

Quadrant-detector on the basis of InGaAsP heterostructures

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ABSTRACT

A new device called selective quadrant-detector, realized on the basis of InGaAsP heterostructures, is presented in the paper. It consists of a circular photodiode-quadrant with protective peripheric ring, having selective sensibility optimized for $\lambda = 1.06 \mu\text{m}$, in the center of which a photodetector integrated in the same crystal is formed. The photodetector has own capacity $C = 1\text{-}5 \text{ pF}$ and can be used for receiving the high frequency ($f > 1 \text{ GHz}$) optic signals and the small duration ($t \leq 1 \text{ ns}$) unitary signals. The presence of central photodetector decreases the coordinate characteristic abruptness ($K = 8 \cdot 10^3 \text{ V} \cdot \text{W}^{-1} \cdot \text{mm}^{-1}$) and photocurrent intensity with 8-10 %. Absolute spectral sensibility is $S_{\lambda=1.06} = 0.57 \text{ A/W}$ and photosensitivity spectrum semiwidth is $\Delta\lambda \leq 100 \text{ nm}$.

Keywords: photodiode, quadrant, InGaAsP heterostructure, infrared radiation, photosensitivity.

1. INTRODUCTION

Photodiode-quadrant (PDQ) with selective sensibility, elaborated and manufactured previously, is optimized for receiving the optic signals with $\lambda = 1.06 \mu\text{m}$ and is used in optoelectronic systems for orienting and directing the high velocity objects.^{1,2} According to calculations and measurements, the PDQ has an absolute spectral sensibility $S_{\lambda=1.06} = 0.57 \text{ A/W}$, an abrupt coordinate characteristic $K = 8 \cdot 10^3 \text{ V} \cdot \text{W}^{-1} \cdot \text{mm}^{-1}$ and can be successfully used for receiving the unitary optic signals with impulse duration $\geq 10 \text{ ns}$ and with incident optic power $\sim 1 \text{ mW}$ or for receiving the optic signals with limit frequency $\sim 20 \text{ MHz}$. The obtained values are limited here by relatively big area of PDQ, necessary to ensure the coordinate characteristic, which is the main characteristic of all photoreceivers with coordinate sensibility.

2. ESTIMATION OF PDQ LIMIT FREQUENCY AND ANSWER TIME

The photoanswer time of PDQ was determined for a standard load resistance $R_l = 50 \Omega$ to appreciate its limit possibilities. Two methods were utilized: after frequency characteristic and after transition characteristic of photodiode illuminated by a rectangular light impulse.

The photocurrent depending on frequency of optic signal throb was measured using the scheme presented in Fig. 1.

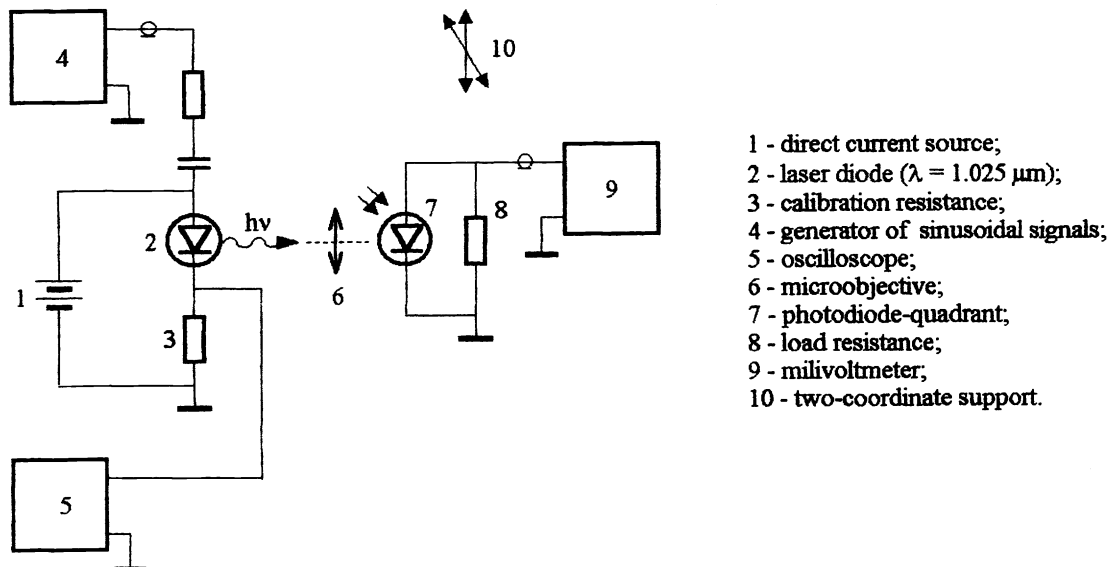


Fig. 1. Scheme of instalation for measuring the photocurrent depending on frequency of optic signal throb.

