PHYSICAL PROPERTIES OF SENSOR STRUCTURES ON THE BASIS OF SILICON p–n JUNCTION WITH INTERDIGITATED BACK CONTACTS

O.V. KOZYNETS', S.V. LITVINENKO

Taras Shevchenko National University of Kyiv, Institute of High Technologies of Kyiv
(2, Bld. 6, Academician Glushkov Ave., Kyiv 01033, Ukraine; e-mail: alk@univ.kiev.ua)

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The influence of the adsorption of water molecules on the photosensitivity of a silicon p–n junction with interdigitated back contacts has been studied. It has been shown that the examined structures can be used for the creation of effective chemical sensors.

1. Introduction

One of the principles of the creation of semiconductor-based sensors consists in the use of the influence of the molecular physical adsorption on the charge state of a working surface. Just such physical principles are used in chemical sensors based on the field-effect transistor structure [1]. The charge variation induces a change in the near-surface band bending and, as a consequence, a modification of the surface recombination rate S or the emergence of an induced p–n junction. In the case where the substantial variations of the current in some semiconductor structure are associated with namely adsorption processes at the surface, such a device is expedient to be used for further experimental researches, as well as for the optimization of sensors and their development. In the case where the base region of a silicon junction is illuminated with light belonging to the strong absorption interval, the photocurrent is known to depend substantially on S. It is also known that the shorter the illumination wavelength, the stronger is this dependence [2]. In the presented work, we study the structure of this kind, namely, the p–n junction with interdigitated back contacts [3, 4]. The main domain of its usage is solar power engineering. The indicated design of a solar cell was proposed in 1977 in order to create thin-film photoconverters to be used in sunlight collectors. It allowed the developers to completely avoid losses associated with shadowing the "useful area" by the contacts, reduce losses stemming from the recombination of photoinduced carriers in the emitter, diminish the dark current and the series resistance of ohmic contacts, and facilitate operations at composing the unit from separate structures [5–10].

The arrangement of ohmic contacts on the same wafer surface and the peculiarities in the formation of a photosignal in structures of this type can be used while developing chemical sensors as well. The main advantages expectable from such devices include the elimination of the aggressive influence of adsorbed substances on the transmission of a useful signal into an external electric circuit for its registration. Just those reasons were responsible for the determination of the complex of researches, whose results are reported in this work.

2. Experimental Technique

The doping levels of the p-type silicon substrate, n-type emitter, and p^+-region in the structures under study were 10^{16}, 10^{20}, and 10^{19} cm^{-3}, respectively. The area of ohmic contacts amounted to 0.5 cm^2. The thickness of the p^+-region (this region creates an electric field that "repels" photo-induced carriers from the ohmic contact) was 1 μm. The distance between interdigitated back contacts was about 50 μm, and the diffusion length of minority charge carriers in the substrate was equal to 100 μm. The total substrate thickness was 70 μm. No layer for the surface passivation or optical loss reduction at the light reflection was intentionally formed at the front face of the described structures. The uniform spreading of the substances over the surface was ensured by the use of a cover glass about 0.1 mm in thickness. To create the immediate contact with interdigitated combs at the dark surface, a silver paste was applied.

The spectral distribution of the photosensitivity was determined with the help of a standard automated installation on the basis of an IKS-12 spectrometer equipped with a mechanical modulator. The modulation frequency was about 445 Hz.

The spatial distribution of the photosensitivity was studied by scanning the specimen surface with a laser beam. The illuminating source was a helium-neon laser with the wavelength $\lambda = 0.63$ μm. The beam was positioned, by using a device based on acousto-optic crystals.

The modulation frequency of the illumination intensity was 700 Hz [6].

3. Experimental Results and Their Discussion

In Fig. 1, the spectral distributions of the photosensitivity, $Q(\lambda)$, for the described structure in the air environment and for the same structure with distilled water between the cover glass and the illuminated surface are depicted. Each curve is normalized by the corresponding maximum value $Q_{\max}$. Additionally, we measured the dependences of the dark current (Fig. 2,*a*) and the current under the illumination of the specimen is with an incandescent lamp (Fig. 2,*b*) on the external voltage. It should be noted that the specimens under investigation were characterized by a good current rectification of a few orders of magnitude at changing the voltage polarity (Fig. 2,*a*), which evidenced a high quality of the barrier structure in the *p*–*n* junction. Figure 3 illustrates the surface distribution of the photosensitivity of structures.

