ABSOLUTE RADIOMETER FOR THE VISIBLE REGION BASED ON SELF–CALIBRATING PHOTODIODES WITH THE HETEROGENEOUS STRUCTURE OF In_2O_3–SiO_x–nSi

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We discuss in this paper the physical grounds of self–calibration technique and describe a radiometer for the visible region (400–750 nm) based on self–calibrating photodiodes of In_2O_3–SiO_3–nSi. *A complex measurements of parameters of this radiometer are also discussed in the paper.*

The energy measurements of light fluxes are of great importance for practice of optical investigations in the atmosphere.[1] As this takes place, the radiometers are applied not only to measuring radiation fluxes, but to calibrating light sources and detectors as well.

In discussed radiometer we used the self–calibrating silicon photodiodes, whose spectral characteristic is directly measured from its electrical and optical parameters (Refs. 2, 3).

1. PHYSICAL GROUNDS OF SELF–CALIBRATION TECHNIQUE

The self–calibration technique firstly put forward in Ref. 3 uses the fact that calibration of a photodiode absolute spectral sensitivity (ASS) can be directly conducted based on its electrical and optical parameters. The advantages of such a technique are easy performance and high accuracy of measurements.

In this work we used the self–calibrating photodiodes with the heterogeneous structure of In_2O_3–SiO_x–nSi of the "semiconductor – tunelling–transparent dielectric – semiconductor" type. In such structures the induced in silicon p–n junction immediately emerges onto nSi–SiO_x interface.

As a result of the exchange of electric charges between nSi and degenerate wide–band semiconductor In_2O_3 of n–type near the interface of nSi–SiO_x the p–n junction is induced in silicon. The depth of penetration of the p–n junction field into silicon is determined by the expression

$$l = [2\varepsilon_0\, \varepsilon(\varphi_0 + U) / e\, n]^{1/2}\,, \qquad (1)$$

where ε_0 is the electric constant; ε is the absolute dielectric constant of a semiconductor; n is the concentration of majority carriers in Si; e is the electron charge; φ_0 is the potential barrier value; and, U is the back bias voltage.

The monochromatic radiation flux $N(\lambda)$ incident on a photodiode (PD) and partially reflected by its surface becomes equal $N(\lambda)\,\rho(\lambda)$, where $\rho(\lambda)$ is the spectral reflection factor of the PD surface. The rest of the radiation $[1 - \rho(\lambda)]N(\lambda)$ penetrates into interior of PD.

Radiation with quantum energy smaller than the width of the In_2O_3 forbidden band (~ 3.6 eV) is not essentially absorbed in In_2O_3 and penetrates into Si, where the quanta which are larger in energy than the width of the Si forbidden band (~ 1.1 eV) are effectively absorbed.

The probability of the electron–hole pair formation in range of quanta energies from 3.6 to 1.1 eV (spectral range of 400–1000 nm) is close to unity, since the absorption on free carriers is infinitesimally low ($\alpha_e \sim 10^{-20}\,\lambda^2$).

The coefficient of collection of the minority photocurrent carriers depends on the ratio of the speed of the leading minority carriers from the recombination region and the effective rate of recombination. For present structure the speed of the leading minority carriers is 10^8–10^9 cm/s, and the effective rate of recombination is approximately equal to 10^3 cm/s. Thus, the coefficient of collection of the minority photocurrent carriers $\varepsilon(\lambda)$ in PD differs from unity by the value of 10^{-5}–10^{-6}, i.e., in fact it is unity. The sensitivity of PD at zero back bias can be determined from the expression

$$S(\lambda) = [1 - \rho(\lambda)]\, \varepsilon(\lambda)\, \lambda / k\,, \qquad (2)$$

where $\varepsilon(\lambda) = J_0/J_s$, J_0 and J_s are the photocurrents corresponding to the back bias values of U_0 and U_s; $k = 1.24$ μmW·A^{-1}.

In the case of complete absorption of an incident monochromatic flux the spectral sensitivity of the self–calibrating PD linearly depends on wavelength

$$S(\lambda) = \lambda / k\,. \qquad (3)$$

2. RESULTS OF MEASUREMENTS OF THE SELF–CALIBRATING PHOTODIODES CHARACTERISTICS

We determined the absolute spectral sensitivity (ASS) of the photodiode using the technique of comparison with a reference detector, whose ASS is known.[2] For the most part of measurements we used the silicon photodiodes of PD–24 K type as reference ones.

