

Photoelectric and Electrical Properties of a Reverse-Biased p -Si/ n -CdS/ n^+ -CdS Heterostructure

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Abstract—We have demonstrated a photosensitive p -Si/ n -CdS/ n^+ -CdS structure. A reverse bias voltage applied to this structure leads to electron injection from the narrow-band-gap material p -Si to the high-resistivity, wide-band-gap semiconductor n -CdS. Evidence is presented for mutual compensation of opposite drift and diffusion flows of charge carriers in this structure. At current densities in the range $I \sim 10^{-8}$ to 10^{-7} A/cm², the opposite drift and diffusion flows of nonequilibrium minority charge carriers cause the photosensitivity of the structure to change sign in both the short- and long-wavelength regions of the spectrum. The mutual compensation of the opposite drift and diffusion flows at current densities on the order of $\sim 10^6$ A/cm² leads to sublinear behavior of the reverse current–voltage characteristic in a wide range of bias voltages.

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INTRODUCTION

There are reports on the fabrication of injection photodiodes based on II–VI compounds, in particular, based on cadmium sulfide, cadmium telluride, and solid solutions between them [1–4]. Koldaev et al. [1] considered a Ni/ n -CdS/ n^+ -CdS structure based on CdS single crystals, which ensured photocurrent amplification under illumination with light at $\lambda = 0.22$ μ m and majority carrier injection into a high-resistivity n -region on the backside of the n^+ - n junction. No cadmium-sulfide-based internal-gain injection photodetector capable of operating at room temperature in a wide spectral range has been reported to date. Such an injection photodetector with improved output parameters can be produced using p - i - n structures. p -Type conduction and related p - i - n structures are difficult to achieve in II–VI compounds, in particular in CdS, because of the self-compensation effect. In a p - i - n structure with a heterojunction where the i -layer consists of a highly compensated, high-resistivity wide-band-gap semiconductor (n -CdS) and the p -type semiconductor is a narrow-band-gap material (p -Si). In such a structure, electrons can be injected from p -Si into n -CdS under reverse bias. In view of this, we have created a p -Si/ n -CdS/ n^+ -CdS heterojunction structure. In this structure, a high-resistivity, highly compensated n -type CdS layer serves as an i -layer. The choice of the p -Si/ n -CdS heterojunction was prompted by the fact that it had been described in the literature [5]. In addition, silicon is a well-studied material. This has led us to create a p - i - n structure with a p -Si/ n -CdS heterojunction based on cadmium sulfide films.

EXPERIMENTAL

A photosensitive p -Si/ n -CdS/ n^+ -CdS structure was grown by depositing semiconductor-grade CdS powders (in a quasi-closed system under a vacuum of 10^{-5} Torr) on the surface of a 300- μ m-thick p -type silicon wafer with a resistivity $\rho \approx 10$ Ω cm (KDB-10 boron-doped Si). The CdS source temperature was $T_{\text{source}} \approx 800$ – 850 °C, and the p -Si substrate temperature was maintained in the range $T_s \approx 250$ – 270 °C. Examination under an MII-4 optical microscope showed that the CdS films consisted of columnar crystallites (grains) aligned along the growth direction of the films and orientation-disordered in the azimuthal direction. The crystallite size was found to be highly dependent on process conditions, primarily on Si substrate temperature. For example, the CdS films grown at $T_s = 300$ °C had a crystallite size of ≈ 3 – 4 μ m, which exceeded the thickness of the films: $d \approx 2$ μ m. Thus, the CdS films had high resistivity, $\rho \sim (2$ – $3) \times 10^{10}$ Ω cm, and were n -type. A (heavily doped) n^+ -CdS layer was grown by depositing indium onto the surface of a CdS film under a vacuum of 10^{-5} Torr for 25–30 s at a substrate temperature of 373 K, followed by annealing at a temperature of 673 K for 5 min.

Next, a Π -shaped electrical contact to the film was made by vacuum evaporation of indium.

