INFLUENCE OF THE MAGNETIC FIELD ON THE PHOTOCURRENT THROUGH SILICON—POROUS SILICON HETEROSTRUCTURES

A.V. KOZINETS, O.I. NICHIPORUK, N.N. MOMOT, V.V. KISLYUK, V.A. SKRYSHEVSKY

Taras Shevchenko Kyiv National University, Faculty of Radiophysics
(64, Volodymyrska Str., Kyiv 01033, Ukraine),

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The influence of the magnetic field on the photocurrent through heterostructures with thin layers of porous silicon (PS) has been studied. A reduction of the photocurrent, which accompanies the deflection of charge carriers by a magnetic field towards the illuminated surface, is associated with the charge recombination at the interface between porous silicon and the crystalline silicon substrate. It has been shown that such heterostructures can be useful in fabricating the magnetic field sensors.

1. Introduction

Porous silicon is one of the promising materials for semiconductor optoelectronics. Thin layers of this material can reduce optical losses; therefore, they are used as antireflection coatings or diffusers in silicon-based solar cells [1, 2]. The developed porous surface of PS and its activity in oxidation-reduction reactions are effective from the viewpoint of its application in chemical sensors [3,4]. Nevertheless, the recombination properties of the PS–silicon substrate interface, as well as the mechanisms of the transport of nonequilibrium charge carriers in similar structures, still remain the subject of researches. The influence of the magnetic field on the radiative recombination and the charge carrier transport has been considered in a few publications only [5, 6].

For example, the spectral characteristics of the photomagnetic voltage are known to be sensitive to the amplitude and the sign of the near-surface band bending and display peculiarities for the samples which include heterogeneous regions and regions with a varying band-gap. In work [6], where the spectral dependence of the photomagnetic voltage in the PS–single-crystalline n-silicon was studied, the existence of two components was found: a long-wave component associated with the charge generation in the silicon substrate, and a component caused by the charge carriers generated in the PS film. It has been demonstrated that the latter component arises owing to the diffusion and drift of nonequilibrium charge carriers away from the illuminated surface in the internal field of the PS. The shape of the spectral distribution was explained in the framework of the model that supposes the existence of a heterojunction PS–single-crystalline silicon [6]. In work [7], a 10%-decrease of the photoluminescence intensity of the PS layers in a magnetic field of 0.5 T oriented in parallel to the film surface was observed. This effect was associated with the reduction of the mean free path of "hot" electrons due to the action of the Lorentz force.

In this work, we studied the features of the influence of a magnetic field on the photocurrent through heterostructures with PS layers and on the near-surface recombination of nonequilibrium charge carriers.

2. Experimental Methods and Samples

Heterostructures of two different types were selected for investigations. Heterostructures N 1 were fabricated using 350-μm p-silicon wafers with the specific resistance of 4 $\Omega \times$ cm. Phosphorus atoms were made diffuse into them to form n^{++}-regions with the doping level up to 10^{20} cm^{-3} and the depth of 0.6 μm. Three-component ohmic contacts Ti/Pd/Ag were deposited on the surface of those regions in the form of 2-mm stripes separated by 2- or 4-mm intervals. A layer of PS 0.2 μm in

