ISSN 1068-3356, Bulletin of the Lebedev Physics Institute, 2017, Vol. 44, No. 8, pp. 243–245. © Allerton Press, Inc., 2017.
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Development of the Device Prototype Based on the Semiconductor–Carbon Nanotubes Structure for Optical Radiation Detection and Study of its Parameters

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Received July 20, 2017

Abstract—A light-receiving device prototype based on the semiconductor–carbon nanotubes (CNTs) structure consisting of 16 cellular structured sensitive elements grown on the same substrate is developed. The topology of sensitive cells represents holes through metallization and insulator layers to the semiconductor from which the CNT array grows to the top metallization layer. The device prototype parameters are determined as follows: the effective wavelength range is within 400–1100 nm, the operational speed is no longer than 30 μs, the coefficients of peak sensitivity reached at wavelengths of 640 and 950 nm are 197 and 193 μA/W, respectively.

DOI: `10.3103/S1068335617080061`

Keywords: optical detector, carbon nanotubes, semiconductor, optoelectronics.

Introduction. Currently, the development of optical receivers is an urgent problem in various fields of science, production, and special technology. According to the operating principle, all currently existing photodetectors can be divided into two main types, i.e., the photothermal and photoelectric ones [1]. In photothermal photodetectors, the mechanism of optical to thermal and then to electrical energy conversion is implemented. Such disadvantages as high inertia (as a result, low speed) and the environmental susceptibility are inherent to photodetectors. The operating principle of photoelectric detectors is based on direct optical-to-electrical energy conversion. Semiconductor photodetectors can be attributed to this type, which feature high speed and are less susceptible to external conditions than photothermal receivers.

Modern studies showed promising application of semiconductor-type carbon nanotubes (CNTs) which are direct-gap semiconductors as components of sensitive elements in photodetectors. Despite their significant advantages, photodetectors based on CNTs has not yet been widely used due to the following features:

1. The band gap for semiconductor nanotubes of various diameters varies from 0.1 to 2 eV (λ from $\sim$1 μm to $\sim$10 μm) [2].

2. Minor changes in the nanotube parameters (sizes, composition, structure, and others) entail significant changes in their properties. Hence, the high degree of equivalence of synthesized nanotubes is required [3] to retain the reproducibility of characteristics of photodetectors based on CNTs.

3. Size effects (e.g., depletion bands and space charge regions) in the regions of CNT contacts with the semiconductor (metal) matrix (functional heterojunction) should be taken into account, since these effects play a significant role in the possibility of increasing the detector operating temperature [4].

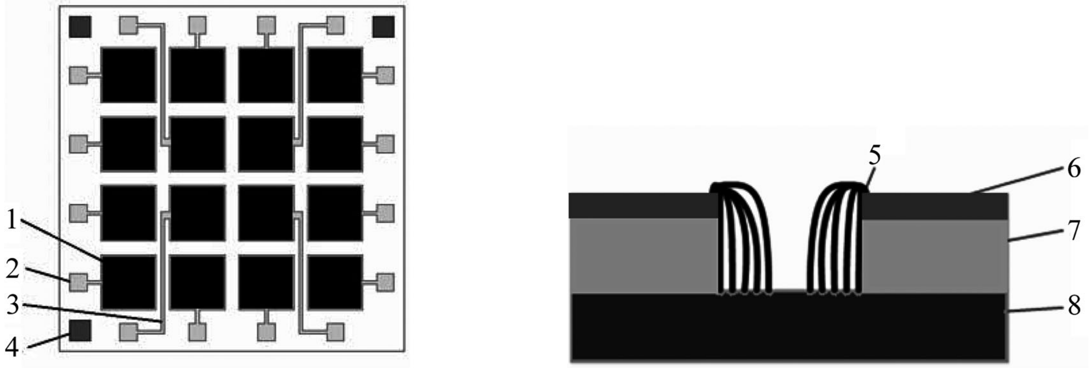

Fig. 1. Topology of the matrix detector based on the CNT array (left) and the sensitive cell (right): (1) sensitive element, (2) its contact area, (3) contact metallization, (4) contact window of the silicon substrate, (5) carbon nanotubes, (6) top metallization layer, (7) silicon oxide (insulating layer), and (8) silicon substrate.

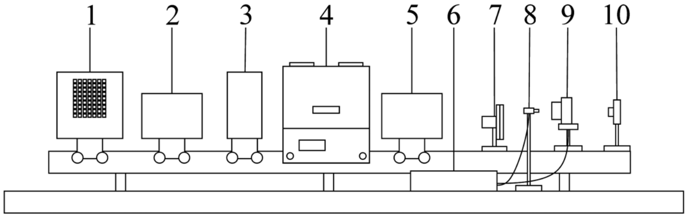

Fig. 2. Experimental setup for studying the parameters of the device prototype based on the semiconductor–CNTs structure: (1) radiation source, (2) input condenser, (3) unit of light filters, (4) monochromator, (5) output condenser, (6) data acquisition device, (7) attenuator, (8) high-speed light-emitting diode, (9) sample holder, (10) reference meter of the optical radiation power.

4. The small size of an individual nanotube provides low signal intensity during the interaction with optical radiation [5]; to amplify the signal, many tubes are required, e.g., in the form of a grown array.

