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Investigation of temporal characteristics of photosensitive heterostructures based on gallium arsenide and silicon

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The paper briefly describes the methodology for studying the temporal characteristics of near-IR photodiode structures under the influence of pulsed radiation from a semiconductor laser with a wavelength of 1100 and 1320 nm. The results of studying the response time of multilayer photosensitive Au-nCdS-nSi-pCdTe-Au and Au-nInP-nCdS-νGaAs:O-Au structures with potential barriers are presented. It has been experimentally shown that the structures under study are not inferior in response time to known analogs based on gallium arsenide and silicon heterostructures, and can also be used in a wide optical range.

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Keywords: Rise time, Fall time, Reverse current, Response speed, Photodiode, Structure, Photocurrent, Light pulse

1. Introduction

Currently, complex theoretical and practical work is being carried out on the research of optical properties of various wide bandgap materials and Si-based structures [1-3]. Recently, intensive research has been conducted to improve the response time of photodiode structures based on various semiconductors, such as InGaAs-based photodiodes [4], p-i-n diodes based on silicon and germanium [5] providing coverage of the long-wave optical range of the near IR spectrum [6]. Fast p-i-n photodiodes must have a sufficiently thin i-layer of intrinsic conductivity, a small area of the active region, low resistance and capacitance of the i-layer [7]. Along with the area of the active region, the thickness of the i-layer is the only factor determining the response of the photodiode. The thickness of the i-layer is estimated from the experimentally measured rise time of the signal from the photodiode, which occurs as a response to the action of the input laser pulse [8].

As is known, one of the main parameters of a photodiode - the response speed is determined by the structure of the photodiode, the material, the electric field strength in the weakly doped region. Usually, the response speed is defined as the time required for the rectangular pulse to grow from the level of 0.1 to 0.9 from the established maximum value of light pulses. The maximum value (usually τ_r) is taken as a characteristic of the photodiode response time.

In [9], a new topology of the photodiode is proposed to increase the speed of response, providing short current recovery times. In the proposed topology of the photodiode, the photosensitive area is surrounded by a “pocket” that eliminates slow diffusion components from the peripheral region.

This paper presents the results of a study of the performance characteristics of photodiodes based on gallium arsenide and silicon with potential barriers.

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2. Experimental procedure

An important parameter of a photodiode is its response speed. As is known, the response speed of a photodiode is determined by the following parameters: 1. The carrier's flight time through the space charge region; 2. The diffusion time of electron-hole pairs created by radiation to the space charge region of the p-n junction; 3. The charge-discharge time of the p-n junction's own capacitance, which is the value of the capacitance and load resistance R [10]. At a high level of base conductivity, the response speed of a photodiode is determined by the lifetime of longer-lived carriers.

With increasing modulation frequency of the input optical pulse, the maximum value of the photocurrent decreases. The limiting frequency is defined as the modulation frequency at which the current sensitivity decreases to 0.7 of the maximum value of the current sensitivity at low modulation frequencies. The rise and fall times mainly affect the bandwidth or the signal transmission rate. The time characteristics (intrinsic time constant, rise time, and fall time) of the experimental samples were determined using the device diagram shown in Fig. 1 and the structural diagram shown in Fig. 2.

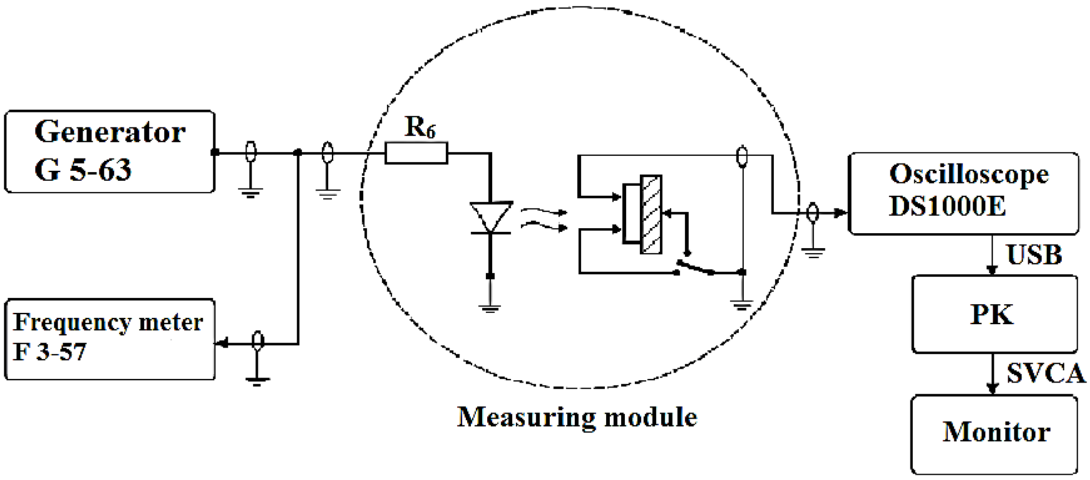

Fig. 1. Electrical circuit for measuring the time characteristics of photodiode structures.

