

2D Carbon Material/Silicon Heterojunctions for Fast Response Self-Powered Photodetector

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Received 19 January 2019

Accepted 6 February 2019

Published 13 May 2019

Photodetectors (PDs) based on single-walled carbon nanotube film/silicon and graphene/silicon heterojunctions have been realized for fast applications. We investigated the response of the PDs to femtosecond pulsed laser using a three-electrode configuration for photoconductive operations. Both junction PDs exhibit rise times of some nanoseconds, detecting light from ultraviolet (275 nm) to infrared (1150 nm). Applying a gate voltage V_G , the rise time decreases down to about 1 ns, making our devices comparable to most commercial PDs.

Keywords: Graphene; carbon nanotube; heterojunction; photodetector; pulsed laser.

1. Introduction

An emerging pathway to overcome the low efficiency in the near ultraviolet (UV) region of Si photodetectors (PDs) and to improve their response time is to replace the p - n Si junction with a graphene (G)/ n -Si¹ or single-walled carbon nanotube

(SWCNT)/ n -Si heterojunction (GSH or NSH, respectively). In such a way, it is possible to exploit the inherent optoelectronic properties of such carbon allotropes. Indeed, not only G² and SWCNT thin films³ are characterized by low light absorption in the visible and near infrared region, but they also

possess a very high absorption peak in the near UV region.² Moreover, G and SWCNT have a very high charge mobility and the diffusion time is estimated to be very low (for graphene < 1 ps). In this paper, we present a comparison between the response times of the GSH and NSH PDs as a function of the incident photon wavelength.

2. Experimental

The core of our PD schematically shown in Fig. 1 is an *n*-doped Si substrate (average donor density $N_D = 10^{16} \text{ cm}^{-3}$, average resistivity $\rho = 0.53 \Omega\text{-cm}$), 100 μm thick. On its bottom side, a Cr/Au ohmic contact have been grown. On its front side (the one exposed to the light radiation), two sets of Ti/Pt interdigitated electrodes have been fabricated on 300-nm thick SiO_2 template. The electrodes show a multifinger geometry formed by five fingers per each top electrical contact,⁴ leaving free *n*-Si active area of 7.8 mm^2 .

G has been grown on Cu by an atmospheric pressure chemical vapor deposition (CVD) process, using *n*-decane as a precursor gas. G deposition on the Si substrate occurred through wet-chemical room temperature transfer process without the use of a polymer support.² The as-grown G was fully characterized by optical absorption measurements, Raman spectroscopy and scanning tunnel microscopy (STM) showing a homogeneous film composed of several large sheets which in some places are composed of 1, 2 or maximum 3 layers.

The SWCNT film was realized with vacuum filtration and dry transfer process.³ It consists of an interconnected and self-assembled network of 90% semiconductor and 10% metal SWCNTs with the optical transmittance of 65% and sheet resistance of 450 Ω/sq , corresponding to the thickness of 30 nm. G or SWCNT film is deposited on the device surface to connect the Ti/Pt electrodes and to be in contact with the *n*-Si surface. Therefore, the PD has three

external controls, two are in contact with the G or SWCNT film (the interdigitated ones called source and drain) and the other with the Si (called gate).

To measure the response time of GSH and NSH PDs, we used as a light source a pulsed laser system consisting of a chirped pulse amplifier, seeded by a Ti:Sa oscillator and matched with a parametric optical amplifier. The laser system has the pulse duration of 35 fs with the repetition rate of 1 kHz and can change the wavelength from UV to IR. The signal is acquired by a 30 GHz Tektronix oscilloscope using coaxial cables connected to the device terminals, without using electronic filters or amplifier.

3. Results and Discussion

We report a comparison on the performances of the GSH and NSH PDs, working in a photoconductive mode, i.e., measuring the source–drain I_{SD} electrical current as a function of the gate voltage, V_G . We start with the response speed of NSH and GSH PDs without powering the device ($V_G = 0$). Indeed, we are able to measure a source–drain current, thanks to the built-in voltage present at the heterojunction. The mechanism underlying the process can be described as follows. The impinging light is absorbed (mainly in Si) and generates $e-h$ pairs. These pairs able to reach the heterojunction are separated, thanks to the built-in potential. Then, the electrons cross the Si substrate and reach the gate electrode (G), while the holes are injected into the G (or in the SWCNT film) and an electrical current I_{SD} can be measured.

The response speed of NSH and GSH PDs has been tested using the pulsed laser source, measuring the rise time (τ_r), defined as the time difference between the 90% and 10% of the full-scale signal. Figure 2 reports the photocurrent response of the two PD types for a single laser pulse ($\lambda = 275 \text{ nm}$) and incident photon energy of 100 nJ.

Both PD types have τ_r of a few nanoseconds. It is worth noting that our PDs are able to detect UV very fast signals without a need of power supply ($V_G = 0$) and signal amplification. This is essential for applications where it is important to keep limited the costs, dimensions and weight of the detection system. Figure 3 exhibits the rise time versus incident wavelength for photon energy of 200 nJ. Our PD skills in detecting ultra-fast signals from UV to IR, responding with τ_r of few ns. The results have two characteristics: the increase of τ_r with

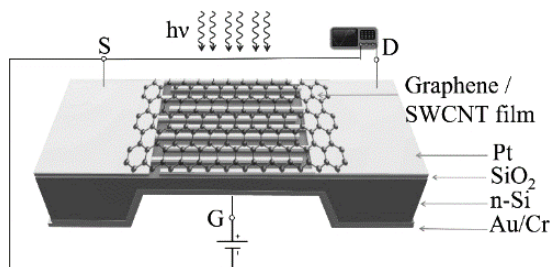


Fig. 1. 3D device schematic.

