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Detector with High Internal Photocurrent Gain Based on ZnO:N

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The photoresponsive structures prepared by magnetron sputtering of ZnO:N on *p*-Si substrates followed by vacuum evaporation of semi-transparent Ni film on ZnO surface were investigated. The mentioned structures show high sensitivity that sharply enhances with increase of applied voltage. Under a bias 5 V, the responsivities at $\lambda = 390$ and 850 nm are equal to 210 A/W and 110 A/W which correspond to the quantum efficiencies of 655 and 165, respectively. It is suggested that the observed high response is attributed to internal gain in phototransistor structure containing Ni/*n*-ZnO Schottky contact as emitter junction and *n*-ZnO/*p*-Si heterostructure as collector junction.

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1. Introduction

In recent years there has been increased an interest to ZnO-based photodiodes with the *n*-ZnO/*p*-Si heterojunction used as a photosensitive element [1–5]. In such photodiodes, the responsivity 0.28 A/W was achieved at 670 nm that corresponds to the quantum efficiency about 0.5 [3, 5] while in Ref. [2] the responsivity at 310 nm was 0.5 A/W that corresponds to the quantum efficiency about 2. In Ref. [6] the fabrication and characterization of an Au/*n*-ZnO/*p*-Si UV enhanced bipolar phototransistor are presented. The sensitivity at 370 nm of such device is more than 5–10 times that of a ZnO/Si photodiode. In this communication we report on the results of investigation of Ni/*n*-ZnO:N/*p*-Si structure with quantum efficiency which can achieve several hundreds due to an internal gain.

2. Photoelectric characteristics of Ni/*n*-ZnO/*p*-Si structure and discussion

The ZnO films with thickness 0.1 μm were deposited by DC magnetron sputtering in N_2/Ar plasma on *p*-Si wafers having resistivity 9–10 Ω cm. To compensate oxygen vacancies acting in ZnO as intrinsic donor defects, we introduce the nitrogen into ZnO during film deposition by sputtering ZnO target in N_2/Ar (10/1) gas ambient [7]. A semi-transparent Ni layer with thickness about 10 nm was deposited as a Schottky contact on the ZnO surface by vacuum thermal evaporation. Aluminum ohmic contacts to *p*-Si were also evaporated using the same technique.

The spectral distribution of radiation at the outlet slit of the system was determined in absolute units using a Si reference photodiode D286.

The investigated samples reveal photoresponsivity only at the polarity with low current ("+" to Ni contact, "−" to *p*-Si). As one can see from Fig. 1, the photoresponsivity spectra cover a wide spectral region. Evidently, in the regions $\lambda < 500$ nm and $\lambda > 500$ nm, responsivities are caused by photogeneration of electron–hole pairs in ZnO and Si, respectively.

Our experiments showed that at a bias voltage higher then ≈ 0.5 V, the responsivity of Ni/*n*-ZnO/*p*-Si structure is higher than the same of Si reference photodiode with 0.45 A/W at a maximum. High values of spectral responsivity S mean that photoelectric conversion in Ni/*n*-ZnO/*p*-Si structure is characterized by heightened quantum efficiency $\eta = Shc/\lambda$ (Fig. 2). At the lowest bias voltages, quantum efficiencies $\eta(\lambda)$ at $\lambda = 390$ and 850 nm increase drastically with V but at higher voltages such increase becomes slower. Nevertheless, at $V = 5$ V the $\eta(\lambda)$ values at $\lambda = 390$ and 850 nm become equal to 655 and 165 which correspond to the responsivities 211 and 110 A/W, respectively

All obtained results allow us to assume that the investigated Ni/*n*-ZnO:N/*p*-Si structure is a peculiar kind of bipolar transistor that operates as a photodetector with photocurrent gain, i.e. as a phototransistor [8]. If voltage sign on Ni contact is positive in respect of *p*-Si, Ni/*n*-ZnO emitter junction and *n*-ZnO/*p*-Si collector junction are

