UDC 538.9

# TIME RESPONSE CHARACTERISTICS OF PHOTODETECTOR BASED ON GRAPHENE/n-Si HETEROJUNCTION

***L.A. Dronina, N.G. Kovalchuk, V.A. Papou,***
***A.V. Patapovich, Dr Hab S.L. Prischepa***
*Belarusian State University of Informatics and Radioelectronics,*
*Minsk, Belarus*

*This study presents the time response characteristics of graphene/n-Si heterojunction photodetector that have been estimated by using the room temperature on–off measurements under 450 nm and 642 nm illumination with a frequency of 175Hz and 1kHz. We obtained rise time values of at most 12.5 µs and 10.6 µs for the device measured under 642 nm and 450 nm light illumination with a frequency of 1kHz, respectively. Numerical calculations at the same frequency show that the light penetration depth (L) increases with increasing λ, and the main mechanism is diffusion in the graphene layer, while the drift time is insignificant.*

***Keywords:*** *graphene-based photodetector, chemical vapor deposition, time response characteristics, diffusion length.*

**Introduction.** In the past decade graphene has been one of the most studied material due to several unique and excellent properties that make it an ideal candidate for light detection in optical communications and optoelectronic devices. Moreover, the response time is an important factor in the detection of rapid modulated optical signal, which is in close relation with the photo-generated carriers recombination process. Response characterization analysis is used not only to measure the charge-transport properties of organic semiconductors and quantify the initial amount of photogenerated charge, but also to study the recombination kinetics in semiconductors, average doping density, and carrier mobility [1]. Since such measurements are ultimately a major determinant of benchmark material properties, it is especially important that their physics be thoroughly understood both conceptually and analytically.

**Results and discussion.** A graphene/Si heterojunction were fabricated as follows. First, graphene growth was performed through the atmospheric pressure chemical vapor deposition using methane as a precursor. After the growth graphene was transferred onto structured n-Si substrates with metallic contacts by a wet-chemical process without using polymeric frame. The area of the heterojunction A formed was A = 0.087 cm$^2$, low doped *n*-Si ($N_D$= 10$^{16}$ cm$^{-3}$) was used as a substrate. More details about samples fabrication and characterization can be found elsewhere [2, 3].

To characterize the optoelectronic performance of the SWCNT/Si heterojunction photodetectors, time response characteristics were measured under 642 nm and 450 nm illumination with a frequency of 175 Hz and 1 kHz. By connecting the SWCNT-based photodetector to an external resistor we measured the dynamic voltage of the resistor with an oscilloscope with an incident power of 0.32 W/cm$^2$ and 0.57 W/cm$^2$ respectively. It should be noted, that further in this paper results of time response studies performed only under 642 nm light illumination will be present.

The time response characteristics of our photodetector are shown in Figures 1, 2. It is clear that the sharp voltage switch is observed when the light is turned on or off. It is also worth noting that the rise time () and fall time ($\tau_{fall}$) were extracted from the dynamic voltage signal waveform (Figure 1 a, b) and both these values do not exceed 12.5µs and 10.6 µs for device measured under 642 nm and 450 nm light illumination respectively.

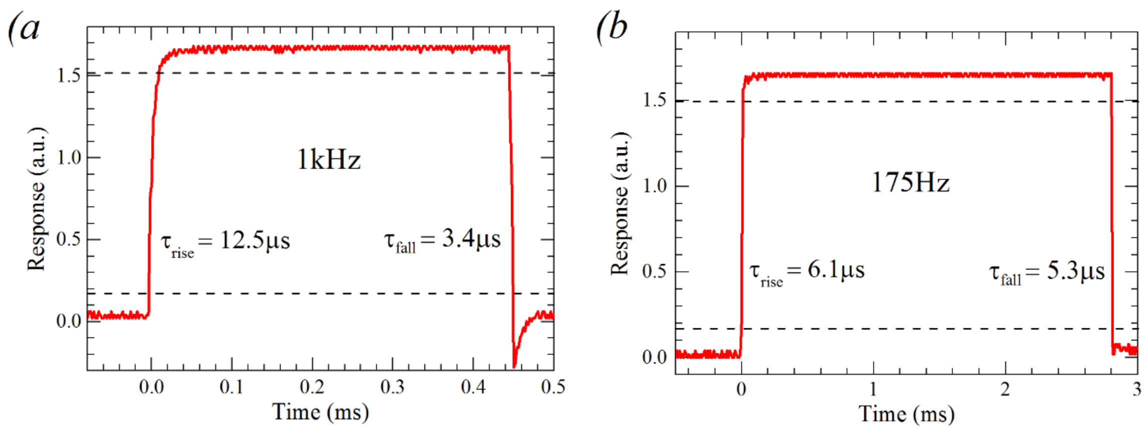


**Figure 1. – One normalized cycle at (a) 1 kHz and (b) 175Hz. Rise (fall) time measured in PV mode between 10% and 90% of the rise (fall) fronts**

We also measured the cyclic photoelectric response of the graphene/n-Si photodetector. As shown in Fig. 2, the photoinduced voltage amplitude of the photodetector remains almost unchanged after experiment, indicating a good photoresponse stability.

Finally, the photodetectors based on graphene/Si heterojunctions fabricated in this work are highly stable over time. In particular, measurements of photodetectors after 2 years of storage in laboratory conditions in air demonstrated that the response characteristics changed by no more than ~5%.

