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Current-voltage characteristics and photoelectric properties of por-Si/Si-*p*/Si-*n* diodes with different porous layer thickness

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Abstract: In this work, the current-voltage and photoelectric spectral characteristics of double heterodiodes por-Si/Si-*p*/Si-*n* and a reference diode with a *p*—*n* junction at room temperature are analyzed and compared with data on the thickness of porous silicon layers and photoluminescence spectra for the synthesized heterostructures. It is shown that photospectral sensitivity in the region of 400—800 nm is exhibited by diodes with a single-layer structure of porous silicon whose thickness does not exceed 2 μm. In this case, the amplitude of the spectral photoresponse decreases with a decrease in the thickness of the porous layer. As for diodes with a two-layer structure of porous silicon (ordinary porous and tree-like porous) and thicknesses from 4.5 μm to 17.4 μm, currents do not flow due to rapid oxidation of such structures. A band energy diagram of a double heterodiode with a layer of porous silicon is proposed based on the experimental data.

Keywords: Silicon, built-in *p*—*n* junction, illumination, porous layer thickness, tree-like porous structure, double heterodiode, current blocking, photoresponse spectra, diode band diagram

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Вольтамперные и фотоэлектрические свойства диодов por-Si/Si-*p*/Si-*n* с разной толщиной пористого слоя

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Аннотация. В данной работе проведен анализ вольтамперных и фотоэлектрических спектральных характеристик двойных гетеродиодов por-Si/Si-*p*/Si-*n* и эталонного диода с *p*—*n* переходом при комнатной температуре и сопоставление с данными о толщине слоев пористого кремнияспектров фотолюминесценции синтезированных гетероструктур. Показано, что фотоспектральной чувствительностью в области 800-400 нм обладают диоды с однослойной структурой пористого кремния и его толщиной не более 2 мкм. При этом с уменьшением толщины пористого слоя амплитуда спектрального фотоотклика уменьшается. В диодах с двухслойной структурой пористого кремния (обычный пористый и древовидный пористый) и толщиной от 4,5 мкм до 17,4 мкм токи не протекают из-за быстрого окисления такой структуры. На основе экспериментальных данных предложена зонная энергетическая диаграмма двойного гетеродиода со слоем пористого кремния.

Ключевые слова: Кремний, встроенный *p*—*n* переход, освещение, толщина пористого слоя, древовидная пористая структура, двойной гетеродиод, блокировка тока, спектры фотоотклика, зонная диаграмма диода

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Introduction

Studies dedicated to creating LEDs based on porous silicon (por-Si) heterostructures on single-crystal silicon with a built-in p—n junction are well known [1, 2]. They focus on two issues: increasing the efficiency of electroluminescence and improving the stability of this type of LEDs. It is known that the formed LED structures based on porous silicon lose up to 75% of their integrated electroluminescence intensity for half an hour during operation in ambient conditions [2, 3], which is associated with a decrease in the injection of carriers from por-Si due to rapid oxidation of nanocrystals in an applied electric field even at room temperature. At the same time, the question of the influence of the thickness of the porous silicon layer in a Si wafer with a built-in *p*—*n* junction on the current-voltage and photospectral characteristics of diode structures remained unexplored.

The goal of this study is to establish a correlation between the thickness and microstructure of the porous silicon layer in the double por-Si/S-*p*/Si-*n* mesa-diodes of and their current-voltage and photospectral characteristics.

Experimental

In this work, porous silicon layers were created on *n*-type Si(100) wafers with a resistivity of 0.1 Ω cm with an epitaxial layer of *p*-type silicon (3 μm) with a resistivity of 7—10 Ω·cm by anodizing in a solution of HF:C_3H_8OH = 1:1 at two current densities: 10 and 20 mA/cm^2, etching times from 10 to 30 minutes and under illumination with a 150 W tungsten halogen lamp from a distance of 30 cm from the sample. Eight samples were formed at of 10 and 20 mA/cm^2.

