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ScienceDirect

Physics Procedia 73 (2015) 177 – 182

Physics Procedia

4th International Conference Photonics and Information Optics, PhIO 2015, 28-30 January 2015

Threshold sensitivity of the mid-IR sensors

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Abstract

The report presents expected threshold characteristics of photosensors based on uncooled mid-infrared (2-5 μm) A3B5 photodiodes characterized by a fast response time (tens of ns) and high detectivity (10^{-10}-10^{-11} W / cm$^2\sqrt{\text{Hz}}$), but low (from few Ω to kΩ) shunt resistance. The calculations are based on the noise analysis of the sensors using various types of photodiodes and operational amplifiers. The proposed "vector" noise description method was used to optimize the A3B5 sensor design elements and to estimate the value of their threshold sensitivity at the required speed of operation. As an example of promising A3B5 sensor application in the measurement technologies, the metrological characteristics of these sensors estimated for infrared thermometry (pyrometric sensors) are presented. It is shown that they are superior to known analogues in the low temperature detection limit (from 0 ^{o}C) and high response time (a few microseconds), while maintaining the high accuracy (at 1%) at low temperatures.

Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

Keywords: photodiode sensor; A3B5 photodiodes; mid-IR range ; detection limit; pyrometric sensors; IR-thermometry

1. Introduction

One of the main problems of photonics is the development of optoelectronic technologies and optical signal detecting systems. In this connection, a key photonics element is the photosensor. The structure of this sensor includes a photosensitive element that transforms the optical radiation to the electric signal and also an electronic gain and pre-processing circuits to signal transmission, conversion and storage of information in analog or digital form.

The great interest in the use of A3B5 photodiodes [www.vigo.com.pl, www.hamamatsu.com, www.ibsg.ru,

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Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
doi:10.1016/j.phpro.2015.09.151

www.ioffeled.com, Zakheim et al. (2009), Karandashev et al. (2007), Mikhailova et al. (2011), Starostenko et al. (2011)] to create photosensors applicable to the IR - measuring techniques (IR PhDS) is associated not only with their high sensitivity in the mid-IR range and the ability to work without bias and cooling, but mainly, with fast response time allowing the creation of broadband measuring devices for recording fast processes at the constant radiation level.

The main metrological characteristics of photosensors are their sensitivity, accuracy and time stability, i.e, the possibility of maintaining a predetermined accuracy and reproducibility of measurement results for a long time (calibration interval). Quantitative assessment of the PhDS accuracy is the uncertainty (error) of the photodiode current measurement that is usually characterized by PhDS equivalent input noise current.

This paper estimates the quantitative values of the effect of temperature fluctuations on the accuracy and sensitivity of sensors fabricated on the basis of different components. These evaluations are based on the analysis of mid-IR PhDS noise performance and they identify the requirements for temperature stabilization of mid-IR PhDS elements. As an example of the practical use of the obtained results, we present the expected characteristics of IR thermometers developed on the basis of A3B5 mid-IR PhDS. In total, they are superior to the known analogues by the set of parameters such as low detection limit, fast response time, high accuracy and reproducibility of the measurements.

2. Mid-IR PhDS noise analysis

PhDS noise consists of the photodiode thermal noise determined by its shunt resistance R_0 (t) and operational amplifiers (OP-amps) noise primarily characterized by the spectral density of current ($\sqrt{i_{OP}^2}$, A/√Hz) and voltage ($\sqrt{e_{OP}^2}$, V/√Hz) noise .

The temperature drift of the zero offset at the input of OP-amp, $dU_{OP\text{-}d}$ / dt, and 1/f noise described by the parameter $V_{OP\_p\text{-}p}$, represent in the whole the low frequency noise component of the PhDS which depends on the range of variation of operating temperature Δt and is superimposed in the form of an additive noise on the sensor output signal. Thus, the total equivalent PhDS input noise current can be written as:

$$I_n(\Delta f, t, \Delta t) = \\ = \sqrt{(i_{OP})^2 \cdot \Delta f + (\frac{e_{OP}}{R_0(t)})^2 \cdot \Delta f + \frac{4kT}{R_0(t)} \cdot \Delta f + \left(\frac{1}{R_0(t)} \cdot \frac{V_{OP\_p-p}}{6}\right)^2 + \left(\frac{1}{R_0(t)} \cdot \frac{dU_{OP\_d}}{dt} \cdot \Delta t\right)^2}, [A] \quad (1)$$

where the index «OP» designates the noise components inherent to the OP-amp.

