СЕКЦИЯ 4

НАНОМАТЕРИАЛЫ: ФОРМИРОВАНИЕ И СВОЙСТВА ПРИ ВОЗДЕЙСТВИИ ИЗЛУЧЕНИЙ

SECTION 4

NANOMATERIALS: FORMATION AND PROPERTIES UNDER THE INFLUENCE OF RADIATION

ANALYSIS OF THE PHOTOCURRENT IN SWCNT/Si BASED PHOTODETECTORS

Lizaveta Dronina[1)], Nikolai Kovalchuk[1)], Evgenii Lutsenko[2)], Aliaksandr Danilchyk[2)], Alexander Danilyuk[1)], Serghej Prischepa[1)]

[1)]*Belarusian State University of Informatics and Radioelectronics,*
6 P. Browka Str., 220013 Minsk, Belarus,
lizadronina@yandex.by, n.kovalchuk@bsuir.by, danilyuk@bsuir.by, prischepa@bsuir.by

[2)]*Stepanov Institute of Physics of NAS Belarus,*
68 Nezavisimosti Ave., 220072 Minsk, Belarus,
e.lutsenko@ifanbel.bas-net.by, a.danilchyk@ifanbel.bas-net.by

In this work, measurements of the dark current-voltage (I–V) characteristics of the formed heterojunctions were carried out in the temperature range from 20 K to 300 K, as well as the I–V characteristics under illumination with different powers and a wavelength of 632.8 nm. This work represents a promising approach to understanding low-temperature mechanisms of photoinduced charge carrier transport across single-walled carbon nanotube film/Si heterojunctions, which will subsequently facilitate the development of high-performance photodetectors with the ability to operate at low temperatures.

Keywords: single wall carbon nanotubes; graphene; irradiation; silicon; junction; photodetector.

Introduction

Heterojunctions between single-walled metallic-conducting carbon nanotube films and silicon have attracted significant attention in the past decade [1]. First, Si photonics remains a mainstream technology due to substantial developments, the widespread availability of silicon, and its low cost. Second, the single-walled carbon nanotube (SWCNT) film that coats the Si acts as a conductive electrode for charge carrier collection and establishes a built-in potential for separating photocarriers. In addition, because of the SWCNT film's extremely high optical transparency, most of the incoming light is absorbed in Si; thus, the efficiency of the SWCNT/Si device is comparable or even greater than that of a conventional Si one.

Although significant progress has been made in developing SWCNT-based heterostructures for high-performance photodetectors and the interface properties of the SB have been studied, there remains a lack of detailed information on photoinduced charge carrier transport at the metal-conducting SWCNT/Si interface, particularly at low temperatures. For example, the mechanism behind the photoelectric performance of SWCNT/Si heterojunctions has not been completely clarified due to the complexity and diversity of the SWCNT films used. Furthermore, achieving an optimal Schottky interface for SWCNT on Si is quite challenging, as the barrier height strongly depends on the morphological features of the SWCNT film. Along with the difficulty of controlling the structure and properties of SWCNTs, the lack of understanding regarding the nature of the contact between the SWCNT film and semiconductor presents a critical issue for improving and stabilizing photodetector figures of merit and integrating them into complex circuits.

In connection with the above, this study measured the photoelectric characteristics of the formed SWCNT/Si heterojunctions in the temperature range from 20 K to 300 K.

Materials and methods

To form the Schottky barrier, 30 nm thick SWCNT films were deposited directly onto a pre-cleaned phosphorus-doped (N_D= 10^{16} cm^{-3}) Si (n-type) using floating catalyst chemical vapor deposition [2]. The effective area of the photodetector window was S_{eff} = 0.061 cm^2 [3]. The single-walled nature of the nanotubes and the prevalence of their metallic conductivity were confirmed by Raman and IR spectroscopies. More details about the sample's fabrication and characterization can be found elsewhere [2, 3].

The dark I–V characteristics of the SWCNT/Si heterojunction were analyzed within the framework of an analytical model adapted to the theory of thermionic emission, which assumes a Gaussian distribution of the Schottky barrier amplitude.

The temperature dependencies of the parameters were calculated based on the known temperature dependencies of the concentration of charge carriers and ionized impurities in Si using Poisson's equation based on Fermi-Dirac statistics.

Results and discussion

In Figure 1, we plot $I_{ph}(T)$ dependencies measured at different P_{in}. It follows that there is a decrease in photocurrent as the temperature decreases. On the other hand, it is noteworthy that with a decrease in radiation power, the changes in current with temperature become slower.

The obtained Schottky barrier (SB) parameters allow us to explain the temperature dependence of the photocurrent (Figure 2).