The current–voltage (I – V) characteristics of the p -Si/ n -CdS/ n^+ -CdS structures were measured at room temperature under forward and reverse bias in the dark and at an illuminance $E = 0.1$ – 50 lx. The structures were illuminated by the output of an LG-75 laser at a wavelength of 0.625 μ m and incident power densities from 0.75 to 10 μ W/cm² or by an incandes-

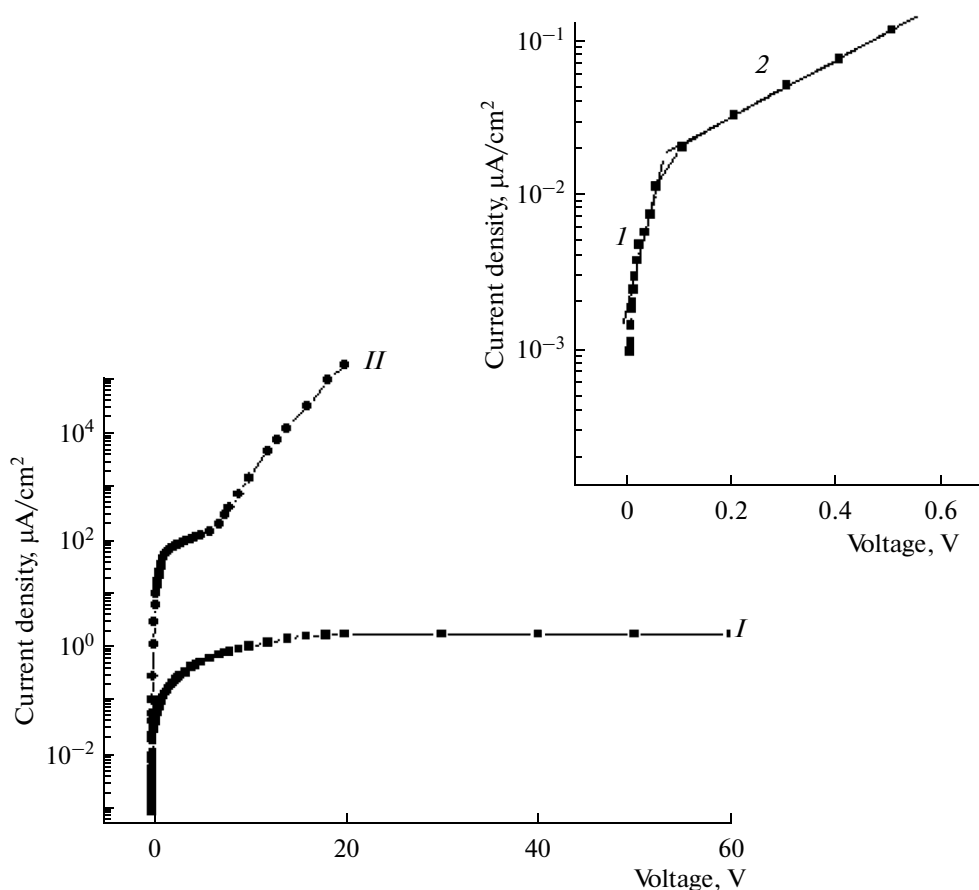


Fig. 1. Semilog dark current–voltage curves of a p -Si/ n -CdS/ n^+ -CdS structure: (I) forward bias, (II) reverse bias. Inset: (1) first and (2) second portions of the reverse I – V curve.

cent lamp whose parameters were similar to those of a standard lamp. One lumen corresponds to 9.1×10^{-3} W of power of electromagnetic radiation in the visible range [6]. The spectral dependence of the photosensitivity of the structures was measured at room temperature using a 3MR-3 monochromator. The light source used was a DKSSh-1000 xenon lamp operated at its lowest output power. The lamp ensured a luminous flux of 53×10^3 lm and brightness of up to 120 Mcd/m² in the spot center. The lamp was calibrated in absolute units using an RTE-9 thermoelectric element with a quartz window. The DKSSh-1000 has a continuous spectrum in the ultraviolet and visible regions. The capacitance–voltage (C – V) characteristic of such a structure was measured under forward and reverse bias at frequencies $f = 0.4$ – 50 kHz. Since C – V characteristics in this frequency range are similar in shape, we give only the one at $f = 10$ kHz.

