Nuclear Instruments and Methods in Physics Research A 610 (2009) 314–316

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

On the mechanism of spectral selective sensitivity of photonic biosensors ☆

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ARTICLE INFO

Available online 23 May 2009

Keywords:
Photo detector
Optical sensor
Selective sensitivity
Spectral components

ABSTRACT

We report a new optical sensor exploiting the innovative operation principle developed for the selective registration of UV and visible radiations. The operation is based on the mutual influence of depletion regions in the photovoltaic structure composed by Schottky barrier and $n-p$ junction. The important feature of this structure is that the depletion regions expand over the whole base so that they contact each other. We have shown that the position of the contact point in the base is a function of voltage applied to the structure. Also absorption spectrum for each of the depletion regions and the photoresponse of the structure are functions of the applied voltage. We have revealed that the change induced by the applied voltage in the photoresponse, ΔI, is proportional to the change $\Delta\lambda$ induced in the spectrum, $\Delta\lambda \sim \Delta I$. This linear correlation between ΔI and $\Delta\lambda$ is a very important spectrophotometric property required for the precise selective registration of bio signals in dynamic and static biological processes.

1. Introduction

Recently the role of biosensors has strongly increased due to their application in social spheres like medical diagnostics, medicine making, environmental protection, etc. [1–2]. Application of biosensors in nanobiosystem studies is of special interest as, for instance, optical spectroscopy of biological objects gives information on electron transitions in separate organic molecules, which can be used for molecular identification of bio-cells and investigation of the so-called "specificity" of cellular interactions. The last is critical for nano-biological applications including adhesion, aggregation and formation of tissues as self-correlating systems [1,3]. As the ratio between the absorbed and reflected radiations depends on the composition and quantity of bio-objects, the spectral line and peaks can be used for the identification of specific impurities or their concentration [4–6].

Today silicon photo-detectors and porous silicon (*PSi*) films are widely used in modern spectrophotometric biosensors [1,2,7,8]. Both theoretical and experimental studies have confirmed that due to favorable morphological and physical properties *PSi* promises to be a universal platform for chemical and biological sensors [2,7]. However, surface passivation is required for stabilizing *PSi* surface and covalent bonding of bio-probes as *PSi* is highly hydrophobic [8]. Also lack of spectral selectivity limits the application of photo-detectors in sensors.

Here we report a new spectrophotometric biosensor exploiting the innovative operation principle developed for the selective registration of UV and visible radiation. The sensor contains minimum number of optical components (a micro-source of radiation and an innovative photo-detector selectively sensitive to the radiation spectra). We perform numerical simulation of this innovative photo-detector.

2. Model

The innovative photo-detector is composed of *Si* $n-p$ junction and *n*-doped *Si* Schottky barrier. The energy band diagram of this semitransparent metal – *n*-doped *Si* – *p*-doped *Si* – ohmic contact structure is shown in Fig. 1, where the density of doping is $N_d = 3.36 \times 10^{15}\,\mathrm{cm}^{-3}$ and d is the thickness of the base. There are potential barriers for electrons at contacts, φ_1/q and φ_2/q ($\varphi_2 - \varphi_1 = 0.1$ eV), respectively. These barriers are oppositely directed and their depletion regions completely cover the base so that they create a potential well in the conduction band. The applied voltage can shift the connection point of the depletion regions in the base, x_m, from zero to d position, along with changing the depths of the depletion regions one at the expense of another.

The function $x_m(V)$ can be calculated from the Poisson equation connecting potential energy of electrons $\varphi(x)$ with volume density

☆ The work is done within the framework of the EN-bioen-1120 ANSEF program.
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doi:10.1016/j.nima.2009.05.094