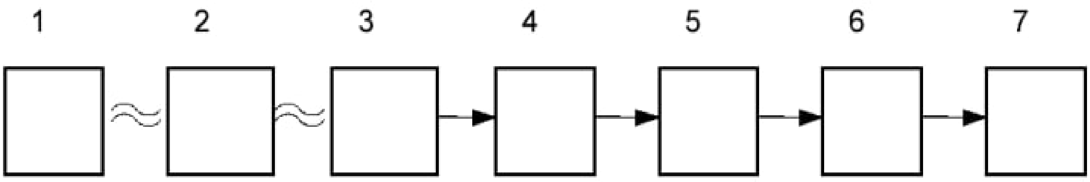

Fig. 2. Structural diagram of the installation for determining time characteristics: 1. Broadband light source; 2. Mechanical light modulator; 3. Photodiode structure under study; 4. Low-noise preamplifier; 5. Signal detector; 6. Low-pass filter; 7. Digital storage oscilloscope

A continuous radiation source forms trapezoidal pulses through a modulator. The rise time and fall time are calculated based on the pulse duration, with a countdown (rise 0.1-0.9 and fall 0.9-0.1 from the pulse duration) of the radiation flux must satisfy the following condition: $t_{0.1-0.9} \leq 0.3t$, $t_{0.9-0.1} \leq 0.3t$. The width of the pump pulse maximum at half height was 25 ps. The response time of experimental samples - photodiode structures was studied [11] when pumping with radiation pulses from a laser with a wavelength of λ = 1300 nm of the OP-MA635F1S3-20 type.

3. Results and discussion

The performance of the Au-nCdS-nSi-pCdTe-Au photodiode structure under study was investigated under pumping by pulses of radiation from a semiconductor laser with a wavelength of 1100 nm and 1320 nm [12]. At half the maximum of the pump pulse, the width was for a laser with a wavelength of λ: 1100 nm (40÷41 ns) and 1320 nm (26.5÷65 ns). The shapes of the photocurrent pulses formed in the photodiode illuminated from different surfaces by a rectangular light pulse with a wavelength of λ=1100÷1320 nm for the Au-nCdS-nSi-pCdTe-Au sample are shown in Fig. 3.

The results of the studies of time parameters determined for the studied sample are presented in Table 1.

Table 1. Time parameter data for the studied multilayer heterofilm photosensitive structure based on silicon.

Sample	Receiving surface	t_r-rise time, ns	t_d-decay time, ns	τ_c-lifetime of minority carriers, ns
Emitter 1100 nm, radiation power 400 mW				
Au-nCdS-nSi-pCdTe-Au	P→Au-nCdS	3,8	79	90,5
	pCdTe-Au ←P	124	81,5	42
Emitter 1320 nm, radiation power 250 mW				
Au-nCdS-nSi-pCdTe-Au	P→Au-nCdS	3,3	89	88
	pCdTe-Au ←P	80	40	23

From this table it is evident that for the studied structure with metal-semiconductor barriers under the radiation of a semiconductor laser with a wavelength of 1100 nm and 1320 nm, directed to the receiving surface of the studied photodiode structure, the rise time of the optical signal is in the range from 3.2 ns to 125 ns, and the decay time from 40 ns to 82 ns, and the lifetime of minority carriers from 23 ns to 91 ns.

If we take into account that in silicon p-i-n photodiodes [4], as the diameter of the structure area increases from 0.1 mm to 5 mm, the rise and fall times increase from 10 ns to 40 ns, then the time characteristics data given in Table 1 meet the requirements for photodiodes for optical communication systems.