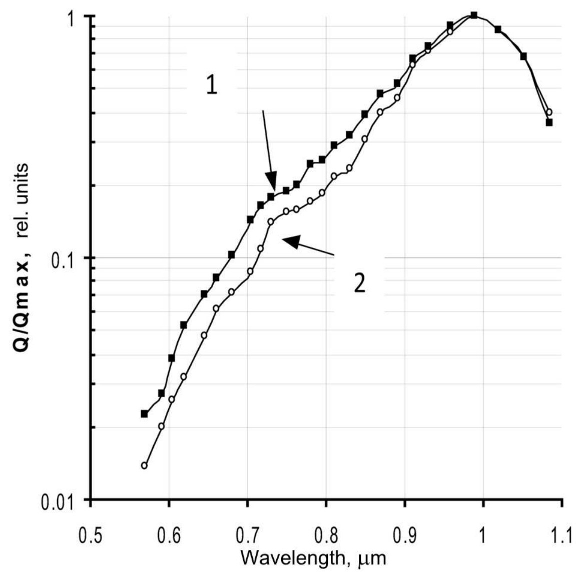


Fig. 1. Spectral distributions of the quantum efficiency for a *p*–*n* junction with interdigitated back contacts, which either contacts with distilled water (*1*) or is in the air environment (*2*)

To explain the results obtained, we assume that the physical adsorption of water molecules brings about a modification of the near-surface band bending in a vicinity of the illuminated surface and a change of the surface recombination rate S. If the base region in the silicon junction is illuminated with light belonging to the strong absorption interval, the photocurrent considerably depends on S. It is a result of competition between the recombination flux of charge carriers toward the illuminated surface and the charge carrier flux toward the space charge region, just this difference governing the photocurrent magnitude.

Our calculations were carried out with the use of the software package PC-1D for simulating a one-dimensional problem. The results obtained show that, in the case of a silicon *p*–*n* junction with ohmic contacts arranged at opposite surfaces (provided that the rear surface is illuminated, the base thickness is 150 μm, the emitter one is 0.3 μm, and the diffusion length of minority charge carriers is 70 μm), the recombination flux toward the illuminated surface substantially reduces the photocurrent induced at short wavelengths. Moreover, the shorter the wavelength, the stronger is the photocurrent dependence on S. In particular, a decrease of the wavelength by an order of magnitude results in a photocurrent variation by a factor of five. In our case, the situation is qualitatively similar to that described above; although the design features of the examined structure bring about a distortion of current curves, a considerable influence of the recombination near the illuminated surface on the photocurrent can be expected.

It is evident that, besides the photocurrent component directed along the light propagation direction (the y-axis), there also exists a component directed between the comb contacts (the x-axis). Therefore, the expression for the quantum distribution of the photosensitivity in the range of the strong absorption by silicon cannot be applied straightforwardly for carrying out the numerical estimations [11]. The recombination flux toward the surface can modify the current component directed along the y-axis owing to the "capture" of charge carriers by the surface. For the correct results to be obtained in this case, it is necessary that the model calculations should be executed with regard for the current components along both indicated directions.

With the help of the numerical two-dimensional simulation, it was calculated the dependences of the short-circuit current and the open-circuit voltage on the recombination rate at the illuminated surface for photoconverters with interdigitated back contacts under AM 1.5 illumination conditions (Fig. 4) [3]. Although the computer program Mdraw ISE TCAD 8.5 does not allow the calculations to be fulfilled for a fixed wavelength, the results obtained testify that the photocurrent substantially depends on the recombination processes occurring at the surface. This conclusion remains true, of course, in the case of the surface illumination with separate short-wave spectral components as well.

