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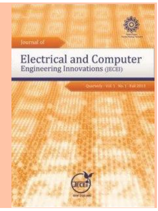

Simulation of IR Detector at Communications Window of 1550nm based on Graphene

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ABSTRACT

In this paper, photodetection properties of a Graphene-based device at the third telecommunication window have been reported. The structure of the device is a Graphene-silicon Schottky junction which has been simulated in the form of an infrared photodetector. Graphene has specific electrical and optical properties which makes this material a good candidate for optoelectronic applications. Photodetection characteristic of Graphene-silicon Schottky junction is investigated by measuring the (current-voltage) curve at the third telecommunication window under 1550nm radiations. The DC electrical characteristic of the device is calculated. The simulated rectifier junction has a potential barrier of 0.31eV, the ideality factor of 2.7 and the saturation current of 10-11A. The detector responsivity under 1550nm radiations is measured about 20mA/W which is an order of magnitude larger than other Si-based detectors in this wavelength. The internal quantum efficiency (QEin) is calculated about 60% while the external quantum efficiency (QEex) is measured to be 1.6%. A comprehensive theoretical justification is presented based on Fowler theory which allows comparison between the simulation results and the theoretical predictions. For simulating Graphene, a user-defined material is introduced to TCAD-SILVACO software which includes all electrical and optical properties of this novel 2D material. Graphene optical properties, specifically at near-IR region (up to 2um wavelength), have been extracted from the real measurement results. Graphene is a Si-compatible material which can provide a sensitive IR detector integrated with other Si-based devices.

1. Introduction

Graphene which is a two-dimensional material, discovered by Andre Geim and his colleagues in 2004 at the university of Manchester, has created a great revolution in science and technology [1]. First of all, Graphene has no energy gap. This feature can increase the number of Graphene carriers under radiation in a wide range of electromagnetic waves [2]. This spectrum contains ultraviolet, visible, short wave infrared (SWIR), near-infrared (NIR), mid-infrared (MIR), far infrared (FIR) and terahertz (THz) [3]-[10]. In addition, Graphene has ultrafast carriers, wideband absorption which is wavelength independent, tunable optical properties through electrostatic doping, low loss and high mobility [11]-[15]. Graphene also has unique mechanical and electrical features such as its nanometer size, high hardness and mechanical strength, high electrical conductivity, strength and flexibility [3].

The profiles of optics and photonics (a combination of electronic and optical characteristics), make Graphene an ideal photo-electronic material in the fabrication of optoelectronic devices such as solar cells, lasers and photodetectors [11], [15]-[16]. Different structures have been proposed to use graphene in optoelectronic devices. Graphene FETs (GFETs), graphene diodes, Graphene-based optical filters, graphene antennas and Graphene heterojunctions are some of these examples which are proposed for detecting, receiving, filtering and mixing of the electromagnetic waves [2]-[7], [9]-[11], [13]-[15]. Among these structure, Graphene-semiconductor junction has attracted much attentions due to its simple structure and easy fabrication process [3], [6]-[7], [17]-[27]. When such a junction is biased with a negative voltage, it can be used as an optical detector [11], [15].

When a Graphene-semiconductor junction is radiated by electromagnetic waves, the electron-hole pairs can be generated in both Graphene and semiconductor substrates. Considering Si as a semiconductor, it can absorb radiations with wavelengths shorter than 1um. So, if the junction is illuminated by longer wavelenghts such as mid-IR, Silicon substrate cannot absorb the radiations.

On the other hand, the most widely used wavelength in the third optical communication window is 1550nm. This wavelength cannot be absorbed by Si and it is a main problem in Si-based technology which cannot integrate all the necessary components of an optical data transmission system based on Silicon on a single chip. Although there are more sensitive detectors in comparison with our proposed structure at 1550nm wavelength, but the integration capability of the detector with other Si-based components like mixers and amplifiers on a single IC chip is very important from application view point. The application of Si-compatible materials, which can also absorb the long wavelengths like graphene, in the detector structure is of great interest and importance.