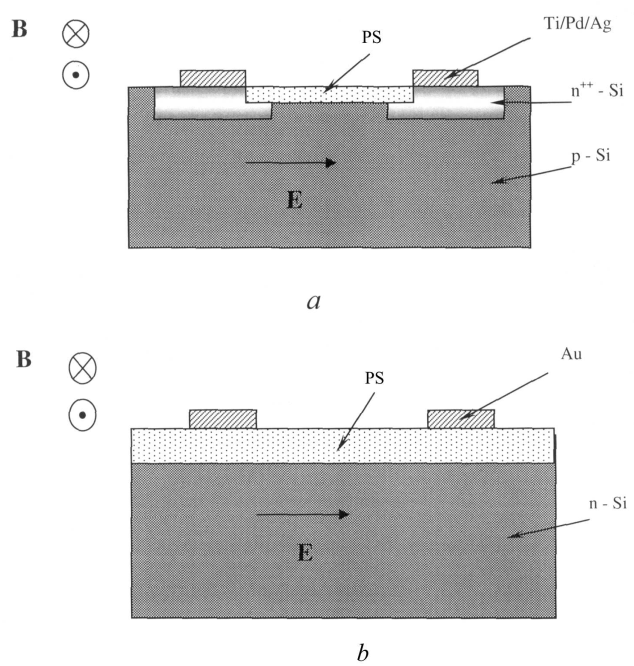


Fig. 1. The scheme of heterostructures N 1 (a) and N 2 (b). The orientations of the magnetic induction vector and the drawing electric field vector are shown

thickness was deposited between the contact stripes (Fig. 1,a) by electrochemical etching in an electrolyte prepared as a 1:1 mixture of 40% HF and 95% C_2H_5OH aqueous solutions. In such a heterostructure, the dark current between ohmic contacts flows through the silicon substrate (because the resistance of the porous layer is high), while PS plays the role of a passivating and antireflecting layer.

In heterostructures N 2, the metal (Au) contacts were deposited directly on the PS layer with the thickness up to 1 μm, which was formed on an n-Si wafer (5 $\Omega \times$ cm). The distance between the contact Au films was 3 mm. The current in such heterostructures flows directly through the PS layer (Fig. 1,b). This means that structure N 1 should be rather considered as a structure of the "resistive" type, while structure N 2 is a circuit composed of a silicon-based resistor inserted between two diodes connected in series contrarily to each other. In this case, PS also plays the role of a passivating and antireflecting layer.

In order to measure the photosensitivity spectra, we took advantage of the classical setup which was composed of an IKS-21 spectrometer, a selective amplifier, a modulator, and a light source. The photocurrent was measured in a linear mode; it was proportional to the voltage drop across the load resistance $R_{\rm lr}$ = 10 kΩ ($R_{\rm lr}$ was selected much lower than the resistance of the sample $R_{\rm sp}$), which was applied to the input of a U2-6 broadband amplifier tuned to the modulator frequency of 440 Hz. The amplified signal was sent to the sound card of a computer which