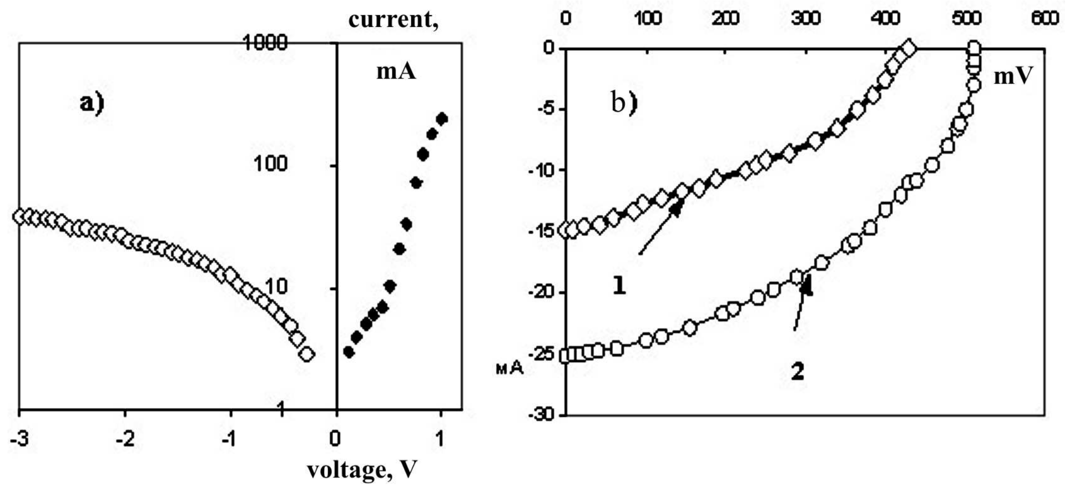
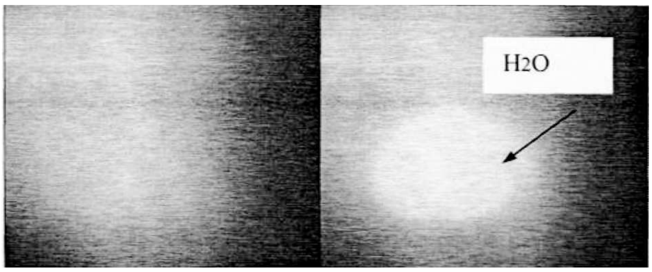


Fig. 2. Current-voltage characteristics of the examined structure: (a) in dark and (b) under the illumination in air (*1*) or when contacting with distilled water (*2*)



a *b*

Fig. 3. Surface distributions of the photosensitivity in a p–n junction with interdigitated back contacts in air (a) and when contacting with distilled water (b). Lighter grey colors correspond to higher photocurrent densities

That is why it can be used for the following consideration.

If the adsorption of water molecules affects the initial band bending near the illuminated surface (the band bending increases or decreases with respect to the initial value), then, according to the Stevenson–Keyes model, the rate of surface recombination can also change [12,13]. Accordingly, if the parameter S diminishes, the recombination flux of minority charge carriers (electrons) along the y-axis decreases, and the total photocurrent density increases. Therefore, the growth of the photosensitivity in the spectral range 0.5 μm $< \lambda <$ 0.8 μm is quite probable just according to this circumstance (Fig. 1). These results are in good agreement with increase of the open-circuit voltage by 10% and the short-circuit current by 25% (Fig. 2,b), as well as with experimental data (Fig. 3). Really, when the parameter S diminishes from 10^4 to 10^2 cm/s (Fig. 4), the results of numerical simulations and the experimentally determined photoconversion parameters become comparable at the qualitative level. Additional arguments in favor of the substantial role of recombination processes in a vicinity of the illuminated surface can also be obtained from photocurrent measurements under a permanent illumination with the use of a violet light-emitting diode with λ = 0.4 μm (Fig. 5).

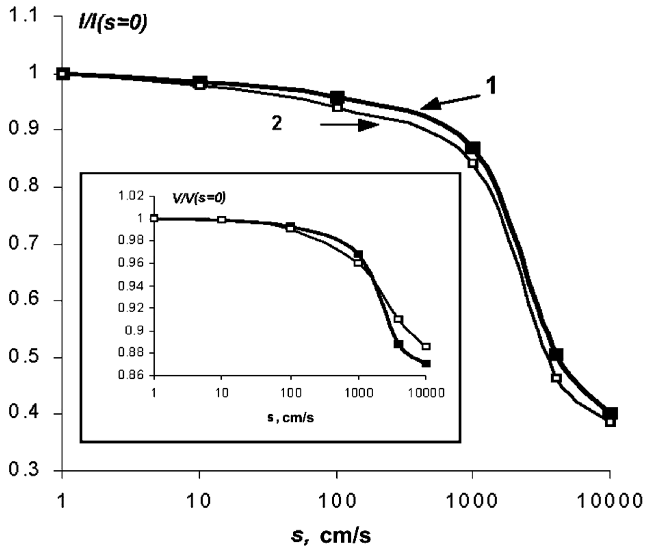


Fig. 4. Calculated dependences of the short-circuit current and the open-circuit voltage (in the inset) on the recombination rate at the illuminated surface for a p–n junction with interdigitated back contacts. The diffusion length is 300 (*1*) and 100 μm (*2*)