The ASS of photodiode under study was determined by measuring photocurrents of the studied photodiode $J_{pd}(\lambda)$ and the reference one $J_{ref}(\lambda)$ in a chosen spectral range

$$S_{pd}(\lambda) = [J_{pd}(\lambda) / J_{ref}(\lambda)]\, S_{ref}(\lambda)\,, \qquad (4)$$

where $S_{ref}(\lambda)$ is the ASS of the reference photodiode.

The measurement results show that for the oxide of In_2O_3 30 μm thick the spectral reflection factor of a PD in the spectral range from 400 to 1000 nm does not depend on wavelength, and the ASS linearly depends on λ (see Fig. 1) in the spectral range from 400 to 750 nm in accordance with Eq. (3).

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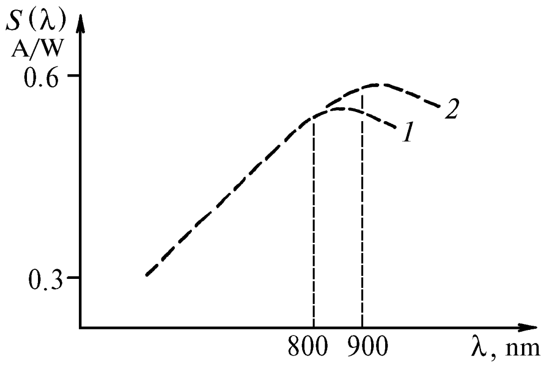

FIG. 1. The photodiodes spectral sensitivity for the silicon specific resistance of 100 *(1) and* 400 Ω/cm *(2)*.

We have also experimentally determined that the back bias voltage applied to a PD widens operating spectral range of the self–calibrating up to λ = 900 nm.

It is evident from the physical grounds of the self–calibrating PD that there are not physical reasons for the occurrence of nonlinearity in WAC for the photodiodes whose coefficient of the minority carriers collection is equal to hundred per cent.

The nonlinearity of PD sensitivity is determined by the following expression at zero back bias voltage:

$$\eta = 1 - J_0 / J_s , \quad (5)$$

where J_0 is the photocurrent at zero back bias, and J_s is the saturation photocurrent for back bias on the p– n junction.

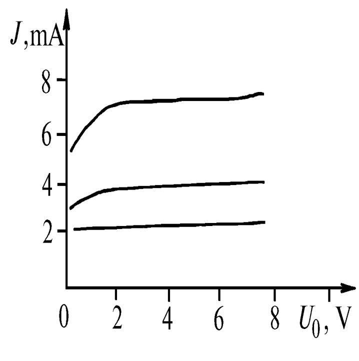

FIG. 2. Photocurrent dependence on the back bias value U_0 *at various illuminance E*.

The results of measurements of the photocurrent dependence on the back bias value applied to PD are shown in Fig. 2. The PD nonlinearity η does not exceed 0.02% in the photocurrent range of 10^{-7}–10^{-2} A. As is follows from the above mentioned data the violation of linearity at zero back bias imposed across PD begins when photocurrent is approximately equal to 1.5 mA. As this takes place, the storage of photocurrent increases with the increase in illuminance. The back bias restores the linearity range of a PD operation.

Generally, the PD time lag is determined by the diffusion time or the time of the nonequilibrium carriers drift through base (τ_{dif}), as well as the time of its flight through the spatial charge region (SCR) of p–n junction (τ_i), and the circuit time constant (τ_{RC}) (see Ref. 4)

$$t_{pd} = (\tau_{dif}^2 + \tau_i^2 + \tau_{RC}^2)^{1/2} , \quad (6)$$

where t_{pd} is the PD time constant.

To attain simultaneously both high speed and high quantum efficiency the region of light absorption must reside within the spatial charge region. There is no a front diffusive region (τ_{dif} = 0) in the self–calibrating PD with the heterogeneous structure In_2O_3–SiO_x–nSi. In this case t_{pd} depends on τ_i and τ_{RC} only.

