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PHOTOCONDUCTIVITY OF CARBON NANOTUBES

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Abstract- In recent years, both physical-chemical and electrical properties of nanotubes based on carbon nanomaterials have been actively studied. At the same time, the photoelectric properties of carbon nanotubes are of undoubted interest. A study was made of the photosensitivity spectrum of a nanotubes based on pure carbon (CNTs) in the wavelength range λ=400-900 nm at five values of the bias voltage U applied to the sample: U=1 V, 3 V, 5 V, 7 V and 9V. The analysis shows that that an increase in the bias voltage applied to the sample of the CNTs under study leads to an expansion of the range of zero or weak photosensitivity and to a decrease in the magnitude of the photosensitivity peaks. In particular, at U=9 V, the sample loses photosensitivity in almost the entire studied wavelength range λ=400-900 nm, and therefore it is not effective to use it as a detection detector at such a voltage value. The widest photosensitivity range and the highest sensitivity value are observed at a voltage of U=1 V. At the same time, at a wavelength of λ~715 nm, the most significant photocurrent peak is reached, equal to I_p~0.2 μA. This means that CNTs at voltage U=1 V can be effectively used as radiation detectors in several radiation ranges. Experimental points and curves approximating them for *I-V* characteristics of the studied nanotube samples are presented at six wavelengths: λ~640 nm, λ~720 nm, λ~740 nm, λ~760 nm, λ~780 nm, and λ~880 nm. It is shown that the approximating curves are well described by polynomials of the fourth degree. It has been determined that at λ~720 nm the *I-V* characteristic exhibits a very weak photosensitivity in almost the entire voltage range of 1-9 V. As the wavelength increases, there is a tendency for the photosensitivity peak to shift to the left towards lower voltage values, while the photocurrent peak decreases with each shift.

Keywords: Carbon Nanotubes, Negative Photoconductivity, Positive Photoconductivity, Photocurrent, Photosensitivity Spectrum.

1. INTRODUCTION

With the development of modern nanoscience, there has been a growing interest in the study and research of carbon and graphene-based samples. R.G. Abaszade and others synthesized graphene-based samples by Hummer method and analyzed the synthesized sample by various research methods [1]. In [2-6] structural and electrical properties of graphene, properties of graphene based solar panels and modeling of hybrid energy systems, negative differential resistance and modeling of voltage-ampere characteristic of graphene-based samples were studied. In recent years, both physical-chemical, mechanical and electrical properties and characteristics of nanotubes based on carbon nanomaterials have been actively studied. Carbon nanotubes (CNTs) successfully combine increased strength characteristics with electrical conductivity and thermal and chemical stability. In [7], X-ray diffraction analyzes, Raman scattering and IR luminescence analyzes of CNTs and carbon nanotubes alloyed with 15% gadolinium were performed and it was determined that the degree of addition had a significant effect on the physical properties of carbon nanotubes. In paper [8] the purity, quality and morphology of carbon nanotubes and 10% gadolinium-alloyed carbon nanotubes were studied by SEM method, and the sample structure was studied by X-ray diffraction method. In [9] investigated some different physical properties of CNTs with gadolinium-based samples.

At the same time, the photoelectric properties of CNTs are of undoubted interest. Bergemann [10] reported a new C60 activated carbon nanotube detector, which exhibits a high photoresponsivity of up to 10^8 A/W, a detectivity of 1.6×10^{11} Jones (1Jones=1cm×$Hz^{1/2}$×W^{-1}), and a gain of more than 10^8. Such studies are important from the point of view of revealing new functional capabilities of the material and nanotubes based on it and determining the areas of effective use of such structures, in particular, for solving problems of photo electronics and optoelectronics.

In this work, we studied the photosensitivity spectra of CNTs in the wavelength range λ=400–900 nm at five values of the bias voltage U applied to the sample: U=1 V, 3 V, 5 V, 7 V and 9 V. The number of small interest is the study of trends and regularities in the change in the photosensitivity ranges and their peaks for CNTs with a change in the bias voltage applied to the samples. For this purpose, the paper presents experimental points and curves approximating them for *I-V* characteristics of the studied nanotube samples at six wavelengths: λ~640 nm, λ~720 nm, λ~740 nm, λ~760 nm, λ~780 nm and λ ~880 nm and analyzed them.

2. EXPERIMENT AND DISCUSSION

Figure 1 shows the photosensitivity spectra of CNTs in the wavelength range λ=400-900 nm at two values of the bias voltage U applied to the sample: U=1 V, 3 V.

