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INVESTIGATION OF THE PHOTOELECTRIC CHARACTERISTICS OF PHOTODIODE STRUCTURES WITH SILICON-BASED POTENTIAL BARRIERS

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Based on silicon with a base region thickness of 300 μm, phototransforming Au–nSi–Au structures with potential barriers are prepared. The diode structures obtained possess high photosensitivity in the spectral region 0.9–1.1 μm at low illumination intensities of 10 lux (up to 5 A/W). Based on investigations of the photoelectric characteristics, it has been established that the Au–nSi–Au structures in the range of temperatures from room temperature to 40°C at low working voltages (0.1–0.2 V) are distinguished by the weak temperature dependence of photocurrents. In principle, in the spectral range 0.7–1.1 μm the Au–nSi–Au structures obtained can easily replace both gallium arsenide and classical silicon photodiodes with one rectifying junction in optoelectronic devices.

Keywords: *photoelectric characteristics, photocurrent, potential barriers, base region, silicon, photodiode structure.*

Introduction. The obtaining and processing of optical signals, as well as the design of optoelectronic multipurpose devices, require the development of special photodetectors receiving weak optical signals in the given spectral range. The reception of weak optical signals implies the presence of photoelectric amplification, i.e., of the photoelectric transformation of optical radiation into electric one with the aid of semiconduction photodetectors of the class of photoelectrotransformers fitted with metal-semiconductor barriers [1]. In turn, the use of semiconductor emitters as information detectors (a light-emitting diode or laser) with a comparatively narrow radiation spectrum impose additional requirements on the design of photodetectors, in particular, of those to be used in the visible and near-infrared regions (0.6–1.1 μm) and having the corresponding efficient light diodes and semiconductor lasers.

The technologies of the production of photodetectors are based on the application of semiconductor compounds based on gallium arsenide [2]. This technology is better understood than the technology of preparing semiconductor compounds based on silicon.

The present work contains the results of investigation of the photoelectric characteristics of photodiode structures with potential barriers based on silicon.

Technique of Fabrication of Au–*n*Si–Au Structures and Investigation of Their Current Characteristics. To carry out the investigations, we selected photoelectrotransforming diode Au–*n*Si–Au structures based on silicon with a concentration of impurities in the basal region $N = 10^{15}$ cm^{-3}. They were fabricated from silicon of *n*-type conductivity with a specific resistance of 4 Ω·cm doped with phosphorus and obtained by the zone melting method. The thickness of the basal region of the Au–*n*Si–Au structure was equal to 300 μm. Preliminary processing included grinding and subsequent polishing, with an ACM-1.5 diamond polishing paste, of both surfaces of the original silicon sample. Prior to deposition of metal layers, silicon washers were first treated in a polishing pickling agent $HF:HNO_3:CH_3COOH$ (1:8:1), then rinsed in deionized water and dried. Semitransparent layers of Au of thickness ~100 Å that created potential barriers were vacuum-deposited onto both surfaces of the low-resistance *n*Si at a pressure of about 10^{-5} Torr. To decrease dark currents, the structures were annealed in a hydrogen flow at 300°C for 30 min.

