E3S Web of Conferences **413**, 04010 (2023) https://doi.org/10.1051/e3sconf/202341304010
*INTERAGROMASH 2023*

# Obtaining new types of compounds between silicon and cadmium sulfide

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**Abstract.** The n+CdS-nCdS-nSi+ structures were obtained and their volt-ampere characteristics at different temperatures were studied. From the dependence of the volt-ampere characteristic it is shown 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/cm2 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. On the basis of 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, as well as, these structures absorb electromagnetic radiation from violet to infrared. Such a structure can be obtained on the basis between two compounds as in the works [3,4]. But in these structures the spectral and integral sensitivities were not so great. And we used Si and CdS for 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 vacuum $10^{-5}$ torron the surface of an n-type silicon wafer with ρ≈15 Om·cmand a thickness of 300-400 μm. 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 in the order of 500 Å was formed by vacuum deposition of indium(In) atoms on the surface of the CdSfilm.

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It is known that CdSof hexagonal modification ($\alpha_{CdS}$=5.84Å) and Si ($\alpha_{Si}$=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 smoothing the difference between the crystal lattice constants of silicon and cadmium sulfide. In order 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).

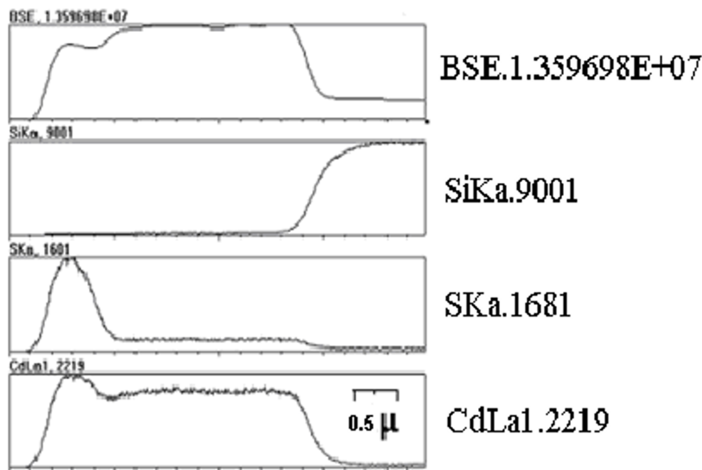


**Fig.1**. Distribution of the Cd, S and Si element content at the nCdS- nSiinterface of the heterojunction obtained on a Jeol- JXA - 8900 micro analytical complex

Measurement conditions: V=20 kV, I=10 nA. Standards: native Cd, and Si, for S - synthetic FeS. The measurement results and microphotographs show that the elements of Cd, S, and Si 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.

Based on cadmium sulfide, $n^+$CdS-nCdS-nSi heterostructures 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 in semi-logarithmic scale, were studied. Measurements were carried out in the temperature range 20 - 120$C^0$.

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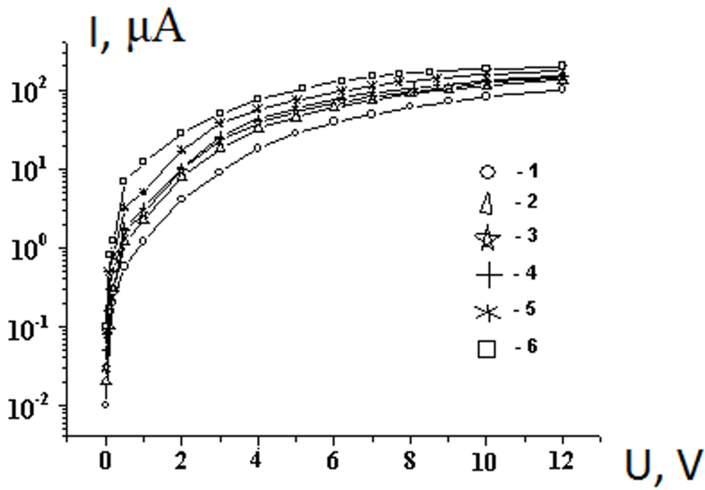


**Fig. 2.** Volt-ampere characteristic of In-nCdS$^+$ - nCdS- nSi-In structure at different temperatures T. $^0$C: 1 - 20, 2 - 40, 3 - 60, 4 - 80, 5 - 100, 6 - 120.

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 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.