Along with the decrease in the barrier height with decreasing temperature, there is

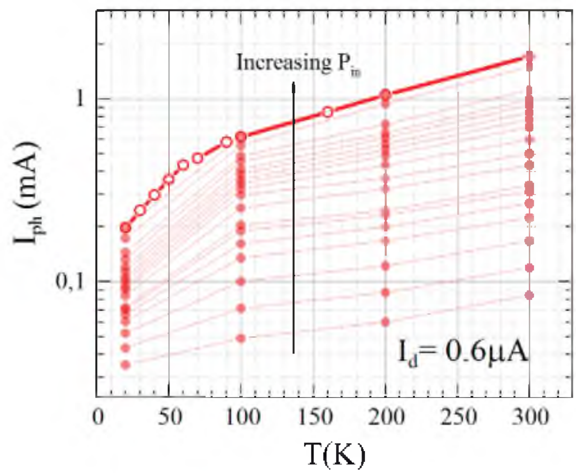

Fig. 1. Photocurrent as a function of T at various P_{in}

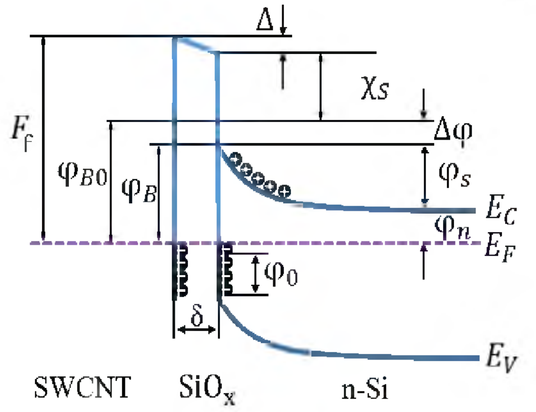

Fig. 2. Band diagram of the SWCNT/Si heterojunction with its main energy parameters

also a decrease in the work function F_f of the SWCNT array, an increase in $φ_0$, and a decrease in $φ_n$, $φ_s$, E_s, and an increase in the density of interfacial states on the SiO_x/Si interface D_{is}. Note that the growth of D_{is} is associated with an increase in both the nonideality factor and the extension of the depleted Si layer. Decreasing the SB height, other parameters being equal, should lead to an increase in the photocurrent, which is not observed in our case. This is counteracted by such effects as a decrease in the potential $φ_s$, leading to a decrease in the field strength E_s, as well as an increase in the extension of the depleted layer W. The decrease in SB height and E_s contributes to a decrease in the separation efficiency generated by the emission of nonequilibrium electrons and holes in the SB region. An increase in the CNL leads to a decrease in charge Q_{is} with decreasing temperature, despite an increase in the density of states D_{is} and a decrease in SB height. An increase in D_{is} along with a decrease in Q_{is} leads to an increase in the surface recombination rate of the generated electrons and holes, while an increase in W leads to an expansion of their bulk recombination region.

Based on the calculations performed in this work, it can be concluded that the decrease in photocurrent is ultimately the result of competition between the effects of reducing the Schottky barrier height and the processes of decreasing the efficiency of separating non-equilibrium charge carriers and increasing their recombination rate.

Responsivity R_λ is a significant parameter to evaluate the photodetector sensitivity, $R_\lambda = (I_{ph} - I_d)/(P_{in} \times S_{eff})$. Note that the dark current did not exceed 0.5 μA over the entire temperature range. In general, a decrease in photoresponsivity is observed with decreasing temperature for all light intensities. However, if for high light intensities ($P_{in} > 200$ mW/cm^2) the decrease in P_{in} occurs by an order of magnitude, then for low powers ($P_{in} < 10$ mW/cm^2) it is only 2 times. Therefore, this experimental result demonstrates that at low illumination powers, the photoresponsitivity of the SWCNT-based photodetector at low temperatures is quite stable and varies slightly over a wide temperature range.

In Figure 3 we show the responsivity as a function of P_{in} for different temperatures. The noticeable behavior of the $R_\lambda(P_{in})$ dependence at low powers is noteworthy. Up to $P_{in} = 25$ mW/cm^2, responsivity at $T > 20$ K increases quite quickly, and at higher illumination powers, it begins to gradually decrease. On the other hand, at $T = 20$ K, the $R_\lambda(P_{in})$ dependence is a monotonic, smoothly decreasing function with a tendency to saturate at high powers.

This result indicates that at low temperatures the transfer of photoinduced charge carriers across the SB is not effective at any value of P_{in}, while at $T \geq 100$ K, at first, with

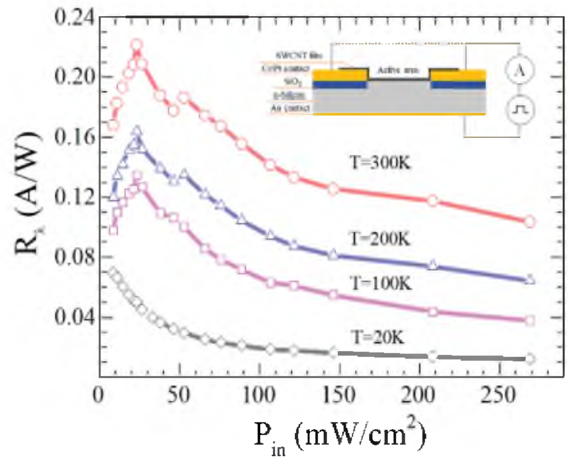

Fig. 3. Responsivity versus P_{in} at different T. Inset: Schematic view of the sample studied

an increase in the illumination power, the generation of photoinduced charge carriers increases, and then, after exceeding the threshold power, recombination of these carriers occurs.

Conclusions

The calculations presented in this study indicate that the decrease in photocurrent arises from a complex interplay between two effects: the reduction in Schottky barrier height and the simultaneous decline in the efficiency of non-equilibrium charge carrier separation, accompanied by an increase in their recombination rate.

References

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