Injection photodetectors operating in a wide spectral range

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Abstract. New types of injection photodetectors are shown. The primary amplification of photocurrent in injection photodetectors is discussed. The photosensitivity of such photodetectors has been experimentally determined.

1 Introduction

Injection photodiodes (IPDs) are a new class of semiconductor photodetectors whose operating principle is based on redistribution of the external applied voltage due to base resistance modulation. This effect is clearly seen in "long diodes" with the thickness of the high impedance compensated base region (distance d between the injecting p-n junction and the second ohmic contact) significantly exceeding the diffusive length of nonbasic charge carriers[1,2].Such diodes operate when an electric bias is applied to the barrier in the forward direction. In this case, most of the external voltage V falls on the high impedance base region (V_b). At high injection levels, the concentration of nonequilibrium carriers exceeds that of the equilibrium carriers, and they determine the conductivity of the base region. The applied voltage V is distributed between the p-n junction (V_{p-n}) and the base region (V_b).

$$V= V_{p-n} + V_b.$$

When the base resistance of the structure decreases as a result of injection, the voltage fraction at the contact V_{p-n} increases, leading to an increase in base injection and a further decrease in base resistance. Injection of charge carriers as if intensifies the effect of resistance change in the volume.

High photosensitivity of photodiodes in the transmission direction was first discovered in diodes made of germanium with an admixture of gold (Ge(Au)) at liquid nitrogen temperature [1,3,4]. Illumination reduces the base resistance of the p^+-i-n^+- structure. As in darkness, this results in a redistribution of the applied bias voltage. The voltage at the p-n junction increases, and the injection of charge carriers into the base increases, which further reduces its resistance. This is the mechanism of injection amplification of the primary photocurrent due to positive feedback (PFF). There is another mechanism of photocurrent amplification in SPDs [5-8], the so-called parametric amplification. Injection of charge

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carriers into a compensated semiconductor (semi-insulator) creates a non-uniformly distributed in space nonequilibrium plasma of electrons and holes in it [9]. Illumination not only increases the concentration of charge carriers, but also affects the parameters determining their distribution in the base region (lifetime, bipolar drift mobility, bipolar diffusion coefficient, etc.). These parameters depend on the intensity of impurity illumination, which directly changes the filling of impurity centers (trap levels). Therefore, the conductivity of the base region changes, there is a redistribution of voltage between the base and the p-n junction, an additional increase in injection, etc. It is this effect that makes the main contribution to the amplification of the primary photocurrent in injection photodiodes made on the basis of germanium, silicon, and gallium arsenide.

Industry produces a large number of types of photodetectors with high sensitivity, for example avalanche photodiodes [7]. However, their spectral range of sensitivity is limited by the region of the intrinsic photosensitivity of the materials of which they are made. For the detection of light signals in the infrared regions of the spectrum, along with narrow-band semiconductors, impurity semiconductors are widely used. Practically only photoresistors are receivers of radiation exhibiting sensitivity in the impurity region of the spectrum. Hence, it follows that exactly IFDs, which can be represented as photoresistors controlled by injection from contacts, can be photodetectors exhibiting high sensitivity in the spectral range, from the ultraviolet (UV) to the far infrared (IR) region. The undoubted advantage of the IFD is their great photosensitivity to extremely weak light signals.

Let us first consider what progress has been made in this field of science, i.e., what scientific articles of fundamental and applied importance have been published in the world press.

2 Methods

2.1 Mechanisms of injection amplification.

Injection photodiode with drift charge carrier transfer.

In diode structures with $d/L \geq 10$ (L is the diffusion length of non-basic charge carriers), the currents flowing are determined by the bipolar drift of charge carriers [10-12]. The distribution of injected carriers in a volume is associated with bipolar mobility μ, which characterizes the direction and velocity of a packet of nonequilibrium charge carriers in an electric field. At voltage, when the base conductivity is determined by carriers injected from the contacts under the action of "impurity" illumination, the amplification is associated with the direct modulation of μ, i.e. it is parametric. When the base conductivity is modulated by injection from the contacts

$$I = \frac{9}{8} q[\text{n-}\gamma p_{oo}]\mu_{n}\mu\tau_{pp}\frac{V^2}{d^3} S, \quad (1)$$

where $\gamma = \tau/\tau_{np}$, τ_n and τ_p are elastic relaxation times of electrons and holes. The quadratic dependence of current I on voltage V is caused by modulation of semiconductor conduction by injected charge carriers at their bipolar drift in electric field [10].

Spectral characteristics shown in Fig. 1 were obtained at low injection level (V = 1 V), at high injection level (V = 20 V), and at intermediate voltage value - at quadratic section (V = 10 V). It can be seen that as the injection current increases, the sensitivity in the impurity absorption region grows faster than in the native absorption region. The given experimental data on photosensitivity of SPDs can be explained on the basis of the theory of injected photocurrent enhancement in long diodes [11]. At low temperature, the concentration of carriers in the p-Ge(Hg) diode base even at sufficiently high injection levels is several orders of magnitude lower than the concentration of deep-level centers.

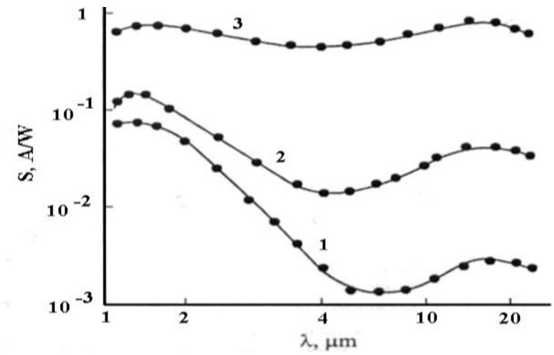

Fig. 1. Spectral sensitivity of injection photodiode. Bias voltages U, V: 1- 1, 2-10, 3-20, T=55 K.