RESULTS AND DISCUSSION

Figure 1 shows semilog current–voltage curves of a typical p -Si/ n -CdS/ n^+ -CdS structure under forward and reverse bias (with the p -Si contact positively and

negatively biased, respectively). Analysis of the I – V data demonstrates that the structure shows rectifying behavior, with a rectification ratio (defined as the ratio of the forward current to the reverse current at a constant bias voltage $V_b = 20$ V) $K \approx 10^5$.

Spectral distribution of photosensitivity. Figure 2 shows the spectral dependence of the relative photocurrent through the p -Si/ n -CdS/ n^+ -CdS structure under zero bias and at various reverse bias voltages. Curve 1 in Fig. 2 demonstrates that, at zero bias voltage, the spectral sensitivity range of the structure extends from $\lambda = 350$ to 1350 nm and its sensitivity has the highest values at $\lambda_1 \approx 480$ nm and $\lambda_2 \approx 1248$ nm, where the photocurrent is negative. With increasing wavelength, the photocurrent (I_{ph}) in the short-wavelength region of the spectrum decreases, down to zero at $\lambda \approx 865.45$ nm, changes sign, and rises as λ increases further. In the long-wavelength photosensitivity region, $I_{ph}/I_{ph\max}(\lambda)$ has a maximum at $\lambda \approx 949.5$ nm, where the photocurrent is positive. At longer wavelengths, $I_{ph}/I_{ph\max}(\lambda)$ decreases again and crosses zero at $\lambda \approx 1000$ nm. The photosensitivity then changes sign and sharply rises in magnitude at wavelengths of up to $\lambda \approx 1130$ nm. At still longer wavelengths, it decreases again. With increasing bias voltage, the zero crossing

point in the short-wavelength region of the spectrum shifts to far shorter wavelengths. The magnitude of the photocurrent decreases with increasing bias voltage. Similar behavior of $I_{\text{ph}}/I_{\text{ph,max}}(\lambda)$ is observed in the long-wavelength photosensitivity region, but here the zero crossing point shifts to longer wavelengths. Moreover, the magnitude of the photocurrent as a function of bias voltage varies much slower than in the short-wavelength region of the spectrum. For example, the zero crossing point shifts by ~ 260 nm at $V_b = 6$ mV, whereas in the long-wavelength region of the spectrum it shifts by 168 nm. According to the present experimental data, when a bias voltage of 8.5 mV is applied to the structure, the $I_{\text{ph}}/I_{\text{ph,max}}(\lambda)$ curve lies entirely in the region of negative photocurrent values. This behavior of $I_{\text{ph}}/I_{\text{ph,max}}(\lambda)$ for a reverse-biased $p\text{-Si}/n\text{-CdS}/n^+\text{-CdS}$ structure can be accounted for as follows: First, the $n^+\text{-CdS}/n\text{-CdS}$ junction and $p\text{-Si}/n\text{-CdS}$ heterojunction effectively separate photogenerated nonequilibrium electron–hole pairs. Second, the $p\text{-Si}/n\text{-CdS}$ heterojunction injects electrons into the $n\text{-CdS}$ base when a reverse bias voltage is applied to the structure. Third, the main component of the current through the structure under investigation is the diffusion current. In the $p\text{-Si}/n\text{-CdS}/n^+\text{-CdS}$ structure under consideration, electrons will be injected from the $p\text{-Si}$ layer into the high-resistivity, compensated $n\text{-CdS}$ layer if the electron concentration in the $p\text{-Si}$ layer is sufficiently high or if its thickness is comparable to the electron diffusion length. In our silicon samples, the equilibrium hole and electron concentrations are 1.3×10^{15} and $7.7 \times 10^4 \text{ cm}^{-3}$, respectively, with electron and hole mobilities $\mu_n = 1500 \text{ cm}^2/(\text{V s})$ and $\mu_p = 480 \text{ cm}^2/(\text{V s})$, respectively, and intrinsic carrier concentration $n_i = 10^{10} \text{ cm}^{-3}$. Therefore, the nonequilibrium electron concentration in the $p\text{-Si}$ substrate is comparable to the electron concentration ($n_0 \approx 10^5 \text{ cm}^{-3}$) in the base ($n\text{-CdS}$ layer), which was determined using the following values: $\rho_{\text{CdS}} \approx 3 \times 10^{10} \Omega \text{ cm}$ and $\mu_n = 100 \text{ cm}^2/(\text{V s})$. This resistivity was evaluated from the resistance of a CdS film of thickness $d = 2 \mu\text{m}$. In addition, one should take into account the possibility of electron injection from the Ohmic contact (In) to the $p\text{-Si}$, because the thickness of the silicon wafer is on the same order as the electron diffusion length (L_n), which is $\sim 400 \mu\text{m}$ at $\tau_n \approx 50 \mu\text{s}$ and $\mu_n = 1500 \text{ cm}^2/(\text{V s})$ [7].