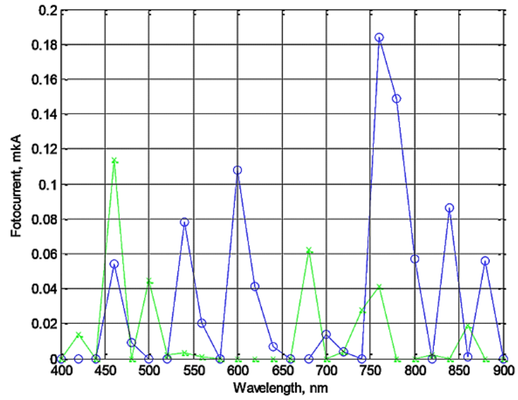

Figure 1. The photosensitivity spectra of CNTs in the wavelength range λ=400-900 nm at two values of the bias voltage U applied to the sample: U=1 V and 3 V. The experimental points marked "o" in blue correspond to a voltage of 1 V; points marked with "×" in green correspond to 3 V

At U=1 V, seven photocurrent peaks are fairly evenly distributed in the range λ=450-900 nm: λ_{p1}~460 nm, λ_{p2}~540 nm, λ_{p3}~600 nm, λ_{p4}~710 nm, λ_{p5}~765 nm, λ_{p6}~840 nm, λ_{p7}~880 nm. The highest photosensitivity I_{p5}~0.2 μA is achieved at λ_{p5}~765 nm. The peak λ_{p4}~710 nm is quite insignificant. The remaining peaks have a photocurrent value of the order of I~0.5-0.11 μA. In the wavelength range λ=660-740 nm ($\Delta\lambda$=80 nm) zero photosensitivity is observed.

At U=3 V, the number of peaks (six) and their magnitude decreased: λ_{p1}~410 nm, λ_{p2}~460 nm, λ_{p3}~502 nm, λ_{p4}~680 nm, λ_{p5}~755 nm, λ_{p6}~860 nm. Now the maximum peak is at λ_{p2}~460 nm, however, its value has decreased and is I_{p2}~0.115 μA. As can be seen, the maximum peak has shifted to the low-wave region. In the wavelength range λ=520-660 nm ($\Delta\lambda$=140 nm) zero photosensitivity is observed. That is, the range of zero photosensitivity has expanded.

Figure 2 shows the photosensitivity spectrum of CNTs in the wavelength range λ=400-900 nm at three values of the bias voltage U applied to the sample: U=5 V, 7 V, and 9 V.

At U=5 V, the number of peaks is four: λ_{p1}~640 nm, λ_{p2}~720 nm, λ_{p3}~800 nm, λ_{p4}~880 nm. Now there are two maximum peaks: at λ_{p1}~640 nm and λ_{p3}~800 nm.

However, the magnitude of the peaks has decreased and is I_{p1}~0.065 μA and I_{p3}~0.077 μA. It is important to note that the range of zero photosensitivity λ=400-615 nm has expanded and reached $\Delta\lambda$=215 nm.

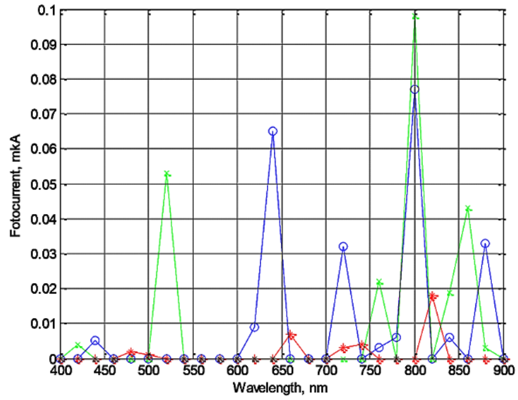

Figure 2. The photosensitivity spectrum of CNTs in the wavelength range λ=400-900 nm at three values of the bias voltage U applied to the sample: U=5V, 7V, and 9 V. The experimental points marked "o" in blue correspond to voltage 5 V; dots marked with "×" in green correspond to 7 V, and points marked with "*" in red correspond to 9 V

At U=7 V, the number of peaks is still four: λ_{p1}~520 nm, λ_{p2}~755 nm, λ_{p3}~800 nm, λ_{p4}~855 nm. The range of weak photosensitivity λ=400-740 nm expanded and reached the value $\Delta\lambda$=340 nm, however, a weak peak at λ_{p1}~520 nm appeared in this range. The maximum peak at a wavelength of λ_{p3}~800 nm was preserved and amounted to I_{p3}~0.098 μA.