Here, we present a Si-compatible, Graphene-based, mid-IR detector. The structure is based on Graphene/Si heterojunction. The Graphene carriers in front of the junction potential absorb mid-IR radiations and get enough energy to surmount the potential barrier. It causes an increase in the reverse-biased current and in this way, can detect the radiations.

The two major problems in Graphene-based photodetector are the limits in the Graphene short carrier life time and small detection area [3]. Graphene-semiconductor Schottky diodes can effectively address these problems and produce higher response with the benefit of compatibility with semiconductor technology [3], [17].

In this Article, firstly, an introduction to two-dimensional Graphene material in combination with nano-material applications in electronic and optoelectronic devices is given. The detector structure of Graphene-silicon junction is physically examined. The simulation results are shown in various charts. Finally, a short discussion on responsivity calculation is presented.

2. Device Structure

Contact between a metal and a semiconductor can result in both cases of ohmic and Schottky junctions, and the latter is called the rectifier diode [14]. Ohmic contact is usually formed with a highly-doped semiconductor. In contrast, ideal Schottky junctions are usually formed by semiconductors with low level of doping. Compared to the conventional P-N junctions, Schottky diodes feature more current flow, that is why Schottky diodes are preferred in applications that require low voltage and high current [3],[6],[7]. A great advantage of Schottky diodes is that they do not include minority carrier recombination time. This makes it significantly faster and more convenient in digital logic circuits as high-speed switches [8]. The application of Schottky photodiodes in high-speed optical communication have been widely studied and practically implemented [9], [12], [28].

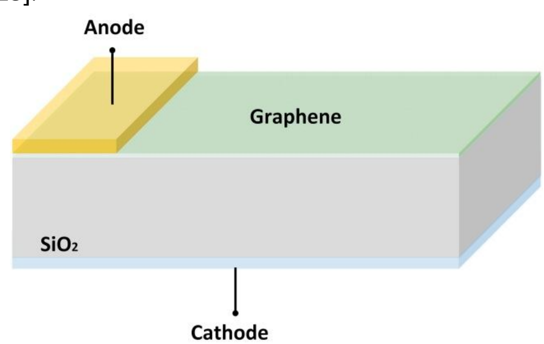


Figure 1: Three-dimensional structure of Graphene-Silicon heterostructure.

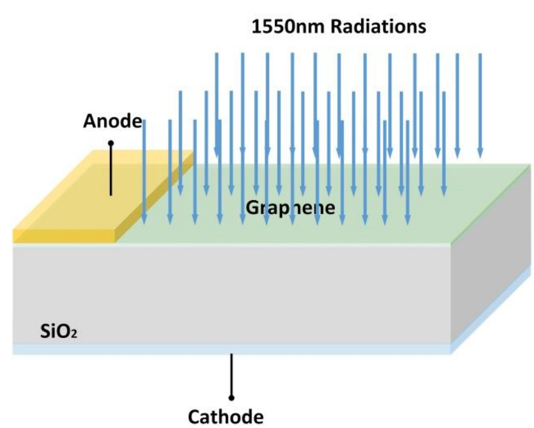


Figure 2: Three-dimensional structure of Graphene-Silicon Schottky diode under 1550nm mid-IR radiations.

Fig. 1 shows the structure of a Graphene-based photodetector which is simulated by TCAD-SILVACO software. The device is composed of two main materials, one is a p-type Silicon substrate with doping level of 10×10^{17}, dimensions of 100nm× 100nm and a thickness of 100 nm. The other is a Graphene layer with a thickness of 2nm and dimensions of 100nm×100nm which is formed on silicon substrates. The structure is simulated in nanometer scale. The two metals on the top and bottom of the device are considered as diode contacts. The junction is formed between Graphene and Silicon layers.

In Fig. 2, the structure simulated by applying radiation, is displayed. The radiations with the wavelength of 1550nm and different powers are applied on the Graphene layer.