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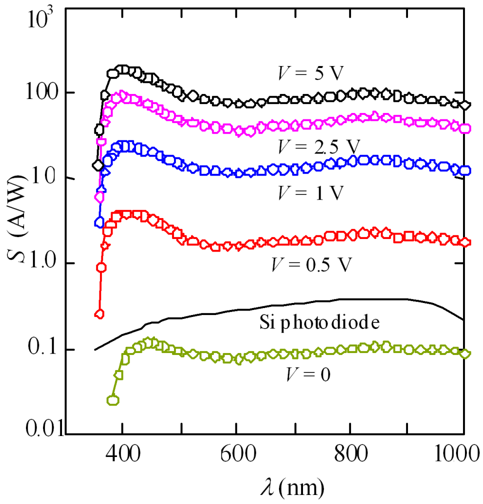

Fig. 1. Spectral response S of Ni/n-ZnO:N/p-Si structure at different voltages (circles) and the spectral curve of Si reference photodiode (solid line).

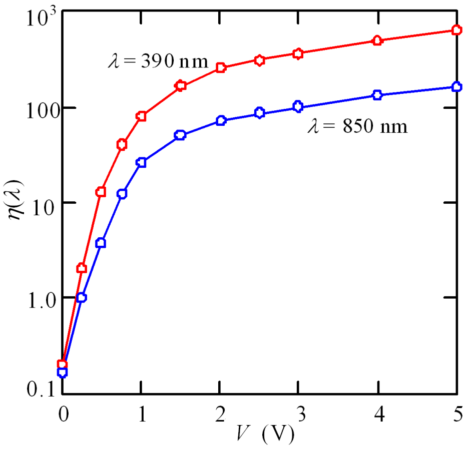

Fig. 2. Voltage dependences of quantum efficiency $\eta(\lambda)$ of Ni/n-ZnO:N/p-Si structure at 390 and 850 nm.

switched on in the forward and reverse directions, respectively, just as in the bipolar transistor with a common emitter. Electron–hole pairs generated by the absorbed photons in the space-charge region of n-ZnO/p-Si heterojunction are separated by the electric field in opposite directions constituting the "primary" photocurrent and participating in forming the observed spectra. In both cases electrons are injected into the neutral part of the ZnO film, i.e. in transistor base. To provide stationary process, the same quantity of holes is injected in ZnO from the emitter (i.e., from the Ni contact). Of course, band bending at the Ni/n-ZnO Schottky contact should be large to provide the formation of inversion p–n junction and thus effective injection of holes into the base.

In a bipolar transistor, the current of minority carriers injected in the base from the emitter is amplified by a factor of $\beta = \alpha/(1-\alpha)$, where β is the common-emitter current gain of the transistor, and α is the common-base current gain. The current gain α depends on a ratio between the base thickness d and the diffusion length of minority carriers $L_\mathrm{p} = (\tau_\mathrm{p} D_\mathrm{p})^{1/2}$, where τ_p and D_p are the lifetime and diffusion coefficients of holes, respectively. Accepting for an estimation the hole mobility μ_p in ZnO equal to 1–10 $\mathrm{cm}^2/(\mathrm{V\,s})$ [9 1], from Einstein's ratio one can obtain $D_\mathrm{p} = \mu_\mathrm{p} kT/q = 0.025$–$0.25\ \mathrm{cm}^2/\mathrm{s}$ at 300 K. Accepting further $\tau_\mathrm{p} = 10^{-8}$–$10^{-7}$ s for holes in ZnO [10], for the hole diffusion length one can obtain $L_\mathrm{p} = 0.5$–$1.5\ \mu\mathrm{m}$ that is longer than the film thickness $d = 0.1\ \mu\mathrm{m}$. If $L_\mathrm{p} > d$, the value of the common-base current gain α is close to 1. It means that $\beta \gg 1$, i.e., a photocurrent in Ni/n-ZnO/p-Si structure is significantly amplified.

3. Conclusions

Our experimental results correlate with the assumption that the investigated Ni/n-ZnO:N/p-Si structure possesses properties of the phototransistor providing internal gain of the photocurrent. The parameters of the structure (the ZnO thickness layer and the lifetime of minority carriers) allowed us to get a gain exceeding several hundreds at moderate bias ≤ 5 V.

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