As can be seen from (1), the contribution of the OP-amp noise is the more important the less is the PhD shunt resistance which is the main limiting factor for the A3B5 mid-IR PhDS sensitivity in a wide detection frequency band. Table I lists the published values of the specific dynamic resistance $R_0 \cdot A$ for PhDS of different spectral ranges and the estimated value of R_0 for the typical size of the photosensitive PhD area A~0.1 mm2.

The analysis of senor noise performed accomplished by Gavrilov et al.(2011) for the PhDS on the basis of different types of PhD and OP-amp has demonstrated that modern hardware components allows the implementation of the utmost threshold sensitivity of the A3B5 PhDS in the mid-IR region at room temperature, but only if the values of photodiode shunt resistance $R_0 > 50\Omega$. To achieve the limiting sensitivity threshold it is necessary to use amplifiers with voltage noise $e_{n\_OP} \leq 1$ nV/√Hz.

The differentiation of (1) with respect to the parameter R_0 (t) has shown that the total noise of the PhDS increases in proportion to the resistance temperature coefficient which is of the order of 4-5% at the change in temperature of 1 degree for the materials used for the manufacture of A3B5 mid-IR photodiodes (InAs, InAsSb, InGaAsSb solid solutions). Thus, to ensure the stability of the PhDS characteristics within 1% it is necessary, primarily, to provide the appropriate stability of the R_0 (t) value which can be achieved by maintaining a predetermined operating temperature within ± 0.1ºC. However, in some cases, the photodiode temperature stabilization is not enough. So, the last term under the square root in equation (1) depends on the range of possible changes in the operating temperature of the first amplifier stage. The analysis of OP-amp characteristics of different manufacturers indicates that typical temperature drift coefficient (dU_{OP_d}/dt) of the zero level (U_{OP_d}) for precision OP- amp is of the order of 200-500 nV / ºC, while for consumer OP- amp these values may reach few μA / ºC. Thus, the contribution of this noise component can be crucial for practical applications.

Table 1. The published values of the $R_0 \cdot A$ and the estimated value of the R_0 for the typical size of the photosensitive area A~0.1 mm^2 for photodiodes of different spectral ranges

	Spectral range				
	visible	near IR	mid-IR		
	0.2-1μm	1-2 μm	2-3 μm	3-4 μm	4-5 μm
$R_0 \cdot A$, Ω·cm^2	10^7-10^9 [www.hamamatsu.com]	~$5 \cdot 10^3$ [www.hamamatsu.com]	20 [Matveev et al. (2007), www.ioffeled.com] 27 [www.hamamatsu.com] 10-40 [www.ibsg.ru]	0.2-0.3 [Mikhailova et al.(2007)] 0.5-0.8 [www.ibsg.ru] 0.1-0.5 [www.vigo.com.pl] 1-1.5 [www.ioffeled.com]	0.01-0.002 [www.vigo.com.pl] 0.1-0.015 [Zakheim et al. (2009),www.ioffeled.com] ~0.15 [Starostenko et al. (2011)]
R_0, Ω (A=0.1 mm^2)	10^{10}-10^{12}	~$5 \cdot 10^6$	$(1\text{-}4) \cdot 10^4$	10^2-10^3	2-150

Aleksandrov et al. (2014) proposed a clear "noise vector" method for the PhDS noise analysis in order to select the best type of OP-amp to achieve extreme sensitivity characteristics of the sensor at the required speed and in a predetermined temperature range. The method consists in the fact that each of OP-amp can be characterized by some "noise vector" ON whose projection on the X-axis is defined by a frequency dependent current and voltage OP-amp noise components in the desired frequency band Δf (term 1 and 2 under the square root in equation (1)) and the projection on the Y-axis is defined by the low-frequency OP-amp noise components (terms 4 and 5 under the square root in equation (1)) whose total value depends on the range of variation of its operating temperature Δt. The optimization of a OP-amp choice in terms of minimizing the total sensors noise at the required speed of operation consists in the search of a OP-amp with a "noise vector" top that is inside the circle of radius $r = \sqrt{4kTR_0 \cdot \Delta f}$ equal in magnitude to the intrinsic photodiode thermal noise. Using the proposed method we can show that for high-frequency applications (Δf> 1 MHz), for the PhDS based on low-resistance photodiodes, the OP-amps spectral density of the voltage noise and zero offset temperature at the OP-amp input become crucial:

$$I_n(\Delta f, t, \Delta t) \approx \frac{1}{R_0(t)} \sqrt{(e_{OP})^2 \cdot \Delta f + 4kT \cdot \Delta f + \left(\frac{dU_{OP\_d}}{dt} \cdot \Delta t \right)^2}, [A] \qquad (2)$$

The analysis of the Analog Device products showed that the best sensitivity of the PhDS based on A3B5 photodiodes can be achieved by using the low-noise "zero drift" OP-amp of the AD4528 or ADA4895 / 96 types.

3. The threshold sensitivity of the mid-IR PhDS: evaluation and testing

The value P_{min} determines the threshold, or the lower power detection limit which generally corresponds to the photodiode current that equals or exceeds the PhDS current noise level by 2-3 times. It also determines the PhDS detection error (accuracy and sensitivity). The PhDS threshold sensitivity calculations were performed for two types of Analog Device manufacturers low-noise "zero drift" OP- amps with different levels of noise spectral density and temperature drift: AD4528 (i_n=0.7 pA/√Hz, e_n=5,6 nV/√Hz, dU_d/dt=0.8, nV/ºC) and ADA4895/96 (i_n=1.6 pA/√Hz, e_n=1 nV/√Hz, dU_d/dt=150 nV/ºC). The analysis was performed for the "fast" (Δf = 1MHz) PhDS that are of the greatest practical interest. The results of calculations of the maximum attainable PhDS sensitivity threshold depending on the A3B5 shunt resistance are represented as a graph in Figure 1 for two types of OP-amps. Dotted lines represent the threshold values (P_{d_limit}) of the PhDS detection limit (I (P_{min}) = In (Δf, t0, Δt)) defined only by the value of the photodiode shunt resistance R0 (t). Typical values of R0 (20 °C) for the considered A3B5 photodiodes [www.ioffeled.com] are marked on the charts by arrows. Changes in the P_{min} level depending on the various degrees of PhDS temperature stabilization are plotted as a shaded area. The lower boundary of the shaded area corresponds to the stabilization of the operating temperature of the sensor at Δt = 0.1 °C, and the top corresponds to a change in the operating temperature of the sensor at Δt = 40 °C.

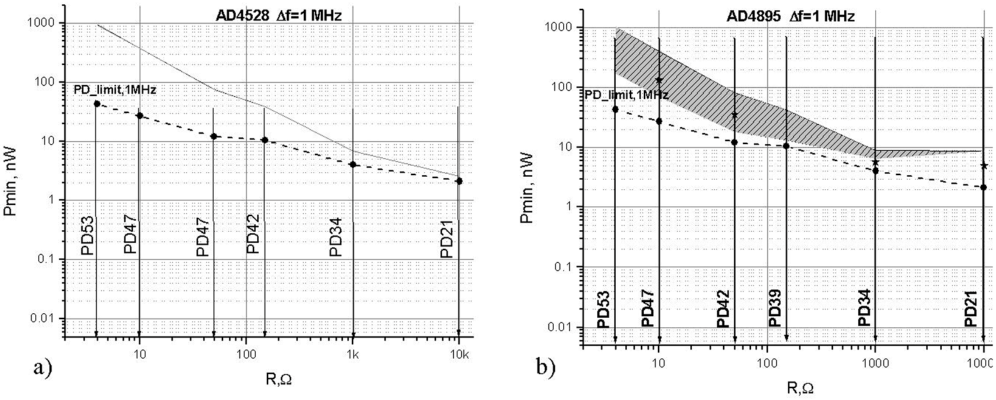

Fig.1. Threshold of the sensitivity for the PhDS based on A3B5 photodiodes with different R_0 values and OP-amps of AD4528 (a) and AD4895 (b) types in the frequency bandwidth 1 MHz and operating temperature variations from Δt = 0.1ºC to Δt = 40 ºC

As can be seen from the graphs in Figure 1, the upper and lower boundaries of this region for the detection frequency band 1 MHz for the "zero drift" OP-amp type AD4528 are almost identical, so you can use this OP-amp in most practical applications without additional temperature stabilization efforts. However, the PhDS based on OP-amp type ADA4895 with a minimum value of the voltage noise spectral density e_n = 1 nV/ √Hz could provide a possible lower detection threshold on condition that its temperature at Δt =0.1 ºC is stabilize.