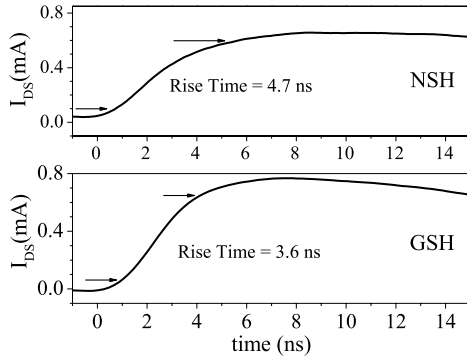


Fig. 2. Response to a single 35-fs laser pulse of NSH PD (top panel) and GSH PD (bottom panel) for incident light energy of 100 nJ and wavelength of 275 nm. The arrows indicate the 10% and the 90% of the pulse height used as a criterion for the rise time estimation.

increasing wavelength and a slightly longer τ_r , for all the investigated λ , for NSH compared to the GSH PD.

The first effect is due to the light penetration depth inside the *n*-Si layer: it increases with λ with a consequent *e-h* pair generation farther from the NSH (or GSH) interface resulting in a higher time necessary to reach the top electrode. The second one is due to a better-quality interface created between Si and G compared to that with the SWCNT film. Thanks to the high quality of the growth, to the deposition techniques but also to the 2D nature of the G that manages to contact the Si surface following the profile of the interdigitated electrodes, a sharper heterojunction is created. Moreover, the SWCNT film, though being interconnected and showing excellent electrical properties, has a thickness of about 30 nm. The charges take longer time to cross it. The same behavior is observed in the photon energy ranging from 1 nJ to 1 μ J. Moreover,

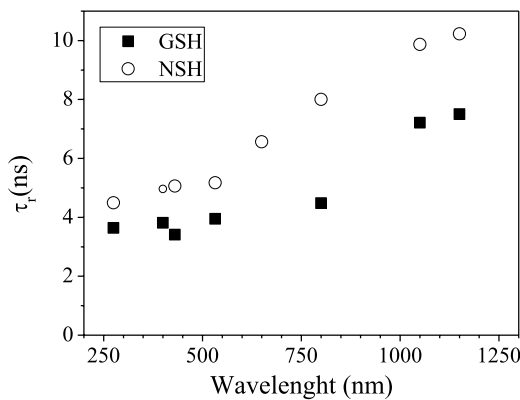


Fig. 3. Rise time versus wavelength under 35-fs pulsed laser source for incident light energy of 100 nJ.

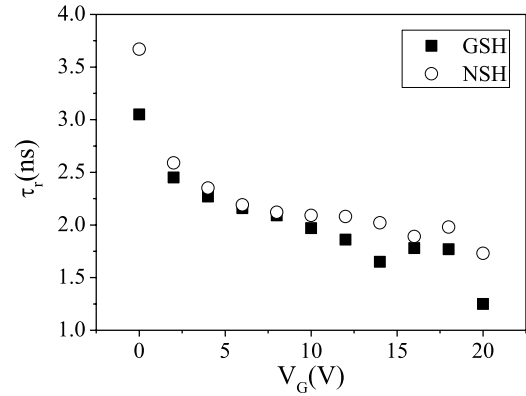


Fig. 4. τ_r as a function of V_G .

our PD shows a linear photocurrent response, confirming the possibility to be used for different applications with sources of various light intensity while maintaining the same response speed in ns regime.

For $V_G > 0$, the NSH and GSH are reverse polarized and there occurs a voltage doping effect: the holes of the *n*-Si region flow towards the G or the SWCNT film driven by the built-in potential present at the interface and by V_G . Figure 4 shows the rise time versus V_G for NSH and GSH PD for $E = 1$ nJ and $\lambda = 275$ nm. The voltage doping effect decreases τ_r . This means that photogenerated holes reach the G or the SWCNT film in a shorter time compared to the condition $V_G = 0$ because the charge drift velocity increases with increasing the applied voltage, thus making the PD faster as V_G increases. This trend has been verified for incident light at different λ and intensities. Finally, the current I_{SD} flowing through the G or SWCNT film increases when the junction is in the avalanche regime with respect to the current at $V_G = 0$ (data not shown here). In this avalanche regime, the external quantum efficiency (EQE) of the PD increases from 5% for NSH and 2% for GSH (for λ in the visible region) with $V_G = 0$ up to 100% for NSH and 200% for GSH with $V_G = 8$ V.⁴

4. Conclusion

We reported on NSH and GSH PDs able to detect fast signals ranging from near UV to near IR. The results show the response of our PD to be 3–4 ns, in absence of any power supply. This rise time is comparable to that of commercial Si based PDs. Thanks to the gate electrode it is possible to make holes doping within the G and SWCNT film that decrease the rise time to about 1 ns.

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