Obtaining new types of compounds between silicon and cadmium sulfide

I. B. Sapaev[1, 2*]

[1]"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan
[2]Akfa University, Tashkent, Uzbekistan

Abstract. The n^+CdS-nCdS-nSi$^+$ structures were obtained, and their volt-ampere characteristics at different temperatures were studied. The dependence of the volt-ampere characteristic shows that the sublinear and quadratic section of these structures has a section of current growth with voltage. It is determined that the n^+CdS-nCdS-nSi$^+$structures in the current flow direction at low illumination levels work as an injection photodiode. And these structures under laser illumination with λ=0.625 μm and power P=1.2 μW/cm^2 have spectral sensitivity 2042 A/W, bias voltage 10 V. At irradiation by white light with energy W=3.6-10μW·s it has integral sensitivity ≈21 A/I'm (2310 A/W) at bias voltage U=10V.

1 Introduction

Currently, there is a great demand for semiconductor sensors in the field of mechanical engineering and optoelectronics. And the basis of semiconductor sensors consists of semiconductor elements and connections between these elements. Based on these elements, different types of transitions are obtained [1, 2]. Mainly transitions are obtained to improve the parameters of semiconductor elements. We had such a task that the obtained structures had great spectral and integral sensitivity, and these structures, absorb electromagnetic radiation from violet to infrared. Such a structure can be obtained between two compounds, as in the works [3, 4]. But the spectral and integral sensitivities were not so great in these structures. And we used Si and CdSfor this purpose.

2 Methods

This paper presents the results of studies of n^+CdS-nCdS-nSi structures. Such heterostructures were created by sputtering CdSpowders in a quasi-closed system in a vacuum 10^{-5} torron the surface of an n-type silicon wafer with ρ≈15 Om·cmand a 300-400 μm thickness. These studies with the MII-4 microscope show that the CdSfilms consist of columnar crystallites (grains), which are ≈ 3·5 μm in size and completely cover the entire film thickness of ≈2 μm. A heavily doped n^+CdSlayer with a thickness of 500 Å was formed by vacuum deposition of indium (In) atoms on the surface of the CdSfilm.

*Corresponding author: sapaevibrokhim@gmail.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

 https://doi.org/10.1051/e3sconf/202340103076

It is known that CdSof hexagonal modification (α_{CdS}=5.84Å) and Si (α_{Si}=5.43Å) have lattice constants α differ by almost 7%, and to create a heterojunction with low density of surface states, their difference should not exceed 4% [5]. However, the above experimental facts indicate that there are low surface state densities at the interface of contacting semiconductor materials. Therefore, it is assumed that during the formation of the structure, an intermediate layer between CdSand Si is formed, which contributes to smooth the difference between the crystal lattice constants of silicon and cadmium sulfide. To prove this assumption, the distribution of chemical elements over the thickness of the film was investigated by chipping. The measurement was carried out on the microanalytical complex Jeol- JXA - 8900 with the help of EDS LINK ISIS (energy dispersion spectrometer); the error of measurements was ±2.0% (Fig. 1). Measurement conditions: V=20 kV, I=10 nA. Standards: native Cd, and Si, for S - synthetic FeS. The measurement results and microphotographs show that Cd, S, and Si elements at the interface decrease sharply to almost zero at a distance of ≈ 1μm across the film thickness. It follows that there is a solid solution between CdSand Si with a thickness of the order of one micrometer. Determination of the components of this solid solution is the object of further research.