At U=9 V, the number of peaks is four, but their magnitude has decreased significantly. The range of weak photosensitivity λ=400-800 nm has expanded and reached the value $\Delta\lambda$=400 nm. There are three weak peaks at λ_{p1}~480 nm, λ_{p2}~660 nm, and λ_{p3}~735 nm in this range. However, their value is so small I~0.002-0.007 μA that practically they can be ignored. The maximum peak at λ_{p4}~820 nm decreased significantly and amounted to I_{p4}~0.018 μA. That is, almost the entire investigated range λ=400-900 nm at U=9 V is a range of very weak, almost zero sensitivity.

Thus, the performed analysis shows that an increase in the bias voltage applied to the sample of the nanotube under study leads to an expansion of the range of zero or weak photosensitivity and to a decrease in the photosensitivity value. In particular, at U=9 V, the sample lost its photosensitivity in almost entire studied wavelength range λ=400-900 nm, and therefore it is not effective to use it as a detection detector at this voltage.

The widest photosensitivity range and the highest sensitivity value are observed at U=1 V. Here, the most significant peak is reached, equal to I_p~0.2 μA, at a wavelength of λ~715 nm. This means that CNTs can be effectively used as radiation detectors in several radiation ranges. Of undoubted interest is the study of tendencies and patterns of change in the photosensitivity ranges and their peaks for CNTs with a change in the bias voltage applied to the samples. For this purpose, on the basis of the given data on the sensitivity spectrum at different voltages, we construct the voltage dependences of the photosensitivity of CNTs at different wavelengths. *I-V* characteristics of the studied samples for different wavelengths are presented below.

Figure 3 shows the experimental points and the curves approximating them for the *I-V* characteristics of the samples under study at two wavelengths: λ~640 nm and λ~720 nm, well described by the relations

$$I = 0.001034 \cdot U^4 - 0.02075 \cdot U^3 + +0.1358 \cdot U^2 - 0.3183 \cdot U + 0.2092 \quad (1)$$

$$I = 0.0004766 \cdot U^4 - 0.009458 \cdot U^3 + +0.06098 \cdot U^2 - 0.14 \cdot U + 0.09204 \quad (2)$$

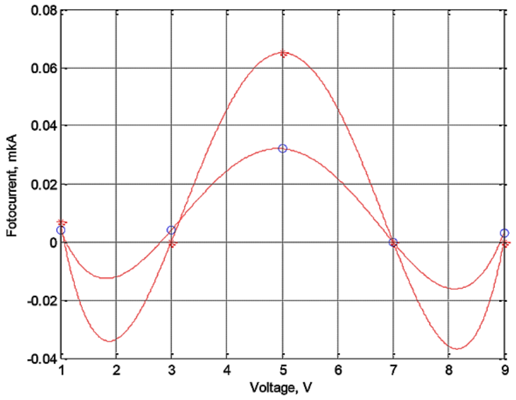

Figure 3. Experimental points and curves approximating them for the *I-V* characteristics of studied CNTs samples at two wavelengths: λ~640 nm and λ~720 nm. Experimental points marked with "*" in red correspond to λ~640 nm; dots marked "o" in blue correspond to λ~720 nm

As can be seen from the characteristics presented in Figure 3 *I-V*, at λ ~ 640 nm in the voltage range of 1-3 V and 5-7 V we have areas of negative photoconductivity (NPC), and in the range of 3-5 V - a region of positive photoconductivity (PPC). The 7-9 V range is the area of zero sensitivity. The photosensitivity peak I_p~0.07 μA is reached at U=5 V.

As can be seen from the *I-V* characteristics presented in Figure 3 at λ~720 nm, the voltage range of 1-3 V and 7-9 V is an area of almost zero sensitivity. In the range of 3-5 V, we have a region of positive photoconductivity, and in the range of 5-7 V, we have a region of negative photoconductivity. A very weak photosensitivity peak I_p~0.03 μA is achieved at U=5 V. Thus, at λ~720 nm, the *I-V* characteristic exhibits a very weak photosensitivity in almost the entire voltage range of 1-9 V.