A home-made Teflon attachment with a Pt wire cathode was used for anodizing and a copper anode, which was pressed through a layer of conductive silver paste to the reverse side of the silicon sample with the burnt Au-Sb contact. The edges of the front surface of the sample with an area of up to 1 cm^2 were protected with a special varnish. After anodizing, the samples were washed in deionized water and dried in a flow of dry nitrogen.

Results and Discussion

After mechanical removal of varnish residues and wiping with isopropyl alcohol, an Al layer was deposited to the por-Si surface at room temperature in a high vacuum through a square-shaped mask with a square hole in the center (Fig. 1, left). A layer of Au-Sb mixture was deposited on

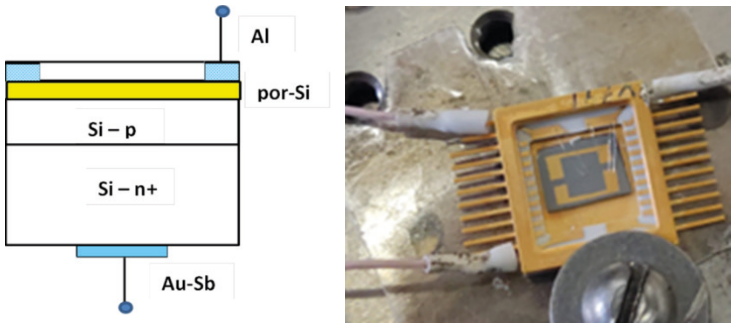

Fig. 1. Scheme of a diode structure (left) based on a layer of por-Si and a built-in *p*–*n* junction in single-crystal silicon. Photo of a diode structure (right) built into the microcircuit package with an aluminum contact (yellow) to a layer of porous silicon

the rear sample surface to form a diode structure. After that, the samples with deposited contacts were subjected to annealing at a temperature of 450ºC for 30 minutes. Next, the samples were placed on silver paste in the package of the integrated circuit, and ultrasonic welding of Al wire with a diameter of 20 μm was carried out from Al-plating to the pads of the microcircuit package (Fig. 1, right). The main parameters of the created samples of mesa-diodes are given in Table 1. At room temperature, the current-voltage (*I*–*V*) characteristics were measured in the dark and under illumination with a 150 W tungsten halogen lamp based on a stabilized power source and a microvoltmeter. The spectral characteristics of the photoresponse were studied using a setup based

Table 1

Parameters of double por-Si/Si-*p*/Si-*n* and reference Si-*p*/Si-*n* mesa-diodes

Diode number	Current density, mA/cm^2	Anodizing time, min	Short circuit current density, μA/cm^2	por-Si thickness, μm	Open circuit voltage, V	Fill factor (FF), %	Photo-response maximum, V/W
2-1	10	20	52	0.675	0.1	38	0.2
2-3	20	10	318	1.67	0.069	33.2	0.09
2-5	10	15	300	0.726	0.15	21	0.08
2-7	10	15	351	0.833	0.097	32	0.104
2-8	10	25	124	0.82	0.19	15.2	0.074
PN_ref	–	–	53	–	0.12	29	0.078

on a monochromator with a radiation source, a modulator, and a differential amplification system.

Studies of the current-voltage (*I*–*V*) characteristics of all diodes in the dark and under illumination showed that currents through them are observed only for samples with an anodizing time of 10 to 25 minutes at a current density of 10 mA/cm^2, and a time of no more than 10 minutes at a current density of 20 mA/cm^2. Fig. 2 (left side) shows the *I*–*V* characteristics for a reference diode with a *p*–*n* junction and sample 2-1 (10 mA/cm^2, 20 minutes).