The frequency dependence of photocurrent transmission coefficient (K) for different reverse polarisation are shown in Fig.2. The mathematical expression of this dependence is:

$$K = 1 / \sqrt{1 + (2\pi f\tau)^2} \quad (1)$$

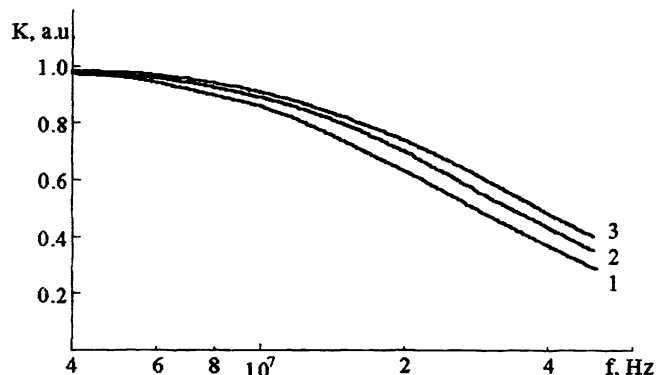


Fig.2. Frequency dependence of photocurrent transmission coefficient:
 U_{rev}, V : 1 - 0; 2 - 0.5; 3 - 1.0.

The photodiode transmission coefficient is determined practically as $K = U_f / U_o$, where U_f and U_o are photosignals at high and low frequency.

The photoanswer limit frequency is estimated from Fig.2 at level $K = 0.707$ and deals with time constant τ by expression:

$$\tau = 1 / (2\pi \cdot f_{lim}) \quad (2)$$

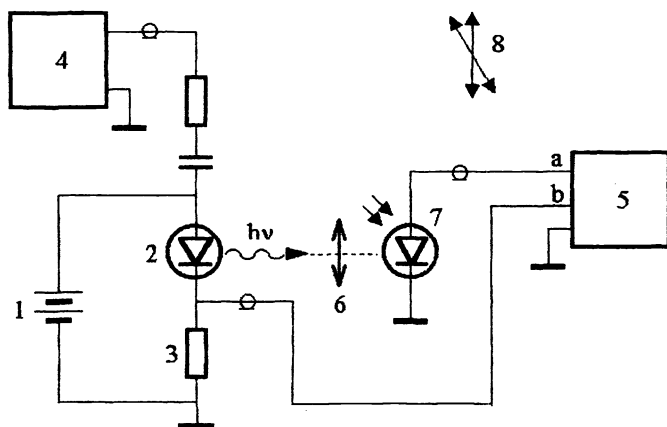
When the time constant is determined by p-n junction capacity and transition characteristic has an exponential form, the photoanswer time is determined at levels 0.1 and 0.9 of photocurrent maximum value or by relation

$$t_a = \tau \cdot \ln 9 \approx 2.2 \cdot \tau \quad (3)$$

Thus, measuring the limit frequency we determine the answer time for all quadrant sectors.

This method requires low intensity optic signals to ensure the straight sector of energetic characteristic $I_{ph} = f(\Phi_o)$. The minimizing of conductor capacity influence is also required. It have been observed for conductor total length $l < 0.4 m$, where conductor capacity is $< 30 pF$.

Measurements had showed that the time constant τ is determined by load resistance R and barrier capacity C. The p-n junction barrier capacity without polarisation is about $C = C_b \approx 200 pF$ for each quadrant sector. The limit frequency is $f_{lim} = 16-18 MHz$ and the answer time is $t_a = 22 ns$. Using the differential connecting of quadrant sectors we had decreased twice the answer time, practically equalizing it to $\tau = t_a \approx 10 ns$. Reverse polarizing the PDQ with $U_{rev} = 1 V$ we had decreased the barrier capacity up to $C_b = 145 pF$ and the answer time up to $t_a = 7 ns$.



- 1 - direct current source;
- 2 - laser diode ($\lambda = 1.025 \mu m$);
- 3 - calibration resistance;
- 4 - generator of nanosecond impulses;
- 5 - stroboscopic oscilloscope;
- 6 - microobjective;
- 7 - photodiode-quadrant;
- 8 - two-coordinate support.

Fig.3. Scheme of instalation for study the photoanswer form.