3. Simulation Results

The simulated structure is tested in forward and reverse biased modes. Different voltage levels are applied to the anode of the detector. Figure 3-a demonstrates the current-voltage curve of Graphene-Silicon Schottky diode in the range of (-5V, +5V). The current-voltage relation of a Schottky diode is defined with the following equation:

$$I == I_s(e^{qV/KT} - 1) \quad (1)$$

In which, I_s is the reverse biased current or the saturation current, q is the charge of an electron, K is the Boltzman constant and T is the absolute temperature in kelvin. The saturation current (I_s) is obtained using:

$$I_s = ABT^2 e^{-q\phi_B/KT} \quad (2)$$

In which, A is the area of the junction, B is the Richardson constant and φ_B is the Schottky potential barrier of the junction. It is possible to calculate the barrier height (φ_B) from equation (2), according to:

$$\phi_B = \frac{KT}{q}\ln\left(\frac{ABT^2}{Is}\right) \quad (3)$$

Equation (1) leads to a rectifying behavior which is compatible with the plot presented in Figure 3-a. Using semi-logarithmic current-voltage curve as shown in Fig. 3-b, we have measured the saturation current of the device about 10^{-11}. By applying equation (3), the Schottky barrier potential is calculated as 0.31 eV. Additionally, we have calculated the ideality factor of the junction by measuring the slope of the semi-logarithmic current-voltage curve. The ideality factor is estimated to be 2.7.

Figure 3-b shows the reverse biased characteristic with greater accuracy in the range of (-5V, 0V). As can be seen, in the reverse biased mode, the current is not constant as a function of voltage and the current increases when the voltage increases. This effect is observed in Schottky diodes and is explained by the image force lowering effect [29]-[30]. This effect reduces the height of the Schottky potential barrier and increases the number of carriers which can surmount the barrier. Consequently, the current increases with increasing the reversed bias voltage.

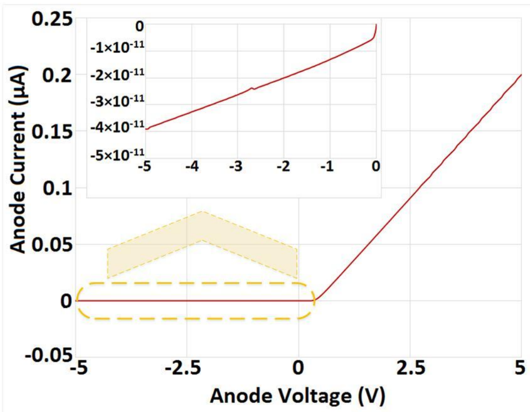
Figure 4 demonstrates the anode current under different power radiations. The power of 1550nm radiations varies from 0.001W/cm^2 to 100W/cm^2. As shown, the minimum current is 3.9pA under 0.001W/cm^2 and the maximum anode current is 0.3nA under 100W/cm^2 radiations.

Logarithmic graph of anode current under various power densities is shown in Figure 5 for the range of (-5^V,0^V). One of the peculiar feature of Schottky detectors is the voltage dependency of photocurrent [3], [29]-[30]. Due to the barrier lowering effect of the image force which is induced in the semiconductor, the photogenerated current grows up under larger voltage basing. It means that the responsivity of a Schottky detecor increases by increasing the voltage bias. But then, by increasing the voltage biasing, the thermal noise increases rapidly [3], [29]-[30]. This large amount of noise is caused by a large current density passing through the junction at larger voltage biases. Accordingly, there is always a trade-off between larger respsonsivity and larger thermal noise. On the other hand, there is no thermal effect in simulation envirment and hence the effect of thermal noise can not be observed. To consider such a source of noise, the noise simulator must be run in the software envirment which is beyond the scope of this paper.