The peak in the photosensitivity curve, with a maximum at $\lambda = 947$ nm, strongly suggests that the $p\text{-Si}/n\text{-CdS}$ heterojunction has high quality and that it has a low density of surface states on the interface. The space charge of the heterojunction effectively drives the nonequilibrium holes generated near the barrier to the $p\text{-Si}$ layer. The rise of the photocurrent peak and its broadening to shorter wavelengths when a bias voltage is applied indicates that the determining current through the base of the structure is the diffusion current of the minority carriers (holes) that accumulate at the $p\text{-Si}/n\text{-CdS}$ heterojunction and ensure electro-neutrality of the injected electrons. Our experiments

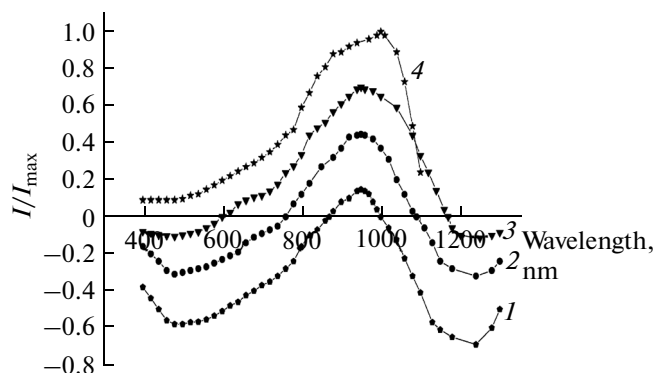


Fig. 2. Spectral dependence of the photocurrent through a $p\text{-Si}/n\text{-CdS}/n^+\text{-CdS}$ structure at various bias voltages: (1) photocurrent at zero bias voltage, (2) 4 mV, (3) 6 mV, (4) 8.5 mV.

demonstrate that, at $V_b = 8.5$ mV, the diffusion current exceeds the drift current even near the $n^+\text{CdS}/n\text{-CdS}$ homojunction (Fig. 2, curve 4). This, in turn, provides further evidence that the $p\text{-Si}/n\text{-CdS}$ heterojunction has insignificant leakage currents at low reverse bias voltages (up to several tens of millivolts). The diffusion current and the shift of the photosensitivity zero crossing point at low reverse bias voltages demonstrate that both the drift and diffusion currents are low.