The complete calculus of coordinate characteristics family $U(x, y_0)$ doesn't present a practical importance. Therefore, we had calculated the coordinate characteristic for the case $y = 0$, i.e. the light spot is symmetrical to axis "x". In this case the coordinate characteristic has four different domains with different mathematical expressions. They are:

- domain I - $0 \leq \bar{x} < 1 - \bar{r}$;
- domain II - $1 - \bar{r} \leq \bar{x} < 1$;
- domain III - $1 \leq \bar{x} < 1 + \bar{r}$;
- domain IV - $1 + \bar{r} \leq \bar{x}$,

where \bar{x} and \bar{r} are light spot coordinate and central detector radius reported to light spot radius ($\bar{x} = x/R$, $\bar{r} = r/R$). The characteristic points are $1 - \bar{r}$, 1 , $1 + \bar{r}$ and are noted in Fig.5 by "A", "O", "B".

Forming the mathematical expressions of coordinate characteristics, it was observed that domains 2, 3 and 4 are divided also in two parts with characteristic points $\sqrt{1 - \bar{r}^2}$ and $\sqrt{3}$.

Thus, the coordinate characteristic has a lot of domains with following analytic expressions:

- 1) $U(x) = 1/\pi (\pi + F_0)$, for $0 \leq \bar{x} < 1 - \bar{r}$;
- 2) $U(x) = 1/\pi (\pi + F_0 + F_1 + F_2)$, for $1 - \bar{r} \leq \bar{x} < \sqrt{1 - \bar{r}^2}$;
- 3) $U(x) = 1/\pi (\pi - F_1 + F_2)$, for $\sqrt{1 - \bar{r}^2} \leq \bar{x} < 1$;
- 4) $U(x) = 1/\pi (\pi - F_1 + F_2 + F_3 + F_4)$, for $1 \leq \bar{x} < 1 + \bar{r} < \sqrt{3}$;
- 5) $U(x) = 1/\pi (-F_1 + F_2 - F_3 + F_4)$, for $\sqrt{3} \leq \bar{x} < 1 + \bar{r}$ (if $1 + \bar{r} > \sqrt{3}$);
- 6) $U(x) = 1/\pi (\pi + F_3 + F_4)$, for $1 + \bar{r} \leq \bar{x} < \sqrt{3}$ (if $1 + \bar{r} < \sqrt{3}$);
- 7) $U(x) = 1/\pi (-F_3 + F_4)$, for $\sqrt{3} < 1 + \bar{r} < \bar{x} < 3$ (if $1 + \bar{r} > \sqrt{3}$).

$U(x)$ here is a parameter proportional with photocurrent through load resistance and show the relative difference of illuminated quadrant sectors, connected differential with load resistance.

The other parameters are:

$$\begin{aligned}
 F_0 &= -2 \operatorname{arctg}(b_0/a_0) + 2a_0 \cdot b_0; & F_1 &= \operatorname{arctg}(b_1/a_1) - a_1 \cdot b_1; \\
 F_2 &= -\bar{r}^2 \cdot \operatorname{arctg}(b_2/a_2) + \bar{r}^2 \cdot a_2 \cdot b_2; & F_3 &= -\operatorname{arctg}(b_3/a_3) + a_3 \cdot b_3; \\
 F_4 &= 4 \cdot \operatorname{arctg}(b_4/a_4) - 4 \cdot a_4 \cdot b_4; \\
 a_0 &= \bar{x}; & b_0 &= \sqrt{1 - a_0^2}; \\
 a_1 &= \frac{\bar{x}}{2} + \frac{1 - \bar{r}^2}{2\bar{x}}; & b_1 &= \sqrt{1 - a_1^2}; \\
 a_2 &= \frac{1}{\bar{r}} \left(\frac{\bar{x}}{2} - \frac{1 - \bar{r}^2}{2\bar{x}} \right); & b_2 &= \sqrt{1 - a_2^2}; \\
 a_3 &= \left| \frac{3}{2\bar{x}} - \frac{\bar{x}}{2} \right|; & b_3 &= \sqrt{1 - a_3^2}; \\
 a_4 &= \frac{3}{4\bar{x}} + \frac{\bar{x}}{4}; & b_4 &= \sqrt{1 - a_4^2};
 \end{aligned}$$

We have to remark that these calculi are true for linear region of PDQ energetic characteristic $I_{ph} = f(Q)$. This region is characterized by low intensities of incident flux Q or by utilizing a load resistance more less than p-n junction resistance (short-circuit regime, $R_s < R_{p-n}$).

