Porous silicon solar cells as a component of an artificial retina of the eye

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Abstract

Progress in the development of modern semiconductor electronics is associated with the development of new semiconductor materials, mainly nanocrystalline semiconductors with effective electrophysical and operational indicators. One of such materials is porous silicon (PS), which has unique physicochemical properties and at the same time is one of the most common materials in nature. This makes it promising for numerous applications not only in electronics, but also in power engineering, semiconductor technology, and in medicine. The ability to use a PS as the basis of composite materials or as a substrate for growth of heterostructures further extends the range of its applications. The use of PS in heterostructures of silicon carbide on silicon makes it possible to practically solve the problem of matching the heterojunction crystal lattices and raise the quality of the structures. However, despite the fact that the PS is known for several decades, there are a number of difficulties in obtaining porous layers with reproducible structural and electrophysical parameters, and in testing such structures.

Keywords: nanotechnology, porous silicon, solar cells.

The technology of producing a porous silica and its properties

Porous silicon is one of form of the chemical element Si, which contains nanoporous clusters in its microstructure, which makes large ratio surface to volume. It was discovered in 1990 and formed on crystalline silicon wafers using electrochemical etching. Porous silicon has photoluminescence and electroluminescence. [1]

First of all we were interested in identifying the impact of geometric and structural parameters of nanocrystals on the features of electronic and phonon excitations in nanostructures and their optical properties, as well as the establishment of regularity and clarify the mechanisms, which responsible for radiation nanocrystals on various stages of structural transformation.

It is known that the morphology of porous silicon affects a number of factors. To them can to be include conductivity type monocrystalline silicon, crystallographic orientation plates, resistivity, dopant type, light regime (the wavelength of light used, light intensity, duration), current density, time of the process of anodizing, the electrolyte composition and etc.[2, 3]

It was necessary at first experimentally and theoretically investigate the mechanisms of growth and formation of silicon nanocrystals in during electrochemical dissolution of the surface in the process of obtaining and subsequent thermal treatments. Creating a porous silicon structures with a fairly wide range of values of the characteristic parameters made possible through the use of different methods for their preparation.[4]

Electrochemical etching the surface of silicon samples was carried out in a special device in galvanostatic mode in the electrolyte with different ratios of $HF:H_2O:HCl:C_2H_5OH$ = 1,5:3,5:1,5:3,5 current density of anodizing was 40mA/cm^2, and the duration of anodizing - from 10 sec. Was used 48% hydrofluoric acid and 96% alcohol. Cathode served platinum wire diameter of 0.3mm. The thickness of the porous silicon layer was 80 nm. Porosity silicon samples was about 50%. After anodized samples were washed with deionized water, blowed flow of hot nitrogen and kept in the dark.

The morphology of porous silicon after anodizing shown in Fig.1.

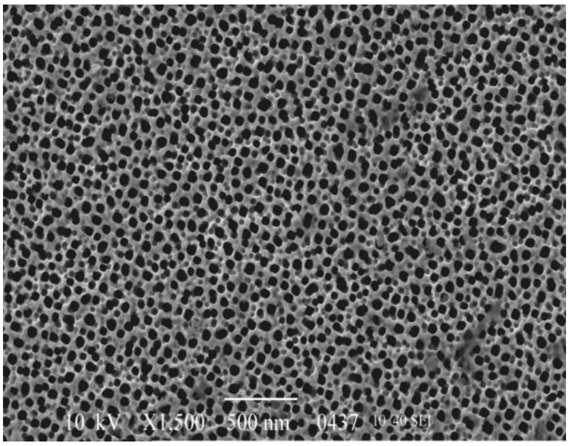

Fig.1. The morphology of porous silicon after anodizing

Formation of porous films on the surface Si leads to improved conversion efficiency of solar cells made on base of them.

Solar cells based on porous silicon

The absolute limiting efficiency of a photovoltaic solar energy converter based on monocrystalline silicon is 25-27%.

