The current-voltage and photoelectric properties of por-Si/Si-p/Si-n diodes with different porous layer’s 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*** and its ***thickness not exceeding 2 μm***. In this case, with a ***decrease*** in the thickness of the ***porous layer***, the ***amplitude*** of the ***spectral photoresponse decreases***. In 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 the rapid oxidation of such a structure. On the basis of experimental data, a **band energy diagram** of a ***double heterodiode*** with a layer of porous silicon is proposed.

Introduction

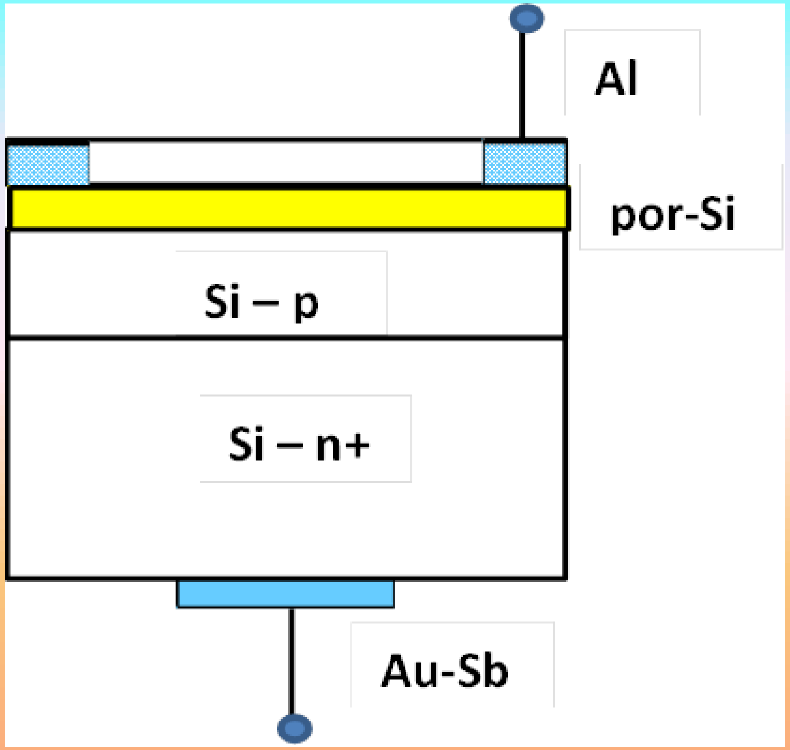
Works on the creation of LEDs based on porous silicon (PS) heterostructures on single-crystal silicon with a built-in *p-n junction* are well known [1,2]. They focused on two issues: (1) increasing the efficiency of electroluminescence and (2) improving the stability of this type of LEDs. It is known that the formed LED structures based on *porous silicon* during operation in ambient conditions lose up to 75% of their integrated electroluminescence intensity for half an hour [2], which is associated with a decrease in the injection of carriers from PS due to the *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.

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 microns**) 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.

A ***home-made Teflon attachment*** with a **Pl 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.



After mechanical removal of varnish residues and wiping with isopropyl alcohol, an Al layer was deposited to the PC surface at room temperature in a high vacuum through a square-shaped mask with a square hole in the center. 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**. At room temperature, the ***current-voltage (C-V) characteristics*** were measured in the **dark** and *under illumination with a tungsten halogen lamp* based on a stabilized power source and a microvoltmeter. The **spectral characteristics** of the **photoresponse** were studied using a setup based on a monochromator with a radiation source, a modulator, and a differential amplification system.