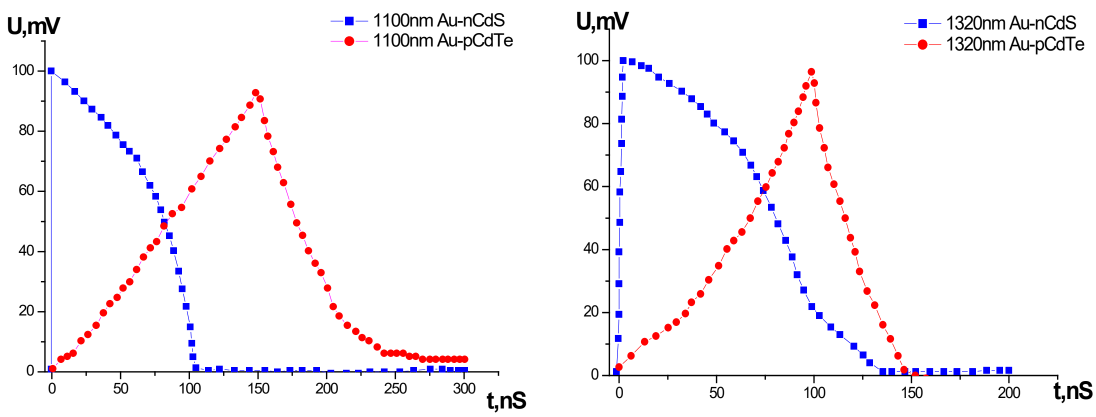

Fig. 3. The shape of the photocurrent pulses when illuminating an Au-nCdS-nSi-pCdTe-Au photodiode with a rectangular light pulse from different surfaces. a) When illuminating a photodiode with a light-emitting diode with a wavelength of λ=1100 nm on the surface from the side of Au-nCdS and pCdTe-Au; b) When illuminating a photodiode with a light-emitting diode with a wavelength of λ=1320 nm onto the surface from the side of Au-nCdS and pCdTe-Au.

The shape of the reference pulse supplied to the LED emitter and the photocurrent pulses formed in the photodiode illuminated from various surfaces by a rectangular light pulse with a wavelength of 1300 nm for one of the Au-nInP-nCdS-νGaAs:O-Au samples are shown in Fig. 4.

The shape of the pulse formed on the photodiode from the supplied rectangular light pulse from the emitter with a wavelength of 1300 nm, also for samples based on silicon (Au-nSi-Au) and heterojunction photodiodes formed on gallium arsenide, is shown in Fig. 5.

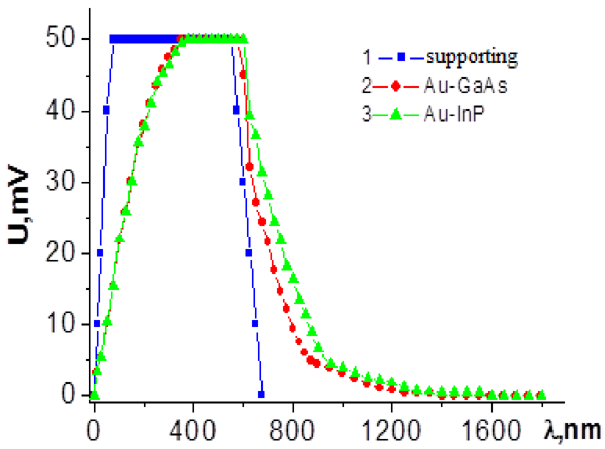

Fig. 4. The shape of the reference pulse and photocurrent pulses when illuminating the Au-nInP-nCdS-νGaAs:O-Au photodetector with a rectangular light pulse from different surfaces.

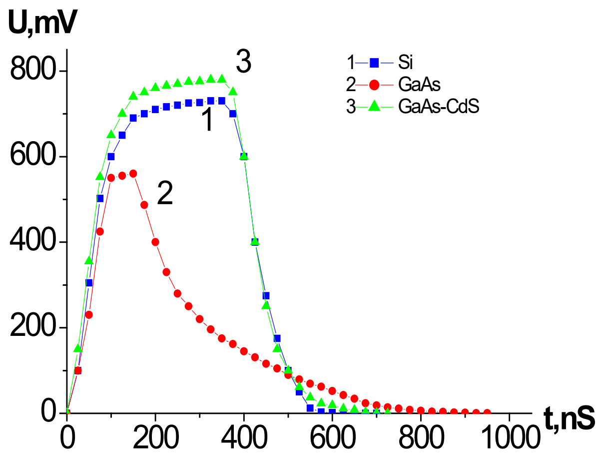

Fig. 5. Pulse shape generated on photodiodes: Au-nSi-Au; Au-νGaAs-Au; Au-νGaAs:O-nCdS-nInP-Au.