The maximum value of the efficiency of a silicon solar cell is obtained in a silicon structure with a surface relief in the form of pyramids coated with an oxide layer of optimum thickness (the "textured" surface). The efficiency of such a solar cell, manufactured by Kyocera (Japan), reaches 18.5% [5].

Any structure based on crystalline silicon as absorbing material can not avoid losses due to the inability to absorb photons whose energy is less than the width of the forbidden band of silicon and the thermalization of photons with an energy exceeding the width of the forbidden band. To eliminate these losses in the construction of silicon solar cells of the third generation, the strategy of increasing the number of forbidden zones of the initial material is applied. The change in the structure of silicon zones in the transition to nanoscale crystals, the use of wide-band materials such as In_2O_3, SnO_2, and ZnO in photosensitive devices make it possible to significantly expand the absorption spectrum of the solar cells and increase the dose of absorbed light energy. Laboratory studies show that when using multi-layer photosensitive structures based on nanocrystalline materials, the efficiency of a silicon solar cell can be significantly improved.

An effective nanocrystalline material is porous silicon, whose pore walls are a system of disordered nanocrystals. The problem of high electrical resistance of porous silicon can be solved due to local pore formation on a textured surface [4], when etched, the pores are formed only at the junction of the pyramids, and the faces of the pyramids serve as their walls (Fig. 2). In this case, etching in depth proceeds fairly evenly, forming a porous structure with vertical pores several tens of microns in depth.

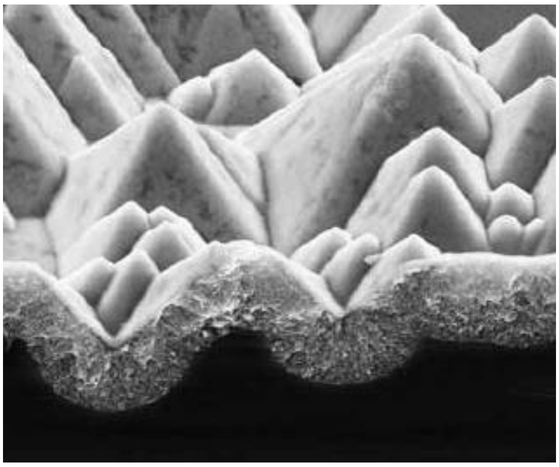

Fig.2. The local pore formation on a textured surface

The formation of pores on the textured surface significantly changes the entire course of the spectral characteristic of the photosensitivity, substantially increasing it in the short-wave part (Fig. 3). The maximum spectral sensitivity shifts from 880-900 nm (position for single-crystal silicon) to the region of 600nm. This change can be explained by the absorption of photons in a material with a larger forbidden band width than in single-crystal silicon. Such material can be silicon nanocrystals (silicon "filaments") formed in pores with deep anode etching. Photoelectric measurements on structures with a specially created p-n junction located inside the macroporous layer. They provided for measuring the open-circuit voltage and short-circuit current, depending on the level of illumination. All the structures showed good photosensitivity: when illuminated with white light with a level of 3500 lux, the idling voltage was 300-600 mV, the short-circuit current density was 3-35 mA/mm^2 for an illuminated area of 200-1000 mm^2. This is significantly higher than the corresponding parameters of photosensitive structures made using a similar technique on a textured silicon surface without a macroporous layer [6].

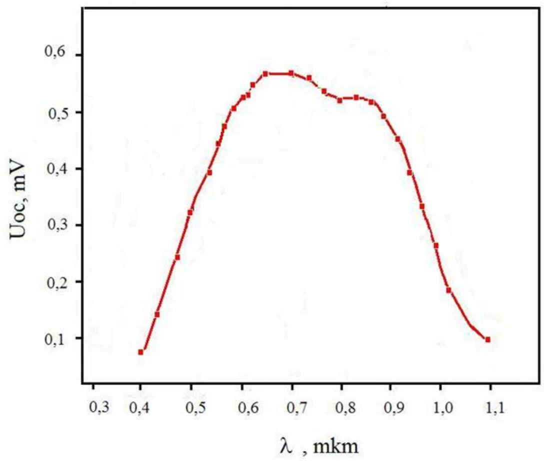

Fig.3. The spectral characteristic of the photosensitivity

It should be noted that the parameters were stable for a long time.