Results and Discussion

C-V

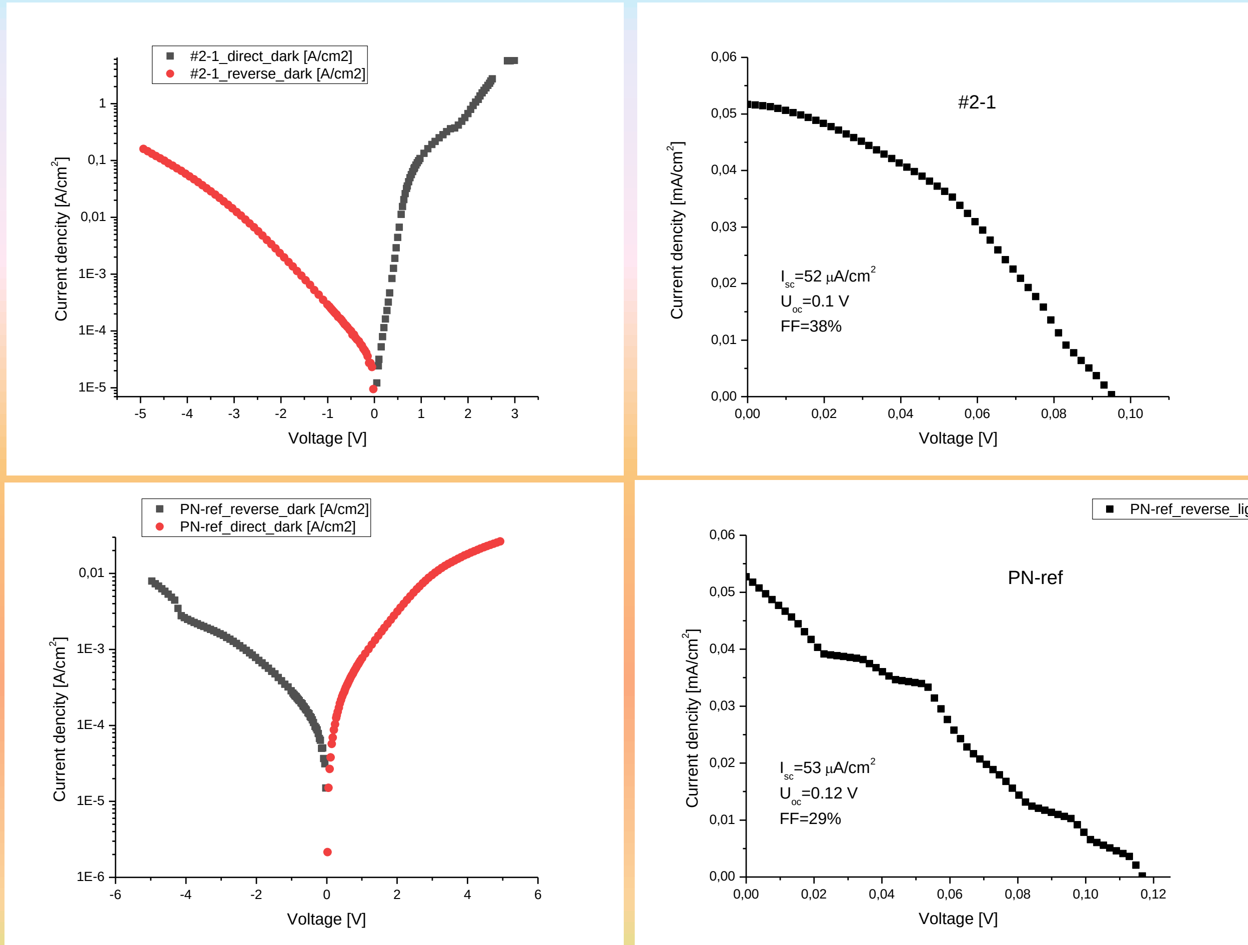


Fig. 1. C-V characteristics in the dark (left side) and under illumination with a W-lamp (right side) for sample #2-1 (*10 mA/cm^2*, 20 min) and a reference sample with a p-n junction. The graphs on the right side show the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and fill factor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

Studies of the ***current-voltage (C-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**. Figure 1 shows the ***C-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 C-V (**black squares**) ***increases faster*** than for the reference sample. And when ***illuminated***, the **characteristics are close**. 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 [3], which ensures ***rapid oxidation*** of the **PS layer**.