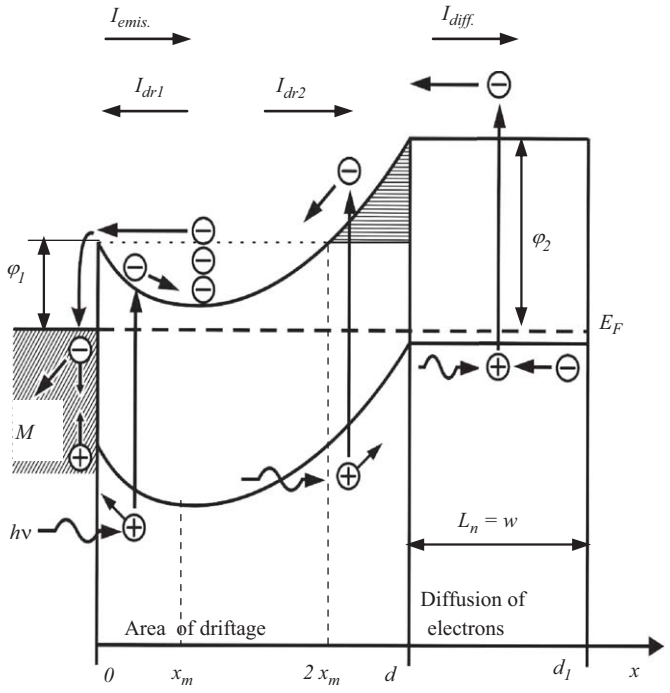

Fig. 1. The energy band structure and the flow of photocurrents through the innovative photo-detector.

of charges

$$\frac{d^2\varphi}{dx^2} = \frac{q^2}{\varepsilon\varepsilon_0}\left[N_d - n_f \exp\left(\frac{\varphi_m - \varphi}{kT}\right)\right] \tag{1}$$

Here n_f and φ_m are the density and the potential energy of electrons at x_m, q the electron charge, ε the dielectric constant and ε_0 the free space permittivity.

If $\varphi_1 < \varphi_2 + qV$, then under the conditions (see Fig. 1) that the potential energy for electrons is φ_1 at both $x = 0$ and $x = 2x_m$, is $\varphi_2 + qV$ at $x = d$, is φ_m at $x = x_m$ and that $\varphi' = 0$ at $x = x_m$, the Poisson Eq. (1) yields for φ_m and x_m are given by

$$\begin{aligned} &2\tfrac{\varphi_1-\varphi_m}{kT} + 2\tfrac{n_f}{N_d}\left[\exp\left(\tfrac{\varphi_m-\varphi_1}{kT}\right) - 1\right] \\ &= \left[\left(\tfrac{\varphi_2-\varphi_1+qV}{kT}\right)\tfrac{L_s}{d-2x_m} - \tfrac{d-2x_m}{L_s}\right]^2 \end{aligned} \tag{2}$$

$$\int_0^{\frac{\varphi_1-\varphi_m}{kT}} \frac{dy}{\left[y + \frac{n_f}{N_d}(e^{-y} - 1)\right]^{1/2}} = \frac{\sqrt{[]}2x_m}{L_s} \tag{3}$$

Here $y = (\varphi - \varphi_m)/kT$, $L_s = \sqrt{[]}\varepsilon\varepsilon_0 kT/q^2 N_d$ is the Debay screening length, and the condition is also used that due to the emission, only few electrons are above φ_1. Another feature is that the structure is thin, $d < 1.5\,\mu$m, so that electrons and holes rather escape than recombining in the base. Therefore, the density of electrons increase in the potential well so much that their emission from the well I_f balances the generation of electrons in the structure

$$\begin{aligned} I_f &= qn_f v_T S \exp\left[(\varphi_m - \varphi_1)/kT\right] \\ &= qF_0 S\left[1 - \exp(-\alpha d_1)\right] \end{aligned} \tag{4}$$

where v_T is the thermal velocity of carriers, $F_0 = P_{opt}(1-R)/S\,h\nu$ the total flow of incoming photons per unit area, P_{opt} the radiation power, h the Planck's constant, ν the frequency of radiation, S the irradiated area, β the quantum efficiency and R the reflection coefficient.

Eq. (4) determines the density n_f that should be used in Eqs. (2) and (3) to find out functions $\varphi_m(V)$ and $x_m(V)$.

Note illumination increases φ_m, however, not more than φ_1 if $\varphi_1 < \varphi_2 + qV$ and $\varphi_2 + qV$ if $\varphi_1 > \varphi_2 + qV$.