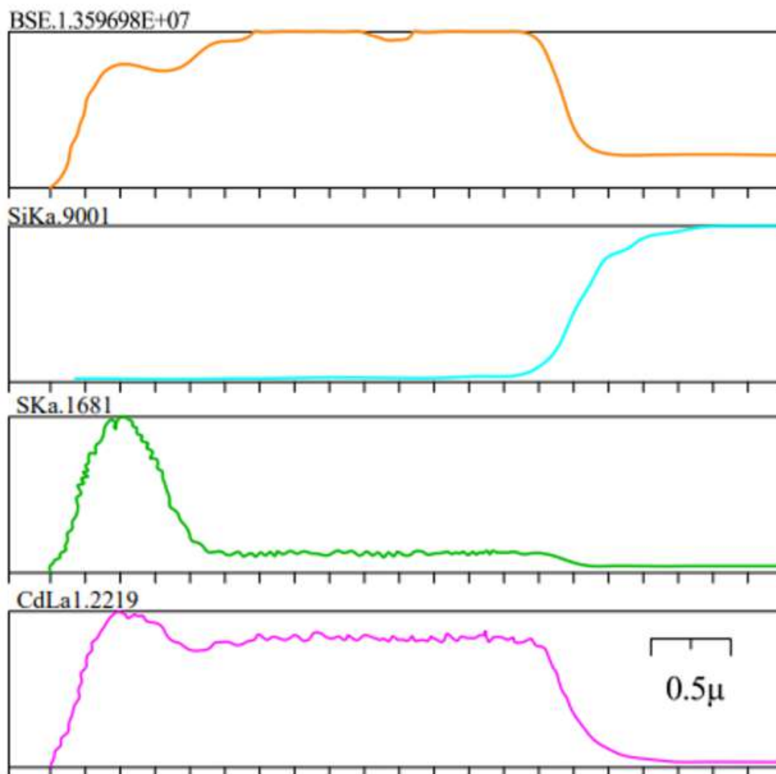

Fig. 1. Distribution of Cd, S, and Si element content at nCdS- nSiinterface of the heterojunction obtained on a Jeol- JXA - 8900 micro analytical complex.

Based on a cadmium sulfide, n^+CdS-nCdS-nSiheterostructures with the thickness of the base n-layer W = 2 μm were fabricated. In the study of the structure by vacuum deposition, contacts were created - solid on the back side and "P" shaped with an area of 3 mm^2 from indium on the surface of CdS.

3 Results and discussion

The volt-ampere characteristics (VAX) of the obtained structures in the forward direction, shown in Fig. 2a,b in semi-logarithmic scale, were studied. Measurements were carried out in the temperature range of 20 - 120C^0. The initial section of the VAX (up to 0.4 V) is well approximated by the well-known Stafeev dependence [6]:

$$I = I_0 \cdot e^{\frac{qV}{ckT}} \tag{1}$$

Where the exponent "c", calculated from the CVC, has values c ≈ 12.6, typical for the so-called "long diode," i.e., W/L_p> 1, where W-is the base length, $L_p = \sqrt{D_p T_p}$ is the diffusion length of non-base carriers. According to the theory of V.I. Stafeev, the exponent exponent "c" is described by the expression:

$$c = \frac{2b + ch(\frac{W}{L}) + 1}{b + 1} \tag{2}$$

where is the $b = \frac{\mu_n}{\mu_p}$ ratio of electron and hole mobility.