Analysis of the spectral sensitivity of the long-wavelength peak indicates that the $p\text{-Si}$ substrate contains electrons injected from the Ohmic contact (In), which give rise to diffusion and drift electron flows toward the $p\text{-Si}/n\text{-CdS}$ heterojunction. Moreover, there are diffusion flows of nonequilibrium electrons from the heterojunction to the metallic contact, which result from electron accumulation near the heterojunction. The shift of the photocurrent zero crossing point in the long-wavelength region of the spectrum to longer wavelengths indicates that the diffusion current opposite to the drift and diffusion electron currents from the metallic contact increases with increasing bias voltage [8, 9]. This occurs when the electron concentration and its gradient near the heterojunction exceed the electron concentration near the metallic contact (In). This effect takes place when the $p\text{-Si}/n\text{-CdS}$ heterojunction has a potential barrier and not all of the electrons coming from the opposite indium contact pass through it. The shift of the long-wavelength region of the spectrum at $V_b = 8.5$ mV is smaller than at $V_b = 6$ mV (Fig. 2, curve 4). This indicates that the $p\text{-Si}/n\text{-CdS}$ heterojunction becomes transparent for electrons; that is, the electron accumulation process decreases because of the changes in the properties of the heterojunction.

It is well known that the injection and accumulation properties of barriers determine the shape of current–voltage characteristics of the structure. For this reason, we investigated the current–voltage characteristic of the structure, which is presented in Fig. 1 as a semilog plot. Analysis of the current–voltage charac-

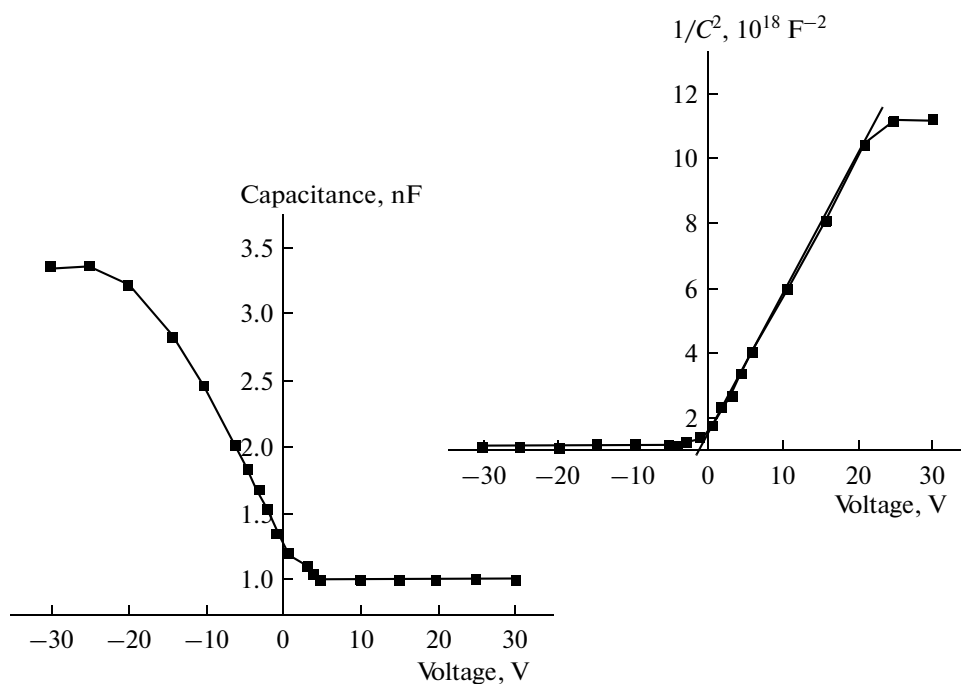


Fig. 3. Capacitance–voltage curve of the p -Si/ n -CdS/ n^+ -CdS structure at a frequency $f = 10$ kHz and $T = 300$ K. Inset: C^{-2} as a function of voltage for this structure at a frequency $f = 10$ kHz and $T = 300$ K.