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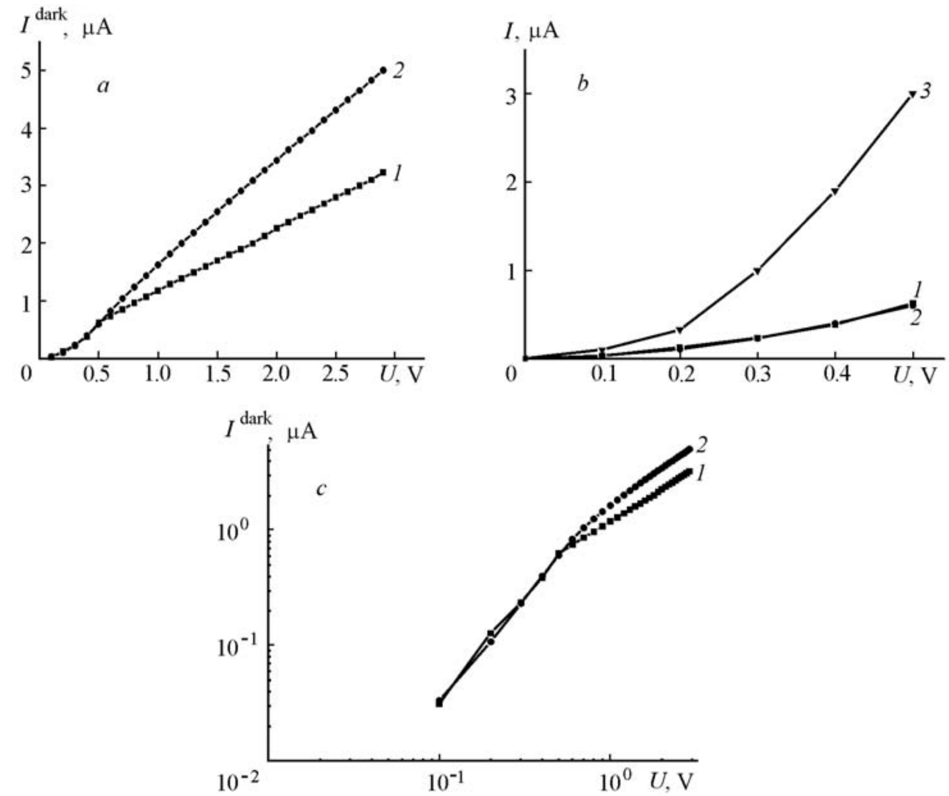


Fig. 1. Dark volt-ampere characteristic of the Au–nSi–Au structure in an ordinary scale (a), (b) and in a double logarithmic scale (c): 1) direct; 2) back; 3) light back.

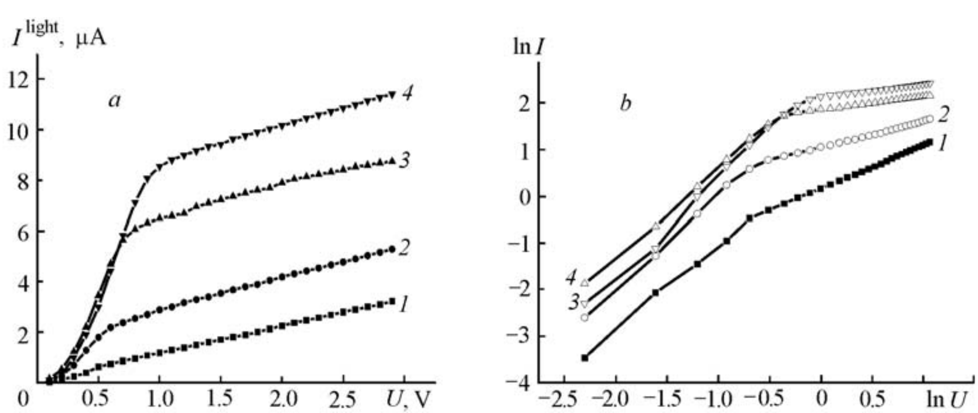
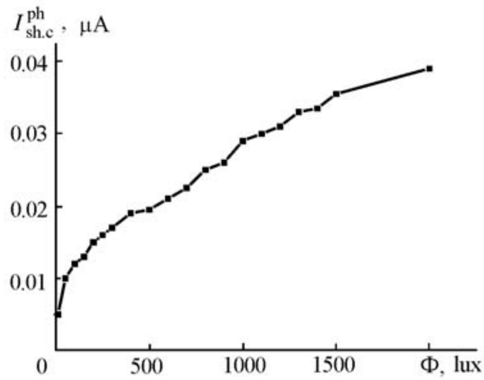


Fig. 2. Light volt-ampere characteristic ($\Phi \rightarrow$ (–)Au–nSi–Au(+) structure) in the blockage regime of illuminated barrier in an ordinary regime (a) and in a double logarithmic regime (b) at different light intensities: 1) Φ = 0.2 lux; 2) 10; 3) 50; 4) 100.