In the dark, the direct branch of the *I*–*V* (sample 2-1, black squares) increases faster than for the reference sample (PN-ref, red circles), but has an order of magnitude greater reverse current. And when illuminated, the characteristics are close, but with minimum short circuit current density (52–53 μ/cm^2) (Fig. 2, right side). With an increase in time from 20 to 30 minutes at a current density of 10 and 20 mA/cm^2, no currents flow through the diodes, both in the dark and in the light. This fact is associated primarily with an increase in the thickness of the porous layer and its tree structure [4], which ensures rapid oxidation of the por-Si layer.

Separately, we compared (Fig. 3, left panel) the *I*–*V* characteristics of diodes formed at two current densities (10 mA/cm^2 and 20 mA/cm^2) and close anodizing times (10 and 15 minutes) in the dark. Sample 2-3 has the maximum forward current density at 1.5 V bias (20 mA/cm^2, 10 minutes). However, sample 2-5 (10 mA/cm^2, 15 minutes) has a lower reverse current, indicating less leakage in the diode structure. Under white light illumination, short circuit current density (J_{sc}), open circuit voltage (V_{oc}), and fill factor (FF) were determined for two diodes (Fig. 3, right panel and Table 1). Sample 2-5 showed the highest V_{oc}, but a lower fill factor (FF = 2%). As for sample 2-3, the maximum fill factor (FF = 33.2%) was observed at the maximum short circuit current (318 μA/cm²). Comparison of the diode in sample 2-1 with the maximum anodization time (Table 1) and diodes 2-5 and 2-3 (Table 1) showed that an increase in the anodization time leads to a decrease in current through the diodes and a deterioration in their sensitivity to illumination with white light. These facts are related to the additional contribution of the por-Si layers to the photocurrent due to the additional photogeneration of carriers in them upon illumination and separation by the *p*–*n* junction field.

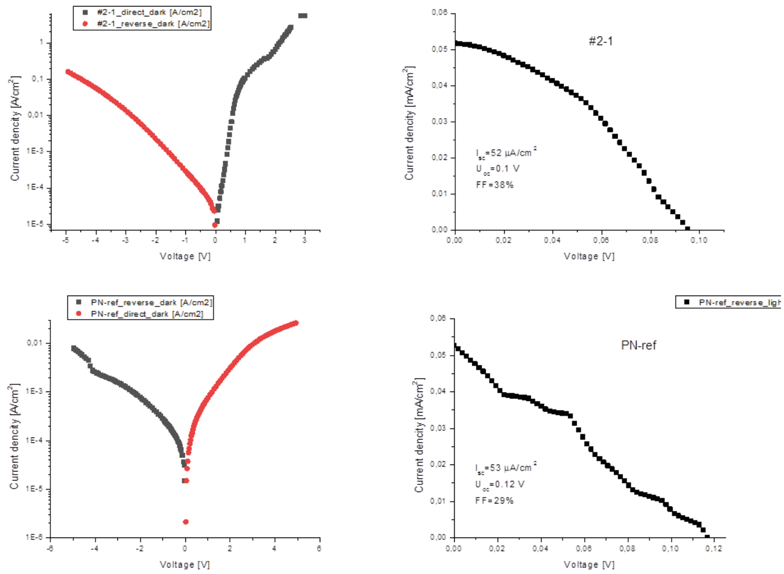

Fig. 2. *I*–*V* characteristics in the dark (left side) and under illumination with a W-lamp (right side) for sample 2-1 (10 mA/cm², 20 min) and a reference sample (PN-ref) with a *p*–*n* junction
The graphs on the right side show the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and fill factor (FF)