teristic of the p -Si/ n -CdS/ n^+ -CdS structure indicates that it decreases exponentially with decreasing reverse bias voltage and plateaus at $V \approx -16$ V. This demonstrates that the structure behaves as an ideal diode structure. This behavior of the I – V characteristic is somewhat doubtful because the base in the structure under investigation is a high-resistivity, highly compensated polycrystalline semiconductor containing high concentrations of impurities and defects. In view of this, to clarify the situation we examined the capacitance–voltage characteristic of the structure in Fig. 3. As seen in Fig. 3, the capacitance–voltage characteristic corresponds to a metal–insulator–semiconductor (MIS) structure [10]. In the p -Si/ n -CdS/ n^+ -CdS (MIS) structure under investigation, the role of the insulator is played by the n -CdS layer, the CdO_x and SO_x oxide layers on its surface, and the SiO_x on the p -Si surface, which were formed during cadmium sulfide film growth. From the capacitance of the insulator, $C_i = 3.36$ nF, we determined its thickness, $d_i \approx 0.065$ μm , at an active area of the structure $S \approx 0.1$ cm^2 . It can be seen that the calculated thickness of the insulator differs from the thickness of the high-resistivity base (n -CdS), which is ≈ 2 μm . The difference can be accounted for by the fact that as the insulator in this structure we use oxide layers of thickness d_i much smaller than that of the n -CdS layer. These results reflect the actual design of the structure under investigation. From the minimum capacitance of the structure, $C_{\min} \approx 1$ nF (Fig. 3), we evaluated the space charge thickness, $W \approx 0.073$ μm [10], which is considerably smaller than the thickness of the p -Si

semiconductor (300 μm) and that of the n -CdS layer. This experimental finding demonstrates that the p -Si and n -CdS layers are in a quasi-neutral state. From the steep portion of the capacitance–voltage characteristic plotted as C^{-2} against V and from the flat-band capacitance [10, 11], the hole concentration in p -Si was determined to be $\approx 3 \times 10^{15}$ cm^{-3} , in good agreement with the equilibrium hole concentration in p -type silicon. Moreover, we determined the potential barrier height, $V_D \approx 0.89 \pm 0.02$ eV, by extrapolating the $C^{-2}(V)$ data to the voltage axis. Therefore, when the structure under investigation behaves as an MIS structure, p -Si plays the role of the semiconductor in it. The present C – V data and the spectral distribution of photosensitivity attest to electron injection from the indium contact to the p -Si and then to the base of the structure.

For convenience of analysis, the inset in Fig. 1 presents the reverse I – V curve of the structure at positive currents. Analysis indicates that, at current densities in the range $I \approx 1.3 \times 10^{-9}$ to 1.1×10^{-8} A/ cm^2 , there are thermionic currents through the structure. A thermionic current can be represented by the following formulas [12]:

$$I = AT^2 e^{-\frac{V_D}{kT}} \left(e^{\frac{eV}{kT}} - 1 \right) = I_{01} \left(e^{\frac{eV}{kT}} - 1 \right), \quad (1)$$

$$I_{01} = AT^2 e^{-\frac{V_D}{kT}}, \quad (2)$$

where A is the Richardson constant, $A = 12 \times 10^5$ A/(m^2 K²); V_D is the potential barrier height; V is

the bias voltage; T is the absolute temperature; k is Boltzmann's constant; and c is an exponent.

Using the experimentally determined preexponential factor $I_{01} = 2.9 \times 10^{-9}$ A/cm² for the current density corresponding to the onset of the exponential portion with an exponent $c \approx 1.05$, evaluated using relation (2), the potential barrier height was determined to be $V_D = 0.91 \pm 0.02$ eV, in good agreement with the $V_D \approx 0.89 \pm 0.02$ eV evaluated from the above $C(V)$ data.