The evolution of coordinate characteristic depending on central detector radius is presented in Fig.6. One can see that coordinate characteristic abruptness doesn't change practically up to $d/R_Q = 0.5$ and maximum voltage on the load resistance decreases with $< 10\%$ for central detector diameter $d \leq 400 \mu\text{m}$ ($d/R_Q = 0.4$). Therefore, the PDQ center can be used without any essential losses in coordinate characteristic to fabricate an integrated photodetector with low own capacity, capable to receive optic signals with high frequency ($> 1 \text{ GHz}$) and unitary ones with impulse duration $< 10 \text{ ns}$.

The second method permits to visualize the form of photoanswer impulse by a stroboscopic oscilloscope. The precision of this method is less because of difficulty in small duration rectangular photoimpulses forming and in measuring the low intensity ($\sim 10\text{-}20\text{ mV}$) and duration ($\sim 1\text{ ns}$) electric signals.

The scheme of instalation for study the photoanswer form is presented in Fig.3.

The photocurrent of one PDQ sector increases from $0.1 \cdot I_{\max}$ to $0.9 \cdot I_{\max}$ in $t_a \approx 20\text{-}25\text{ ns}$, what corresponds to result obtained by the first method.

Obtained values are extreme because the relatively big area of PDQ, necessary to ensure the coordinate characteristic, determines the big capacity of quadrant sectors. To extend the functional possibilities of PDQ we have elaborated and manufactured a new structure with an integrated central detector.

3. STRUCTURE, CHARACTERISTICS, PARAMETERS

The new structure ensures a selective spectral sensibility with maximum for $\lambda = 1.06\text{ }\mu\text{m}$, an abrupt coordinate characteristic, the detection of unitary optic signals with impulse duration $< 10\text{ ns}$ or of optic signals with frequency $> 1\text{ GHz}$. Fig.4 shows the structure section (a) and the frontal view (b) of selective photodiode-quadrant with integrated detector.

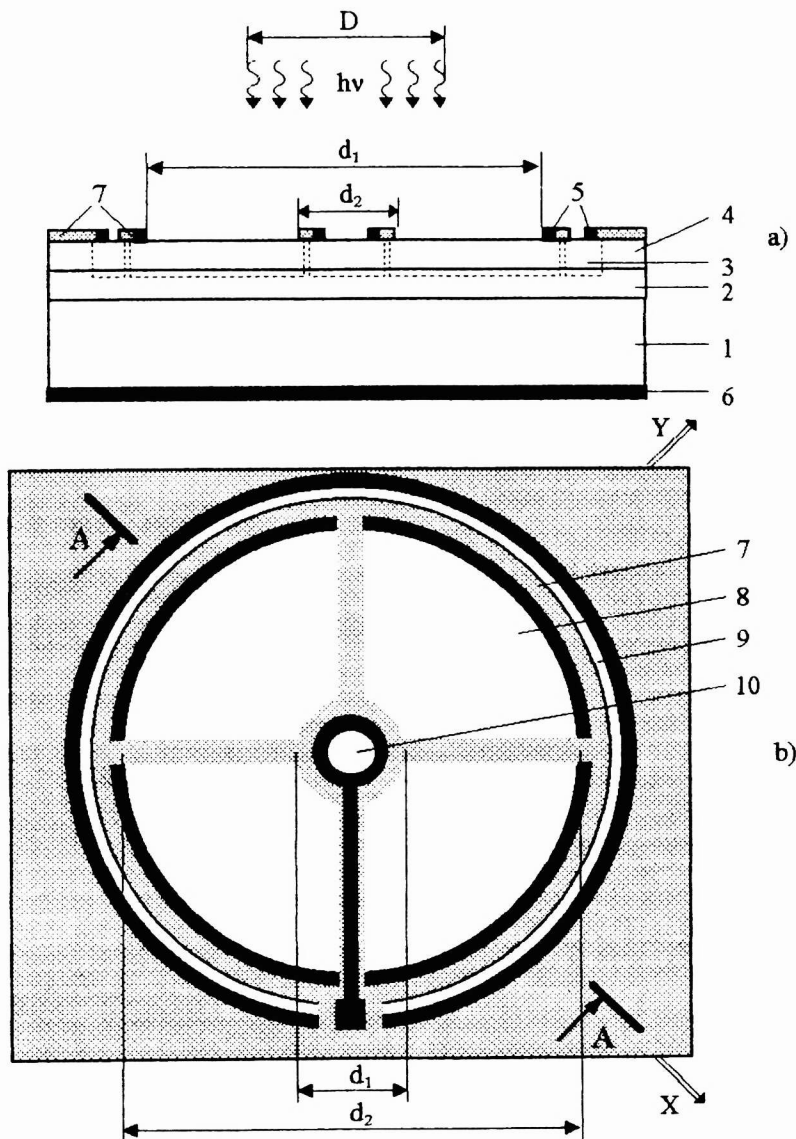


Fig.4. Selective photodiode-quadrant with integrated detector:
a - cross-section of structure; b - frontal view.

