PHOTOCONDUCTIVITY OF CARBON NANOTUBES


1. Azerbaijan State Oil and Industry University, Baku, Azerbaijan
mamedov_a50@mail.ru, abaszada@gmail.com, imranb1963@mail.ru, khanman.ea@gmail.com
2. Vasyly Stefanyk Precarpathian National University, Ivano-Frankivsk, Kyiv, Ukraine, kotsyubinsky@gmail.com
3. Ataturk University, Erzurum, Turkey, emregur@atauni.edu.tr
4. V.E. Lashkarev Institute of Semiconductor Physics, National Academy of Science of Ukraine, Kyiv, Ukraine, cccsavchuk-olja@ukr.net

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 9 V. 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 l=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 10^6. 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 $\lambda=400$-$900$ 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: $\lambda=340$ nm, $\lambda=720$ nm, $\lambda=740$ nm, $\lambda=760$ nm, $\lambda=780$ nm and $\lambda=880$ nm and analyzed them.

2. EXPERIMENT AND DISCUSSION

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

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

At $U=3$ V, the number of peaks (six) and their magnitude decreased: $\lambda_{p1}=410$ nm, $\lambda_{p2}=460$ nm, $\lambda_{p3}=502$ nm, $\lambda_{p4}=680$ nm, $\lambda_{p5}=755$ nm, $\lambda_{p6}=860$ nm. Now the maximum peak is at $\lambda_{p2}=460$ nm, however, its value has decreased and is $I_p=0.115$ $\mu$A. As can be seen, the maximum peak has shifted to the low-wave region. In the wavelength range $\lambda=520$-$660$ 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 $\lambda=400$-$900$ 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: $\lambda_{p1}=640$ nm, $\lambda_{p2}=720$ nm, $\lambda_{p3}=800$ nm, $\lambda_{p4}=880$ nm. Now there are two maximum peaks: at $\lambda_{p1}=640$ nm and $\lambda_{p3}=800$ nm.

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

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

At $U=9$ V, the number of peaks is four, but their magnitude has decreased significantly. The range of weak photosensitivity $\lambda=400$-$800$ nm has expanded and reached the value $\Delta\lambda=400$ nm. There are three weak peaks at $\lambda_{p1}=480$ nm, $\lambda_{p2}=660$ nm, and $\lambda_{p3}=735$ nm in this range. However, their value is so small $I=0.002$-$0.007$ $\mu$A that practically they can be ignored. The maximum peak at $\lambda_{p4}=820$ nm decreased significantly and amounted to $I_{p4}=0.018$ $\mu$A. That is, almost the entire investigated range $\lambda=400$-$900$ 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 wavelengths range $\lambda=400$-$900$ 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 $I_{p1}=0.2$ $\mu$A, at a wavelength of $\lambda=715$ 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: $\lambda\sim640$ nm and $\lambda\sim720$ nm, well described by the relations

\begin{equation}
I = 0.001034 \cdot U^4 - 0.02075 \cdot U^3 + 0.1358 \cdot U^2 - 0.3183 \cdot U + 0.2092
\end{equation}

\begin{equation}
I = 0.0004766 \cdot U^4 - 0.009458 \cdot U^3 + 0.0002813 \cdot U^2 - 0.14 \cdot U + 0.09204
\end{equation}

As can be seen from the characteristics presented in Figure 3 I-V, at $\lambda\sim640$ 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 $I_p=0.07 \mu A$ is reached at $U=5$ V.