For the silicon specific resistance of 300–400 Ω/cm the depth of junction penetration into PD is equal to 10 μm. In this case the radiation with wavelength from 400 to 750 nm is completely absorbed in SCR. The SCR field accelerates generated carriers up to the drift saturation speed $V = 2\cdot10^4$ m/s, for such a heterogeneous structure. For a photodetector with the photosensitive area of 130 mm^2 and the SCR depth of 10 μm the junction capacitance is $1.43\cdot10^3$ pF and, consequently, $\tau_{RC} \approx 70$ ns.

To determine the temporal parameters of individual photodiodes with a heterogeneous structure, which are incorporated into radiometer, we used YAG laser operating in regime of self–synchronizing modes with separation of a single pulse from train. The pulse duration t_p was approximately equal to 20 ns at the wavelength of the second harmonic λ = 0.532 μm. The pulse repetition frequency was equal to 50 Hz. The response pulse was recorded with a stroboscopic oscilloscope S9–9. The rise time of a photodiode is 70 ns for 50 Ω load, at back bias voltage U_{back} = 12 V the rise time is 45 ns (see Ref. 4).

The temperature dependence of the PD spectral characteristic measured with the technique,[3] which is an analog of the technique for ASS measurements, is presented in Fig. 3. Coefficient of temperature sensitivity is 0.005%/°C in the spectral range from 400 to 750 ns.

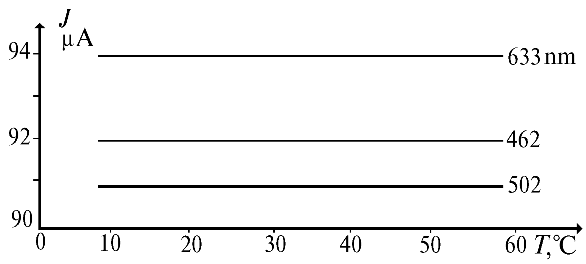

FIG. 3. Temperature dependence of ASS.

3. RADIOMETER CONSTRUCTION

From the physical model of charge transfer in the heterogeneous structure of In_2O_3–SiO_x–nSi it follows that when the monochromatic light flux incident on PD is completely absorbed, and coefficient of collection of the minority photocurrent carriers is equal to unity, the spectral sensitivity of PD linearly depends on λ (see Eq. 4).

Designed construction of the radiometer consists of four self–calibrating photodiodes positioned in body so, that the radiation coming to the radiometer undergoes seven reflections (Fig. 4). The radiometer reflectivity does not depend on λ and is about 0.02% in the spectral range 400–750 nm.

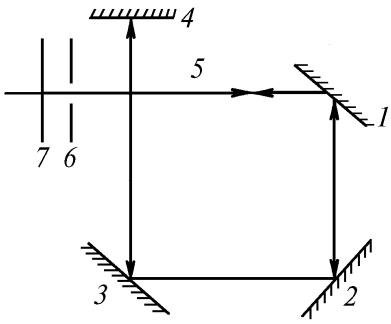

FIG. 4. Construction of radiometer with complete absorption. Shown in the figure are photodiodes (1–4), light beam (5), diaphragm (6), and filter (7).

Determination of the deviation of the coefficient of minority photocurrent carriers collection from unity from measurements of the photocurrent dependence on back bias voltage is sufficient for self–calibration of designed radiometer over ASS.

In "element by element" estimating (in oder to determine inherent systematic error (ISE) of the ASS measurements for radiometers with complete absorption) we obtained the value of ISE being equal to 0.06%.

We also carried out the comparison of sensitivities of several radiometers at various wavelength. During one year variations in measurements results did not exceed 0.19%.

CONCLUSION

Designed radiometer with complete absorption is the self–calibrating one and provides high linearity of ASS in the photocurrent range from 10^{-2} to 10^{-7} A. As this takes place, the temperature variations coefficient does not exceed 0.005%/°C in the temperature range from +10 to +60°C. Small time lag allows the pulse light sources to be used in studies. The linearity of ASS in combination with other radiometer characteristics allows the radiometer to be used in solving a wide range of the problems of atmospheric optics, the optical location and sensing problems as well as for calibration of photodetectors and light sources.

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