The mobility of the basic carriers, determined by the Hall method, was at room temperature $\mu_n$ = 286 cm/$^2$(V·s). Assuming that, as usual, in $A^{II}B^{VI}$groupmaterialshole mobility is much less than electron mobility [7], for the evaluation we took the value $\mu_p$ = 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].

$$\mu_P \tau_P = \frac{qL_P^2}{kT} \tag{3}$$

The values of these parameters calculated at different temperatures are shown in Table I.

Table 1. Dependences of exponent (*c*) (equation 1), pre-exponential multiplier ($I_0$) (equation 1) and hole diffusion length ($L_p$) (equation2) on temperature. 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 |

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. 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.

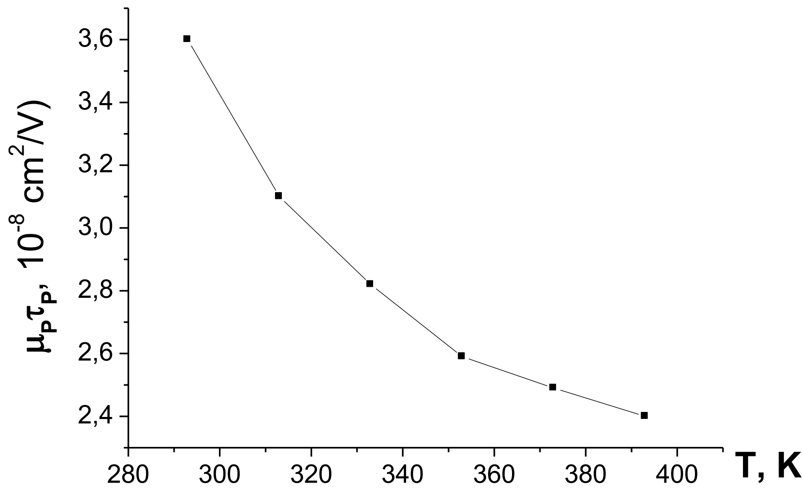


**Fig. 3.** The dependence of the mobility product ($\mu_P$) on the lifetime ($\tau_P$) of nonessential carriers - holes of the $n^+$ - n structure on the temperature.

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 CdS with ρ = 1.5-$10^8$Om·cmat room temperature.

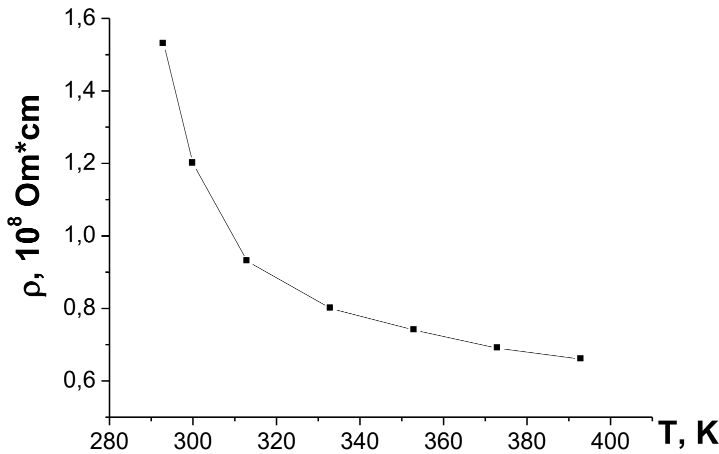


**Fig. 4.** The dependence of the resistivity of the high-resistance transition layer of the substrate-film $n^+$ - n structure on the temperature.

From Fig. 4 shows that the resistivity of the layer decreases with increasing temperature due to thermal generation of charge carriers in it.

From the VAX shown in Fig. 2a, that 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.

