ISSN 1068–3372, Journal of Contemporary Physics (Armenian Academy of Sciences), 2016, Vol. 51, No. 4, pp. 345–349. © Allerton Press, Inc., 2016.
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The Effect of Shifting of the Absorption Edge in the Silicon Nanowire

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Received May 20, 2016

Abstract—The dark and photo current–voltage characteristics (CVC), the absorption spectrum and the photosensitivity of the field effect transistor based on the silicon nanowires have been investigated. The spectral dependences of the photocurrent have been obtained. It is shown that the absorption capacity of the silicon nanowire is shifted to the shorter wavelengths. In contrast to the bulk silicon, the photocurrent and the photosensitivity rise at room temperature and have the record high values in the ultraviolet region. It is proposed to use the field-effect transistors based on the silicon nanowires operating at the room temperature as the highly-sensitive detectors for the ultraviolet spectral region.

DOI: 10.3103/S106833721604006X
Keywords: silicon, nanowire, field effect transistor, photocurrent, absorption

1. INTRODUCTION

The structures based on the silicon nanowires (Si-NWs) are of great interest for applications in the optoelectronics. One of the areas of these applications can be the use of interaction of radiation with the group of nanowires deposited on the substrate. The nanosize structures with the dimensions close to the wavelengths of the incident radiation exhibit the interesting optical properties such as the low reflectivity and the high absorption coefficient. The studies of optical absorption of the Si-NW show the significant dependence of the absorption ability on their size [1]. The measurements of the optical spectrum of absorption of the Si-NW samples show the high values of absorption coefficients [2]. It is also shown that they significantly attenuate the reflection power as compared to the bulk sample of silicon [2−3]. The optical absorption rises with the decrease in the wavelength of incident radiation. It should be noted that in contrast to the bulk silicon, the Si-NW is the direct gap semiconductor, which makes it an excellent material for optical applications [4−7]. On the other hand, the width of the bandgap of the NW increases with the decrease in its diameter [4]. From the foregoing it follows that we can expect the significant shift of the absorption spectrum of the Si-NW into the region of short wavelengths.

This work presents the results of experimental investigations of the absorption spectra, as well as of the photosensitivity of the field effect transistor based on the p^+-p-p^+ structure prepared of the Si-NW.

2. SAMPLES AND EXPERIMENTAL TECHNIQUE

Structures consisting of the top layer silicon oxide p-SiNW, of the lower silicon oxide layer p-Si substrate (Fig. 1) were prepared by the silicon-on-insulator (SOI) technology. The thicknesses of the upper and lower layers of SiO_2 are equal to 9 nm and 145 nm, respectively, the diameter of the nanowire is equal to 250 nm and its length is equal to 20 μm. The peculiarities of the sample preparation have been presented in [8]. The Si-NW has been doped with 10^{15} cm^{-3} of boron atoms. The region of source (S) and drain (D) (the extreme p^+-regions) were produced from the same NW highly doped by boron atoms

(10^{19} cm^{-3}). Spectral measurements were carried out at room temperature with use of the YM-2 monochromator. For lighting, the filament lamps were used, which are at the distance of 15 cm over the top layer of SiO_2. The density of the radiation incident on the sample W was 1.1 W/cm^2 and 1.6 W/cm^2 in the wave range 0.25–0.6 μm.

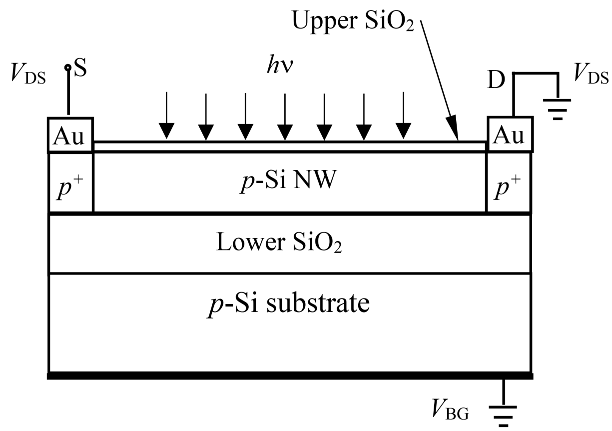

Fig. 1. Scheme of the field effect transistors structure SiO_2/*p*-Si NW/SiO_2/*p*-Si-substrate: S and D are the source and the drain, respectively, and V_{DS} and V_{BG} are the voltages at the source and back gate, respectively.

3. RESULTS AND DISCUSSION

Figure 2 represents the dark and photo CVCs. As can be seen, the CVCs have the usual form for the field effect transistors.