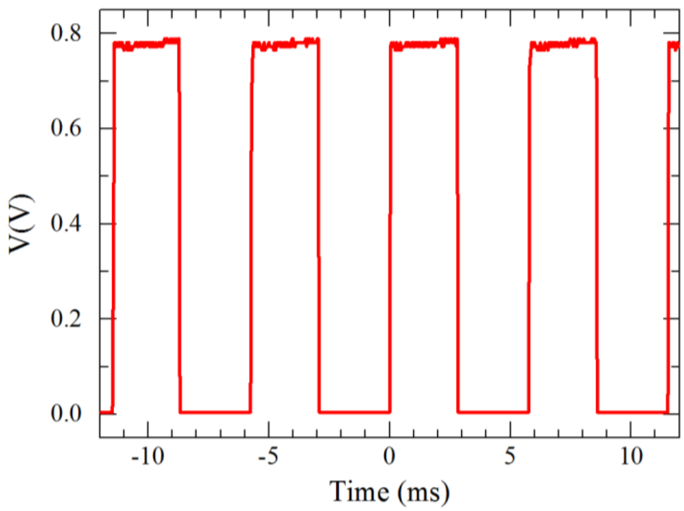


**Figure 2. – Time-dependent measurement under 642 nm illumination with a frequency of 175Hz**

For semiconductor photodetectors, the collection of nonequilibrium carriers created via light absorption at a depth L inside the photodetector is treated conventionally through drift and diffusion processes.

The drift component of the photocurrent is determined by a relatively fast movement of nonequilibrium carriers in the electric field of a space-charge (depletion) region toward its edges (L ≤ W). The diffusion component of the photocurrent is determined by a relatively slow movement of nonequilibrium minority carriers driven by carriers' concentration gradient in the charge-neutral (nondepleted) region of a photodiode toward its edges (L > W). In both the cases, once the holes have reached the graphene counter electrode, they diffuse along this layer to reach the metallic interdigitated electrodes. Therefore, the maximum path the holes must travel to be collected by the interdigitated electrodes is L + d/2 where d=200 µm is the distance between two adjacent electrode edges. From the Schottky theory, the width of the depletion region in a metal/semiconductor junction is given by:

$$W = \sqrt{\frac{2\varepsilon_{\text{Si}}\varepsilon_0 V_{bi}}{qN_D}}, \quad (1)$$

where$q$ is the magnitude of electronic charge, $\varepsilon_{\text{Si}}$ = 11.8 and $\varepsilon_0 = 8.85\times10^{-14}$ F/cm$^2$ are the permittivity in Si and in vacuum, respectively.

In the case of the photovoltaic configuration, the electrodes used for the charge collections are the top shorted S-D and the bottom G. In all the cases (L ≤ W or L > W) the electrons, separated by bult-in potential $V_{bi}$, must cross the whole Si substrate. The $V_{bi}$ is given by the expression:

$$V_{bi} = \varphi_b - \left(\frac{k_B T}{q}\right)\ln\frac{N_C}{N_D}, \quad (2)$$

where $k_B$ is the Boltzmann constant, $N_C = 2.8\times10^{19}$ cm$^{-3}$ is the density of the states at conduction band for Si and Schottky barrier height ($\varphi_b = 0.42eV$) as calculated before [3]. $V_{bi}$ = 0.22 Vhas been obtained and, consequently, W = 0.17 µm. The time required for the charges to cross the depletion zone under the action of the potential $V_{bi}$ is:

$$t_{dr} = \frac{W}{\upsilon_{dr}}, \quad (3)$$

where the drift velocity

$$\upsilon_{dr} = \frac{\mu V_{bi}}{W}. \quad (4)$$

Considering the calculated values for $V_{bi}$ and W and taking μ = 400 cm$^2$/V·s as the mobility of the holes in n- Si with the given donor concentration, one obtains $t_{dr} \approx 3.26\times10^{-12}$ s. The calculated value of $t_{dr}$ is too low to be associated to the response time measured in the presented. At the same time, based on the above calculation, the drift mechanism can be considered insignificant and that the holes generated at a depth of $L \leq W$ spend most of their time to reach the interdigitated electrodes along the graphene layer.

In the future, it is useful to analyze the dependence of $\tau_{rise}$ on λ. In this case, $\tau_{rise} \approx 12.5$ μsand $\tau_{rise} \approx 10.6$ μs was measured for λ = 642 nm and λ = 450 nm light illumination with a frequency of 1 kHz, respectively. Assuming for the graphene mobility the value of μ = 200 $cm^2/V \cdot s$ [4], a diffusion length

$$L_p = \sqrt{\left(\frac{k_B T}{q}\right) \mu \tau_{rise}}. \quad (5)$$

According to the calculations, for $\tau_{rise} \approx 12.5$ μs, corresponding to λ = 642 nm, the holes travel for a distance $L_p$ = 80 μm, and for $\tau_{rise} \approx 10.6$ μs, corresponding to λ = 450 nm, the holes travel for a distance $L_p$= 73 μm. Both distances are comparable with the Si substrate thickness.

## REFERENCES


1. Goushcha A. O. On response time of semiconductor photodiodes / A. O Goushcha [et al.] //Optical Engineering. – 2017. – Vol. 56. – P. 097101–097101.
2. Femtosecond light pulse response of photodetectors based on Graphene/n-Si heterojunctions / M. Scagliotti [et al.] // Carbon. –2019. – Vol. 152. –P. 643–651.
3. Komissarov, I. V. Shottky barrier and ideality factor of CVD graphene-n-Si heterojunction/ I. V. Komissarov [et al.] //2021 19thInternational Workshop on New Approaches to High-Tech. – NDTCS. – P. 91–93.
4. Ковальчук, Н.Г. Подвижность носителей заряда в двухслойном твистированном графене легированном азотом/Н.Г. Ковальчук, С.Л. Прищепа //15-я ежегодная Международная научно-практическая конференция по физике и технологии наногетероструктурной СВЧ-электроники «МОКЕРОВСКИЕ ЧТЕНИЯ». – М.: НИЯУ МИФИ, 2024. – С.146.