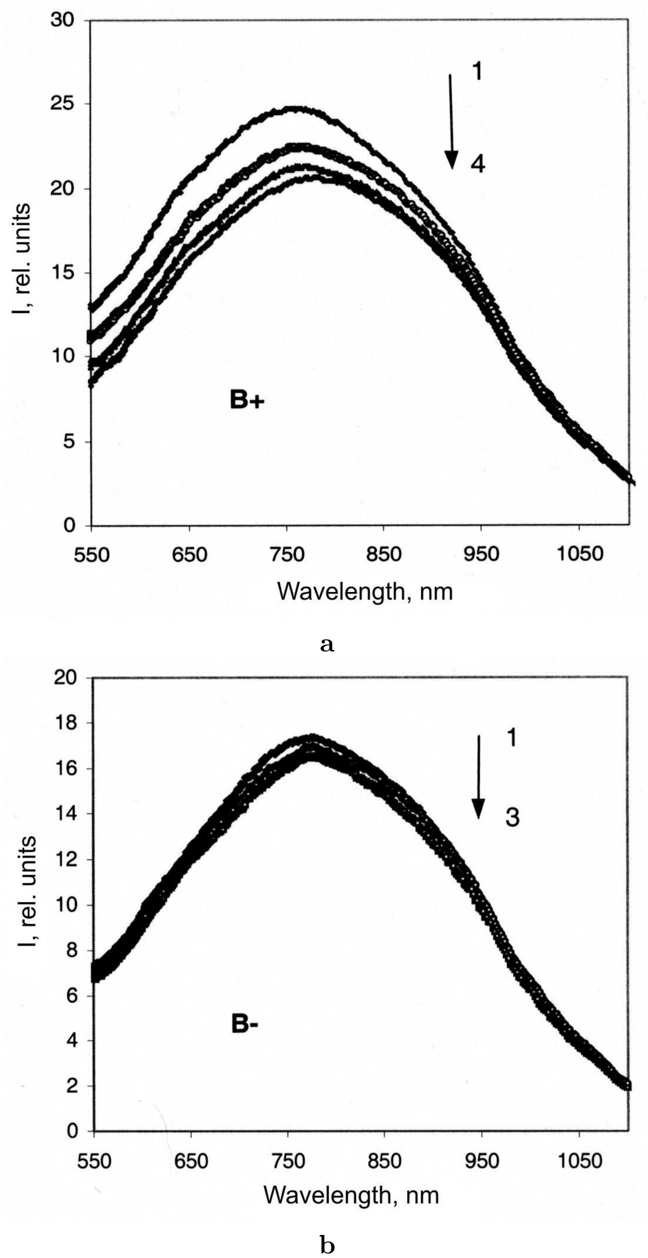


Fig. 2. Photosensitivity spectra of samples N1 in various magnetic fields which deflect charge carriers (a) towards the PS surface ($B^+ = 0$ (1), 0.199 (2), 0.409 (3), and 0.525 T (4)) and (b) away from it ($B^- = 0$ (1), 0.437 (2), and 0.525 T (3))

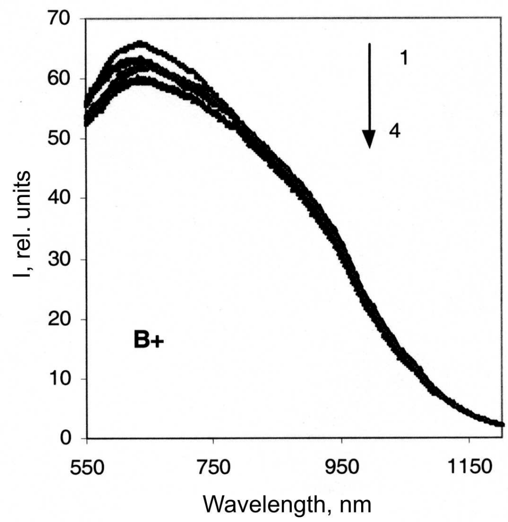
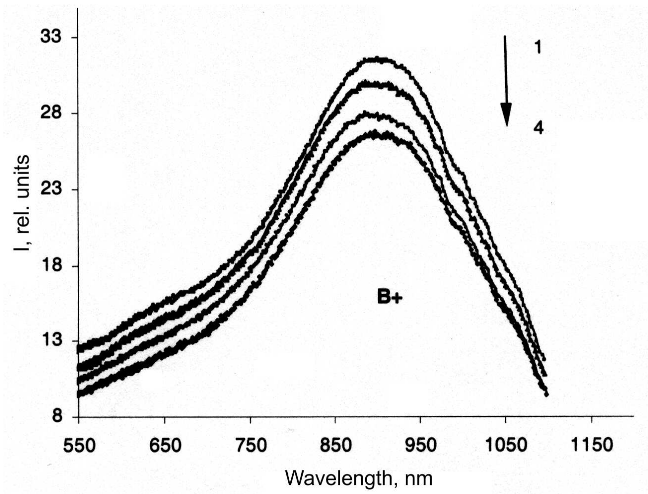
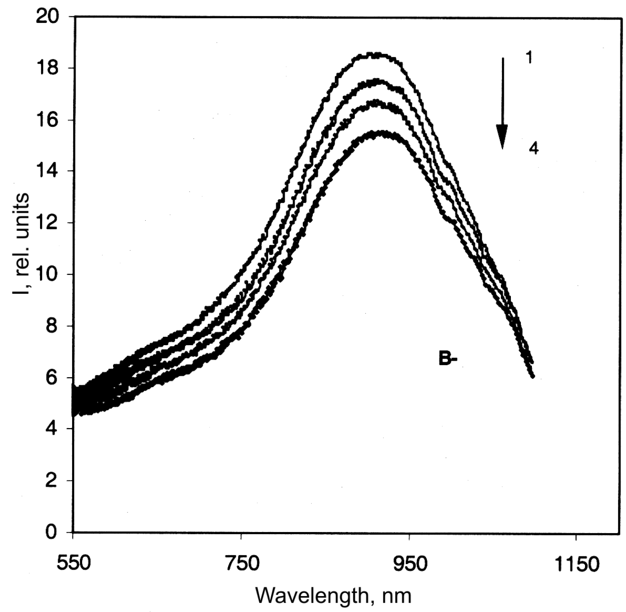