The photocurrent pulses generated in the photodiode illuminated by a radiation wavelength of 1300 nm are shown in Fig. 6. As can be seen from the figure, the amplitude of the pulse generated on the photodiode from a rectangular light pulse with a wavelength of 1300 nm from the blocking voltage increases to 307.7 mV, and the rise time is 252 ns. In turn, the decay time is determined by the time during which the photocurrent decreases by a factor of 2.718 after the end of the light pulse. Based on this dependence on the decay of the rectangular pulse, the lifetimes of minority carriers are determined:

$$\tau_c = \frac{kT}{e}\frac{\Delta t_c}{\Delta U}.$$

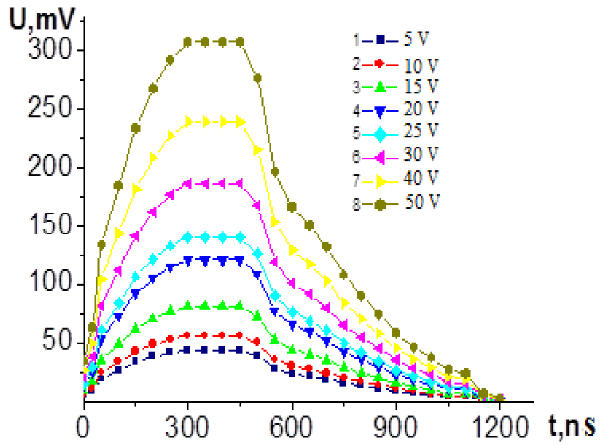

Fig. 6. Pulse shape generated on the Au-nInP-nCdS-vGaAs:O-Au photodiode from a rectangular light pulse with a wavelength of 1300 ns at different blocking voltages.

The results of the studies of time parameters determined for several studied samples are summarized in Table 2.

As can be seen from Table 2, for the studied multilayer photosensitive structures with metal-semiconductor barriers, the rise time of the optical signal is in the range from 100 ns to 250 ns, and the decay time from 160 ns to 500 ns and the lifetime of minority carriers from 90 ns to 150 ns.

If we take into account that in photodiodes based on InAs/InAsSbP heterostructures [4], as the diameter of the structure area increases from 0.1 mm to 2 mm, the rise and fall times increase from 10 ns to 300 ns, then the time characteristics data given in Table 2 meet the requirements for photodiodes for optical communication systems. In particular, experimental photoreceiving modules [13] for receiving optical signals in the spectral range of 0.7 μm were manufactured based on these multilayer photosensitive structures.

Table 2. Data of time parameters for the studied multilayer photosensitive structures based on silicon and gallium arsenide.

№	Sample	Receiving surface	t_r-rise time, ns	t_d-decay time, ns	τ_c - lifetime of minority carriers, ns
Emitter 1300 nm					
1	Au-nSi-Au	P→ Au-Si-	106	165	99
2	Au-nInP-nCdS-vGaAs:O-Au	P→Au- nInP-CdS	240	318	148
		GaAs-Au←P	239	276	120
3	Au-nInP-CdS-nGaAs:Te-(In+Sn)	P→ Au-nInP	97,3	532	94
4	Au-Ge-nInP-CdS-nGaAs:Te-(In+Sn)	P→Au-Ge-nInP	159	200	90

As can be seen from the table, for the studied multilayer photosensitive structures with metal-semiconductor barriers, the rise time of the optical signal is in the range from 100 to 250 ns, and the fall time is from 160 to 500 ns and the lifetime of minority carriers is from 90 to 150 ns. If we take into account that in photodiodes based on InAs/InAsSbP heterostructures [14], as the diameter of the structure area increases from 0.1 to 2 mm, the rise and fall times increase from 10 to 300 ns, then the data on the time characteristics presented in Table 1 meet the requirements for photodiodes for optical communication systems. In particular, experimental photodetector modules [13] for receiving optical signals in the spectral range of 0.7 μm were manufactured on the basis of these multilayer photosensitive structures.

4. Conclusion

It was experimentally found that the response time of Au-vGaAs:O-nCdS-nInP-Au structures is from 100 ns to 250 ns for a wavelength of 1.3 μm, respectively, due to the prevalence of the electronic mechanism of photocurrent formation and low capacitance values 10 ÷ 26 pF [15], which are not inferior to known analogs based on InGaAs heterostructures in a wide optical range used for receiving and transmitting an optical signal. And the photosensitive Au-nCdS-nSi-pCdTe-Au heterostructure with metal-semiconductor barriers, having a photosensitivity of 0.57 A/W, the response time reaches from 3.3 ns to 89 ns for a wavelength of 1.1 and 1.32 μm in a wide spectral range in the interval (1.0 ÷ 1.4 μm).

As a result of the conducted studies, it was established that the photodetector structures manufactured on the basis of gallium arsenide and silicon are not inferior to known analogs in terms of speed of operation in a wide optical range used for receiving and transmitting optical signals. They are operational at room temperature, in terms of dark current and capacity.

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