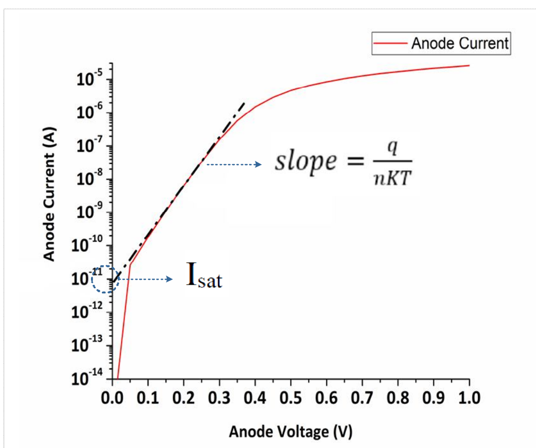
One of the parameters that is studied in detectors is the responsivity which is the portion of the photo-generated current to the power of the incident photons on the detector [13], [31]. The responsivity can be calculated using the following equation [29]-[30]:

$$R = \frac{\Delta I}{W} \quad (4)$$

In this equation, ΔI is the difference between the light and dark currents and W is the power of the incident photons. Using equation (2), the responsivity is calculated and shown in Figure 6 under different powers of radiations. As mentioned above, the incident photons are near-IR photons with the wavelength of 1550nm. Due to this figure, at medium power of radiations (from 1W/cm^2 to 100W/cm^2), the resonsivity is almost constant, but when the radiation power increases to very large values, the responsivity starts to decrease. The average value of the responsivity is around 20mA/W.



(a)



(b)

Figure 3: a) Current-Voltage characteristic curve in the range of (-5V,+5V). The inset of the figure shows the characteristic graph in the interval (-5, 0) volts, b) The semi-logarithmic view for current-voltage curve.

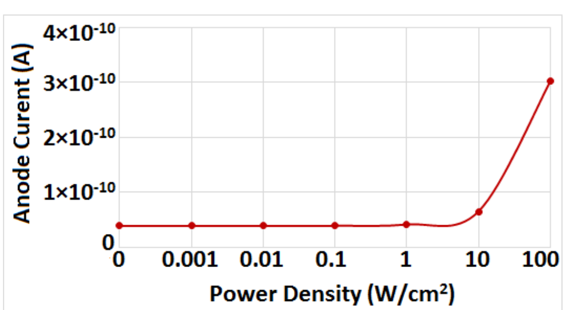


Figure 4: The anode current under different power radiations.

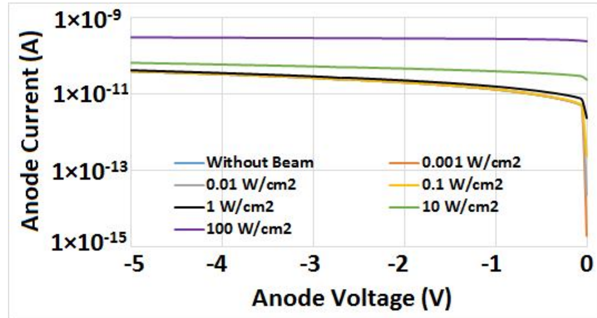


Figure 5: Logarithmic graph of anode current versus anode voltage under various power densities.

The reason can be explained by the absorption saturation in Graphene. Each photon can generate an electron-hole pair in Graphene. Increasing the power of the near-IR 1550nm illuminations will increase the number of photo-generated electron-hole pairs. On the other hand, the number of the generated pairs is restricted by the valency of the material. As the result, increasing the power to very large values, will result in the responsivity saturation in the presented detector.

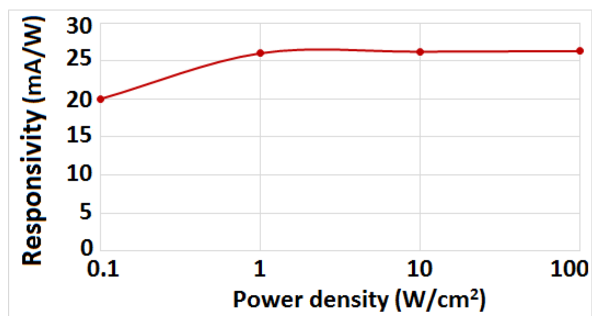


Figure 6: Responsivity as a function of input power.