Fig. 3. Photosensitivity spectra of samples N1 embedded into the water–vapor environment in various magnetic fields $B^+ = 0$ (*1*), 0.299 (*2*), 0.4 (*3*), and 0.5 T (*4*)



a



b

Fig. 4. Photosensitivity spectra of the samples N2 in various magnetic fields B^+ (*a*) and B^- (*b*): 0 (*1*), 0.234 (*2*), 0.363 (*3*), and 0.525 T (*4*)

served as an analog-digital device. The load resistance was connected in series with the researched sample and an 8-V galvanic cell. Magnetic fields within the range 0—0.525 T were used.

3. Results and Their Discussion

The photosensitivity spectra of structures under investigation and the influence of the magnetic field on them are presented in Figs. 2–4. In the general case, if $B = 0$, the detected photosensitivity signal is determined by the photocurrent in the bulk of the sample (the photoconductivity of the silicon substrate), the photocurrent along the spatial charge region (SCR) located in the silicon near its boundary with the PS, and the photoconductivity of the highly resistive PS layer. Nevertheless, the photosensitivity spectra manifested the sensitivity of their shapes (Fig. 2) only in the range of intrinsic silicon absorption, while the characteristic maximum in the spectral range about $h\nu \approx 2$ eV, which corresponds to photogeneration in PS, was not observed. Therefore, the photocurrent in PS can be neglected [8].

In order to analyze the spectra, let us consider feasible mechanisms, which affect the photocurrent amplitude in a weak magnetic field ($\mu B < 1$).

1) Under the action of a drawing electric field E between the ohmic contacts, the photogenerated electrons and holes move with oppositely directed drift velocities. In a magnetic field, under the action of the Lorentz force, these fluxes of nonequilibrium charge carriers are deflected towards the same side: either towards the illuminated surface (this direction of the magnetic field will be designates as B^+) or towards the sample depth (the field B^-).

2) The barrier field, which emerges at the heterogeneous interface PS—p-silicon, deflects nonequilibrium electrons, which have been photogenerated in the SCR, towards the PS, and photogenerated holes towards the silicon depth. In the presence of the magnetic field, there

appears an additional flux of charge carriers of both signs along the surface.

3) The photogenerated electron-hole pairs diffuse into the substrate depth along the direction of light propagation, and the oppositely directed magneto-diffusion fluxes along the surface emerge (the photomagnetic effect).

4) The excess concentration of charge carriers at the interface PS–silicon changes depending on the direction and the amplitude of the magnetic field, which results in the variation of the recombination rate on the surface.

Fig. 2 shows the photosensitivity spectra of samples N1 for various amplitudes and orientations of the magnetic field. In the wavelength range $\lambda = 950 \div 1100$ nm, the photocurrent slightly falls down for both B^+ and B^- orientations. The coefficient of absorption α in silicon in this range is insignificant ($\alpha d < 1$); therefore, (i) the main contribution to the photocurrent is made by the volume of the silicon substrate, and (ii) the gradient of the nonequilibrium charge carrier concentration towards the substrate depth is practically absent, so that the magneto-diffusion components of the current may be neglected. In such a case, when considering the long-wave illumination, the reduction of the photosensitivity signal for B^+ and B^- orientations can be associated, first of all, with the variation of the magnetoresistance. In particular, for the magnetic field $B = 0.525$ T and the mobility of electrons in silicon $\mu_n \approx 1350$ cm^2/(V $\times$ s) (for holes, $\mu_n \approx 450$ cm^2/(V $\times$ s)), the value of the ratio $\Delta\rho_n(B)/\rho_n(B=0) = \frac{1}{2}(\mu_n B)^2$ amounts to 0.0025 (for holes, to 0.0003), i.e. does not exceed 0.25%(0.03%).