As a consequence, the injection recharge of deep centers in a large part of the base is negligible, and carrier lifetime practically coincides with the equilibrium values. Therefore, at low levels of injection the SVC of the injection photodiode coincides with the SVC of an equivalent photoresistor. At "natural" illumination for p-Ge(Hg)-based SPDs at low injection level when exposed to light with λ=0.96 μm injection gain is practically not observed. It takes place only at a high level of injection, which can be explained in the following way. In the numerator of the known expression for bipolar drift mobility

$$\mu=\frac{n-p\frac{dn}{dp}}{n\mu_n+p\mu_p}\mu_n\mu_p \quad (2)$$

is a value that depends on the difference in the concentration of the charge carriers. "Impurity" illumination, in which carriers of the same sign are generated, changes this difference, thus modulating μ, which strongly affects the concentration of charge carriers injected from the contacts. This circumstance can explain the deformation of the spectral sensitivity characteristics at different external bias voltages (Fig. 1).

The gain of radiation receivers can be defined as the ratio of photocurrent (photodetector output current), expressed in electrons per second, to the number of photons absorbed during the same time. It is assumed that each absorbed photon causes generation of nonequilibrium charge carriers. Under influence of "own" illumination the photoresistor gain, as it is known [16], is equal to:

$$K=_r\frac{\tau_n}{t_n}+\frac{\tau_p}{t_p}. \quad (3)$$

Here$_n$, ti t_p is the time of electron and hole passage through the diode base. At "impurity" illumination in (3) there remains only one summand.

The photoelectric gain of an injected photodiode with a VAR corresponding to (1) under impurity illumination (e.g., if p>$_{ph}$> n_{ph}) is [17].

$$K=\frac{\tau_n}{t_n}\frac{\tau_p}{t_p} \quad (4)$$

Accordingly, the K coefficient exceeds the gain of the impurity photoresistor by the gain of the generation current of non-essential charge carriers. The ratio τ/t_{nn} for p-semiconductor-based SPDs is actually the photoelectric injection amplification coefficient at the drift mechanism of transfer of nonequilibrium charge carriers in the diode base. Thus, due to injection amplification, the sensitivity of diode structures to light can be increased by tens, hundreds, and thousands of times.

2.2 Other injection amplification mechanisms

There are other mechanisms leading to base resistance modulation, such as τ-mechanism, heating of charge carriers and increase in the entailed bipolar diffusion coefficient. The effective lifetime of the charge carriers due to deep center recharge can also change when the photodiodes are illuminated. In [6], the IAC of an n-Ge(Hg) diode was theoretically investigated taking into account "intrinsic" illumination. And in [18] an analytical model τ-mechanism of base resistance modulation was used to explain the effect of injection amplification. The condition for applicability of this model is the possibility of a significant (by three orders of magnitude or more) increase in the lifetime of non-basic charge carriers with increasing current. As the injection level increases, the base region adjacent to the p-n junction is "flooded" by nonequilibrium charge carriers and its resistance decreases. As the current increases, the length of the low-resistance part grows, the voltage drop across it decreases, and an injection breakdown may occur. The most sensitive to light is the high impedance region of the diode base adjacent to the cathode (for the n-type base), which is not reached by the charge carriers injected from the p-n junction. The photosensitivity of such a structure is much higher than that of an equivalent photoresistor. In p-i-n-diodes with a not too long base (d/L= 3-5), the concentration distribution of dark nonequilibrium charge carriers along the base is described by a bipolar diffusion coefficient at both low and high levels of injection. In such structures, the parametric injection gain under "parimetric" illumination can be determined by the D coefficient changing under the action of light. Diodes based on p-Ge(Hg) with d/L< 4 were investigated experimentally in. The diode's WAV (Figure 2) is basically described by the diffusion breakdown theory developed in, which reflects the injection breakdown in a number of materials quite well. The bipolar diffusion coefficient D in this structure changes due to the capture of holes to mercury levels coming from the p-contact$^+$ to neutralize nonequilibrium electrons. When the current exceeds the injection breakdown current, the voltage drop across the base decreases due to an increase in D with a further increase in the injection level (because the hole capture rate decreases as deep mercury levels are recharged). Figure2 shows the dependence of the photocurrent density J_{ph} on the voltage when exposed to "impurity" illumination with λ = 10.6 μm .

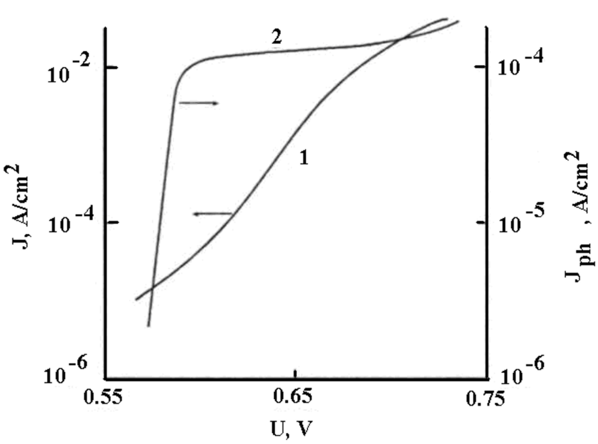

Fig. 2. Dependence of dark current density J(1), and photocurrent J_{ph}(2) on voltage. T=55 K, λ=10.6 μm

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In the region of voltages corresponding to the exponential section on the dark CVC, the photocurrent practically does not depend on the voltage, which agrees with the theory [19]. The diode exhibits injective gain of the impurity photocurrent with the coefficient K=10.[2]

The parameters determining the distribution of nonequilibrium electrons and holes in the diode base can change not only as a result of carrier photogeneration, but also due to their heating by light, which leads to injection enhancement of the photocurrent. The mobility of charge carriers depends on their energy, which increases with the absorption of electromagnetic radiation. The absorption coefficient increases with increasing wavelength. Therefore, in the presence of this effect, the photosensitivity extends to the submillimeter range of the spectrum [22]. In long diodes, even with low heating of carriers by the electric field and incident light, corrections to mobility, probabilities of carrier capture, and the occupancy of recombination levels should be taken into account. Weak heating of carriers by the electric field can lead to the appearance of a vertical section of a constant voltage on the CVC. In this case the stationary impurity photocurrent greatly increases and additional (compared to the absence of field heating [11]) injection amplification occurs.