Materials and methods. The developed device prototype represented a matrix detector consisting of 16 sensitive elements grown on the same semiconductor substrate (Fig. 1). Each sensitive element contains 10000 sensitive cells arranged as a 100×100 square with a distance between cells of 5 μm. The basic topology of sensitive cells was a two-electrode system representing holes passing through metallization and insulator layers to the semiconductor from which the CNT array grew to the top metallization layer (Fig. 1).

Experimental. The parameters of the matrix detector based on CNTs, such as the effective wavelength range, speed, and peak sensitivity coefficients were studied using the experimental setup shown in Fig. 2. The major elements of the experimental setup were an MDR-41 monochromator (OKB Spectr, Russia) and an NI USB-6218 data acquisition unit (National Instruments, USA). The study was automated using a software specially developed in the LabVIEW environment.

To determine the effective wavelength range, the device prototype under study was sequentially exposed to radiation with different wavelengths using the monochromator; in this case, the current generated by each sensitive element was synchronously measured. The speed was determined by exposing the device prototype to pulsed radiation of a high-speed light-emitting diode and measuring the time dependence of the generated current amplitude. In this case, the time dependence of the light-emitting diode current was also measured. To study the sensitivity, the dependences of the generated current amplitude on the incident radiation intensity were measured using the monochromator and an attenuator with calibrated neutral light filters for the wavelengths of 640 and 950 nm.

Experimental results. The dependence of the current on the incident radiation wavelength (Fig. 3) allowed us to determine the spectral range of the operation of the device prototype under study as 400–1100 nm. The curve of this dependence also exhibits several characteristic points at 640, 800, and 950 nm, which distinguishes the device under study from existing silicon photodetectors.

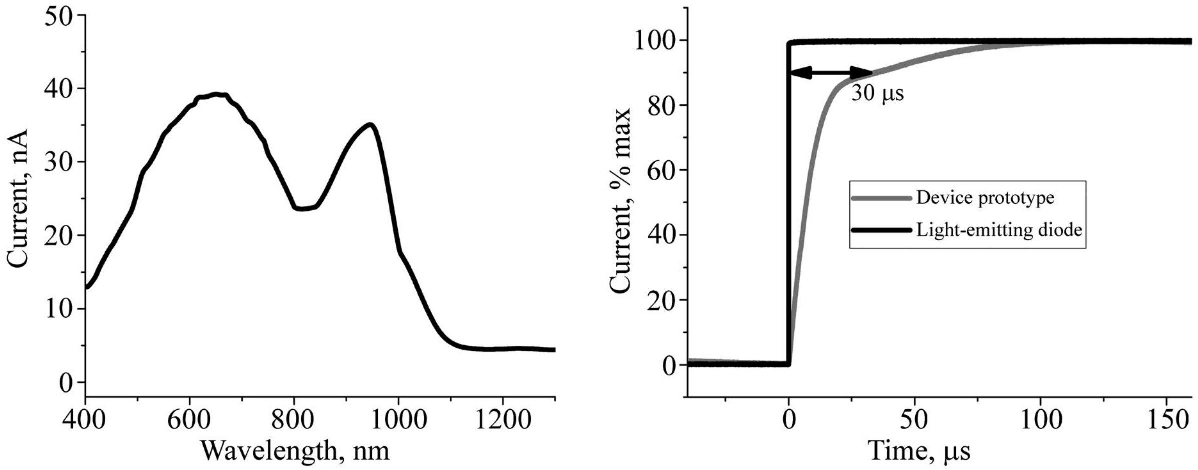

Fig. 3. Dependences of the current on the incident radiation wavelength (left) and time (right) of the device prototype based on the semiconductor–CNTs structure. The gray curve and bold line correspond to the device prototype and light-emitting diode.

The obtained curves of the dependences of the generated current amplitude on the incident radiation intensity linearly ascended, which indicates the linearity of the photocurrent formation in the detector during the interaction with radiation. These curves were linearly approximated using the least-squares method, and the sensitivity coefficient was determined as the linearized curve slope. The peak sensitivity coefficients at the wavelengths of 640 and 950 nm were 197 and 193 μA/W, respectively.

From the time dependence of the generated current amplitude (Fig. 3), the studied device speed was determined to be $\sim$30 μs as the sum of the data acquisition device response time (which was negligible in the case at hand) and the current rise time to 90% of the maximum amplitude.

Conclusions. The results of the development of the device prototype based on the semiconductor–carbon nanotubes structure are presented. The device prototype parameters were determined as follows: the effective wavelength range is 400–1100 nm, the operational speed is no longer than 30 μs, the coefficients of peak sensitivity reached at wavelengths of 640 and 950 nm are 197 and 193 μA/W, respectively. This device is a result lying in the field of new silicon–carbon nanoelectronics; as the technology is improved and worked out, it should provide higher parameters than those of currently existing semiconductor detectors.

ACKNOWLEDGMENTS

This study was supported by the Ministry of Education and Science of the Russian Federation, project no. 16.9007.2017/BCh.

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Presented at the 6th International Youth Scientific School-Conference "Current Problems of Physics and Technologies".