The usefulness of the above conclusions is confirmed by studies of experimental models of high-speed PhDS based on various narrowband A3B5 photodiodes sensitive in the 2-5μm spectral range and Analog Device OP-amps taking the received recommendations into account. For all PhDS samples, the signal detection frequency band from 0 to 1 MHz ranged. As a part of the first stage of photodiode current amplification/conversion circuit (transimpedance amplifier), the OP-amp type AD4895 was chosen and mounted on a Peltier element (TEP) directly into the photodiode housing (Fig. 2, left).

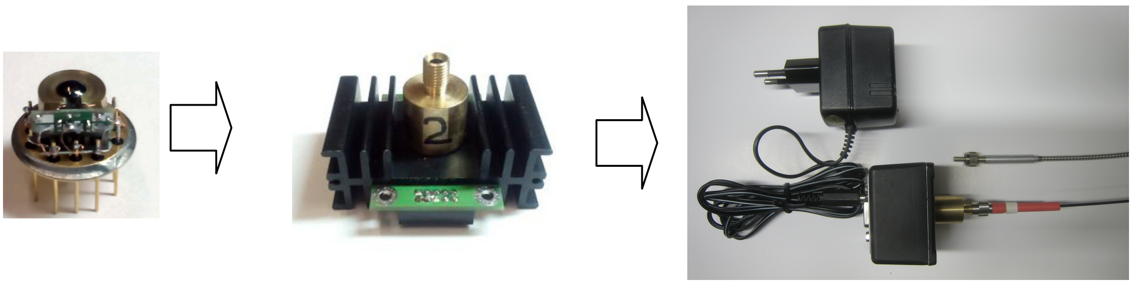

Fig.2. The design of the PhDS with OP-amp mounted on the TEP inside photodiode housing (left), PhDS hardware configuration (middle) and sensor external view in the set with a power supplier (plug pack) and fiber pigtail (right).

This design enables the ability to simultaneously stabilize the operating temperature of the photodiode and OP-amp chips. External electronic framing (Fig. 2, middle) of the PhDS contains additional signal amplification and TEP stabilization circuits with an accuracy of ± 0.1ºC at ambient temperature (20 ± 5 °C), which provides the lowest TEP power consumption. In the embodiment of the PhDS shown in Fig. 2, the photodiode housing is made with the input screw connector that allows one to deliver the input radiation by the fiber optic cable with a standard connector type SMA (Fig. 2, right).

The experimental values of the threshold sensitivity for experimental PhDS samples derived from the measured values of the noise dispersion are represented by the symbols (*) in Fig. 1b). The obtained values agree well with the results of the theoretical analysis. The deviations can be explained by differences of OP-amps parameters and values of the shunt resistance of actual photodiodes from the typical values used in the calculations.

4. Practical use: IR thermometers based on A3B5 PhDS.

Remote photometric measurements of the true temperature at the local areas of objects of different shape and composition with high temporal resolution are in great request in all areas of industry, medicine and research. They become especially important when developing new technologies as they allow real-time information on the phase transformations in materials of different composition and structure, on the kinetic features of the process, the quality and reproducibility of its results. Peculiarities of modern additive technologies state a complicated problem of the precise temperature measurements and its rapid fluctuations at the local (tens of microns) points of an object with high speed (tens of microseconds) in the low pyrometric temperature range (100 to 500 °C) and, therefore, they require the development of appropriate pyrometric sensor. From the point of view of the theory of the pyrometry the optimal spectral range for temperatures of 100-500 ° C is a mid-IR 2-5 μm spectral range (common relation λopt • T ~ 1500 μm • K to 100-500 °C gives the values of λ = 2-4 μm), which caused great interest to the use of A3B5 mid-IR PhDS in pyrometry.