2.3 Injection photodiodes based on Ge and Si

Some properties of germanium IFDs have been discussed in the previous sections. The effect of "impurity" illumination on a germanium injection diode with a drift and τ-mechanism of nonequilibrium charge carrier transfer was studied in et al. Under monochromatic illumination, the direct branch of the CVC of n-Ge(Au) diodes deforms at illuminances $\approx 10^{-5}$ lx or more. As the bias voltage increases, the photosensitivity of the diode increases. Thus, at voltage V=8B and illumination $3.5\cdot 10^{-7}$ lx current sensitivity $S \approx_i$ 120 A/lm. At the same illumination sensitivity of ordinary germanium photodiodes is no more than 30A/lm, and phototransistors - less than 10A/lm.

In, IFDs obtained by high-temperature fusion of indium into germanium have been studied. The τ-mechanism model of the injection breakdown was used [18]. The diodespectral response has a maximum at λ ≈ 1.6 μm. The sharp drop in the photoresponse with decreasing wavelength is related to the effect of recombination, the rate of which on the surface of the structures. At λ ≈ 3.1 μm the current sensitivity $S \approx_i 9\cdot 10^2$A/W, the volt sensitivity $5\cdot 10^8$V/W. In, the effect of inhomogeneous nonstationary "impurity" illumination on the direct current of a $p\text{-}^+$ i - n-diode made of Ge(In). It was shown that injection photodiodes have inhomogeneous photosensitivity on the quadratic section of the CVC.

The properties of SPDs and their characteristics are largely determined by the starting material. Thus, the maximum spectral sensitivity of silicon SPDs is observed at λ ≈ 0.98 μm, their impurity photosensitivity extends up to λ = 6 μm. Among the silicon SPDs studied, the most sensitive are diodes whose bases are compensated by zinc or sulfur. When the Si(Zn) diodes were exposed to "native" and "impurity" light in combination, non-additive photoconductivity was observed. It is expressed in a significant increase in the impurity photocurrent when the "native" illumination is switched on. A possible reason for such non-additivity is the reduction of surface recombination when exposed to illumination.

2.4 Injection photodiodes based on $A^{III}B^{V}$ semiconductors

Wide-gap GaAs, GaP, GaP_xAs_{1-x}, etc. compounds are used for creation of the UV-visible (UV) band. They have sensitivity up to λ ≈ 200 nm. GaP-based SPDs have maximum sensitivity at λ = 430-440 nm. $_{max}$Typical threshold power $P_{NEP} = (1\text{-}2)\cdot 10^{-14}W/Hz^{1/2}$ for GaP diodes with a 15-mm diameter photosensitive pad at λ. They have a wide dynamic range, the linearity of the ampere-watt characteristic is preserved within the specific power of 10-^{-12} 10^{-5}W/cm^2.

GaAs(Cr)-based SPDs and GaAlAs-$GaAs_{x1-x}$ heterojunction SPDs have the best parameters in the UV and visible spectral regions. Their spectral sensitivity begins at λ = 300 nm. The maximum sensitivity is at λ = 800 nm. The "impurity" photosensitivity extends up to λ = 1300 nm. It is especially pronounced at T = 77K. The highest short-wave sensitivity of the IFD is at illumination from the side opposite to the injecting p-n junction. Current photosensitivity at λ_{max} reaches 500 A/W. Currently, IDFs with threshold sensitivity P_{NEP} = 10^{-14} W/Hz$^{1/2}$ at T=300 K and P_{NEP} = 10^{-15} W/Hz$^{1/2}$ at T=77 K have been created. An example of a GaAs(Cr) IDF is an infrared radiometer - a system for detection of infrared radiation on the background of noise exceeding the signal by several orders of magnitude [22]. The input photodetector of the device (IFD) is sensitive in the spectrum region λ = 0.7 - 0.95 μm. The threshold sensitivity of the SPD is P_{NEP} = 10^{-15} W/Hz$^{1/2}$ at T=77 K.

Double injection (taking into account diffusion and drift of charge carriers) explains the photosensitivity of GaP-based SPDs with silver and gold admixture [13]. High sensitivity in the native and impurity absorption region (S_I = 10^4 - 10 ^{5}A/W) on GaP(Cu) basis is related to the injection modulation of deep levels charge, leading to the change of the bipolar drift mobility sign μ [13]. Stimulation of the photocurrent in GaP diodes from their own illumination has been observed [14] when exposed to "impurity" light. The injection amplification coefficient reached the value of $3{\cdot}10^3$. Photoelectric injection amplification under the influence of "impurity" illumination (λ = 6 - 12 μm) was studied in a p-i-n structure with drift transfer based on p-InSb [15]. A model assuming recombination through two independent levels proved to be acceptable. The best agreement between the experimental and theoretically calculated I-V curves of InSb-based S-diodes was obtained just for such a case [16]. The sensitivity of the SPD in the region of intrinsic and impurity absorption can be controlled by a magnetic field [16], as well as by radiation irradiation.

2.5 Injection photodiodes based on $A^{II}B^{VI}$ semiconductors

Injection amplification on the IFDs based on high resistivity ZnS by silver thermodiffusion [19] was observed under irradiation with light from the UV and visible spectral regions. At comparatively low direct bias voltages (40-50 V) and exposure to light with wavelength λ= 0.3 μm the integral current sensitivity reached (0.2 - 1.5)$\cdot$ 10^3 A/W, the volt sensitivity was $3{\cdot}10^8$ V/W. The possibility of realization of τ-mechanism of injection amplification was supposed. In favor of it there is a section of superlinearity on ampere-watt characteristic at weak light fluxes. The sensitivity on this section was the highest.