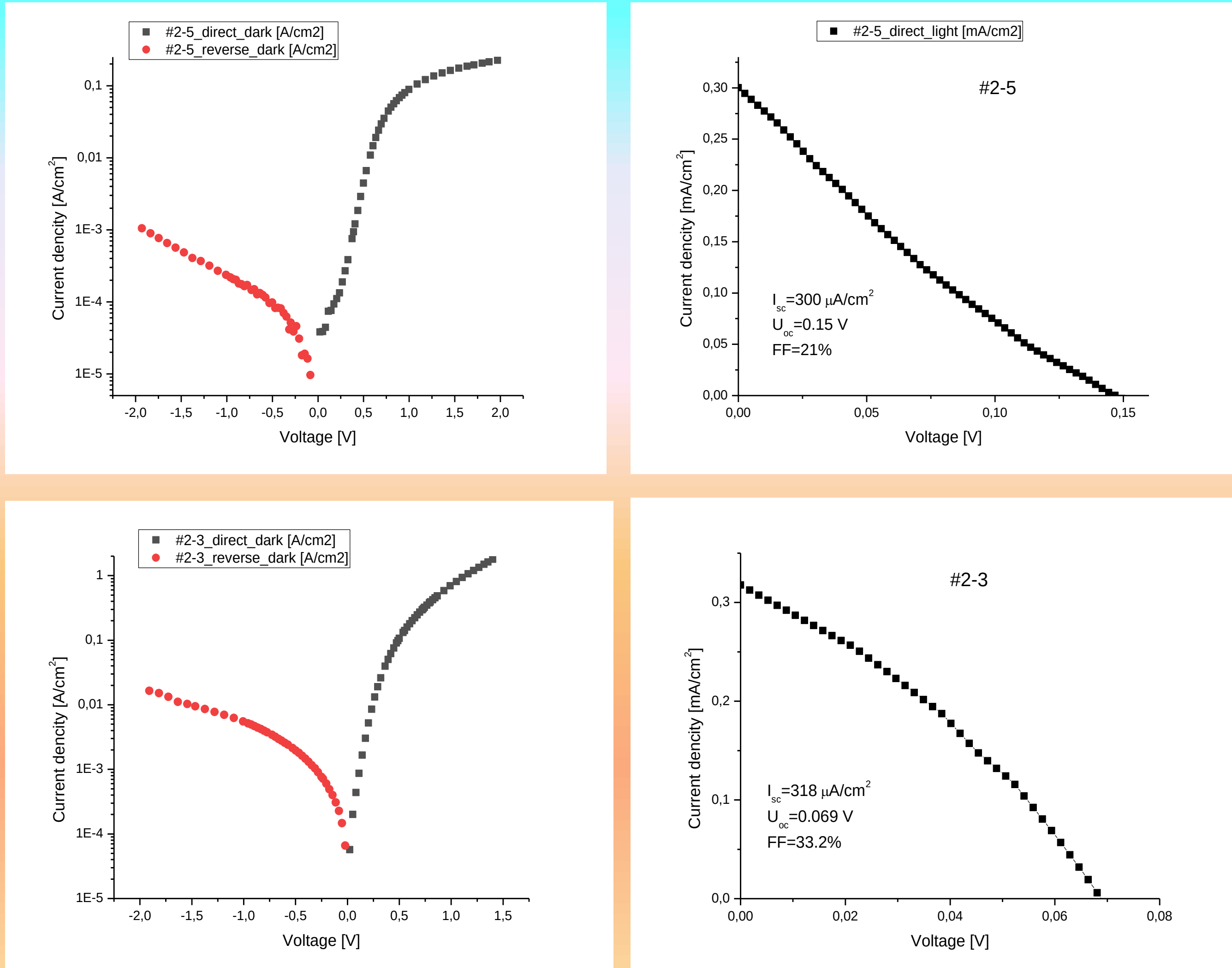


Fig. 2. C-V characteristics in the dark (left side) and under illumination with a W-lamp (right side) for sample #2-5 (*10 mA/cm²*, 15 min) and sample #2-3 (*20 mA/cm²*, 10 min). The graphs on the right side show the *short circuit current* (I_{sc}), *open circuit voltage* (V_{oc}) and fill factor (FF).