The volt-ampere characteristic of the Au–nSi–Au structure at different regimes of switching-on is split into two portions (Fig. 1a and b). Over the first portion, the dependence of current on voltage is close to an exponential one with an ideal separation factor of about 8. The second portion is characterized by the exponent $I \sim U^{\gamma}$ close to unity (Fig. 1c). The changes over the first portion are due to the recombination processes in the rectilinearly displaced transition when the values of the current flowing through a locked barrier are higher than its value in the rectilinearly displaced transition. Next, the values of the dark current are compared and limited by the locked transition in which the mechanism of current transfer is governed by thermoelectron emission of carriers (γ



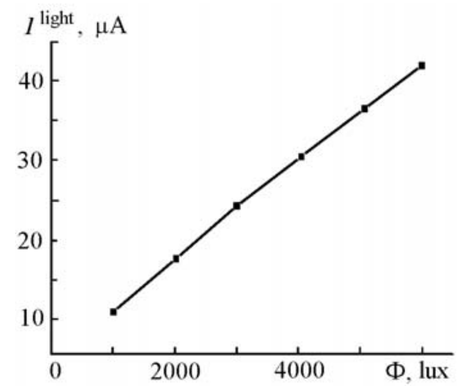


Fig. 3. Dependence of $I_{sh.c}^{ph}$ on Φ at room temperature.

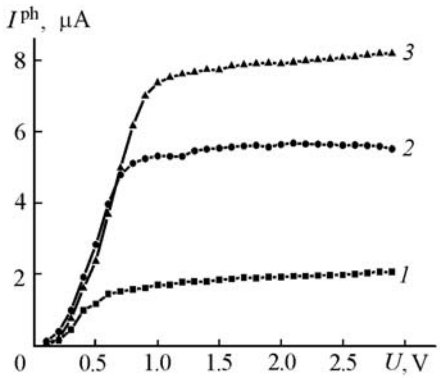
Fig. 4. Dependence of light current on illumination intensity at the blocking operating voltage U = 2 V.

= 1) [3]. The light characteristics are also determined by analogous dependences (Fig. 2). Here, as the intensity of integral illumination increases, the first portion becomes more extended and at illumination of 100 lux it attains a diode bias voltage of 0.7 V. If in darkness over the second portion the mechanism of current transfer in a wide voltage range is determined by the thermoelectron emission of "dark" electrons ($\gamma \approx 1$), then, as the illumination intensity increases, the length of this portion decreases, and the mechanism of current transfer is already determined by generation processes in the region of the space charge of the barrier being locked. This means that initially the current strength is determined by the prevailing quantity of charge carriers tunneling through the unilluminated barrier and then by the limitation of this current by photogenerated carriers of the illuminated barrier, i.e., by generation processes in the region of the space charge of illuminated transition.

It is interesting that the given photoelectrotransforming Au–*n*Si–Au structure can receive optical signals also in the regime of short circuit, which allows one to use this structure as a noiseless photovoltaic detector. The lux–ampere characteristics of the structure are presented in Fig. 3, where it is seen that the highest increase in the photocurrent strength is observed at low illumination intensities and thereafter the photocurrent tends to saturation with increase in the illumination intensity. Such a behavior of the lux–ampere characteristics is indicative of the advantages of using the photocurrent in receiving weak light signals. At given fixed blocking voltages of illuminated transition, the photocurrents increase with the illumination intensity (Fig. 4). Experiments show that the photoelectric characteristics of photocurrents are determined by generation-recombination processes in the region of the space charge and by thermoelectronic processes that make it possible to overcome the potential barrier.

It is known that in structures with a Schottky barrier, depending on the value of the concentration of charge carriers in the basal region, three basic mechanisms of current transfer are observed: thermoelectron emission, tunneling, and field emission. Here, in the case of a high-resistance basal region, the temperature sensitivity of silicon increases and the background (thermal) radiation exerts its influence on the silicon structures. At the same time, the creation of the second potential barrier enables one to control the mechanisms of current transfer. This will increase the photosensitivity of the structure at the cost of both the effect of internal photoelectric amplification and the decrease in the dark current simultaneously with the introduction of the second layer of space charge with a high resistance. In the case of a one-barrier structure, to register an optical signal a larger level of signal is required (which can cause heating of the structure) than for a two-barrier structure, i.e., the influence of heat in a two-barrier structure becomes insignificant due to the increase in the photosensitivity of the structure. It was shown in [4, 5] that in a multibarrier structure, due to the internal photoelectric amplification, it is possible to increase the photosensitivity by one order of magnitude in comparison with one-barrier structures. In other words, the needed level of optical signal in a multibarrier structure can be obtained already at smaller levels of the input signal at the first order of intensity (0–10 lux).