The current photosensitivity of longitudinal SPD polarons based on CdS monocrystals [20] is 10 ^{5}A/W when irradiated with light at λ= 510 nm (radiation power 2$\cdot$ 10^{-8} W/cm^2, offset ~1 V, dark current 5$\cdot$ 10^{-10} A). This is significantly higher than the known semiconductor polarized radiation analyzers. Significant change in pleochroism (from - 0.9 to + 0.8) with wavelength variation (from 515 to 508 nm) can be used for precise wavelength determination of monochromatic radiation in this range.

The IFDs based on other groups of semiconductors were also investigated. For example, GaSe-based diodes exhibit sensitivity in the short-wave region of the spectrum [21,22]. At λ = 0.36 - 0.65 μm, the current sensitivity is 5$\cdot$ 10 $^{-2}$A/cm^2.

2.6 Injection photodiodes with a varon base

A peculiarity of current conduction in varisonic semiconductors (smooth heterojunctions) is the effect on the electron-hole plasma not only of an externally applied electric field, but also of an embedded quasielectric field determined by the slope of the forbidden zone boundaries of the material, which provides a great variety of effects in structures with a bandgap gradient Δ E_g. In , injection amplification at intrinsic absorption of a semiconductor associated with positive current feedback was investigated. We studied n-AlGaAs$^{+}_{x1-x}$ - p-Al$_x$GaAs$_{1-x}$ - p^{+-}-GaAs structures obtained by liquid-phase epitaxy (Fig. 3).

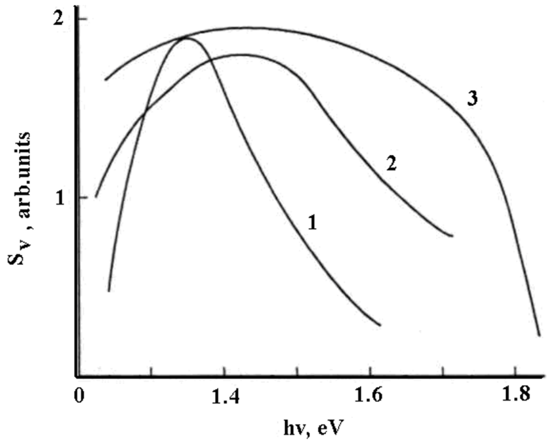

Fig. 3. Spectral characteristic of volt sensitivity of injection photodiode. Bias current I, mA: 1-2.5, 2-1.5, 3-0.4, T=77 K.

The bandgap width of the basic material p-AlGaAs$_{x1-x}$ changes with the coordinate according to the linear law. The injecting n-p-$^{+}$ heterojunction is located at z = o, p - p-contact^{+} at z = d. The band gap widths at the n^{+} - p-contact are E$_g$ (0) ≈ 1, 95 eV, at the p - p $^{+}$region E$_g$ (d) = E_g^{min} ≈ 1.4eV. The structures were illuminated from the n-contact side^{+}.

The dependence of the differential volt photosensitivity S$_v$ = dV/dP at T = 77-300 K on the spectral composition of radiation was studied (3). The spectral characteristic of photosensitivity measured at current I = 2.5 mA (high level of injection) is selective and corresponds to the light generation of nonequilibrium charge carriers in the high-resistance unmodulated by the charge carriers injected from n^{+} - p-heterojunction near the p - p^{+} contact (hv ≈ 1.4eV). As the level of injection decreases, the high resistivity region of the base expands. Accordingly, the short-wave edge of photosensitivity spectrum shifts (Figure3, curves 2 and 3).

The photosensitivity spectra of the varispeed-base SPDs can be controlled by a magnetic field [18], which, due to the galvano-magnetic recombination effect [19], affects the distribution of charge carriers in the semiconductor volume. The functionality of photodetectors is significantly expanded.

Some conclusions from scientific articles on injection photodiodes in the periodical press before the beginning of our research in this field of science.

1) Injection photocurrent enhancement was observed in p-n junctions with an ohmic contact and with a thick, high-resistance, compensated base or in p-i-n structures only in the forward current direction.

2) IFDs have been derived mainly from germanium, silicon and gallium arsenide, which are effective at low temperatures and have a current sensitivity of no more than 500 - 1000 A/W.

3) Injection photovoltaic amplification is practically unexplored in semiconductors of $A^{II}B^{VI}$ compounds, as IDFs based on them can operate at room temperature.

4) Virtually no output parameters of IFDs based on varicon semiconductors.

5) IDFs with rectifying metal-semiconductor contact or metal-semiconductor with an intermediate thin oxide layer (MOS-structure), which provide a fairly high level of injection and sharply reduce the recombination of nonequilibrium charge carriers at the semiconductor surface, have not been studied. These effects greatly increase the output parameters of the

photodiodes, such as current sensitivity and extend the sensitivity in the UV region of the spectrum.
6) Injection amplification is considered in structures in which the direction of drift and diffusion fluxes of nonequilibrium charge carriers coincide. It is of scientific and practical interest to study the injection amplification of photocurrents when the drift and diffusion fluxes of nonequilibrium carriers are directed towards each other, because in this case the mutual compensation of these fluxes occurs and very small currents are observed in the structure or there is a complete compensation of nonequilibrium carriers and the resulting current in the structure becomes equal to zero.
7) Our research in the last 3-4 years has been aimed at solving the above-mentioned problems.