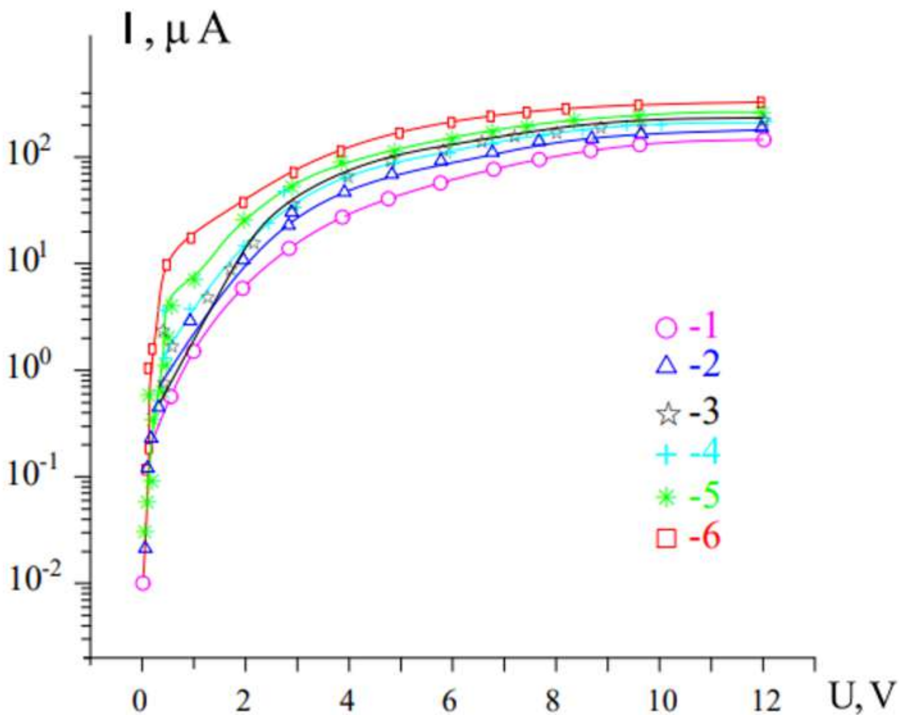

Fig. 2a. Volt-ampere characteristic of In-nCdS$^+$ - nCdS- nSi-In structure at different temperatures T. ^{0}C: 1 - 20, 2 - 40, 3 - 60, 4 - 80, 5 - 100, 6 - 120.

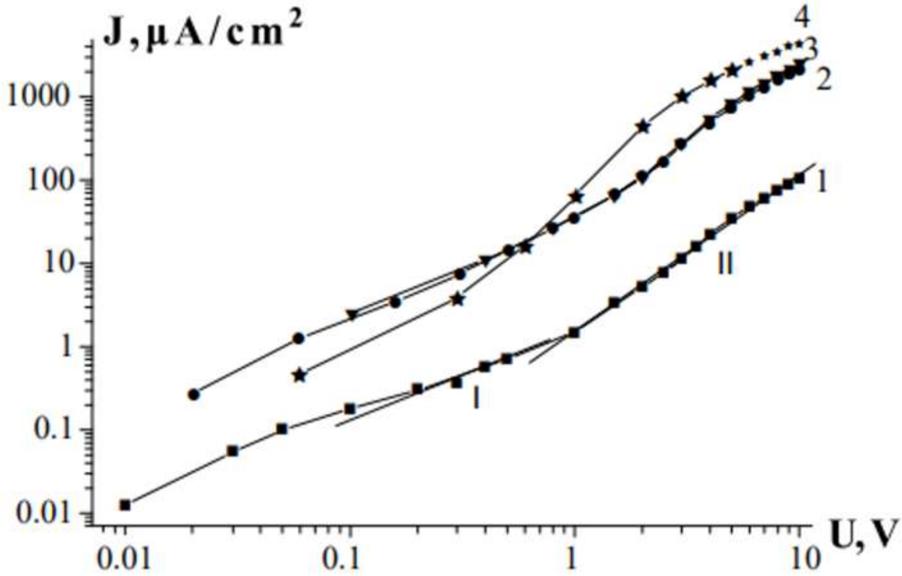

Fig. 2b. Volt-ampere characteristic of In-n$^+$CdS- nCdS- nSi-In structure in double logarithmic scale: direct branch in darkness (1), which is described by dependences I~V (I), I~ V^2 (II); direct branch during white light irradiation with E = 3- 10^{-2}lux (2), direct branch during laser irradiation with λ = 0.625 nm power P = 1.2 μW/cm^2 (3), the direct branch at laser irradiation with λ = 0.625 nm with power P = 0.75 mW/cm^2 (4)

The mobility of the basic carriers, determined by the Hall method, was at room temperature μ_n = 286 cm/^{2}(V·s). Assuming that, as usual, in $A^{II}B^{VI}$ group materials, hole mobility is much less than electron mobility [7], for the evaluation, we took the value μ_p = 8 cm/^{2}(V·s). In this case b = 36, from relation (2), we can find the ratio W/L_p ≈ 6.7, which really turns out to be greater than 1. Then we can find the diffusion length of non-base carriers. This allows us to determine the product of mobility on the lifetime of the non-basic carriers $\mu\tau_{pp}$[8].

$$\mu_P \tau_P = \frac{qL_P^2}{kT} \quad (3)$$

The values of these parameters calculated at different temperatures are shown in Table I. At room temperature, the product of $\mu\tau_{pp}$ has values ~3.6-10 $^{-8}$cm/V.^{2} Table I shows that in the temperature range of 293-403 K, the diffusion length of non-base carriers weakly depends on the temperature. Table 1. Dependences of exponent (c) (equation 1), pre-exponential multiplier (I_0) (equation 1), and hole diffusion length (L_p) (equation2) on temperature