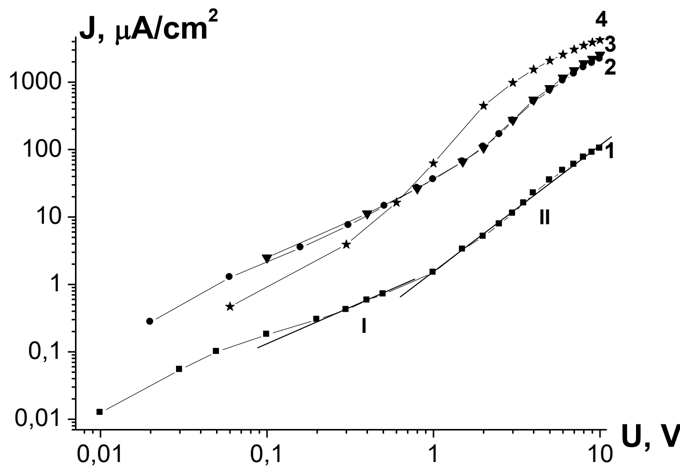


**Fig.2**. Volt-ampere characteristic of In-n⁺CdS- nCdS- nSi-In structure in double logarithmic scale: direct branch in darkness (1), which is described by the dependences I~V (I), I~ $V^2$ (II); direct branch during white light irradiation with E = 3- $10^{-2}$lux (2), direct branch during laser irradiation with λ = 0.625 nm power P = 1.2 μW/cm² (3), the direct branch at laser irradiation with λ = 0.625 nm with power P = 0.75 mW/cm² (4)

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

$$V \approx V_0 e^{JaW}, \qquad (5)$$

Where

$$a = \frac{1}{2qD_P N} \qquad (6)$$

- 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

$$JaW > 2 \qquad (6)$$

which is freely performed at all temperatures (e.g., at T = 20C⁰, S = 0.8 cm², $JaW \approx 3.5$).

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:

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

where S is the cross-sectional area, I is the current strength. The values of parameter "a" found from the ERA at different temperatures are shown in Table II.

**Table 2.** Values of the parameter *an 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 |

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). From Fig. 5 shows that in the temperature range 293-393 K the $\mu$-$N_{pt}$ value decreases with increasing temperature.

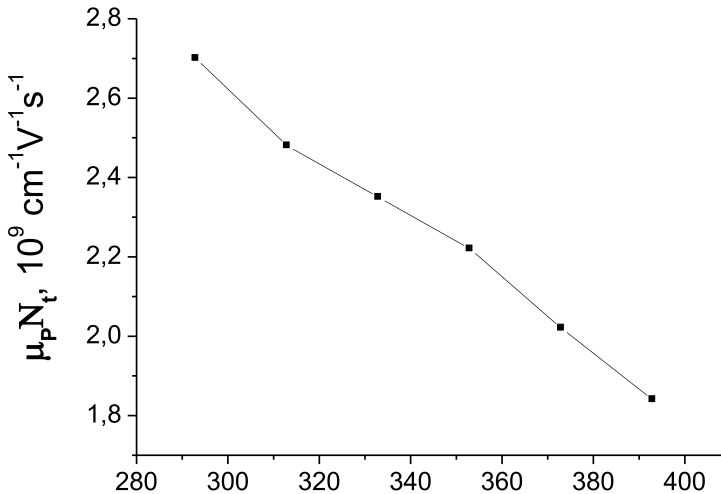


**Fig. 5.** The dependence of the product of the mobility ($\mu_P$) of nonessential carriers - holes of the $n^+$ - n structure on the concentration of deep impurities ($N_t$) on the temperature.

This apparently allows us to conclude that the scattering of carriers on ionized impurities plays a major role in the mobility mechanism in the VAX.

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 have two sections and they are almost

 https://doi.org/10.1051/e3sconf/202341304010

parallel to the corresponding sections of the dark voltammetry characteristic. These experimental data show that the mechanism of current flow in the dark and in the light is the same and they only differ in the value of current. 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 the 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 III, that the $n^+$CdS- nCdS- nSi-structure under study has the highest spectral sensitivity $S_\lambda$ ≈2042A/W.

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

| WhiteLight $E = 3\cdot10^{-2}$ lux | | | | Laserirradiation $W = 0.75\frac{mW}{cm^2}$ | | Laserirradiation $W = 1.2\frac{\mu W}{cm^2}$ | |
|---|---|---|---|---|---|---|---|
| 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 |

Note that the laser irradiation (λ=0.625 $\mu$ m) for cadmium sulfide 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 ($S_\lambda$) increases. It follows that this value of light energy is sufficient for modulation of bipolar mobility.

## 4 Conclusion

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 on the basis of a strongly compensated polycrystalline CdSfilm withρ≈- $1.510^8$Om·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 $S_\lambda$ ≈ 2042A/W when irradiated with a laser power P=1.2 μW/$cm^2$ (λ=0.625 μm) and V=10V.

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