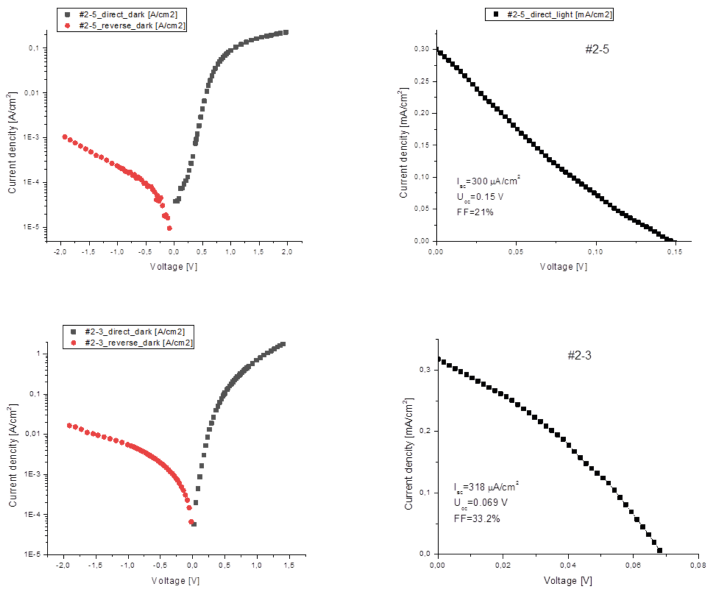

Fig. 3. *I*–*V* characteristics in the dark (left side) and under illumination with a W-lamp (right side) for sample 2-5 (10 mA/cm², 15 min) and sample 2-3 (20 mA/cm², 10 min)
The graphs on the right side show the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and fill factor (FF)

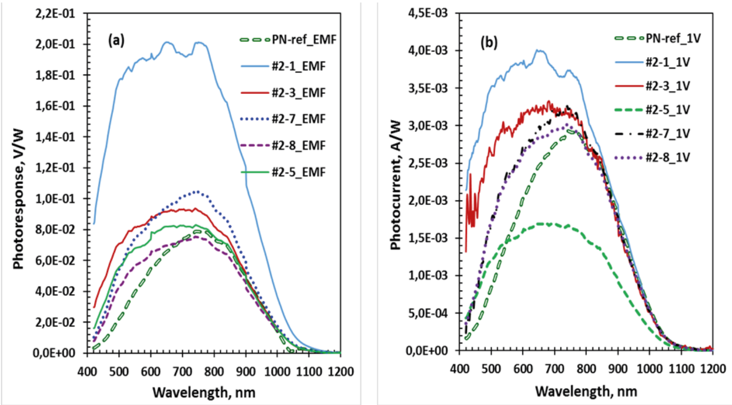

Fig. 4. Spectral dependences of photoresponse (*a*) and photocurrent (*b*) of por-Si *p—n* diodes (2-1, 2-3, 2-5, 2-7, 2-8) and reference Si *p—n* diode)

Measuring the spectral characteristics of the photoresponse and photocurrent, we found (Fig. 4, *a*, *b*) that sample 2-1 with a minimum por-Si layer thickness of 0,675 µm [4] has the maximum photoresponse and photocurrent. With an increase in the thickness of the por-Si layer from 0.8 µm to 1.09 µm and 2.7 µm, a decrease in the amplitude of the photoresponse (Fig. 4,*a*) and photocurrent (Fig. 4,*b*) is observed. A characteristic difference between the photoresponse spectra of working diodes and a reference diode based on a silicon *p—n* junction is an increase in the short-wavelength contribution and a shift in the maximum of the spectra to the short-wavelength region, which is associated with the generation of electron-hole pairs in the wide-gap por-Si layer and their separation by the field of the *p—n* junction. A band model of photodiodes is constructed to explain the dependence of the photoresponse on the por-Si layer thickness.

To plot the band diagrams [5] of diode structures based on por-Si layers located over the *p—n* junction in single-crystal silicon, it is necessary to take into account its thickness and compare it with the initial thickness of the epitaxial silicon substrate of *n*-type conductivity.