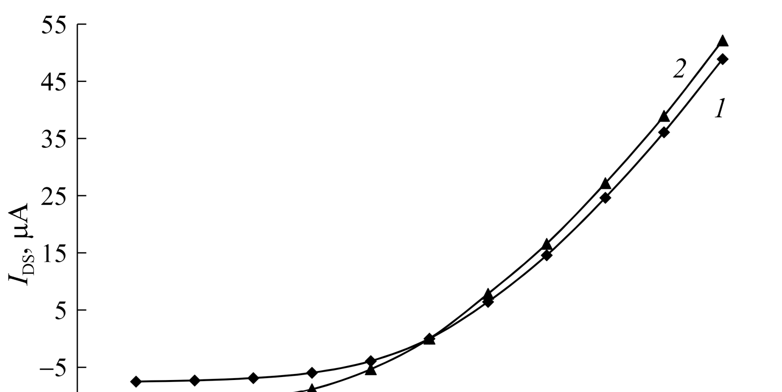

Fig. 2. CVC source–drain at V_{BG} = – 5 V, T = 300 K, and the density of radiation W = 1.1 W/cm^2: *1* – the photo CVC and *2* – the dark CVC.

Figure 3 shows the spectral dependence of the drain–source current I_{DS} at $V_{BG} = V_{DS} = -5$ V. As can be seen, the spectral dependences of the current I_{DS} are shifted into the region of short waves as compared to the bulk sample of silicon (it is known that the spectral sensitivity of the bulk silicon is in the range of more than 1 μm [9]). The current photosensitivity increases in the wavelength region below 500 nm. Obviously, this is caused by the small size of the silicon in the sample under consideration. The spectral shift of the photocurrent with the decreasing in diameter of the Si-NW also was reported [10].

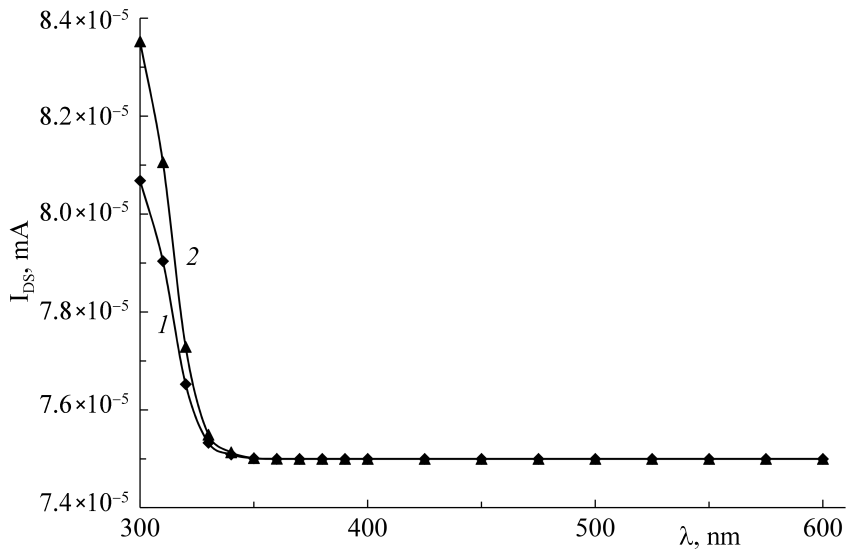

Fig. 3. Spectral dependences of the current I_{DS} at $V_{BG} = -5$ V, $V_{DS} = -5$ V and at the different densities of radiation: *1* – 1.1 W/cm^2 and *2* – 1.6 W/cm^2.

Such a behavior of the photocurrent and the photosensitivity of the Si can be explained as follows: first, the small diameter of the nanowire (250 nm) limits the absorption of the long-wavelength photons; second, unlike the bulk Si monocrystalline, the bandgap of the Si-NW increases with the decrease in the size of nanowire [4]; thirdly, starting from the photon energy $h\nu \geq 3$ eV, the internal quantum yield for silicon is growing and reaches the values of 2–3 [11]; fourthly, it is known [12] that the wavelength of the light emitted from the nanoscale semiconductor samples is controlled by the selection of their size L, since the energy of the emitted quantum is equal to $h\nu = E_g + E_e + E_h$, where E_g is the energy gap, and E_e and E_h are the binding energies of the electrons and holes, respectively. The last (E_e and E_h) increase with the decreasing in size *L*. On the other hand, according to the van Roosbroeck–Shockley