Figure 2 shows the ***I-V*** characteristics for samples **#2-5** (***10 mA/cm²***, ***15 min***) and **#2-3** (**20 mA/cm²**, ***10 min***). In the **dark**, the direct branch of the C-V (**black squares**) of sample **#2–3** increases faster than for sample **#2–5**. When ***illuminated***, the ***I-V*** characteristics of the diodes ***are close***, and the ***short circuit currents*** exceed about **5 times** the ***C-V*** characteristics of the ***reference diode*** (Fig. 1). These facts are related to the ***additional contribution*** of the ***PS layers*** to the ***photocurrent*** due to the ***additional photogeneration*** of carriers in them upon **illumination** and ***separation by the p–n junction field***.

An increase in the anodizing time at a minimum current density (***10 mA/cm²***) from ***10 minutes*** (sample **#2-1**) to 25 minutes (sample **#2-8**) led to a **decrease** in the ***short-circuit current*** and, conversely, to an **increase** in the ***open circuit voltage*** (samples **#2-5** and **#2-7**).

Registration of the spectral characteristics of the **photoresponse** and **photocurrent** showed (Fig. 2 a,b) that sample **#2-1** with a ***minimum PC layer thickness of 0.675 μm*** [3] has the **maximum photoresponse** and **photocurrent**. With an ***increase*** in the ***thickness of the PC layer*** from **0.8 μm** to **1.09 μm** and **2.7 μm**, a ***decrease*** in the ***amplitude of the photoresponse*** (Fig. 2a) and ***photocurrent*** (Fig. 2b) is observed.

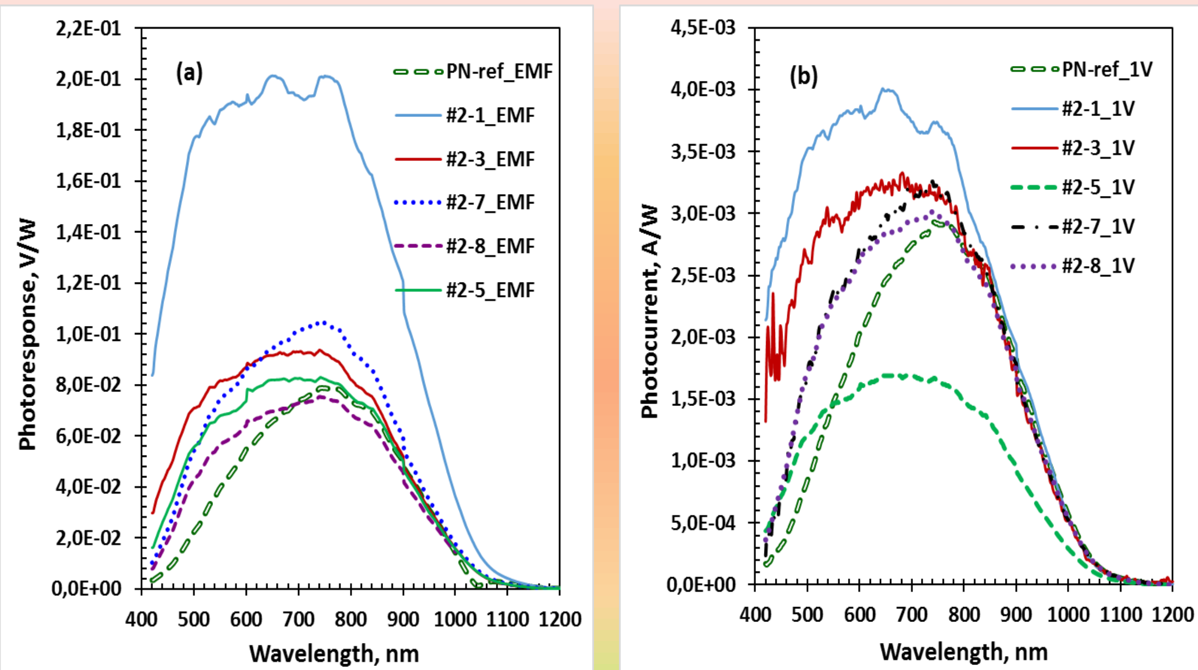
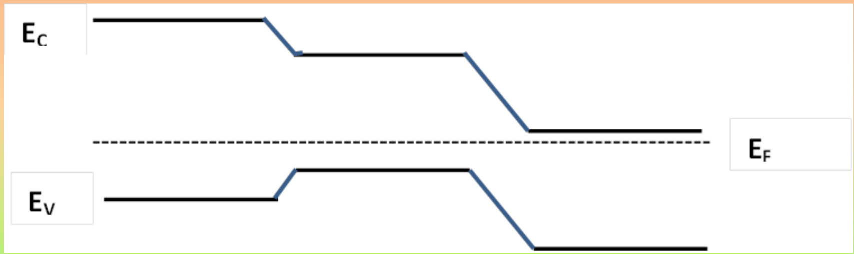