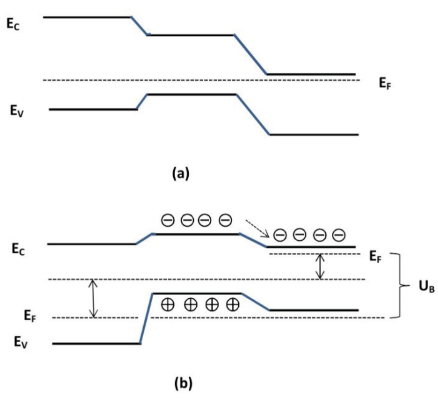

Fig. 5. Energy band diagrams of por-Si/Si-*p*/Si-*n* diodes without bias (*a*) and with bias (U_B) (*b*)

Since anodization began in *p*-type silicon epitaxial layer, the formed por-Si layer should also have *p*-type conductivity. Due to the band gap of 1.7—1.8 eV (from PL data [4]), a heterojunction is formed at the interface with Si-*p* layer. In general, the structure has one *p-p* heterojunction and one silicon *p—n* junction (Fig. 5,*a*), which blocks the flow of current up to a forward bias of 0.5-0.6 V. In this case, the bias is distributed relative to the Fermi level (Fig. 5,*b*). The wide-gap part provides high-energy photogeneration of carriers and their separation by a Si *p—n* junction. This leads to an increase in the contribution to the photoresponse (Fig. 4,*a*) and photocurrent (Fig. 4,*b*) of the por-Si/Si-*p*/Si-*n* diodes at wavelengths from 400 nm to 800 nm compared to the reference photodiode (PN-ref diode). In this case, the maximum photoresponse is observed for sample 2-1 (10 mA/cm^2, 20 minutes) with the maximum por-Si thickness (2 µm), and the minimum for samples with a smaller thickness (2-5 (10mA/cm^2, 15 minutes) and 2-7 (10 mA/cm^2, 15 minutes)). According to [4], there is no direct correlation between the PL signal, which depends on the porosity of the por-Si layer, and the photoresponse, which, on the contrary, is maximum for layers with minimal porosity.

Conclusion

The current-voltage and photoelectric characteristics of diodes based on porous silicon of various thicknesses embedded in a *p*-layer of silicon, which is epitaxially grown on an *n*-type silicon substrate, have been studied. It has been established that *I—V* diode characteristics and photospectral sensitivity are demonstrated by diodes with single-layer porous silicon less than 2 μm thick. In porous Si layers of greater thickness (4–17 μm), a two-layer tree-like structure of porous silicon with different porosity was formed, which was rapidly oxidized, which blocked the flow of current through the diodes. It has been demonstrated that a diode with a porous layer 2 μm thick, low porosity and the absence of photoluminescence has the maximum photosensitivity in the wavelength range of 400–800 nm. Diodes with a noticeable PL signal and a single-layer structure showed a photoresponse close to that of a reference silicon diode. The band energy structure of double heterodiodes is constructed and the photo-emf generation is analyzed.

REFERENCES

1. **Steiner P., Kozlowski F., and Lang W.,** Blue and Green Electroluminescence from a Porous Silicon Device, IEEE Electron Device Letters, 14(7) (1993) 317–319.
2. **Zhang L., Coffer J.L., Gnade B.E., Xu D.X. and Pinizzotto R.F.,** Effects of local ambient atmosphere on the stability of electroluminescent porous silicon diodes, J. Appl. Phys., 77 (1995) 5936–5941.
3. **Gelloz B, and Koshida N.,** Electroluminescence with high and stable quantum efficiency and low threshold voltage from anodically oxidized thin porous silicon diode, Journal of Applied Physics, 88(7) (2000) 4319–4324.
4. **Galkin K.N., Yan D.T., Nepomnyashchiy A.V., Galkin N.G.,** Influence of current density, anodization time and illumination on the thickness of porous silicon in wafers with built-in *p-n* junction and its photoluminescence, ASCO-Nanomat 2022, Proceedings, Dalnauka Publishing, Vladivostok, 2022, –383.
5. **S.M. Sze,** Physics of Semiconductor devices, 2nd Edition, John Wiley and Sons, 1981, p. 868.

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