As shown in Fig. 1, illumination also results in drift and diffusion photocurrents, I_{dr1}, I_{dr2} and I_{diff}, respectively, [9,10]

$$I_{dr1} = qF_0 S[1 - \exp(-\alpha x_m)] \tag{5}$$

$$I_{dr2} = qF_0 S[\exp(-\alpha x_m) - \exp(-\alpha d)] \tag{6}$$

$$I_{diff} = qF_0 S\frac{\alpha L_n}{1 + \alpha L_n}\exp(-\alpha d) \tag{7}$$

As the additional electron emission I_f arises from the base (into the contact with either Schottky barrier if $\varphi_1 < \varphi_2 + qV$), the external photocurrent I_{ph} can be written as

$$(I_{Ph} = -I_{emiss} + I_{dr1} - I_{dr2} - I_{diff}) \tag{8}$$

By substituting φ_m and x_m for functions $\varphi_m(V)$ and $x_m(V)$ in Eq. (4)–(8), also the photocurrent (8) can be written as a function of V, $I_{ph}(V)$.

Note that the drift region of Schottky barrier is responsible for the spectral sensitivity of the structure to the short-wavelength radiation, while in-the-base and out-the-base regions of the n–p junction are responsible for the spectral sensitivity of the structure to long-wavelength radiation.

3. Discussion and results

The detailed volt–ampere characteristics of the structure $I_{ph}(V)$ can be obtained from experiments. Since the dependence of the absorption coefficient $\alpha(\lambda)$ on wavelength λ is known, it is possible to determine $\lambda_m(V)$ that $\alpha(\lambda_m)\cdot x_m(V) = 1$. Under the last condition, elimination of V from the experimental photocurrent $I_{ph}(V)$ will yield I_{ph} as a function of the wavelength λ_m, $I_{ph}(\lambda_m)$. The last function will be used for disclosing the spectral structure of UV and visible radiations. The simulation is performed for quantum efficiency $\beta = 1$ when reflection from the surface $R = 0$.

Fig. 2 shows the spectral dependence of the minimum potential energy of electrons φ_m at different bias voltages and at incoming radiation intensity 10^{17} quantum/sm^2 s, obtained from the solution of the system of Eqs. (2)–(4).

Figure shows the two regularities of the change φ_m. The value does not change with the increase of wavelength up to ~450 nm, and then it decreases, preserving such regularity until the increase of φ_m occurs with the increase of the voltage of the polarity at which the surface barrier is switched directly and the rear barrier is switched in the opposite direction.

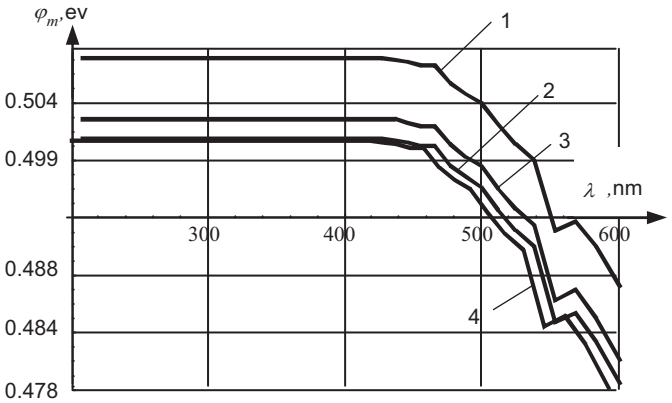

Fig. 2. Dependence of the minimum potential energy of electrons on the wavelength at different voltages: 1–0.3 V; 2–0.09 V; 3–0 V; 4–0.09 V (the specified polarity of voltage is applied to ohmic contact).