2.7 Injection photodetectors based on cadmium telluride and cadmium sulfide and their solid solutions.

In recent years we have developed SPDs based on the following structures: Al-p-CdTe - Mo; CdO - p-CdTe - Mo; n-CdS^+ - n-CdS - pSi; n-CdS^+ n-CdS - n- Si; nCdS-pCdTe; CdO - Zn_xCd_{1-x} Te. These structures have thin dielectric oxide interlayers between the metal and the semiconductor. Such structures are advantageous in that they can be used to create integrated circuits and matrices. Besides, in such structures it is possible to investigate photo-current injection amplification, when in high-resistance, compensated bases the direction of drift and diffusion currents coincide and vice versa, when they are directed towards each other.

2.8 Injection photodiodes based on Al-p-CdTe - Mo

To find out the real structure of this structure we used X-ray phase analysis. The study of the X-ray phase analysis of the basic Al-pCdTe-Mo-structure made it possible to establish its real structure, namely: Al-Al_2O_3-pCdTe-MoO_3 {(or solid solution $(CdTe)_{1-x-y}Mo_x(MoO_3)_y$} - Mo. Such a transistor structure in its final form appears as *an n-p-n⁺ structure* with the base (*pCdTe*) in contact with wide-gap thin oxide layers *of nAlO*$_{23}$ and *nMoO*$_3$ or solid solution $(CdTe)_{1-x-y}Mo_x(MoO_3)_y$ on both sides.

When negative potential "-" (bias voltage V_b) is applied to the Al-pin the structure operates in the direct mode, and when "+" potential is applied in the blocking mode. The analysis of the VVC shows that the structure has rectifying properties and its rectification coefficient "K" (defined as the ratio of forward and reverse current at a fixed bias voltage $V=25_b$ V) is $K\approx10^4$. It follows that the front n-p^+ junction has higher injection properties compared to the rear p-n junction and its injection coefficient is approximately unity. This structure has the highest photocurrent injection gain in the forward current direction when the base thickness is ~ 30-40 μm. Thus the structure exhibits a current integral sensitivity $S_{int} \approx 8\cdot10^3$A/W when illuminated by white light with E=1lux and a spectral sensitivity S_λ = 10^3 A/W when illuminated by laser light with S_λ =0.637μm power P=10 μW/cm^2 at room temperature. With increasing thickness of the base the values of S_{in} and S_λ decrease and at the base thickness d=120 μm the injection photocurrent amplification does not occur completely, which is due to the direct-gap structure of cadmium telluride, known in such semiconductors light is completely absorbed at thicknesses in the order of 1-2 μm, and the main part of the base remains unmodulated. When such a structure is switched on, an extended sublinear section appears in the shut-off current direction on the volt-ampere characteristic (VA). It was shown that the appearance of the sublinear section of the CVC is caused by the injection of electrons from the rear MOS contact and the occurrence of counter diffusion and drift currents in the base (p-CdTe), directed to each other. Compensation of the drift and diffusion fluxes of nonequilibrium charge carriers leads to an increase of the base resistance in a wide bias voltage range ($V_b \approx$ 0.3-70V). The current remains almost constant

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~6.7-10^{-7}A/cm^2 at the beginning and ≈6.9-10^{-7}A/cm^2 of the sublinear section. It has been theoretically shown that in the sublinear section of the CVC, the relaxation processes are conditioned by the time of flight of nonequilibrium carriers through the base [25]. Such a transistor structure with a long base can be used to create nuclear radiation detectors and switching devices.

To create device devices based on CdTe films with the above properties, it is important to know how the sublinear section changes under external influence. Therefore, the temperature dependence of this section of the CVC was investigated (see Fig. 4). The study shows that the shape of the sublinear section practically does not change with temperature changes from 177 K to 373 K, and only the current value changes from 1.17·10A/cm^{-82} to 2.8·10A/cm^{-52} when the temperature changes by 200 K.

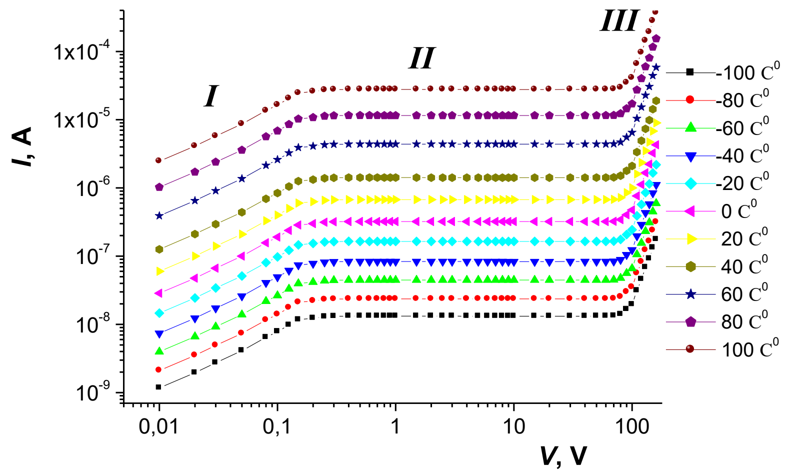

Fig. 4. Temperature characteristic of Al-pCdTe-Mo-structure.

The results of temperature studies allow us to be optimistic about the possibility of creating devices and devices based on advanced accumulation structures, in which the base consists of strongly compensated p-CdTe.

A selective tunable-spectrum photosensitive photodetector based on the pSi-n-CdS-nCdS$^+$ structure, which has a high value of the rectification coefficient (10^5) at room temperature, was created. It was shown that the light and dark volt-ampere characteristics of the structure have the same patterns. It was found that at current densities I = 10 $^{-2}$-5·10^{-4}A/sm^2 the "mode" of long diodes is realized in the structure and the values of integral (S_{int}) and spectral (S_λ) sensitivities increase sharply. It was found that S_{int}= 2.8·10 ^{4}A/lm (3·10 ^{6}A/W) for illumination level E = 0.1 lx and S_λ = 2.8·10^4 A/W for laser irradiation with λ = 637 nm and power 10 μW/cm^2 at bias voltage U = 20 V. It was found that the mechanism of photocurrent enhancement is mainly related to the modulation of ambipolar mobility.