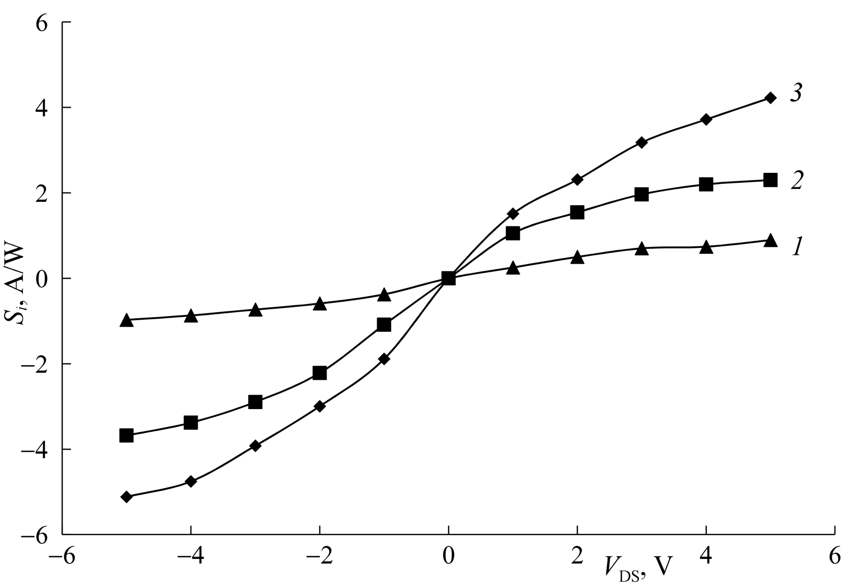

Fig. 4. Dependence of the photosensitivity on the source–drain voltage V_{DS} at $T = 300$ K and the various values at the back gate V_{BG}: *1* – $V_{BG} = -1$ V, 2 – $V_{BG} = -5$ V, and *3* – $V_{BG} = -10$ V.

relation, the absorption and the emission of radiation are the interrelated processes [13]. The shift of the absorption spectrum of the Si-NW into the shorter wavelengths is also linked with this factor. It is shown that such an optical limiting (the blue shift) of energy is proportional to the $1/L^2$ [12]. Consequently, with the decrease in the sizes in samples the short-wave photons can be absorbed more effectively in the Si-NW.

The dependencies of the photosensitivity on the drain–source voltage, and the spectral dependence of the photosensitivity are shown in Figs. 4 and 5, respectively. The dependencies of the current photosensitivity $S_i(\lambda)$ on the drain–source voltage V_{DS} and their spectral dependences are calculated by the use of the formula

$$S_i(\lambda) = \frac{\Delta I_{DS}(\lambda)}{AW(\Delta\lambda)}.$$

Here A is the photosensitive elemental area of the NW, $\Delta I_{DS}(\lambda)$ the photocurrent at the wavelength λ, and $\Delta\lambda = 10$ nm the minimum possible resolution of the wavelength band at the measurement.

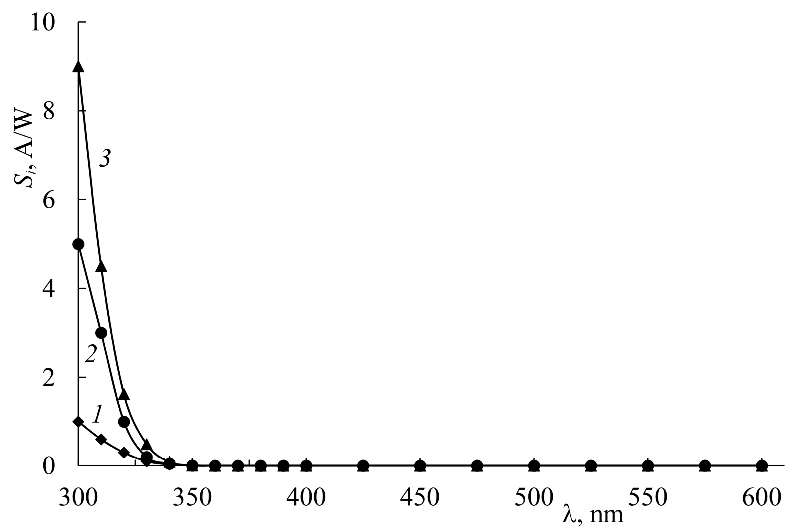

Fig. 5. Spectral dependences of the photosensitivity at T = 300 K: *1* – $V_{BG} = -1$ V, *2* – $V_{BG} = -5$ V and *3* – $V_{BG} = -10$ V.

At room temperature, the photosensitivity reaches 4–6 A/W depending on the value of V_{DS}. In the UV region of spectrum the sensitivity increases and its values are ~10 time greater as compared to the photodetectors based on the bulk silicon [14–18] (see Figs. 4 and 5). For example, in the photodetectors based on the field-effect transistors from graphene, the value of the photosensitivity had reached ~126 mA/W at high voltages (8 V) and with the output power of 20 mW [19].

4. CONCLUSION

It is shown that the absorption capacity of the silicon nanowire is shifted to the shorter wavelengths range of spectrum as opposed to the bulk silicon case, the photocurrent and the photosensitivity are growing at room temperature and obtain the record high values in the UV region.

Thus, the field effect transistors based on the Si-NW can operate successfully at room temperature in the UV range of spectrum.

ACKNOWLEDGMENT

The investigation was sponsored by the State SCS MES of Armenia within the framework of the research project № 15T-1C279.

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