Table 1. Characteristic parameters of the n$^+$ - n structure from temperature

T, K	293	313	333	353	373	393
c	12.6	13.9	15.6	17	16.2	15.7
I_0, 10^{-8} A	1.31	2.31	2.9	3.3	3.8	4.2
L_P, μm	0.3	0.294	0.289	0.285	0.287	0.289

Fig. 3 shows the dependence of the product $\mu\tau_{pp}$ on temperature. As can be seen from this

figure, the value of $\mu\tau_{pp}$decreases with increasing temperature, which is associated with the scattering of nonequilibrium carriers on the thermal vibrations of the lattice, and this leads to a decrease in the mobility of nonessential carriers.

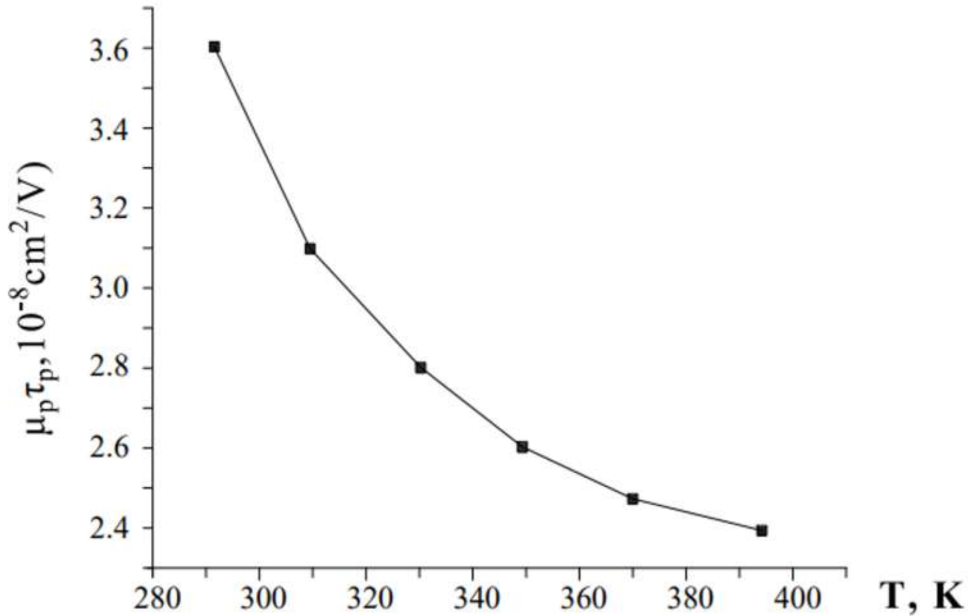

Fig. 3. Dependence of mobility product (μ_P) on lifetime (τ_P) of nonessential carriers - holes of n^+ - n structure on temperature.

The pre-exponential multiplier I_0 in formula (1) has the form [9]:

$$I_0 = \frac{kT}{q} \cdot \frac{S \cdot b \cdot ch(\frac{W}{L_P})}{2(b+1) \cdot L_P \cdot \rho \cdot tg(\frac{W}{L_P})} \tag{4}$$

where S is the sample area, ρ is the transition layer n^+- n transition resistivity. The values of I_0 determined from the experimental points of the VAX curves are given in Table I. Using equation (4) and the data in Table I, the resistivity ρ was calculated as a function of temperature. It can be seen that a strongly compensated high resistivity layer is formed between the substrate and the film from a solid solution between Si and CdSwith ρ = 1.5-10^8Om·cmat room temperature. Fig. 4 shows that the resistivity of the layer decreases with increasing temperature due to the thermal generation of charge carriers in it.