Additional competitive advantage of the A3B5 photodiodes when used in IR thermometry shown by Sotnikova et al. (2011) is the ability to use a monochromatic approach to establish a connection between the temperature of the object and the measured current for the spectrally selective photodiodes made in BSI (back-side illumination) configuration manufactured by "IoffeLED" Ltd. [www.ioffeled.com]. This approach allows one, by using the Planck's law, to evaluate all the metrological characteristics of PhDS and compare them with current analogues. Such estimations have been carried out by us for A3B5 photodiodes with different spectral lines of sensitivity, PhDS speed 10 μs and objects with linear dimensions of the order of 1 mm^2.

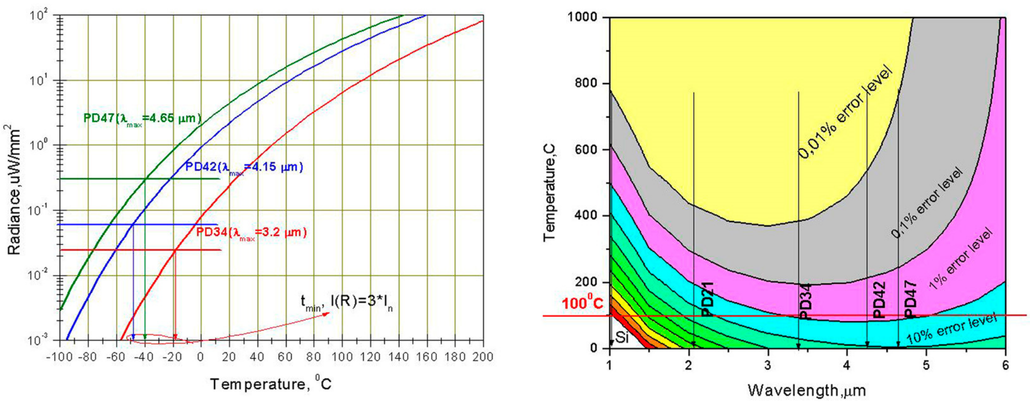

Fig.3. Expected data of the detection limit (a) and accuracy (fractional error) (b) for the pyrometric sensor based on A3B5 photodiodes manufactured by "IoffeLED" Ltd. [www.ioffeled.com] at the operation speed 10 μs and object area under study 1 mm^2.

The left chart of Fig. 3 shows the results of calculations of the expected temperature detection limit and the right one presents the accuracy (relative error) of these measurements. The estimates were obtained for mid-IR PhDS samples with the experimentally measured values of noise parameters plotted in Figure 1b).The calculations show that the proposed pyrometric sensors have a temperature detection limit below 0 °C at a speed of 10 ms for objects with linear dimensions of 1 mm and thus they provide the high accuracy (better than 1% of the measured value) in the temperature range from 100 °C.

5. Conclusion

It was theoretically justified and experimentally confirmed that in the problems of broadband measurements the sensors based on A3B5 mid-IR photodiodes provide the high accuracy and sensitivity, close to the theoretical limit that are restricted only by the thermal noise of the photodiode. This is performed under the condition of temperature stabilization of the photodiode chip and OP-amp within ± 0.1ºC, which is easily implemented via the TEC.

The "noise vector" analysis method allows us to estimate the characteristics of PhDS of different types in various practical applications and operating conditions.

The analysis of the drift component of the OP-amp noise has been carried out, and it became the basis of for the optimization of the PhDS design. Experimental samples of the sensors based on A3B5 photodiodes [8] with different spectral lines of sensitivity in the range of 2-5 microns have been manufactured and studied.

In the context of radiation pyrometry, it was shown that measuring devices, the IR thermometers based on mid-IR PhDS, could eventually provide the performance superior to the one currently known by the set of parameters: temperature measurement threshold (⩽0 ºC), speed of operation (tens of microseconds) and accuracy (not less than ±1°C or 1% of measuring value) in the temperature range from 100 ºC.

Acknowledgements

The authors thank "IoffeLED" Ltd. for providing the samples of the A3B5 photodiodes and for supporting this work.

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