In such a structure, when a reverse bias voltage is applied to it, electrons are injected from narrow-band pSi into highresistance wide-band n-CdS. It was shown that mutual compensation of the counter drift and diffusion fluxes of charge carriers occurs in this structure. The counter drift and diffusion fluxes of nonequilibrium non-basic charge carriers at current densities I ≈ (10^{-8}-10^{-7}) A/cm^2 lead to the appearance of photoresensitivity sign inversion points in the short-wave and long-wave spectral regions. Mutual compensation of counter drift and diffusion fluxes at current densities of the order ≈ 10^{-6}A/cm^2 leads to the appearance of a sublinear area on the reverse volt-ampere characteristic in a wide range of bias voltage (V≈ 8 - 60 V). This experimental fact is also remarkable in that it characterizes quite good properties of the pSi-n-CdS heterojunction. Since when the pSi-n-CdS-nCdS structure is turned on$^+$ in the reverse current direction, the positive "+" potential is applied to the n^+CdS- layer, hence the drift current of the non-basic nonequilibrium hole carriers in the base (n-CdS) is directed toward the heterojunction. However, for the accumulation process to occur near the heterojunction it must not be transparent for holes. Consequently, it must have a perfect band diagram or the density of surface states at the interface must have a negligible value. As is known,the increase in the concentration of nonequilibrium holes and its gradient with an increase in the value of the drift flux of nonequilibrium charge carriers, leads to the opposition of drift and diffusion currents, which are directed towards each other. Also according to the developed theory for manifestation of the extended sublinear region the same change of counter drift and diffusion currents of unequilibrium charge carriers is necessary. It follows that the pSi-nCdS heterojunction has good quality, only in this case the same change of the drift and diffusion currents directed towards each other in the region of bias voltages U ≈ 8 - 60 V is provided.

Experimental studies on the distribution of surface states - N_{ss}on the surface potential value - ψ_{ss} at the interface pSi-n-CdS- heterojunction by the volt-pharad method [21,22] confirm that indeed the heterojunction has small surface state densities and is of good quality. The proof is that N_{ss} = 6-10cm$^{11-2}$ at ψ=$_s$ -0.24 eV (in the upper half of the band gap), and in the lower half of the band gap the value of the surface state density is much lower than the upper one. For example, N_{ss} ≈9.5-10 ^{9}cm $^{-2}$at ψ_s = 0.08 eV and N_{ss} ≈1.9-10^{10} cm $^{-2}$at ψ=$_s$ 0.48 eV. These values of N_{ss}, especially its value in the lower half of the band gap are usually considered small, low.

Here, it should be noted that both the upper and the lower half of the forbidden zone, certain densities of surface states are effective, and they have charged states, which naturally do not include values of neutral surface states like N-acceptor$_a^0$ neutral surface states.

The spectral sensitivity of such a structure in the reverse current direction in the absence of voltage lies in the range of wavelengths λ = 350 - 1350 nm and has the highest values at λ≈$_1$ 480 nm and λ≈$_2$ 1248 nm, where the photocurrents have negative values. In the $S_\lambda(\lambda)$ dependence, we observe points of inversion of the photosensitivity sign in the short-wave and long-wave parts of the spectrum, which shift in opposite directions when the bias voltage is applied. Such behavior of the $S_\lambda(\lambda)$ dependence of the inversely shifted M(In)-pSi-nCdS-M(In)-structure is explained by an accurate compensation of the drift current of equilibrium holes in the base (nCdS) with the diffusion current of injected carriers from the pSi-n CdS heterojunction. The appearance of the sign points of photosensitivity inversion in the dependence of the spectral distribution of the photocurrent gives reason to believe that the oppositely directed diffusion and drift currents completely compensate each other at a certain base thickness. This base thickness corresponds to the absorption depth of electromagnetic radiation with wavelength λ. The shift of the photosensitivity inversion point towards short wavelengths is determined by the magnitude of the bipolar diffusion current, which is associated with the injection of electrons from the pSi - nCdS heterojunction into the base. This point is shifted by applying small reverse bias voltages. The experiment shows that after bias voltage V≥ 8.5 mV is applied, the bipolar diffusion current in the structure becomes determinant and therefore no inversion of the photocurrent sign appears in the photosensitivity distribution spectrum.

The analysis of the I-V curves of pSi-nCdS-n^+CdS - structure shows that the structure has rectifying properties and its rectification coefficient "K" (defined as the ratio of forward and reverse current at a fixed voltage V=25 V) is ≈10^5. It follows that on the basis of such structure it is possible to create fast switches, because in it current transfer of nonequilibrium carriers is carried out at the expense of time of flight of nonequilibrium charge carriers.

In [22] the effect of ultrasonic irradiation on the photoelectric and electrophysical properties of an injection diode based on M(In)-pSi-nCdS-M(In)-structure was studied. The ultrasonic irradiation was performed with a 1W test signal frequency of f=2.5MHz for 15 min. Ultrasonic irradiation does not affect the pattern of current flow in the structure in the forward and reverse branches of the CVC in the dark and in the light, but only increases the values of current at the same value of bias voltage. In the forward branch of the CVC the current increases by ~20%, while in the reverse branch it increases approximately twofold and, respectively, the integral and spectral sensitivity increase by 20% in the forward current direction and twofold in the reverse direction. It was found that these effects have a direct relationship with the annealing of surface states at the pSi - nCdS- heterojunction interface.