In the wavelength range $\lambda = 550 \div 950$ nm, the relative reduction of photosensitivity is more pronounced, and the fields B^+ and B^- bring about different amplitudes of this effect (Fig. 2). The asymmetry of the photosensitivity signal reduction in this spectral range for B^+ and B^- orientations can be explained, if, while considering the statistics of the recombination, one takes simple local centers on the surface into account (the Stevenson—Keyes model) [9].

Let us analyze simple expressions for the photosensitivity spectra, neglecting the processes of generation and recombination in the SCR and making use of the classical approximation for the surface recombination rate. We assume the condition that the injection level is low — $\Delta n = \Delta p < p_p$ for samples N 1, or $\Delta n = \Delta p < n_n$ for samples N 2 — to be satisfied. For a semiconductor of the n-type, the photoconductance is proportional to the concentration of nonequilibrium holes, while the latter can be written down as [10]

$$\Delta p = \frac{\beta(1-R)I\tau\alpha}{h\nu(\alpha^2L^2-1)}\times$$
$$\times\left[\frac{\alpha L^2+S\tau}{L+S\tau}L\left(1-e^{-d/L}\right)-\frac{1}{\alpha}\left(1-e^{-\alpha d}\right)\right], \qquad (1)$$

where β is the quantum yield of photoionization, τ the lifetime of nonequilibrium holes, I the intensity of illumination, d the sample thickness, R the coefficient of reflection, L the length of hole diffusion, and S the rate of surface recombination on the illuminated surface. Expression (1) was obtained for a thick sample ($d \gg L$) and in the spectral range of its intrinsic absorption $d \gg 1/\alpha$.

In the range of intermediate values of the absorption coefficient, where $\alpha d > 1$ and $\alpha L < 1$, we have

$$\Delta p \sim \frac{\beta(1-R)I\tau}{h\nu}\left[1-\frac{\alpha LS\tau}{L+S\tau}\right]. \qquad (2)$$

This means that the photoconductance substantially depends on S in this spectral range. If $S = 0$, the photoconductance is maximal (saturation) and decreases as S grows. The quantity S, which is introduced as the ratio between the recombination rate on the surface and the excess concentration of charge carriers, can be written down in the form [11]

$$S = \frac{\gamma_p\gamma_n N_t(p_0+n_0)}{\gamma_n(n_s+n_1)+\gamma_p(p_s+p_1)}, \qquad (3)$$

where γ_n and γ_p are the probabilities of electron and hole, respectively, capture by the surface recombination centers; $p_s = p_{s0} + \Delta p_s$ and $n_s = n_{s0} + \Delta n_s$ are the concentrations of holes and electrons, respectively, on the surface; n_{s0} and p_{s0} are the equilibrium concentrations of charge carriers on the surface; Δn_s and Δp_s are the excess concentrations of charge carriers on the surface;

$$n_s = n_0\exp(e\phi_s/kT), \quad p_s = p_0\exp(-e\phi_s/kT), \qquad (4)$$

n_0 and p_0 are the equilibrium concentrations of electrons and holes, respectively, in the bulk; ϕ_s is the surface potential; N_t and E_t are the concentration and the energy, respectively, of the surface level with respect to the energy gap midpoint; $n_1 = n_i\exp(E_t/kT)$; $p_1 = n_i\exp(-E_t/kT)$; and $n_i^2 = p_s n_s$.