The effect of photoconductivity is that the conductivity of a material varies with the energy of the incident light. [11] PPC is a phenomenon in which the conductivity increases with the incidence of light. When irradiated with light, the material absorbs light and generates a mass of electron-hole pairs. The electron-hole pairs are separated and controlled by a bias voltage. In this case, the carrier concentration and, accordingly, the conductivity and current increase.

The NPC phenomenon is caused by the trapping effect by capture centers. In this case, the capture centers capture photoinduced carriers, causing a decrease in photoconductivity. The trapping effect is associated with defects [12], surface adsorbents [13], and doping [14].

Figure 4 shows the experimental points and curves approximating them for the *I-V* characteristics of the samples under study at two wavelengths: λ~740 nm and λ~760 nm, well described by the relations

$$I = -0.0002813 \cdot U^4 + 0.00625 \cdot U^3 - -0.04694 \cdot U^2 + 0.1318 \cdot U - 0.09078 \quad (3)$$

$$I = -0.0001302 \cdot U^4 + 0.001083 \cdot U^3 + +0.01093 \cdot U^2 - 0.1241 \cdot U + 0.2962 \quad (4)$$

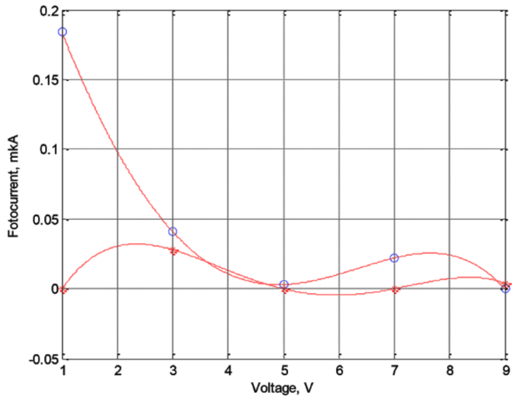

Figure 4. Experimental points and curves approximating them for *I-V* characteristics of studied CNTs samples at two wavelengths: λ~740 nm and λ~760 nm. Experimental points marked with "*" in red correspond to λ~740 nm; dots marked "o" in blue correspond to λ~760 nm

As can be seen from the characteristics presented in Figure 4 shows *I-V*, at λ~740 nm in the voltage range of 1-3 V there is a region of PPC, and in the range of 3-5 V there is a region of NPC. The 5-9 V range is an area of almost zero sensitivity. A very weak photosensitivity peak I_p~0.028 μA is achieved at U=3 V. It can be seen that the *I-V* characteristics at λ~720 nm and λ~740 nm are identical and differ only in the shift of the photocurrent peak to the left towards lower voltage values.

As can be seen from the *I-V* characteristic shown in Figure 4, at λ~760 nm, in the voltage range of 1-5 V, there is a region of negative photoconductivity NPC. In the voltage range of 5-9 V, there is an area of almost zero sensitivity. At U=1 V a rather strong photocurrent peak I_p~0.187 μA is achieved. As can be seen, the tendency for the shift of the photosensitivity peak to the left towards lower voltage values with increasing wavelength is retained.

Figure 5 shows the experimental points and curves approximating them for *I-V* characteristics of the samples under study at two wavelengths: λ~780 nm and λ~880 nm, well described by the relations

$$I = 0.0004818 \cdot U^4 - 0.01119 \cdot U^3 + +0.09212 \cdot U^2 - 0.3168 \cdot U + 0.3844 \quad (5)$$

$$I = 0.0006302 \cdot U^4 - 0.01325 \cdot U^3 + +0.09382 \cdot U^2 - 0.2563 \cdot U + 0.231 \quad (6)$$

Note that small negative values of photocurrents in Figures 3-5 correspond to approximation errors, and these values of photocurrents should be considered equal to zero.

It is important to note that the above approximations of the *I-V* characteristics of the studied samples are of considerable interest from the point of view of purposefully changing the photosensitivity range and choosing the most effective option for each specific application.

As can be seen from the *I-V* characteristic shown in Figure 5 at λ~780 nm, it is identical to the characteristic at λ~760 nm. At the same time, the trend of expanding the voltage range with zero sensitivity remained: this range expanded and amounted to 3-9 V. The peak of the photocurrent was preserved at a voltage value of U=1 V, but slightly decreased and amounted to I_p~0.15 µA.