In an nCdS-$^+$ nCdS-nSi -structure was created and investigated as an injection photodetector. Such a photodetector has a spectral sensitivity of 4700A/W at a bias voltage of 40 V, when illuminated by laser light with $\lambda = 0.637$ μm and power P=10 μ W/cm^2, and when illuminated by white light with power P=3.6-10μW^{-2} has an integral sensitivity of ≈110A/lm (1.2-10^4 A/W) at that bias voltage. And it is very sensitive to small light signals. The photoelectric gain of such an injection photodiode exceeds the gain of the impurity photoresistor by two orders of magnitude. It follows that the lifetime of ungrounded nonequilibrium holes exceeds by more than two orders of magnitude the hole transmission time. Since the ratio $\tau/t_{pp} \approx 10^2$ (where τ_p, t_p are the lifetime and time of flight of the nonessential nonequilibrium holes) is the photoelectric injection amplification coefficient. The direct branch of the I-V curve of such a structure in darkness and in light is described by the power dependences $I \sim V^2$ and $I \sim V^3$, which are realized in long diodes ($d/L \geq 10$, where w is the base thickness, L is the diffusion length of non-base carriers) and where the flowing currents are determined by the bipolar drift of charge carriers. It is shown that the mechanism of photoelectric injection amplification is related to the direct modulation of the bipolar drift mobility.

An injection photodiode with tunable photosensitivity spectrum based on the n-CdS/p-CdTe heterostructure was created. Studies of the photosensitivity spectral response light-VAR showed that the n-CdS/p-CdTe- Mo structure operates as an injection photodiode both in the forward and reverse bias directions. The spectral sensitivity value of such heterostructure in the reverse VAV at bias voltage V=-120 mV in the wavelength range of 50≈0-800 nm varies from 1.6 to 1.8 A/W. It many times exceeds spectral sensitivity of ideal photodetector ($S_\lambda = 0.4 - 0.64$ A/W in this region of radiation spectrum). In the forward direction of VAV at bias voltage V = +120 mV the spectral sensitivity in the wavelength range of 500-800 nm changes from 3 to 1A/W. At the same time there is an inversion of the photo-edes sign in the long-wave and short-wave part of the spectrum. The effective spectral resolving power of the n-CdS/p-CdTe- heterostructure in the short-wave part of the spectrum is 1.37 nm/mV. In the long-wave part of the spectrum it is equal to 0.15 nm/mV. Integral sensitivity of n-CdS/p-CdTe heterostructure $S_{int} \approx 2400$ A/lm ($\approx 2.7 \cdot 10^{5}$A/W) at room temperature under illumination with white light ($E = 3 \cdot 10^{-2}$ lux) and bias voltage V=+4.6 V. Under monochromatic light illumination from laser source LG-75 with wavelength $\lambda = 637$ nm, integral sensitivity of n-CdS/p-CdTe $S_{int} \approx -1400$ A/W) at room temperature, radiation power $P = 18 \cdot 10^{-6}$W/cm^2 and bias voltage V=+4.6 V. Compared with analogues, the created injection photodetector has improved functional characteristics and works at room temperatures. Achievement of high functional characteristics of the photodetector is explained by the effect of redistribution of electric potential between the barriers and the base of the photodetector structure under the action of illumination.

Currently, the development of effective selective noise-resistant photodetectors with internal amplification, sensitive in a wide range of electromagnetic radiation, is an urgent task. Photodetectors with tunable spectrum of photosensitivity are required for many areas of technology, including the detection of chemical elements used for alloying metals and their alloys. The number of such elements widely used in the alloying of metals and their alloys is ~25. It is known that the alloying elements selectively emit electromagnetic radiation in the visible range (λ = 0.42 - 0.67 μm).

From the above it is obvious that there is a problem in the creation of MFLs that are highly sensitive to weak optical illumination in the wide visible spectral range and operate at room temperature.

To solve this problem, the authors of created a cascade injection photodetector with internal amplification based on A^2B^6-junction films. The structure of this photodetector consists of solid solution layers of n-CdS_xTe_{1-x} and p-Cd_xZn_{1-x} Te, which have enhanced photosensitivity in the spectral wavelength range of λ = 500 - 700 nm. Such a structure operates as an injection photodiode in the transmission direction at large offsets and has a high integral sensitivity of $S\approx_{int}$ 700 A/lm (≈ 14500 A/W) at room temperature. It was found that at low light levels and small forward bias voltages (0.05 to 0.5 V) in such a structure, the diffusion and drift fluxes of nonequilibrium carriers are directed toward each other[21]. This effect leads to the appearance of an inversion of the photocurrent sign, which makes it possible to create selective photodetectors with injection properties based on this structure. At opposite directions of a photocurrent the structure, also works in a mode of internal amplification of a primary photocurrent, however integral sensitivity in this mode is much less, than at a through current direction. A distinctive feature of such photodetectors is their high resolving power, as well as a high degree of selectivity, which allows high accuracy in recording the incoming optical signal from a particular wavelength of electromagnetic radiation.

The study of the volt-ampere and volt-farad characteristics of In/ n-CdS^+ - nCdS - n-CdS_xTe_{1-x} - p-Zn_yCd_{1-y} Te/Mo - structure showed that the studied sample is a long diode in which the drift mechanism of current transfer dominates, and, the structure base consists of several layers, which show themselves at different current densities. The results of the volt-farad characteristics show that the investigated sample is a metal-dielectric-semiconductor type structure in which the dielectric (solid solution n-CdS_xTe_{1-x}) consists of four words. The thicknesses of these layers d calculated by the flat capacitor formula C = εS/d (S - area, ε - dielectric permittivity) were respectively equal to 0.3 (1), 0.306 (2), 0.333 (3) and 0347 μm.

Quick Performance. An important parameter of the IFDs, like other photodetectors, is their fast response time. It can be limited by the lifetime, the pulling time of nonequilibrium charge carriers. The conductivity of the IFD base at a high level of injection is determined by longer-lived carriers, so the speed of the IFD is determined by the lifetime of longer-lived carriers.

In a calculation for photosensitivity of p-i-n- structures at double injection of charge carriers taking into account their weak heating by electric field as a function of frequency(f) of "impurity" illumination. It is shown that, in contrast to the situation on the quadratic section of the CVC, the frequency of f_o can be determined by the smaller of the carrier lifetime, i.e. IFDs can be quite low-inertia.