The application of the magnetic field, when the sample is illuminated with short-wave light, leads to the variation of the concentration n_s and p_s at the interface PS–silicon. The magnitude of this variation

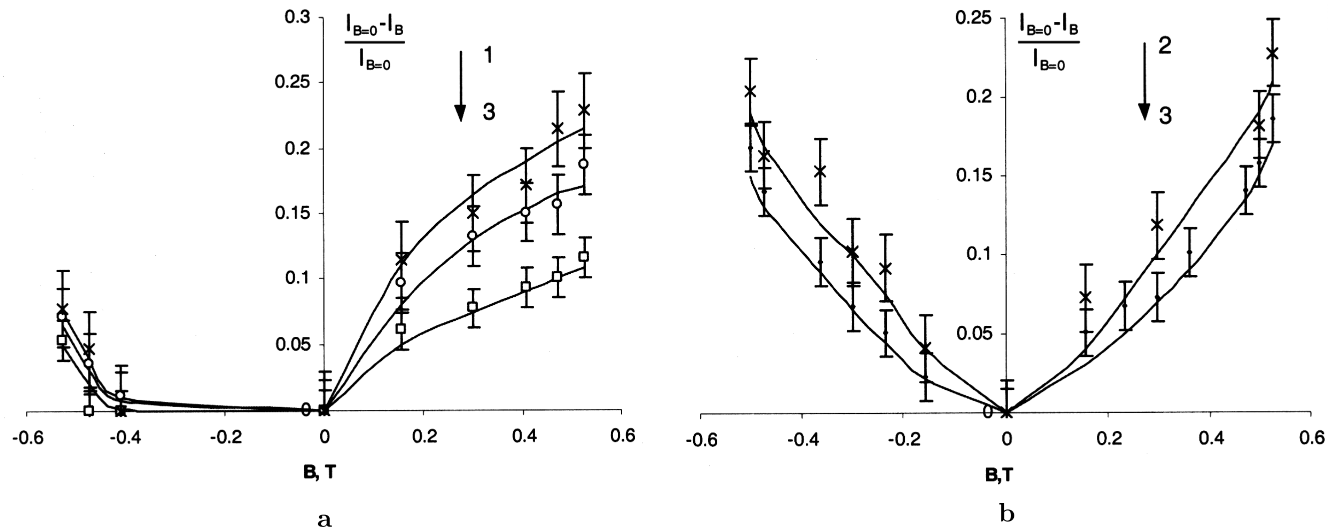


Fig. 5. Tesla-ampere characteristics for the structures of two types (N1 (*a*) and N2 (*b*)) at various wavelengths of illumination light: 650 (*1*), 750 (*2*), and 900 nm (*3*)

depends on the direction of the magnetic field and on the sign of band bending in the PS–silicon heterojunction. In the p-silicon and B^+-field case, the Lorentz force and the electric field in the heterojunction move electrons identically, towards PS; at the same time, on holes, the Lorentz force and the electric field in the heterojunction act in opposite directions. This ensures the fulfillment of the condition that the growth of the magnetic field B^+ should be accompanied by an increase of the concentration n_s at the PS–silicon interface. The maximal value of the surface recombination rate is known to be observed when the relationship $p_s\sigma_p = n_s\sigma_n$ holds true, where σ_p and σ_n are the capture cross-sections of holes and electrons, respectively [11, 12]. Therefore, if the growth of the magnetic field is accompanied by the increase of the free electron concentration at the PS–silicon interface and by the diminishing of photoconductance in the short-wave range due to the enhancement of surface recombination, this means, for samples No. 1, that the inequality

$$p_s\sigma_p \geq n_s\sigma_n \tag{5}$$

holds true, and the cross-section of electron capture in the silicon at the PS–silicon interface is larger that that for holes, $\sigma_n > \sigma_p$. In the case of p-silicon with a resistance of 4 $\Omega \times$ cm, the concentrations are $p_0 = 3 \times 10^{15}$ cm^{-3} and $n_0 = n_i^2/p_0 = 3 \times 10^4$ cm^{-3}, $\sigma_n/\sigma_p = 100$ for the cross-section ratio on the silicon surface [12]. Then formulas (4) and (5) allow one to estimate the surface potential in the heterostructure: $\phi_s < 0.25$ V. Under these conditions, the inversion at the interface does not occur, and the condition $n_s < p_s$ is obeyed in our experiments.

