayer deposition

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on Si/SiO_2 substrate was performed by Graphene Industries. Subsequently, three parallel metallic electrodes forming a CPW were patterned over the graphene monolayer. RF pads were connected to both ends of the CPW for easy connection with probe station. The central electrode is discontinuous and has a fork-finger geometry, as shown in Fig. 1. The central CPW conductor is the signal electrode and the outer conductors are ground electrodes. The Schottky diode on graphene monolayer is also displayed in Fig. 1. All other relevant dimensions are indicated on Fig. 1.

Before fabrication, we have used Raman spectroscopy to certify that we have a graphene monolayer. The spectra were obtained by the Labram Hr800 Raman spectrometer, at a laser wavelength of 633 nm. From the Raman spectrum displayed in Fig. 2 we see the absence of the D band, which reveals the high quality of the graphene layer.[12] The report between the intensities of 2D and G peaks is around 2, which confirm that we have a single layer of graphene. The 2D and G Raman peak positions are 2640 cm^{-1} and 1586 cm^{-1}, respectively.

Briefly, the fabrication of the device depicted in Fig. 1 was realized in the following steps: (i) the CPW pattern, including the central conductor but not the finger-like electrode was realized on PMMA using e-beam lithography. A 2-nm Cr/200-nm Au metallization was evaporated using e-gun evaporation. Within the fork-like gap and in contact with the opposite end of the signal electrode, a metallic finger (100 nm wide) was defined using the same technique. The second metallization was 50-nm Ti/100-nm Au. The graphene flake extending outside the signal electrode towards the ground was removed by oxygen plasma etching. In this way, graphene only exists in the area between the two signal electrodes. The Schottky graphene device was terminated with coplanar lines to reach the final pitch of 150 μm of the probe tips, in order to enable on wafer measurements with a vector network analyzer (VNA). An identical CPW structure, termed as reference, was fabricated on the same wafer, but outside the graphene area on the SiO_2 substrate, to

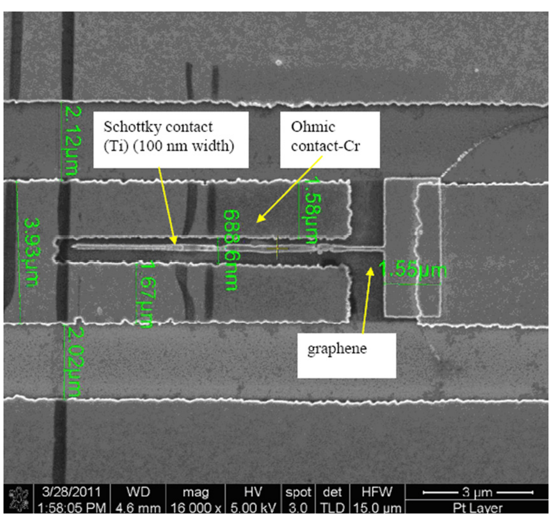

FIG. 1. The SEM photo of the Schottky diode fabricated on a graphene monolayer.

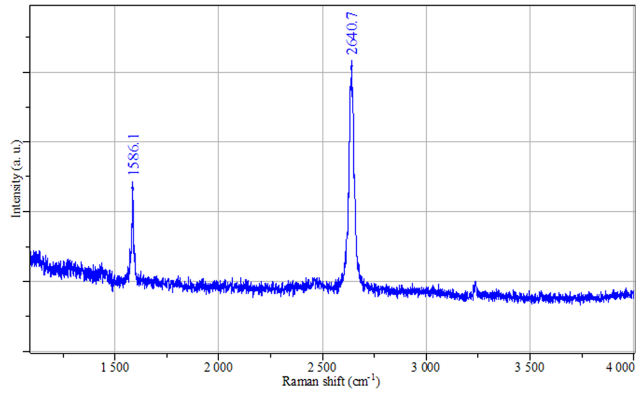

FIG. 2. The Raman spectrum of the graphene monolayer.

be employed for comparison and RF measurements de-embedding.

III. MEASUREMENTS

We have measured the DC characteristics and the millimeter wave response using a probe station connected directly with a VNA-Anritsu-37397D. The SOLT (short, open, load, and thru) calibration standard was used to calibrate the system. The CPW Schottky-like graphene structure was DC biased in the range -5 V to $+5$ V (with + on the finger-like conductor) using the internal bias tee of the VNA coupled to a Keithley 4200 semiconductor characterization system (SCS). The Keithley 4200 SCS is programmed for two tasks: (a) to measure the DC characteristic of the device directly on wafer and (b) to bias the device for a period of time ($\approx$1 min) necessary to measure the S-parameters and to store them on a computer at a given bias point. In this way, the *I-V* dependence and the S-parameters were measured with a single set-up. Moreover, during S-parameter measurements, the DC current in the device is monitored to ensure that it has a similar value to that measured during DC measurements. The obtained *I-V* dependence of the device is displayed in Fig. 3. A Schottky-like behavior is observed. One may clearly identify a breakdown region, a leakage region, where the current flowing through the device is very small (10 nA)