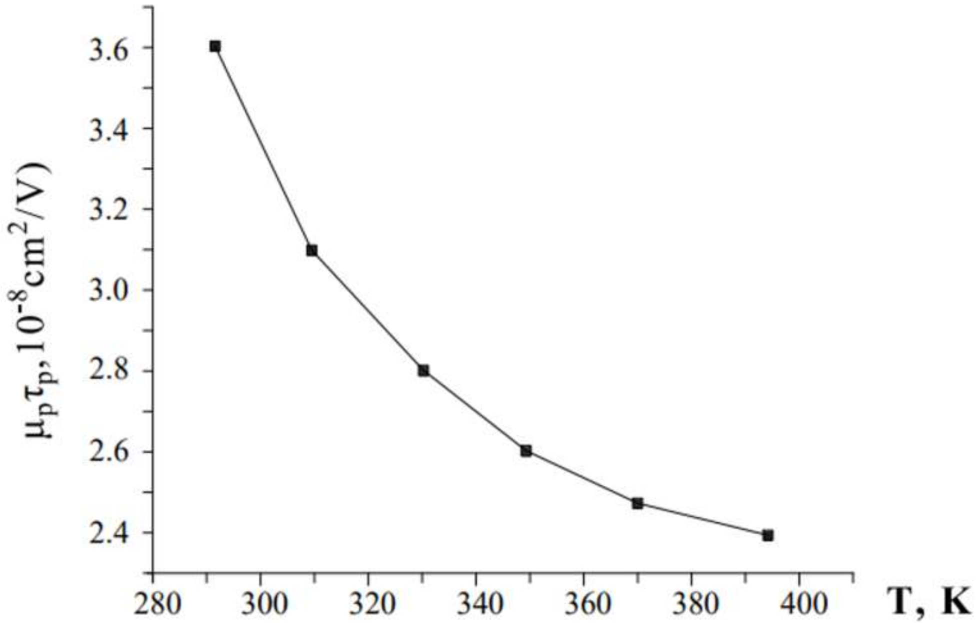

Fig. 4. Dependence of the resistivity of the high-resistance transition layer of the substrate-film n^+ - n structure on the temperature.

From the VAX shown in Fig. 2a, following the usual exponential dependence, extended sublinear sections (in the range from V > 0.4 to 2 V) appear on all VAX, regardless of temperature. These sections of the curves can be well described within the framework of the theory of the so-called "injection depletion effect," which was first predicted theoretically in [10]. In the cases of this effect, the VAXhas a very specific character and is described by a law of the form:

$$V \approx V_0 e^{JaW}, \tag{5}$$

Where:

$$a = \frac{1}{2qD_P N} \tag{6}$$

α- is a parameter that depends only on the diffusion coefficient of non-base carriers (i.e., their mobility, $D_p = (kT/q)\ \mu_p$) and the concentration of deep impurities N, J is the current density. One of the most important conditions for observing the sublinear section of the VAX (5) is the requirement

$$JaW > 2 \tag{6}$$

which is freely performed at all temperatures (e.g., at T = 20C^0, S = 0.8 cm^2, $JaW \approx 3.5$).

Theoretically, the appearance of such a VAX is possible only when the directions of am bipolar diffusion of no equilibrium carriers and their am bipolar drift, which in this case is determined by the injection modulation of the deep impurity charge [11,12] Using expression (5), we can determine the parameter directly a from the VAXdata:

$$a = \frac{\ln(\frac{V_2}{V_1}) \cdot S}{(I_2 - I_1) \cdot W}, \tag{7}$$

where S is the cross-sectional area, and I is the current strength. The values of parameter "a" found from the ERA at different temperatures are shown in Table II. As noted above, the values of the value a allows to determine the concentration of deep impurities N_t, responsible for the appearance of a sublinear section of the VAX, which is at room temperature $N_t \approx 3.4 \cdot 10^9 cm^{-3}$. Using data in Table II and according to formulas, we can $\mu_P \cdot N_t = \frac{1}{2kaT}$ find the dependence of the product of mobility of unground carriers n^+ - n of the heterostructure on the concentration of deep impurities ($\mu \cdot N_{pt}$) on temperature (Fig. 5). Fig. 5 shows that in the temperature range 293-393 K, the μ-N_{pt} value decreases with increasing temperature. This allows us to conclude that the scattering of carriers on ionized impurities plays a major role in the mobility mechanism in the VAX.