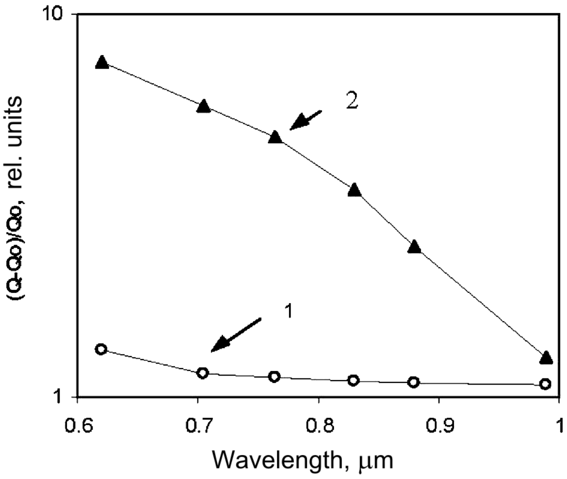


Fig. 5. Relative enhancement of the spectral sensitivity for a structure with interdigitated back contacts when contacting with distilled water (*1*) and under the permanent illumination with a light-emitting diode (*2*)

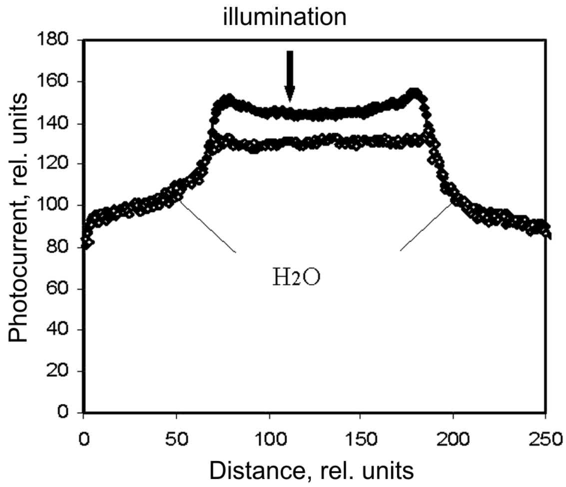


Fig. 6. Distributions of the photo-induced current in a structure with interdigitated back contacts that contacts with distilled water under a permanent illumination with a blue light-emitting diode (solid circles) and without illumination (hollow circles)

The influence of the additional stationary photogeneration in such an experiment can be compared qualitatively with the effect of a constant voltage applied across a near-surface "floating" junction, when the light source is switched on. Such a photogeneration may give rise to changes in the near-surface band bending and the surface recombination rate S. For this reason, the relative variation of the photocurrent, $(Q(\lambda) - Q_0(\lambda))/Q_0(\lambda)$, decreases if the wavelength increases from 0.6 to 1 μm. It this case, the fraction of quanta that are absorbed in the specimen depth increases, and the contribution made by recombination processes at the illuminated surface to the photocurrent diminishes. In Fig. 6, the cross-section of the photocurrent distribution over the surface is depicted in the case where the current is induced by a laser beam, and the permanent illumination with a blue light-emitting diode ($\lambda = 0.47$ μm) is carried out.

Hence, the permanent illumination can enhance the sensor response of the structure concerned. To explain the results obtained, we proceeded from the assumption that the dominant role in recombination processes is played by a level with the energy close to the middle of the energy gap in silicon. However, a discrete or continuous system of donor-acceptor levels can actually exist at the surface. We hope that qualitative conclusions hold true in this case as well. An enhancement of the surface adsorption efficiency can be attained by using additional layers with required structural properties. For instance, porous silicon is known to be characterized by a developed surface with high adsorption ability. Therefore, one may suppose that the creation of a thin (less than 2 μm) porous layer on the surface of a silicon p–n junction with interdigitated contacts in the course of the electrochemical etching will allow the characteristics of the described sensor structure to be additionally improved.

4. Conclusions

A possibility of using the structure on the basis of a silicon p–n junction with interdigitated back contacts for the creation of chemical sensors has been substantiated. It has been demonstrated that the change of a photosignal that takes place when water molecules are adsorbed is associated with the variation of the recombination rate on the illuminated surface.

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ФІЗИЧНІ ВЛАСТИВОСТІ СЕНСОРНИХ СТРУКТУР НА ОСНОВІ КРЕМНІЄВОГО p–n-ПЕРЕХОДУ З ЗУСТРІЧНИМИ ГРЕБІНЧАТИМИ КОНТАКТАМИ НА ТИЛЬНІЙ ПОВЕРХНІІ

О.В. Козинець, С.В. Литвиненко

Р е з ю м е

Досліджено вплив адсорбції молекул води на фоточутливість кремнієвого p–n-переходу із зустрічними гребінчатими контактами на тильній поверхні. Показана можливість використання таких структур для створення ефективних хімічних сенсорів.