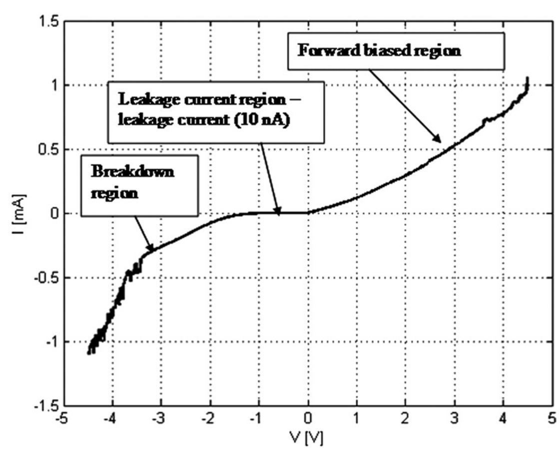

FIG. 3. The I-V dependence of the Schottky-like graphene diode.

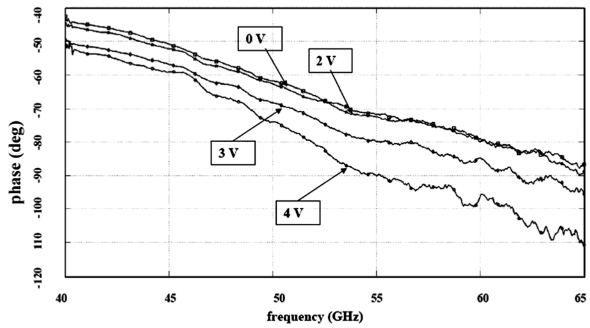

FIG. 4. The phase behavior in the range 40–65 GHz.

and similar to semiconducting Schottky diodes, and finally the forward biased region, where the current is increasing rapidly, reaching 1 mA at 4.5 V.

The S-parameters were also measured at various positive DC voltages. The transmission losses are approximately -10 dB at 40 GHz and decrease down to -5 dB at 65 GHz when no bias is applied. The losses are mainly due to CPW, fact confirmed by the measurement of the CPW reference and the subsequent de-embedding results that identified the source of losses. The phase of S21 is displayed in Fig. 4 at various voltages ranging from 0 V to 4 V. It can be seen that the phase varies almost linearly with the applied DC voltage, and at 65 GHz, the phase shift changes when the applied DC varies from 0 V to 4 V is 22 degrees. A larger phase shift could be obtained by connecting more Schottky-like graphene devices in series or by using more advanced configurations which are beyond the scope of this paper. Phase shifters are of paramount importance in phase antenna arrays and many approaches to implement them are known based on solid state devices, such as ferrites, *p-i-n* diodes, field effect transistors, and microelectromechanical systems, each of them having their advantages and drawbacks. Our Schottky-like graphene diode is the newest addition to this long list incorporating a half century of applied physics. Our Schottky diode is working at mA level and displays good high-frequency characteristics at millimeterwaves. The above performances of our Schottky graphene diode are due to the chosen asymmetric metal configuration.

IV. DISCUSSIONS

The above DC and millimeter wave performances of our Schottky graphene diode are due to the chosen asymmetric metal configuration and the high purity graphene monolayer. Cr is a good resistive contact (with a work function of 4.5 eV, like graphene), while Ti is a Schottky contact (with a work function of 4.33 eV). As expected, the mA current level obtained in our Schottky diode is with orders of magnitude greater than in similar devices with asymmetric contacts based on single CNTs due to a much larger contact area. For example, Ti was used as Schottky contact for the best known CNT Schottky diode with a cutoff frequency in the THz range.[13] However, the current in Ref. 13 is at μA level, because the resistance in a single CNT is about 160 kΩ, while in our case is of only 60 Ω, thus much smaller and more suitable to be matched with RF environment. Moreover, the current in our Schottky diode is with several orders of magnitude larger than in Schottky diodes based on graphene oxides (see Ref. 11), due to the much larger resistance in the last case originating from boundary defects.

However, even if compared with Schottky diodes based on high-quality graphene layers, our device scores well. For instance, in our device, with a contact area of 0.7 μm^2, we have obtained a similar current, of about 0.2 mA at 1 V, as in graphene-silicon Schottky diodes with a contact area one order of magnitude higher (of about 10 μm^2).[10]

Although many techniques were used to fabricate a graphene Schottky diode, it seems that the classical solution, used widely in semiconductor physics, with dissimilar metals termed as asymmetric contacts, is most suitable also for graphene. Due to this asymmetry and the utilization of a graphene monolayer having a high purity, we have reached the mA current level.

V. CONCLUSIONS

In conclusion, we have fabricated and a Schottky diode on a graphene monolayer using asymmetric metallic contacts and have characterized it in DC and at millimeter waves. The current reaches the mA level and the device exhibits a phase shift of more than 20 degrees in the range 40–65 GHz depending on the applied DC voltage.

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