Table 2. Values of parameter as a function of temperature

T, K	293	313	333	353	373	393
a, 10^9 cm/A	4.6	4.66	4.64	4.62	4.8	5

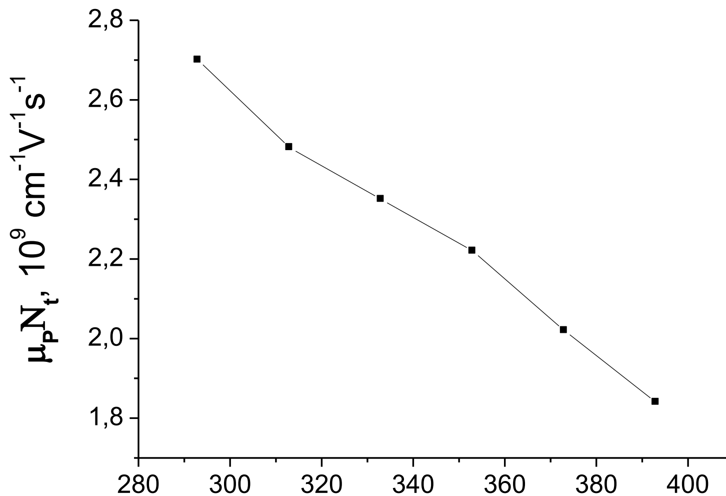

Fig. 5. Dependence of product of mobility (μ_P) of nonessential carriers - holes of the n^+ - n structure on concentration of deep impurities (N_t) on temperature.

Table 3. Dependencies of photocurrent (I_f), integral sensitivity (S_{int}), spectral sensitivity (S_λ) on illumination (E_{lux}), laser irradiation power (P), and bias voltage (U).

White Light $E = 3 \cdot 10^{-2}$ lux				Laser irradiation $W = 0.75 \frac{mW}{cm^2}$		Laser irradiation $W = 1.2 \frac{\mu W}{cm^2}$	
U, V	$I_f, \frac{\mu A}{cm^2}$	$S_I, \frac{A}{lm}$	$S_I, \frac{A}{W}$	$I_f, \frac{\mu A}{cm^2}$	$S_I, \frac{A}{W}$	$I_f, \frac{\mu A}{cm^2}$	$S_I, \frac{A}{W}$
2	105	1.05	115.5	500	0.67	100	83
3	255	2.55	280.5	1000	1.3	260	217
4	490	4.9	539	1600	2.1	530	442
5	712	7.12	783.2	2260	2.9	790	658
6	1025	10.25	1127.5	2750	3.7	1115	926
7	1265	12.65	1391.5	3200	4.3	1450	1208
8	1575	15.75	1732.5	3700	4.9	1875	1562
9	1810	18.10	1991	4000	5.3	2080	1733
10	2100	21	2310	4500	6	2450	2042

As the level of injection of electrons and holes grows, their average lifetime may depend on the level of plasma injection, and the current from the voltage is described by the dependence $I \sim V^2$, which is observed in the experiment (see Fig.2b, dash 1) [13]. The light VAXmeasured at laser irradiation (Fig.2b, cr.2) also has two sections, and they are almost parallel to the corresponding sections of the dark voltammetry characteristic. These experimental data show that the mechanism of current flow in the dark and the light is the same, and they only differ in the current value. According to [14], the features of bipolar drift of no equilibrium carriers in the n-base thickness are crucial when the structures work in the drift double injection mode, and the contribution of the injecting and accumulating contacts to this process is insignificant. In [15], based on the long-base diode model [16], the mechanism of photoelectric injection current amplification was theoretically analyzed. It is shown that when the base conductivity is determined by the injected carriers from the contacts, the current amplification is determined by the mobility modulation (μ) under the action of "impurity" illumination. This also follows from the analytical expression for bipolar drift mobility [15], where the numerator is the value depending on the concentration difference of the charge carriers. "Impurity" illumination, in which carriers of the same sign are generated, changes this difference, thus modulating the parameter μ; this process strongly affects the concentration of the charge carriers injected from the contacts. In addition, it should be noted that bipolar mobility is determined essentially by a small change in the filling of the capture centers, associated with small changes in the concentration of free carriers. This process is not at all obscured by large values of the very concentrations of electrons (n) and holes (p) [6,15]. This circumstance can explain such high experimental values of spectral sensitivity at irradiation by laser (with λ=625 nm) light of very low power P = 1,2μW/cm ^{2}, 0 .75mW/cm^2 (see Fig.2b). As shown in Table I, the n^+CdS- nCdS- nSi-structure under study has the highest spectral sensitivity $S_\lambda \approx$2042A/W. Note that cadmium sulfide's laser irradiation (λ=0.625 m) is an impurity irradiation. Moreover, the investigated structure is very sensitive to small light signals. This is strongly manifested; it has an integral sensitivity of 2310 A/W when irradiated with white light with 3-10lux^{-2} illuminance. The given experiment shows that as the laser irradiation power decreases, the value of spectral sensitivity (S_λ) increases. It follows that this light energy value is sufficient for the modulation of bipolar mobility.