At current densities in the range $I \approx 1.3 \times 10^{-8}$ to 2.2×10^{-7} A/cm², the I - V characteristic can be represented by the exponential relation $I = I_{02} \exp(qV/c_2kT)$ with an exponent $c_2 = 8.2$ and preexponential factor $I_{02} = 1.8 \times 10^{-8}$ A/cm². According to theory [13], in structures with a significant resistance of their base there is a diffusion current, which can be represented by the following analytical relation:

$$I = I_{02} \exp(qV/c_2kT), \quad (3)$$

where

$$c_2 = (2b + \cosh w/L + 1)/(b + 1). \quad (4)$$

Here, $b = \mu_n/\mu_p$ is the ratio of the electron and hole mobilities, w is the thickness of the base, k is Boltzmann's constant, and T is the absolute temperature.

Substituting the experimentally determined value $c_2 = 8.2$ (evaluated from the second portion of the I - V characteristic) in Eq. (4), we find the hole diffusion length $L_p = 0.45$ μm and $\mu_p\tau_p = 7.8 \times 10^{-8}$ cm²/V (the product of the hole mobility and lifetime), with $b = 38$ [14], $w = 2$ μm , $\mu_n = 285$ cm²/(V s), and $\mu_p = 7$ - 8 cm²/(V s). Since I_{02} is roughly equal to the current at which the conductance of the base region is increased by injection by a factor of 2; that is, the equilibrium and nonequilibrium bulk conductances of the base become equal, and a transition to high injection levels occurs. Assuming that $I_{02} = 1.8 \times 10^{-8}$ A/cm² corresponds to the initial voltage (0.1 V) in the second portion of the I - V characteristic, we find that the resistivity of the base is $\rho = 2.6 \times 10^{10}$ Ω cm, in good agreement with the resistivity of the n -CdS film: 3×10^{10} Ω cm. Electron injection is also evidenced by another estimate, with the use of the product $\mu_p\tau_p = 7.8 \times 10^{-8}$ cm²/V. To this end, we obtained relaxation curves at zero bias voltage. From the rise and falloff of the curves, the corresponding relaxation time constants were determined to be $\tau = 7 \times 10^{-8}$ s and $\tau = 1.2 \times 10^{-7}$ s, respectively. Further, assuming these values to be the hole lifetimes, we obtain from the $\mu_p\tau_p$ product $\mu_p = 1.1$ cm²/(V s) and $\mu_p = 0.78$ cm²/(V s), respectively. Thus, the hole mobilities found here agree well with data in the literature [14] given that the base in the structure under investigation consists of polycrystalline material. The above estimates suggest that, at the current densities in question, the hole accumulation process near the n^+ -CdS/ n -CdS junction is insignificant.

Further increasing the bias voltage (V_b) changes the properties of the p -Si/ n -CdS heterojunction, which becomes nonideal and begins to transmit holes toward

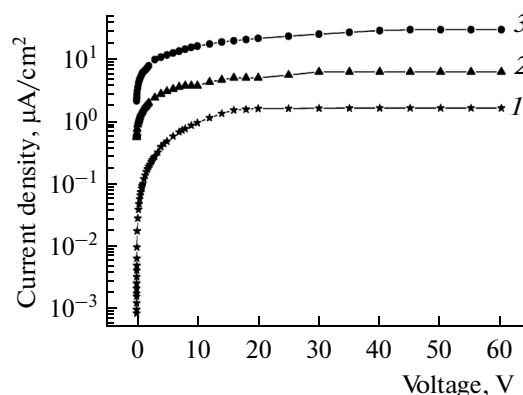


Fig. 4. Semilog reverse current-voltage characteristics of the p -Si/ n -CdS/ n^+ -CdS structure: (1) in the dark, (2) under illumination with white light at $E = 0.1$ lx, (3) under laser irradiation at $\lambda = 0.625$ μm and an incident power density $P = 10$ $\mu\text{W}/\text{cm}^2$.