The role of surface recombination in the considered magnetic field effects is verified by the shape change of the photosensitivity spectra measured for samples in the magnetic field B^+ and in the water-vapor environment (Fig. 3). Earlier, we showed that adsorption of water molecules can passivate the recombination centers on the surface [13]. As the result, the photosensitivity of samples in the water-vapor environment increases just in the short-wave range of the spectrum, which gives rise to both the reduction of the magnetic field influence on the surface recombination rate and the shift of the spectrum towards short waves.

In the case of B^--field, the Lorentz force is directed inward the sample; therefore, the concentration of electrons at the PS–silicon interface is lower than that in the previous case, and the surface recombination rate affects weaker the dependence of the photosensitivity spectrum on the magnetic field. Under these conditions, the variations of spectra in the magnetic fields are governed by other factors.

Specimens No. 2 demonstrated a much stronger magnetic field effect, with the relative reduction of photosensitivity in the magnetic fields B^+ and B^- being more "symmetric" (Fig. 4). This testifies that the photoconductivity of structures of the second type depends weaker on the recombination properties of the PS–silicon interface, and the variation of the silicon magnetoresistance is not the major factor of the magnetic field action. The magnetoresistance may vary because of the circumstance that the current flows through a highly resistive region of PS, and the probable nonequipotentiality of the electric field lines in the vicinity of the ohmic contacts in PS brings about the growth of the series resistance, which is larger than that dictated by the magnetoresistance law for silicon.

The revealed asymmetric influence of the magnetic field on the photocurrent through the PS–silicon heterostructure can be used for the creation of functional microelectronic devices — photodiodes with nonlinear current vs magnetic field characteristics (Fig. 5). For a photodiode of the first type, the "rectification factor" (the ratio between the relative variations of the photocurrent for identical values of magnetic fields but with different signs) and the relative reduction of the photocurrent in the B^+-fields will increase if the illumination wavelength becomes shorter. The dependence of the photocurrent on the magnetic field (linear at small and saturated at large B^+s) is well described by model (2) taking into account the dependence of the surface recombination rate on the magnetic field. The same parameter measured in the B^--field practically does not depend on the illumination wavelength and is described by the law $\Delta\sigma_B/\Delta\sigma_0 \sim 1/B^2$, i.e. it is determined, first of all, by the magnetoresistive effect in silicon. For photodiodes N 2, both branches are close to the dependence $\Delta\sigma_B/\Delta\sigma_0 \sim 1/B^2$, but the amplitude of the ratio $\Delta\sigma_B/\Delta\sigma_0$ variation is much larger than that the classical expression predicts for the magnetoresistance in silicon. A high series resistance, which the PS layer is responsible for, stimulates a substantial enhancement of the magnetic field influence on the photocurrent through such structures.

4. Conclusions

The "asymmetric" influence of the magnetic field polarity on the photosensitivity of silicon heterostructures with thin PS layers has been demonstrated experimentally. A reduction of the sample photosensitivity, when charge carriers are deflected by the magnetic field towards the illuminated surface of porous silicon, is associated with the recombination at the PS—crystalline silicon interface. Such structures are proposed to be used as functional microelectronic devices — photodiodes with nonlinear tesla-ampere characteristics — which can be controlled by varying the illumination wavelength. On the other hand, such heterostructures may serve as the basis for the creation of the magnetic field and chemical sensors, because the recombination properties of the PS—silicon interface depend on the magnitude of the magnetic field and on molecular adsorption.

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ВПЛИВ МАГНІТНОГО ПОЛЯ НА ФОТОСТРУМ
В ГЕТЕРОСТРУКТУРАХ КРЕМНІЙ —
ПОРУВАТИЙ КРЕМНІЙ

О.В. Козинець, О.І. Ничипорук, М.М. Момот, В.В. Кислюк, В.А. Скришевський

Р е з ю м е

Досліджено вплив магнітного поля на фотострум гетероструктур із тонкими шарами поруватого кремнію (ПК). Зменшення фотоструму при зміщенні носіїв магнітним полем до освітлюваної поверхні ПК, пов'язується із рекомбінацією на межі поділу поруватий кремній—монокристалічна підкладка. Показано, що такі гетероструктури можуть бути використані для створення датчиків магнітного поля.