Indeed, the results obtained on the basis of investigation of photoelectrotransforming structures are indicative of the fact that in the Au–*n*Si–Au structure with two potential barriers one can obtain high values of photosensitivity at low levels of an optical signal. Thus, for the photoelectric characteristic of the investigated silicon Au–*n*Si–Au struc-



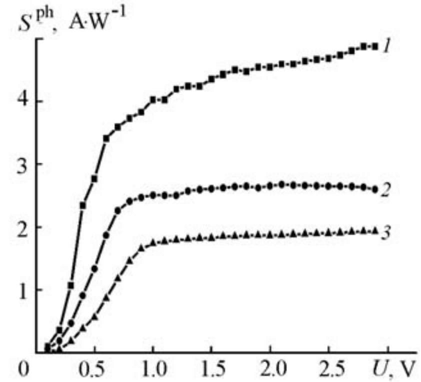


Fig. 5. Dependence of photocurrent on the operating voltage ($\Phi \to$ (–)Au–*n*Si–Au(+) structure) at different illumination intensities: 1) Φ = 10 lux; 2) 50; 3) 100.

Fig. 6. Dependence of photosensitivity ($\Phi \to$ (–)Au–*n*Si–Au(+) structure) on the operating voltage at different illumination intensities. Symbols of 1–3 are same as in Fig. 5.

ture, typically we see an increase in the difference between the light and dark currents (so-called photocurrent) on increase in the operating voltage (Fig. 5):

$$I^{\text{light}}(U, \Phi) = I^{\text{dark}}(U) + I^{\text{ph}}(\Phi)\,, \tag{1}$$

$$I^{\text{ph}}(\Phi) = S^{I}\Phi\,. \tag{2}$$

The expansion of the layer of space charge under a barrier with a simultaneous increase in voltage favors an increase in generated photocarriers. Here, the higher the voltage, the stronger the photocurrent. This is followed by the moment of photocurrent saturation due to the termination of the process of space charge layer expansion under the barrier. With increase in the illumination intensity the photocurrent curve becomes the continuation of the initial portion of the previous illumination intensity and is characterized by higher and higher values of photocurrent, i.e., the resistance of the structure and illumination intensity remain unchanged. With increase in the illumination intensity (Fig. 6), the ratio of photocurrent to the falling light power (so-called photosensitivity) decreases. At low illumination intensities (10 lux), the photosensitivity has higher values in the investigated two-barrier diodes than in gallium arsenide one-barrier diodes [2] and in typical silicon diodes with one rectifying transition [6]. The dependence of photosensitivity on the illumination intensity is explained by the replacement of the thermoelectron mechanism by a generation mechanism on increase in the operating voltage. In other words, for higher illuminance, there is higher operating voltage. Therefore, when generation processes are noted from the initial portion of illumination intensity increase (in the given case at Φ = 10 lux), the amplification of the photocurrent is observed in the whole range of voltages. However, at higher illumination intensities (50 and 100 lux) we observe photocurrent saturation and an invariable dependence of photosensitivity on voltage.

Characteristic Features of the Spectral Characteristic of Au–*n*Si–Au Structure. As is shown in Fig. 7, the spectral characteristic of the Au–*n*Si–Au structure at room temperature has a typical form (Fig. 7a), and as the applied voltage increases from 0.05 to 0.2 V, the photocurrents increase (Fig. 7b). The dependence of a photocurrent on voltage in the region of a maximum photocurrent at λ = 0.98–1.0 μm has a successively increasing character. In this case, in the range of voltages from 0.05 to 0.2 V an increase in the photocurrent of almost by an order of magnitude close to the linear one is observed (Fig. 8), i.e., in a narrow range of voltages there is a higher increase in the photocurrent. Analogous dependences of the spectral photoresponse S_λ on the value of operating voltage in normalized units are also presented in Table 1.