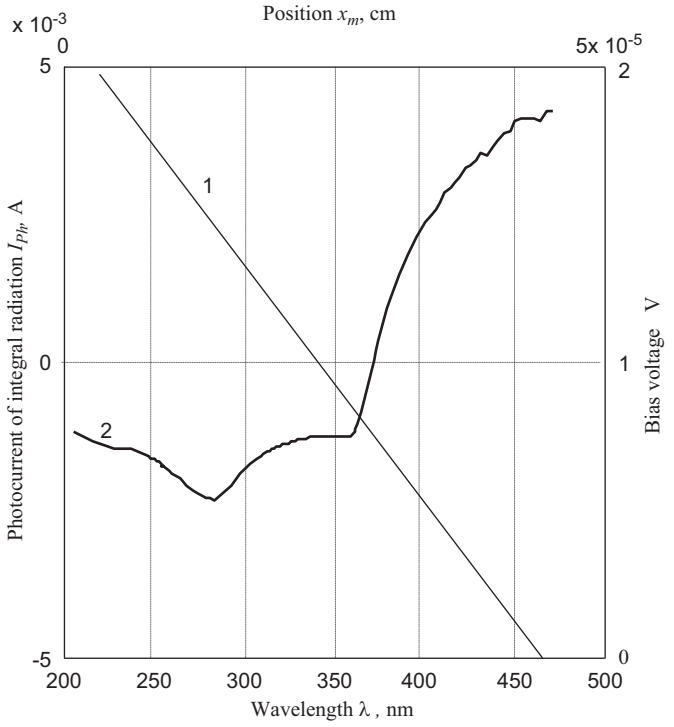

Fig. 3. Dependence of the position of the minimum point of the potential energy of the electron x_m in the base on bias voltage (curve 1) (the specified polarity of voltage is applied to ohmic contact), and dependence of integral photocurrent on the wavelength corresponding to the absorption depth $1/\alpha$. At $w = 0.5\,\mu m$, $d = 1\,\mu m$.

The first regularity may be due to absorption depth. The more is the absorption depth value at $\lambda > 450$ nm, the more quanta stay beyond the active area. As a result the absorption efficiency and the number of photoelectrons stored in the potential well decrease. In the second case, φ_m increases with the increase of voltage that brings to the increase of rear barrier and decrease of surface barrier. The point of minimum potential energy of electrons x_m is linearly shifting towards the surface barrier.

For the evaluation of selective sensitivity, calculations were made by formula (8) for solar radiation AM0 with the use of spectral distribution of energy accurate within 1 nm [11]. In Fig. 3 curve 1 shows the dependence of the position of the minimum point of the potential energy of the electron x_m in the base on bias voltage (Fig. 1).

Curve 2 presents the approximate dependence of integral photocurrent on the change of the position of x_m corresponding to the absorption depth $1/\alpha$. The values of wavelengths corresponding to $1/\alpha$ are presented along x-axis. It is obvious, that at $\Delta\lambda = \lambda_2 - \lambda_1$ the current $\Delta I = I_2 - I_1$ shall characterize the radiation intensity within this range of wavelengths and define the degree of selective spectral sensitivity.

According to the results of calculations, for the described two-barrier silicon structures the approximate selective sensitivity with respect to current changes from 1.5×10^{-5} A/nm to 5×10^{-5} A/nm depending on the section of curve 2, and with respect to voltage from 2.2 mV/nm to 6.2 mV/nm.

Thus, directing the integral flow of radiation onto the bio-object, it is possible to selectively register the informative radiation emergent from it without the use of filters.

The proposed principle allows to catch different regions from the wide spectral range of electromagnetic radiations from UV to IR by changing the structure, the initial material and its parameters.

4. Conclusion

The studies showed that in two-barrier photo receiving structures, it is possible to change the relations between the widths of regions exhausted by charge via changing external voltage for ΔV. This brings to the redistribution of absorbed radiation intensities in them within the range of wavelengths $\Delta\lambda$. The change of external photocurrent for ΔI will define the radiation intensity within the range of wavelengths $\Delta\lambda$ and the degree of selective spectral sensitivity of the structure. Scanning ΔV with respect to voltage, it is possible to shift $\Delta\lambda$ along the spectrum and receive spectral distribution of radiation intensities.

The calculations in the field of solar radiation AM0 showed that selective sensitivity with respect to current changes from 1.5×10^{-5} A/nm to 5×10^{-5} A/nm, and with respect to voltage from 2.2 mV/nm to 6.2 mV/nm. This means that at the change of external voltage into millivolt fractions the resolution with respect to spectrum does not exceed 0.1 nm. The possibility to connect the amplifier to the measuring network of the photo-detector will allow to use the sources with small radiation intensity and high-resolution to study the spectral change of informative radiation running from bio-objects.

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