4 Conclusions

This, a diode in (n^+CdS)-nCdS- nSi-structure with W/L ≥1, in which the direct branch of the ILC is described by the power dependences I ~ V and I ~ V^2, is created based on a strongly compensated polycrystalline CdSfilm withρ≈- 1.510^8Om·cm. In this structure, the flowing currents are determined by am bipolar and bipolar drift of charge carriers. Such a diode structure in the current flowing direction works as an injection photodiode and has a spectral sensitivity S_λ ≈ 2042A/W when irradiated with a laser power P=1.2 μW/cm^2 (λ=0.625 μm) and V=10V.

References

1. Sh. A. Mirsagatov, R. R. Kabulov, and M. A. Makhmudov, Semiconductors, **47**, 825 (2013).
2. Sh. A. Mirsagatov, O. K. Ataboev, and B. N. Zaveryukhin, Fiz. Inzhen. Poverkhn. **11** (1), 4 (2013).
3. A. S. Saidov, A. Yu. Leiderman, Sh. N. Usmonov, and K. T. Kholikov. I-V Characteristic of p-n Structures Based on a Continuous Solid Solution $(Si_2)_{1-x}(CdS)_x$. Semiconductors. **43** (4). 416 (2009).
4. A. S. Saidova, Sh. N. Usmonova, K. A. Amonova, Sh. Niyazovb and A. I. Khudayberdiyevac. Photothermovoltaic Effect in p-Si-n-$(Si_2)_{1-x-y}(Ge_2)_x(ZnSe)_y$Structure. Applied Solar Energy.2019 Vol. 55. No. 5. pp. 265-268.
5. A. G. Milnes and D. L. Feucht. Heterojunctions and Metal Semiconductor Junctions (Academic, London, 1972; Mir, Moscow, 1975).
6. I. M. Vikulin, Sh. D. Kurmashev, and V. I. Stafeev, Semiconductors 42, 112 (2008).
7. V. I. Fistul', Physics and Chemistry of the Solid State (Metallurgiya, Moscow, 1995), Vols. 1, 2 [in Russian].
8. K. Takahashi, S. Yamada, R. Nakazono, Y. Minagawa, T. Matsuda, T. Unno, S. Kuma. Improvement of life time of minority carriers in GaAs epilayer grown on Ge substrate // Solar Energy Materials and Solar cells. V. 50, Issues 1-4 January 1998, P. 273-280.
9. Sh. A. Mirsagatov, A. K. Uteniyazov, and A. S. Achilov, Phys. Solid State 54 (9), 1751 (2012).
10. A. Yu. Leiderman, P. M. Karageorgy-Alkalaev. Sol. St. Commun.,27 , 339 (1976)
11. E. I. Adirovich, P. M. Karageorgii - Alkalaev and A. Yu. Leiderman. Double Injection Currents in Semiconductors (SovetskoeRadio, Moscow, 1978) [in Russian].
12. Sh. A. Mirsagatov and A. K. Uteniyazov, Tech. Phys. Lett. 38 (1), 34 (2012).
13. A. M. Lampert and P. Mark, Current Injection in Solids (Academic, New York, 1970).
14. P.M. Karageorgii- Alkalaev and A. Yu. Leiderman. Photosensitivity of Semiconductor Structures with Deep Impurities (Fan, Tashkent, 1981) [in Russian].
15. V. I. Stafeev and V. M. Tuchkevich, in Reports of the 19th Annual Conference on Physics of Electronics, Mas sachusetts Institute of Technology, Cambridge, Massachusetts, United States, 1959), vol. 1, p. 139.
16. V. V. Osipov and V. I. Stafeev, Sov. Phys. Semicond. 1 (12), 1486 (1967).