With increase in the temperature for the given operating voltages, the values of spectral photocurrent decrease (Fig. 9). It is seen from the figure that in the temperature range 15–30°C the greatest change in the photocurrent is

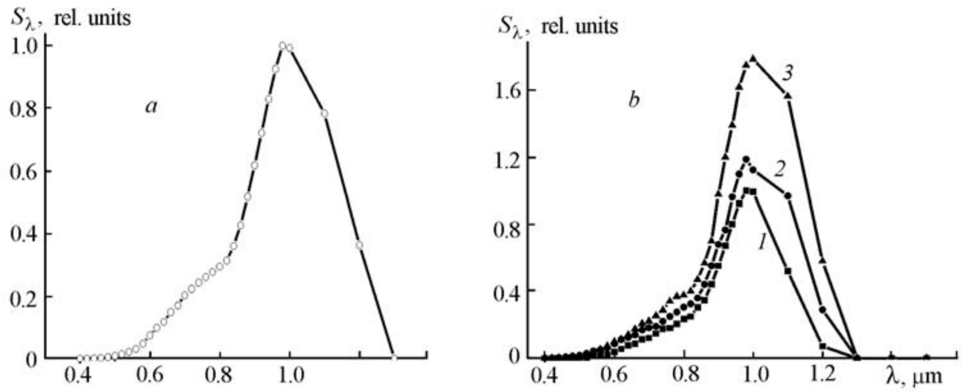


Fig. 7. Dependence of the spectral response on the monochromatic radiation wavelength at the temperature T = 15°C (a) and 30°C (b) at different values of blocking voltage: 1) U = 0.05 V; 2) 0.1; 3) 0.2.

TABLE 1. The Values of $I^{ph}_{\lambda=0.98}$ and S_λ Depending on the Operating Voltage in the Region of Intrinsic Absorption of Phototransforming Au–nSi–Au Structures (λ = 0.98) with the Concentration of Carriers in the Basal Region $N = 10^{15}$ cm^{-3}

U, V	$I^{ph}_{\lambda=0.98}$	S_λ, norm. units
0.05	0.025	1
0.1	0.036	1.2
0.14	0.053	1.39
0.18	0.068	1.75
0.2	0.077	2

TABLE 2. The Values of $I^{ph}_{\lambda=0.98}$ Depending on the Operating Voltage U at Different Temperatures T

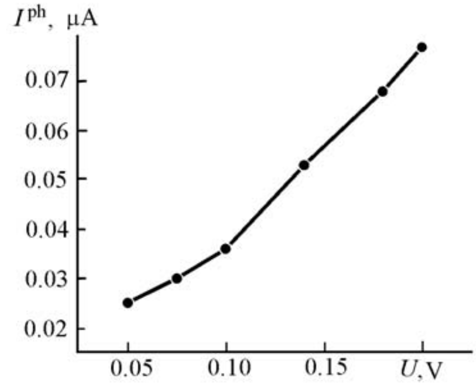
U, V	$I^{ph}_{\lambda=0.98}$, μA					
	T, °C					
	15	20	25	30	35	40
0.05	0.025	0.0243	0.02358	0.023	0.01961	0.016
0.1	0.036	0.0243	0.02358	0.029	0.01961	0.019
0.2	0.077	0.0243	0.02358	0.035	0.01961	0.028

observed on increase in the blocking voltage up to 0.2 V (curve 3), whereas in the temperature range 30–40°C the slope of all blocking voltages is in the limits of one order of magnitude. The data on the values of photocurrents are given in Table 2. The observed decrease in the magnitude of photocurrent ($I^{ph}_{\lambda=0.98}$) on increase in temperature is connected with the decrease in the forbidden-band width of silicon. This leads to an increase in the minority carriers generated by heat, in particular, due to the high temperature dependence of the dark current at voltages above 0.1 V. Such a dependence is primarily connected with the substantial temperature dependence of the concentration of minority carriers, which is stabilized in the temperature range 30–40°C. Since usually in the operating region of temperatures there is complete ionization of impurities and, consequently, the concentration of majority carriers (e.g., electrons) is invariable, from the expression [7]