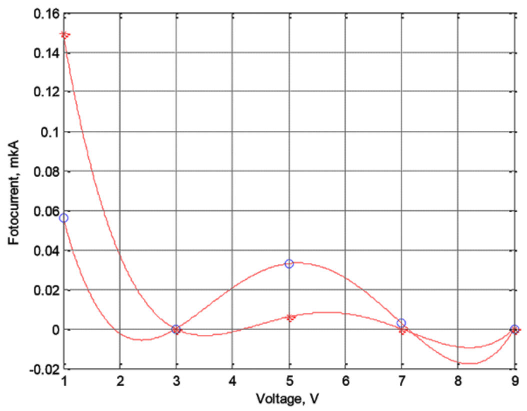

Figure 5. Experimental points and curves approximating them for the *I-V* characteristics of the samples under study at two wavelengths: λ~780 nm and λ~880 nm. Experimental points marked with "*" in red correspond to λ~780 nm; dots marked "o" in blue correspond to λ~880 nm

As can be seen from the *I-V* characteristic shown in Figure 5, at λ~880 nm, in the voltage range of 1-3 V, there is a region of negative photoconductivity NPC. In the voltage range of 7-9 V, there is a region of zero sensitivity. The photocurrent peak is again reached at U=1 V, however, it has significantly decreased and amounts to only I_p~0.058 µA. At U=5 V, an even weaker peak appeared - I_p ~ 0.032 µA. As can be seen, the tendency for the shift of the photosensitivity peak to the left toward lower voltage values with increasing wavelength is retained, while the photocurrent peak decreases with each shift.

From the point of view of using CNTs in optoelectronics, the spectral ranges with high photosensitivity in the ranges of 800-900 nm and 550-900 nm seem to be the most important. The first of these ranges effectively agrees with the emission spectra of GaAlAs- and GaAl-lasers, and the second - with GaP-, GaAsP-, GaAlAs-, GaAs-LEDs.

In addition, spectral regions with photosensitivity peaks at λ~490 nm, λ~630 nm, λ~690 nm are of interest, which are in good agreement with the emission spectra of argon, krypton, helium-neon, and ruby lasers. Comparing the presented photosensitivity spectra shown in Figure 1, 2, it is easy to make sure that at U=3 V the samples under study at wavelengths λ_{p3} ~500 nm and λ_{p4}~680 nm can be effectively used in optoelectronics in tandem with argon, krypton and other specified lasers.

Similarly, at U=1 V, the photocurrent peaks at wavelengths λ_{p6} ~840 nm and λ_{p7}~880 nm; at U=3 V peak photocurrent at wavelength λ_{p6}~860 nm; at U=5 V photocurrent peaks at wavelengths λ_{p3}~800 nm and λ_{p4}~880 nm; at U=7 V, the photocurrent peaks at wavelengths λ_{p3}~800 nm and λ_{p4}~855 nm provide an opportunity for their effective use in optoelectronics coupled with GaAlAs and GaAl lasers.

In addition, at U=1 V, photocurrent peaks in the range 550-900 nm at wavelengths λ_{p2}~540 nm, λ_{p4}~710 nm, λ_{p5}~765 nm, λ_{p6}~840 nm and λ_{p7}~880 nm make it possible to use them effectively in optoelectronics paired with GaP-, GaAsP-, GaAlAs-, GaAs-LEDs.

3. CONCLUSION

A study was made of the photosensitivity spectrum of CNTs in the wavelength range λ=400–900 nm at five values of the bias voltage U applied to the sample: U=1 V, 3 V, 5 V, 7 V and 9 V. The analysis shows that that an increase in the bias voltage leads to an expansion of the range of zero or weak photosensitivity and to a decrease in the magnitude of the photosensitivity peaks. The widest range of photosensitivity and the highest sensitivity value are observed at a voltage of U=1 V. At the same time, at a wavelength of λ~715 nm, the most significant peak is reached, equal to I_p~0.2 µA. Experimental points and curves approximating them for *I-V* characteristics of the studied nanotube samples are presented at six wavelengths: λ~640 nm, λ~720 nm, λ~740 nm, λ~760 nm, λ~780 nm, and λ~880 nm. It is shown that the approximating curves are well described by polynomials of the fourth degree. The simulation was performed using MATLAB R2021a software. It was found that at λ~720 nm the *I-V* characteristic exhibits a very weak photosensitivity in almost the entire voltage range of 1-9 V decreases.

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BIOGRAPHIES

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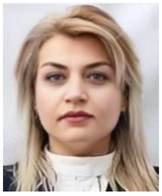

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