As can be seen from the I-V characteristics presented in Figure 3 at $\lambda\sim720$ 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 $I_p=0.03 \mu A$ is achieved at $U=5$ V. Thus, at $\lambda\sim720$ 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: $\lambda\sim740$ nm and $\lambda\sim760$ nm, well described by the relations

\begin{equation}
I = -0.0002813 \cdot U^4 + 0.00625 \cdot U^3 - 0.04694 \cdot U^2 + 0.1318 \cdot U - 0.09078
\end{equation}

\begin{equation}
I = -0.0001302 \cdot U^4 + 0.001083 \cdot U^3 + 0.01093 \cdot U^2 - 0.1241 \cdot U + 0.2962
\end{equation}

As can be seen from the characteristics presented in Figure 4 shows I-V, at $\lambda\sim740$ 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 $I_p=0.028 \mu A$ is achieved at $U=3$ V. It can be seen that the I-V characteristics at $\lambda\sim720$ nm and $\lambda\sim740$ 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 $\lambda\sim760$ 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 $I_p=0.187 \mu A$ 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: $\lambda\sim780$ nm and $\lambda\sim880$ nm, well described by the relations

\begin{equation}
I = 0.0004818 \cdot U^4 - 0.01119 \cdot U^3 + 0.09212 \cdot U^2 - 0.3168 \cdot U + 0.3844
\end{equation}

\begin{equation}
I = 0.0006302 \cdot U^4 - 0.01325 \cdot U^3 + 0.09382 \cdot U^2 - 0.2563 \cdot U + 0.231
\end{equation}

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 \( \lambda \sim 780 \text{ nm} \), it is identical to the characteristic at \( \lambda \sim 760 \text{ nm} \). 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 \( U=1 \text{ V} \), but slightly decreased and amounted to \( I_P \sim 0.15 \mu A \).

Similarly, at \( U=1 \text{ V} \), the photocurrent peaks at wavelengths \( \lambda_{p6} \sim 840 \text{ nm} \) and \( \lambda_{p7} \sim 880 \text{ nm} \); at \( U=3 \text{ V} \) peak photocurrent at wavelength \( \lambda_{p6} \sim 860 \text{ nm} \); at \( U=5 \text{ V} \) photocurrent peaks at wavelengths \( \lambda_{p3} \sim 800 \text{ nm} \) and \( \lambda_{p4} \sim 880 \text{ nm} \); at \( U=7 \text{ V} \), the photocurrent peaks at wavelengths \( \lambda_{p2} \sim 800 \text{ nm} \) and \( \lambda_{p7} \sim 880 \text{ nm} \) provide an opportunity for their effective use in optoelectronics coupled with GaAlAs and GaAl lasers.

In addition, at \( U=1 \text{ V} \), photocurrent peaks in the range 550-900 nm at wavelengths \( \lambda_{p2} \sim 540 \text{ nm} \), \( \lambda_{p3} \sim 710 \text{ nm} \), \( \lambda_{p5} \sim 765 \text{ nm} \), \( \lambda_{p6} \sim 840 \text{ nm} \) and \( \lambda_{p7} \sim 880 \text{ nm} \) 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 \( \lambda \sim 400-900 \text{ nm} \) at five values of the bias voltage \( U \) applied to the sample: \( U=1 \text{ V} \), \( 3 \text{ V} \), \( 5 \text{ V} \), \( 7 \text{ V} \) and \( 9 \text{ V} \). The analysis shows 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 \( U=1 \text{ V} \). At the same time, at a wavelength of \( \lambda \sim 715 \text{ nm} \), the most significant peak is reached, equal to \( I_P \sim 0.2 \mu A \). Experimental points and curves approximating them for I-V characteristics of the studied nanotube samples are presented at six wavelengths: \( \lambda \sim 640 \text{ nm} \), \( \lambda \sim 720 \text{ nm} \), \( \lambda \sim 740 \text{ nm} \), \( \lambda \sim 760 \text{ nm} \), \( \lambda \sim 780 \text{ nm} \) and \( \lambda \sim 880 \text{ nm} \). 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 \( \lambda \sim 720 \text{ nm} \) the I-V characteristic exhibits a very weak photosensitivity in almost the entire voltage range of 1-9 V decreases.