$$n_0 p_0 = n_i^2 = N_c N_v \exp\left(-\frac{\Delta E}{kT}\right) \quad (3)$$

for the concentration of minority carriers we have

$$p_0 = \frac{1}{N} N_c N_v \exp\left(-\frac{\Delta E}{kT}\right) \sim \exp\left(-\frac{\Delta E}{kT}\right), \quad (4)$$



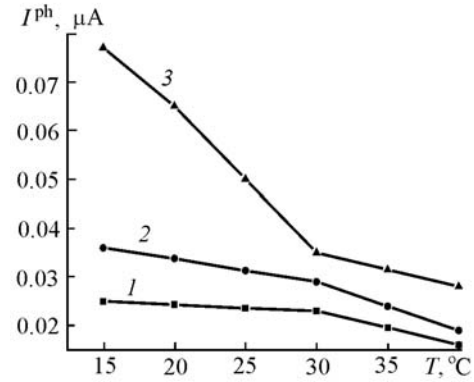


Fig. 8. Dependence of photocurrent on the operating voltage of the Au–*n*Si–Au structure in the region of intrinsic absorption (λ = 0.98 μm).

Fig. 9. Dependence of photocurrent on the temperature of the Au–*n*Si–Au structure at different voltages. Symbols of 1–3 are same as in Fig. 7.

which reflects the exponential increase in the dark carriers with temperature.

Conclusions. The photoelectric characteristics of Au–*n*Si–Au structure are determined by physical processes proceeding simultaneously in both metal–semiconductor transitions. The decrease in the photosensitivity of the Au–*n*Si–Au structure on increase in the illumination intensity is conditioned by the decrease in the increment of the space charge layer for a fixed value as the operating voltage increases. In other words, on increase in the operating voltage the photogenerated carriers decrease the frequency of modulation of the region of the barrier space charge; therefore, with increase in the illumination intensity, the photosensitivity decreases. The decrease of the photocurrent with increase in temperature at low blocking voltages is connected with the decrease in the concentration of minority carriers and increase in the saturation current. The Au–*n*Si–Au structures obtained can be used in the spectral range 0.7–1.1 μm as an alternative to the classical gallium arsenide and silicon photodiodes.

NOTATION

ΔE, activation energy, eV; I, strength of the current passing through the structure, A; I^{light}, strength of the light current passing through the structure, A; I^{dark}, strength of the dark current passing through the structure, A; I^{ph}, strength of the photocurrent passing through the structure, A; $I^{\text{ph}}_{\text{sh.c}}$, strength of the photocurrent passing through the structure in the short circuit regime, A; $I^{\text{ph}}_{\lambda=0.98}$, photocurrent passing through the structure on illumination by monochromatic radiation with a wavelength of 0.98 μm, A; k, Boltzmann constant, J·K^{-1}; N, impurity concentration in the basal region, cm^{-3}; N_c, effective density of state in the conduction band, cm^{-3}; N_v, effective density of state in the valence band, cm^{-3}; n, weakly alloyed layer of electronic semiconductor; n_i, intrinsic concentration of electrons, cm^{-3}; n_0, equilibrium concentration of electrons in the basal region, cm^{-3}; p_0, equilibrium concentration of holes in the base region, cm^{-3}; S^I, current photosensitivity, A·W^{-1}; S^{ph}, photosensitivity, A·W^{-1}; S_λ, spectral photoresponse, norm. units; T, temperature of the *p–n* transition, ^{o}C; U, diode displacement voltage, V; γ, exponent of the power-law dependence $I = f(U)$; λ, monochromatic radiation wavelength, μm; Φ, illumination intensity, lux. Indices: c, conduction band; v, valence band; i, intrinsic; sh.c, short circuit; light, light; dark, dark; ph, photo; 0, equilibrium value.

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