Investigation of the temperature dependence of the characteristics of the photodetector based on the compound InGaAsSb

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Abstract. The article provides information on the temperature dependence of the main characteristics of an uncooled photodetector based on the InGaAsSb compound, for the spectral range 1.7 ... 2.3 μm. Techniques have been developed, data on integral sensitivity, spectral, noise and threshold characteristics of PHD in the temperature range have been studied and presented (223 - 323 K). Analytical expressions for the temperature dependence of the characteristics are obtained. Noise model PHD is proposed. It was found that the increase in noise with increasing temperature is associated with a change in the differential resistance of the photodiode, and the frequency dependence was determined by the characteristics of the preamplifier. The volt sensitivity of the PHD to the ABB radiation of 800 K reached 40 \(10^3\) V/W, and the detecting ability \(D^*(\lambda_{max}, 1000.1)=9.4 \times 10^{19}\) W\(^{-1}\) cm Hz\(^{1/2}\) at room temperature.

1. Introduction

The working temperature of a photo receiver determines most of its most important parameters. It is believed that for semiconductor PHDs their temperature should satisfy the Mohs ratio [1]:

\[ T < 0.05(\Delta E_g/k) \]

If we accept this criterion, then at room temperature (T = 300 K), the photoreceiver should have a band gap of \(\Delta E_g > 0.5\) eV and a long-wavelength limit of sensitivity \(\lambda'' < 2.5\) μm. In this regard, there is a special interest in photoreceivers based on semiconductor materials with a band gap of about 0.5 eV, since they can be quite effective without additional cooling devices. Use of photodiode based on heterostructures InGaAsSb/GaSb is promising for the specified spectral range [2–5]. In many cases, the signal received from the photoreceiver is small and requires pre-amplification to the required level. The main purpose of the pre-amplification unit is to match the photoreceiver with the electronic path and implement the threshold and frequency properties of the photoreceivers [6]. As a rule, the pre-amplification unit is located in the immediate vicinity of the receiver, which reduces the effect of random pickups on the photo signal. The photoreceiver and the pre-amplification unit, combined into a single case, form a photodetector (PHD). An additional advantage of the PHD is to protect the photodiode from the effects of static electricity. The presence of even small static charges, the appearance of which is possible during the installation of products, turned out to be disastrous due to the small breakdown voltages for photodiodes based on a narrow-gap semiconductor material.
If the device is not thermostatically controlled, then one of the most important factors affecting the characteristics of PHD is temperature. Papers are published in which some temperature dependences of the characteristics of photoreceivers are given [7]. However, the use of an amplifier has an additional effect on the characteristics of PHD. In this regard, it seems appropriate to systematize the available and conduct additional studies to establish the temperature dependence of the characteristics of PHD.

2. Structure of PHD
Heterophotodiode $In_{x}Ga_{1-x}As_{y}Sb_{1-y}/GaSb$ of composition $x=0.18$ $y=0.17$ with a band gap at room temperature of about 0.5 eV was used as a photoreceiver. The size of the sensitive area was $2.2 \times 10^{-4}$ cm$^2$. The preamplifier was made according to the current-voltage transimpedance amplifier scheme, based on a low-noise op amp, type 140UD17A. The amplifier ensured the operation of the photodiode in the short circuit mode at a bias voltage of not more than 0.2 mV and was optimally matched in noise with a photodiode having a low differential resistance. The use of a 1–3 megohm resistor in the feedback allowed us to provide the necessary volt sensitivity. Structurally, the preamplifier was made using thin-film technology [8]. An input germanium optical window with an interference anti-reflective coating was used to reduce the likelihood of optical glare. The case of the PHD had precise locating surfaces for installation into the unit. Supply voltage of PHD is ± 10 V, weight about 2 g. Schematic diagram of the preamplifier is shown in the figure 1.

3. Integral sensitivity of PHD
One of the main parameters characterizing the operation of the PHD is the volt sensitivity, the value of which can significantly depend on temperature. Measurements were made of the integrated sensitivity of the PHD to the radiation of the blackbody 800 K at a modulation frequency of 800 Hz. Studies were conducted in two stages. Two stands were made - separately for measurements in the temperature range above room temperature, and for the low temperature range. A typical dependence of the integral sensitivity of the PHD on the ambient temperature is shown in figure 2. As can be seen, the sensitivity increased by more than 2 times with an increase in temperature in the investigated range. The resulting dependence can be approximated by the expression:

$$S_u(T) = S_u(293) \cdot [1 + \beta (T-293)]$$

where: $S_u(T)$ – integral sensitivity of PHD at temperature $T$;
$S_u(293)$ – integral sensitivity at temperature $T = 293$K;
Figure 2. The dependence of the sensitivity of PHD on temperature in relative units (black body 800 K).