Because of the short lifetime of electrons and holes (~10^{-8}) in A^2B^6 semiconductors, injection photodetectors based on them must also be low-inertia.

Threshold characteristics. Among other applications, one of the most important purposes of the photodetector is the detection of extremely weak light signals. Fluctuations of photon flux of the background determine the maximum possible specific detecting ability of the photodetector D^*, working under conditions of background illumination. Detectability D^* of SPD is not worse than that of equivalent photoresistors under the same conditions of functioning (spectral range, temperature, etc.). Sensitivity of the IFD is much higher. A fundamental limit of detectability of photodetectors with volumetric photoeffect is determined by generation-recombination noises. It has been experimentally and theoretically shown that SPDs with a VAZ of the form (1) have several types of generation-recombination noises with different dependence of noise current I_n on voltage. Recombination noise of injected carriers increases with voltage as $I\infty_n V^{3/2}$ ($D\infty^* V^{3/2}$). Generation-recombination noise, associated with fluctuations in the rate of generation and recombination of the generated charge carriers, is voltage dependent in the same way as photocurrent ($I_n \infty V^2$). The noise corresponds to the amplified fluctuations of that part of the background radiation flux that is absorbed in the base. The "limiting D^* by background" mode was observed for diodes based on n-Ge (Au), n-Ge (Cu), p-Ge (Au), and p-Ge(Hg). In such IFDs, the spectral response of the photodetector depends significantly on the wavelength, power, and direction of radiation.

To give a high impedance photodetector a wide bandwidth, the load impedance is usually reduced. In this case the thermal noise may be higher than the load noise. In order to establish a *phonon limiting regime D, the generation and recombination noise associated with the generation of current carriers in the photodetector by the background radiation must be greater than all other noise. This means that the temperature of the receiver must be reduced to a value at which the rate of thermal generation is lower than the rate of optical carrier generation by the background radiation. It is known that precisely this circumstance dictates the necessity of cooling of photodetectors intended for registration of small light signals.

Selective interference-resistant photodetectors with internal amplification developed on the basis of A^2B^6 compounds and solid solutions based on them, are able to register only a certain length of radiation and they do not react to the background radiation. Their main source of noise is inhomogeneous absorption of the registered optical signal. Consequently, it is also important for them to provide a condition in which the rate of thermal generation was lower than that of optical generation. Such photodetectors at room temperature amplify ~ 10^{-5} 10^{6}times the primary photocurrent of illumination power (10^{-8} 10^{-9})W/cm^2. This means that their threshold sensitivity is in the order of $P \approx_{NEP} 10^{-14}$ W/Hz$^{1/2}$ at room temperature. It follows that as the temperature decreases, the D parameter* will undoubtedly improve and reach higher values than those of the IFDs based on germanium, silicon and gallium arsenide.

Injection photodiodes with micro-barriers. Internal gain photodetectors sensitive to "impurity" and "intrinsic" illumination are structures with a nonequilibrium recombination-trap barrier arising from light or electric injections in a compensated semiconductor with a non-uniform distribution of deep impurities. The semiconductor is represented by two alternating regions with different trap concentrations and such compensation levels, when without illumination at the interface the barrier height does not exceed a few kT. When such a structure is illuminated by light from its own absorption region, a potential barrier arises at the interface, the height of which can significantly exceed kT, and the field strength in the barrier can reach 10^5 V/cm or more. The barrier height can strongly depend on the "intrinsic" and "impurity" illumination. Current photosensitivity can exceed one electron per photon, i.e. a structure with such a barrier has intrinsic amplification. It is possible to create a recombination-trap barrier in wideband semiconductors by injecting carriers from rectifying contacts and use them to create linear and matrix photodetectors, which are widely used in information processing. It should be noted that fabricated broadband IFDs based on A^2B^6 semiconductor compounds and solid solutions on their basis have, in all probability, the above property. Firstly, they are created on the basis of wide band compensated semiconductors or solid solutions on their basis, in which the band gap width changes smoothly or jumps, in which a potential barrier is formed between the layers. Besides it should be taken into account that in each composition of solid solution impurities can be distributed inhomogeneously, as each of them is a wide band compensated semiconductor, which also leads to potential barriers in the base of injected gain photodetectors. This is probably why IDFs based on strongly compensated cadmium sulfide sulfide films and CdS_xTe_{1-x} -type solid solutions have a record value of current sensitivity.

3 Conclusion

Injection photodetectors provide several orders of magnitude (10^2-10^6) higher photosensitivity than non-jack structures. It does not require the use of low-noise amplifiers, standing directly after the photodetector and having such large gain coefficients that the stability is very low.

The high injection gain allows to realize the situation when the generation and recombination noise of the charge carriers generated by the ambient background radiation exceeds the excess noise associated with the surface and contacts. This makes it possible to achieve high values of the detection capabilities of D^*.

In a photodetector with injection amplification, both the intrinsic noise and the signal are amplified. At the same time the noise of the load and the preamplifier is insignificant. This is especially important when using the devices in near-short-circuit mode.

Injection photodetectors can operate in a wide spectral range, including ultraviolet, visible, near and far spectral ranges. In contrast to avalanche multiplication photodetectors, for which the spectral range is limited to the region of the intrinsic photosensitivity of the materials, IFDs allow sensitivity in the activation energy region of deep impurity centers.

An important advantage of IFDs is their high processability and weak dependence on the surface properties. This is due to the fact that they operate in the mode of injection of nonequilibrium charge carriers, so the quality of the injection junction and its leakage do not play a significant role. These factors greatly simplify the practical use of photodetectors of this type and ensure their increased stability and reliability

The implementation of injection amplification in recombination-trap barriers opens the prospects for the creation of IFDs based on quantum-dimensional structures. From this point of view the works on the study of the elementary structural units of condensed phases and the phenomena related to their elementary charge are of interest [19].

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