Thus, the conducted studies show that the proposed technology for creating a porous layer on the surface with a pre-created microrelief makes it possible to produce photosensitive silicon structure with a spectral range of sensitivity extended to the shortwave region and good photoelectric properties.

Today, numerous experimental studies have established that porous silicon is a biocompatible material. This property of the PS along with the high photoelectric parameters of the structures on their basis makes it possible to use it as a basis for the artificial retina of the eye.

PS with different values of the porosity index in a living organism can be bioresistant (resistant to the environment of the body), bioactive (interact with this environment) and even resorbed (dissolve in the tissues of the body). It is important to note that neither silicon itself nor the products of its reactions with the environment are toxic to the body.

One of the studied medical applications of PS is an artificial retina of the eye based on a matrix of photodiodes formed on a silicon wafer and allowing to replace non-responsive natural photoreceptors with photodiodes, provided that the optic nerve has not completely lost its ability to translate the signal. The electric pulses of the photodiodes enter the stimulating electrodes and excite the visual nerve endings. This mechanism of the artificial retina does not require external power supplies.

About successful tests of electronic retina on the basis of a silicon photosensitive matrix in 2004, employees of Optobionics (USA) reported [7]. The created artificial retina was a matrix consisting of 5 thousand discrete silicon photodiodes placed on a plate 2 mm in diameter and 25 µm thick. Each photodiode had its own stimulating electrode.

A similar structure can be made by selective electrolytic etching of a layer of porous silicon on a plate with a textured surface.

Thus, a photosensitive matrix of vertical discrete diodes with end surfaces was formed in the form of regular tetrahedra. Studies have shown that the structure has a pronounced anisotropy of electrical conductivity and good photoelectric characteristics.

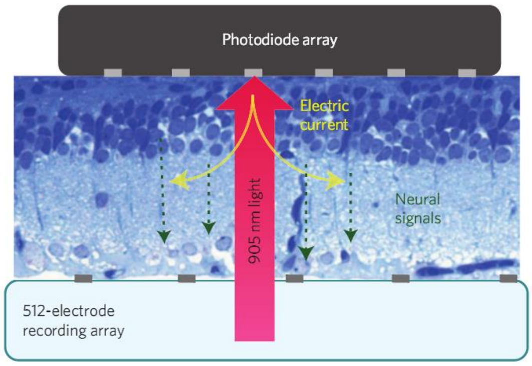

Fig. 4. Schematic of photovoltaic stimulation characterization system [8]

The size of the tetrahedron base did not exceed 10 µm, so that up to 104 diodes were located on an area of 1 mm^2

By virtue of which it is promising for the creation of an artificial retina of the eye [8]. Single photodiode pixels produce up to 0.5 V at physiologically safelight intensities. Data indicate that this voltage can successfully stimulate the retina. However, larger voltages can be safely applied in a physiological environment. The fabricated implants with 70 and 140 mm pixels containing 20- and 40-mm diameter stimulation electrodes; the corresponding pixel densities were 178 and 55 pixels/mm^2 (Fig. 4). All implants were 30 mm thick, to provide sufficient depth for absorption of the light in silicon (penetration depth of 905 nm light in silicon is 35 mm), but this is enough to be implanted subretinally. Two sizes of arrays were constructed: 0.8 × 1.2 mm for implantation into rats, and 2×2 mm for implantation into larger animals. Trenches etched between neighbouring pixels provided electrical isolation, eliminating pixel crosstalk within the silicon device. Each pixel was provided with a local return electrode to constrain stimulation currents to nearby neurons, improving the achievable resolution of the prosthetic device.

Conclusions

It is shown that the proposed technology for creating a porous silicon on the surface with a pre-created microrelief allows the production of photosensitive silicon structures with an extended spectral range of sensitivity and good photoelectric properties, which makes it possible to use it in the manufacture photodiodes array for the artificial retina, allowing the replacement of nature photoreceptors.

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