the silicon. At the same time, the n^+ -CdS/ n -CdS homojunction remains almost ideal, and the potential barrier V_b to holes in it increases with increasing reverse bias voltage. Because of this, the nonequilibrium hole concentration near the homojunction increases, and the hole concentration gradient here is higher than near the heterojunction. This produces hole diffusion flows toward the p -Si/ n -CdS heterojunction. The drift and diffusion flows are opposite to the diffusion flows from the heterojunction. As first shown by Adirovich et al. [8], the opposite diffusion and drift currents lead to "injection depletion;" that is, their mutual compensation occurs. The sublinear current-voltage behavior in a wide range of bias voltages ($V \approx 10$ - 60 V) indicates that the region of mutual compensation of the drift and diffusion flows becomes broader and that the resistance of the base and the electric field strength in the base increase, thereby increasing the ambipolar drift velocity. It was of interest to analyze the behavior of the sublinear portion of the I - V characteristic under illumination with white light and under below-band-gap laser excitation. We obtained I - V characteristics under illumination at $E = 0.1$ lx and under laser irradiation at $\lambda = 0.625$ μm and an incident power density $P = 10$ $\mu\text{W}/\text{cm}^2$. The results are presented in Fig. 4. It follows from these data that the I - V curves obtained in the dark and under illumination are similar in shape and differ only in the magnitude of the current. The difference in current is ~ 1.5 orders of magnitude under laser irradiation and more than one order of magnitude under illumination with white light. Under laser irradiation, the spectral sensitivity is $S_\lambda \approx 7$ A/W. Under illumination with white light at an illuminance $E = 0.1$ lx, the integrated sensitivity is $S_{\text{int}} \approx 3.5$ A/lm (~ 380 A/W). These results demonstrate that, in the sublinear region, the primary photocurrent increases in magnitude. The increase is tens of times greater than the photosensitiv-

ity of an ideal photodetector at a given wavelength, for example, at $\lambda = 0.625 \mu\text{m}$ ($S_\lambda \approx 0.5 \text{ A/W}$) [15]. We also assessed the effect of illuminance on the ambipolar carrier drift velocity (v_a). To this end, using the formula [9]

$$V = V_0 \exp(aIw), \quad (5)$$

we determined the parameter a as a function of illuminance. We obtained the same value of a under illumination with white light, under laser irradiation, and in the dark. It is known that the minority carrier ambipolar drift velocity is given by [9]

$$v_a = D_p I a, \quad (6)$$

where it is a linear function of current density. Therefore, the increase in photocurrent is proportional to the increase in v_a . In our instance, the photocurrent increases by about 1.5 orders of magnitude and, hence, we obtain $v_a \approx 300 \text{ cm/s}$.

The above-mentioned increase in the resistance of the base of the structure in a wide range of bias voltages can be used in designing semiconductor devices for a variety of applications (rectifiers with a large rectification ratio, Zener diodes, and others).

CONCLUSIONS

We have demonstrated a photosensitive $p\text{-Si}/n\text{-CdS}/n^+\text{-CdS}$ structure. A reverse bias voltage applied to this structure leads to electron injection from the narrow-band-gap material $p\text{-Si}$ to the high-resistivity, wide-band-gap semiconductor $n\text{-CdS}$. At current densities in the range $I \sim 10^{-8}$ to 10^{-7} A/cm^2 , the photosensitivity of the structure changes sign in both the short- and long-wavelength regions of the spectrum. With increasing bias voltage, the photosensitivity zero crossing point in the short-wavelength region shifts to shorter wavelengths, whereas the zero crossing point in the long-wavelength region of the spectrum shifts to longer wavelengths. Mutual compensation of opposite drift and diffusion flows of nonequilibrium charge carriers at current densities on the order of $\sim 10^{-6} \text{ A/cm}^2$ leads to sublinear behavior of the reverse $I-V$ characteristic in a wide range of bias voltages. Increasing the bias voltage increases the height of the potential barrier to holes near the frontal $n^+\text{-CdS}/n\text{-CdS}$ homojunction, favoring hole accumulation at the homojunction.

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