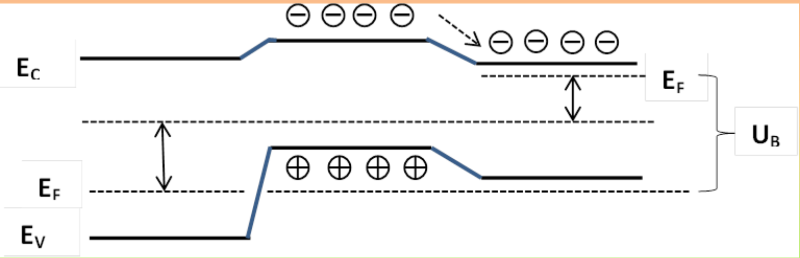
Fig. 2. Spectral dependences of photoresponse (a) and photocurrent (b) of *PS/Si p-n diodes* (#2-1, #2-3, #2-5, #2-7, #2-8) and *reference Si p-n diode*)

A ***characteristic difference*** between the 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 PC 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 PC layer thickness.

To plot the band diagrams of diode structures based on layers of ***porous silicon*** 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 layer of ***n-type*** conductivity.

Since anodization began in **p-type** silicon, the formed ***porous layer*** should also have ***p-type conductivity***. Due to the band gap of **1.7–1.8 eV** (from **PL data** [**3**]), a heterojunction is formed at the interface with **Si–p**. In general, the structure has ***one p-p heterojunction*** and ***one silicon p-n junction*** (Fig. 3 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. 3 b). The ***wide-gap*** part provides ***high-energy photogeneration of carriers*** and their ***separation by a p-n junction***. This leads to an ***increase*** in the contribution to the ***photoresponse*** (Fig. 2a) and ***photocurrent*** (Fig. 2b) of the diodes at wavelengths from **400 nm** to **800 nm** compared to the reference photodiode. In this case, the maximum photoresponse is observed for sample **#2-1** with the ***maximum PS thickness*** (**2.0 µm**), and the ***minimum*** for samples with a ***smaller thickness*** (**#2-5** and **#2-7**). According to [3], there is **no direct correlation** between the PL signal, which ***depends on the porosity of the PS layer***, and the **photoresponse**, which, on the contrary, is ***maximum*** for layers with minimal porosity.





(a) **(b)**

Fig. 3. ***Energy band diagrams*** of por-Si /Si-p/Si-n diodes **without bias** (**a**) and **with bias (U_B)** (**b**).

Conclusions

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 ***C-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 <u>reference silicon diode</u>. The *band energy structure* of ***double heterodiodes*** is constructed and the <u>photo-emf generation is analyzed</u>.

References

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