4. Theoretical Justification

The current of a Schottky junction under reverse biasing is originated by the thermoionic emission [29]-[30]. In a reverse biased Schottky junction, the carriers are placed in front of a potential barrier. Only the carriers whose energy are larger than the Schotkky potential and their momentum are normal to the surface of the junction, can surmount this barrier [3], [32]-[34]. As the number of carriers with such a feature is limited in the material, the quantum efficiency of Schottky detectors are restricted to less than 1. This effect is explained quantitatively by Fowler theory [32]-[34]. Due to this theory, the internal quantum efficiency can be given by:

$$QE_{in} = \frac{(hf - \psi)^2}{8E_f hf} \quad (5)$$

in which hf is the energy of the incident photon, Ψ is the potential barrier and E_f is the Fermi level energy. This equation is obtained as the ratio of the carriers in the metal, which can escape over the barrier into the semiconductor substrate, to the number of total carriers, which are created due to the absorption of photons. Here, we calculate the quantum efficiency of the presented device experimentally and compare the result with theory. The quantum efficiency of a detector is defined as the proportion of the number of photo-carriers collected in the external circuits to the number of photons absorbed in the photo-detection area. Considering 2.3% absorption for the Graphene layer, the internal quantum efficiency can be calculated by the experimental data using the following equation:

$$QE_{in} = QE_{ex} \times \frac{100}{2.3} \quad (6)$$

in which QE_{ex} is the external quantum efficiency of the device and is given by:

$$QE_{ex} = \frac{R_\lambda}{\lambda^{\mu m}} \times 1.245 \quad (7)$$

In equation (7), R_λ is the spectral responsivity and λ is the wavelength of the incident light in microns. Using equation (6), we have calculated the internal quantum efficiency of the detector to be about 60%. Different methods have been applied to achieve complete light absorption in Graphene [35] to improve the *external* quantum efficiency to its *internal* amount. The value of the internal quantum efficiency is larger than the theoretical prediction.

A possible explanation for the high internal quantum efficiency of Graphene-Si Schottky detectors is based on the two dimensionality of Graphene and the presence of π orbitals in Graphene which are normal to Si surface. In other words the large quantum efficiency of Graphene-Si Schottky detector can be explained by Fowler theory for 2D materials [3]. The mobile carriers in Graphene sheets belong to π orbitals which are located up and down the Graphene layer.

The highly mobile carriers in these orbitals can move only in parallel to the Graphene sheets. In Graphene-Si junction, the photo-generated carriers in Graphene under 1550nm wavelength get enough energy to pass the potentials barriers. As explained above, only the carriers whose momentum are perpendicular to the junction surface can penetrate the Silicon layer. Since the Graphene carriers can move only in a plane parallel to the Graphene sheets, at least 50% of carriers have a momentum normal to the junction surface. These carriers have a chance to penetrate the junction. The rest of the carriers which have an opposite momentum cannot leak into the Si substrate [3]. Therefore, it is expected that the maximum quantum efficiency of Graphene-Si Schottky detector increases to 50 and the responsivity of such a junction can be as large as tens of mA/W.

Now, we compare the experimental result with the theoretical calculations of quantum efficiency when the thickness of silicide approaches zero in Si-based schottky diodes. In this case, the internal efficiency is given by [36]:

$$QE_{in} \approx \frac{(hf - \psi)}{hf} \quad (8)$$

Considering 0.8eV energy for 1.55um waves and the height of potential barrier equal to 0.31eV, the internal quantum efficiency is calculated to be 62% which is in very good agreement with the simulation results.

5. Conclusion

In this paper, the sensitivity of Graphene-Silicon Schottky contact was studied as an infrared detector. The current-voltage curves were simulated in both forward and reverse biases. The near-IR radiations with the wavelength of 1550nm were applied on the junction and the responsivity was calculated. The effect of the input power on the photo generated current and also on the responsivity was studied. The responsivity of the diode is around 20mA/W at -5V reverse voltage bias. Increasing the power can cause the saturation of absorption in Graphene. Due to the optical properties of Graphene and its potential for being integrated with Silicon in ICs, this device can be a good candidate for optical communication applications.

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