The numerical value of the temperature coefficient made $\beta_1 = 0.0036 \text{deg}^{-1}$. The absolute sensitivity value for the best samples reached $40 \cdot 10^3 \text{V/W}$ at room temperature (297 K). The decrease in the sensitivity of the PHD with decreasing temperature can be explained by the change in the utilization rate of the radiation due to the temperature shift of the red boundary of the spectral characteristic to the shortwave region.

4. Spectral characteristic of PHD

The spectral dependences of the quantum sensitivity of PHD for different temperatures are shown in figure 3. As the temperature decreased, a shift in the spectral characteristic to the shortwave region was observed.

Figure 4 shows the temperature dependences of the blue ($\lambda'$) and red ($\lambda''$) boundaries of the spectral sensitivity determined by the level of 0.1 of the maximum value.

The long-wavelength limit was determined by the width of the forbidden zone of the photodiode material $\text{In}_{x}\text{Ga}_{1-x}\text{As}_{y}\text{Sb}_{1-y}$, and the shortwave one was formed by a filter (the role of which was performed by the optical window).

The shift of both boundaries on temperature can be approximated by linear dependencies of the form:

$$\lambda(T) = \lambda(297)[1 + \alpha(T-297)].$$

The values of the coefficients $\lambda$ and $\alpha$ for the blue and red boundaries of the spectral sensitivity made:

$\lambda'(297) = 1.65 \mu\text{m}$; $\alpha' = 4.9 \times 10^{-4} \mu\text{m} \cdot \text{K}^{-1}$,

$\lambda''(297) = 2.3 \mu\text{m}$; $\alpha'' = 5.5 \times 10^{-4} \mu\text{m} \cdot \text{K}^{-1}$.
Figure 3. Spectral characteristics of PHD for an equal flux of falling quanta.

Figure 4. Temperature sensitivity of the boundaries of the photosensitivity spectrum.

The integrated sensitivity of the PHD was determined by the utilization rate of the radiation, which depended on the spectrum of the emitter and spectral sensitivity of the photoreceiver. Figure 5 shows the sensitivity spectrum of the photoreceiver and spectral energy distribution of the blackbody with a
temperature of 800 K. As can be seen, only a small part of the energy of the radiator can be perceived by the photoreceiver.

![Figure 5](image)

**Figure 5.** The sensitivity spectrum of PHD (1) and radiation of the black with a temperature of 800 K (2).

The utilization rate of the radiation flux, which makes it possible to evaluate the efficiency of use by a selective receiver of the incident flux, can be defined as:

\[
\varphi = \frac{\int_0^\infty S_{rel} \ast r(\lambda) d\lambda}{\int_0^\infty r(\lambda) d\lambda}
\]

where \(S_{rel}\) – relative spectral sensitivity of PHD;

\(r(\lambda)\) – emission flux spectral density.

The utilization coefficients of black body by photoreceiver with a temperature of 800 K were calculated by numerical methods for various operating temperatures of the PHD. The results are presented in figure 6.

![Figure 6](image)

**Figure 6.** The temperature dependence of the utilization rate of the radiation of the blackbody 800 K.

As follows from the data obtained, the value of the radiation utilization coefficient varied from 1.77% at 223 K to 2.65% at 323 K. It is interesting to note that the change in the integral sensitivity was more intense than the change in the utilization rate. So with a change in temperature from 223 K to 323 K, the utilization rate of radiation increased from 1.77% to 2.65%, i.e. by 1.5 times, and relative sensitivity
increased by 1.57 times. The observed difference can be attributed to the influence of additional factors affecting photosensitivity, in addition to the utilization of radiation. For example, it may be temperature dependences of the lifetime of nonequilibrium charge carriers, affecting the coefficient of collection of photocarriers.

5. Noise characteristics of PHD

To determine the threshold of sensitivity and detectability of PHD, noise characteristics are important. Noise studies were carried out by the method of direct measurement. Figure 7 shows typical dependences of the spectral density of the voltage of PHD noise in the region of positive temperatures at a frequency of 800 Hz.

![Figure 7. Temperature dependence of the spectral density of PHD noise at a frequency of 800 Hz.](image)

It can be seen that with an increase in temperature, the spectral density of the noise voltage increases markedly. In the absence of interference, the noise at the output of PHD was made up of the photodiode noise and the preamplifier noise. A study was made of the preamplifier noise without a photoreceiver to clarify the causes that affect the nature of the noise characteristics of PHD. For this purpose, a constant resistance of 20 kiloohm, simulating the differential resistance of the photodiode, was connected to the input of the preamplifier. The input impedance of the opamp did not depend on temperature (the resistor was removed from the thermostat and is not exposed to heat). Data on the distribution of the spectral density of the voltage noise from the frequency at different temperatures are shown in figure 8.