REFERENCES


BIographies
Azer G. Mammadov was born in Baku, Azerbaijan, in February 1950. He is graduated in the field of Radio Engineering from Moscow Energy Institute, Russia in 1973. Since September 1977, he has worked at Department of Industrial Electronics, Azerbaijan Technical University, Baku, Azerbaijan as a senior engineer, graduate student, junior researcher, senior researcher, assistant, senior teacher, Associate Professor, and since 2008 as a Professor. In 2004, he defended his doctoral dissertation and was awarded the title of Doctor of Technical Sciences. Currently, he is a Professor at Azerbaijan State Oil and Industry University, Baku, Azerbaijan. He is the author of 120 scientific paper, 3 monographs, 2 textbooks and 10 patents.

Rashad G. Abaszade was born in Baku, Azerbaijan, in March 1982. He received the B.Sc. degree from Baku State University, Baku, Azerbaijan in 2003 and the M.Sc. degree in 2006. He received his Ph.D. degree from Institute of Physics, Azerbaijan National Academy of Sciences, Baku, Azerbaijan in 2018. Currently, he is an Associate Professor at Azerbaijan State Oil and Industry University, Baku, Azerbaijan and Head of Innovation Research Department of International Ecoenergy Academy, Baku, Azerbaijan. His research interests are synthesis of carbon nanomaterial’s, their application in Nano composites, nanotechnology and Nano electronics, theoretical and Experimental investigation of Nanomaterials. He is the author of 76 scientific papers, 6 textbooks and 3 patents.

Volodymyr O. Kotsyubynsky was born in Kiev, Ukraine, in November 1976. He graduated from Department of Materials Science and New Technologies, Faculty of Physics with a degree in physics. In 2002, he became a candidate of physical and mathematical sciences. Since 2013, he has been a Professor at Department of Materials Science and New Technology, National University of Precarpathian, Ukraine. His research focuses on testing materials with XRD, Mossbauer spectroscopy, low temperature gas absorption, XRF, thermal analysis and impedance spectroscopy. He has published 30 papers in WOS and Scopus databases.

Emre Y. Gur was born in Cihanbeyli, Konya, Turkey in August 1976. He received his Bachelor degree in 1999 from Department of Physics, Middle East Technical University, Ankara, Turkey. He received his Master degree in 2003 from Department of Solid State Physics, Ataturk University, Erzurum, Turkey. Since 2007, he has been defending his Ph.D. at Department of Solid State Physics, Ataturk University. He is currently a Professor at Ataturk University. He is the author of 86 scientific papers.

Imran Y. Bayramov was born in Dmanisi, Georgia, in February 1963. He received the B.Sc. degree from Baku State University, Baku, Azerbaijan in 1985. He received his Ph.D. degree in 2013. Currently, he is an Associate Professor at Azerbaijan State Oil and Industry University, Baku, Azerbaijan. His research interests are modeling, fuzzy systems, automation simulation, programming, optimization, applied mathematics. He is the author of 60 scientific papers and 4 textbooks.
Elmira A. Khanmamadova was born in Tyumen, Russian, in September 1982. She graduated the Department of Physical Electronics. Currently, she is working at Azerbaijan State Oil and Industry University, Baku, Azerbaijan. Her research interests are electrical and photoelectric characteristics of heterojunctions, production of thin films by photoelectric conversion of hetero-junctions, photosensitive semiconductor materials and devices, nanotechnology and nanoelectronics, theoretical and experimental investigation of Nanomaterials. She is the author of 52 scientific papers, 5 textbooks and 1 patent.

Olga A. Kapush was born in Svirshkivtsi, Ukraine, in March 1986. She is the senior researcher at Department of Optics and Spectroscopy of Semiconductor and Dielectric Materials, V.E. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, and Ph.D in Solid State Chemistry. He received B.Sc. degree from Y.F. Cernivtsi National University, Ukraine in 2007 and the M.Sc. degree in 2008. His research interests are work with development of methods for the formation and study of physical properties of nanosized structures based on semiconductors. She published 150 publications, including 2 chapters in monographs, 23 patents for inventions and utility models.