![Figure 8. The noise spectrum of the preamp.](image)

1 – 296 K, 2 – 313 K, 3 – 318 K, 4 – 323 K
As can be seen, the frequency dependences at different temperatures behaved identically, which could indicate the independence of the preamp noise from the temperature. When the temperature changed by 27 K, the change in the voltage of the noise was comparable with the measurement accuracy (±7%). Probably, the change in the noise of the PHD is mainly due to the temperature change in the differential PHR resistance. In this regard, we can offer the following noise scheme of PHD:

![Figure 9. Noise scheme of PHD.](image)

where $U_n$ – opamp noise voltage; $i_n$ – opamp noise current; $R_d$ – PHR differential resistance.

The total value of the noise current for this circuit can be determined from the expression:

$$i_{n,\Sigma}^2 = U_n^2 \left(\frac{R_d \times R_1}{R_d + R_1}\right)^2 + 4kT\Delta f/R_d + 4kT\Delta f/R_1 + i_n^2.$$

Estimation of the influence of temperature on the components of PHD noise showed that the main contribution to the total noise current makes the first and second term due to a decrease in the differential PHR resistance. So with an increase in the ambient temperature from 293 to 333 K, the differential PHR resistance decreased from 30 kiloohm to 9 kiloohm. Figure 10 shows the calculated noise voltage data for a model with $R_1 = 3$ megaohm and the measured noise values of PHD with a photodiode having a close value with impedances in the model. As can be seen, the proposed model adequately reflects the noise characteristics of PHD.

![Figure 10. Calculation of the noise voltage on the model and the measured values of the noise at the output of PHD.](image)

Figure 11 shows the frequency dependence of the spectral density of the noise signal for a series of positive temperatures. As it can be seen, the spectral density of the noise voltage decreases with increasing frequency. If we assume that the noise was determined by the leakage resistance of the photodiode, then it should have a white spectrum at high frequencies, and flicker noise may prevail at low frequencies. The data on the photodiode noise showed that in the absence of a shift in the PHR in the reduced frequency range, white thermal noise prevailed. Then the fall with the frequency of the spectral density of the noise can be associated with a decrease in the gain of preamplifier. Thus, the increase in PHD noise with increasing temperature is associated with a change in the differential PHR resistance, and the frequency dependence was determined by the characteristics of the preamplifier.
6. Threshold characteristics of PHD
The study of noise properties and sensitivity of PHD allows determining its threshold characteristics. The most common is detecting ability \( (D^*) \), which is defined as [9]:

\[
D^* = \frac{\sqrt{A} \sqrt{\Delta f}}{\sqrt{i_{nu}^2}} S_i
\]

where: \( S_i \) – current sensitivity, \( A \) – area of photoreceiver, \( \Delta f \) – bandwidth, \( i_{nu} \) – noise current.

With a decrease in temperature, on the one hand there was a decrease in the utilization rate of blackbody radiation and a decrease in current sensitivity, and on the other, a decrease in the level of noise current. The second reason was dominant, which resulted in an increase in the detectability with the cooling of PHD. Figure 12 shows the temperature dependence of \( D^* \) for a sample with a differential resistance of \( R_0 \approx 20 \) kiloohm at room temperature.

**Figure 11.** Spectral dependence of PHD noise.

**Figure 12.** Temperature dependence of the integral detectability to blackbody 800 K for the sample with \( R_0 \) 20 kiloohm.
As it can be seen, a 24-fold change in detectability was observed in the usually demanded operating temperature range (from 333 to 213 K). The observed dependence can be approximated by the expression:

\[ D^* = D^*_0 \exp\left(-\frac{E_a}{kT}\right). \]

Energy \( E_a \) made 0.159 eV.

It is interesting to evaluate the detectable ability of PHD for monochromatic radiation. With a radiation utilization factor for room temperature of 2.4%. score gives the value \( D^*(\lambda_{\text{max}},1000,1) = 9.4 \times 10^{10} \text{ W}^{-1}\text{cmHz}^{1/2} \). This is consistent with the data [10], where similar values of the detectability are given for similar photodiodes: \( D^*(\lambda_{\text{max}},1000,1) = (8 – 10) \times 10^{10} \text{ W}^{-1}\text{cmHz}^{1/2} \).

7. Conclusion

Thus, the obtained results testify to the high tactical and technical properties of PHD based on InGaAsSb compound. Temperature dependencies of the most important characteristics can be useful for the practical application of the product and for the formation of technical requirements in the design of optoelectronic devices based on such PHD.

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