PDQ consists of n⁺InP substrate 1, InGaAsP active layer 2, in which p-n junction 3 is placed, InGaAsP frontal layer 4, frontal metal contacts 5 and back contact 6. Separation of the whole surface into photosensible elements was made concomitantly with p-n junction forming by local diffusion of Zn through a SiO₂ mask 7. PDQ contains four elements 8 having circular sector form and a protective peripheric ring 9. A circular photoelement 10 with diameter $d_1 \leq 0.1 \cdot d_2$ (d_2 - diameter of PDQ active surface) was made in the center of PDQ.

The optic signal has a circular spot form with diameter $D = d_2/2$. When the optic signal is symmetrical respecting the center, photocurrents of those four circular sector elements 8 are equal. At optic signal moving after axes "x" or "y" the difference between photocurrents of two opposite sectors linear increases depending on coordinate. The peripheric ring 9 signals the moment when optic signal begin to go out the PDQ. Since the central detector 10 area is minimum 100 times less than PDQ one, the presence of central detector didn't change the coordinate characteristic abruptly. On the other hand, the central detector having a small area possesses a very low own capacity. It means that the time constant $\tau = R \cdot C$ gets small values, what permits to receive optic signals with frequency > 1 GHz and unitary ones with impulse duration < 10 ns.

To determine the utilization fields of quadrant-detector we have to estimate the influence of central detector upon the PDQ characteristics and parameters. Since coordinate characteristic is the most important we study its evolution depending on central detector diameter.

The scheme of quadrant-detector surface is shown in Fig.5. Radius of photosensible sectors was $R_Q = 1$ mm; radius of optic signal spot was $R = 0.5$ mm = $R_Q/2$ and central detector radius "r" was variable. The coordinate of light spot center "x" was changing from zero (quadrant-detector center) to $3R = 1.5$ mm (spot completely went out the PDQ).

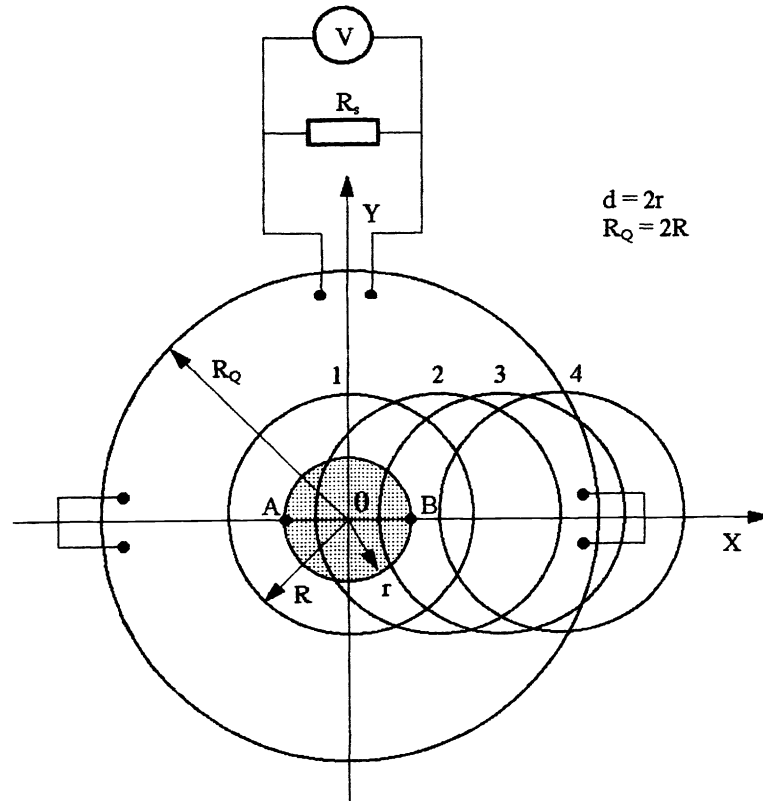


Fig.5. The scheme of quadrant-detector surface.

In general case, for PDQ with or without central detector, at differential connection of quadrant sectors, the electric signal on load resistance and, therefore, coordinate characteristic depend on both coordinate "x" and coordinate "y". To simplify the calculi, the dependence on "y" can be excluded by parallel connecting the sectors from the left and right side of axis "y" (see Fig.5). In this case the coordinate characteristic is transformed in a family of characteristics $U(x, y_0)$, where y_0 is a parameter.

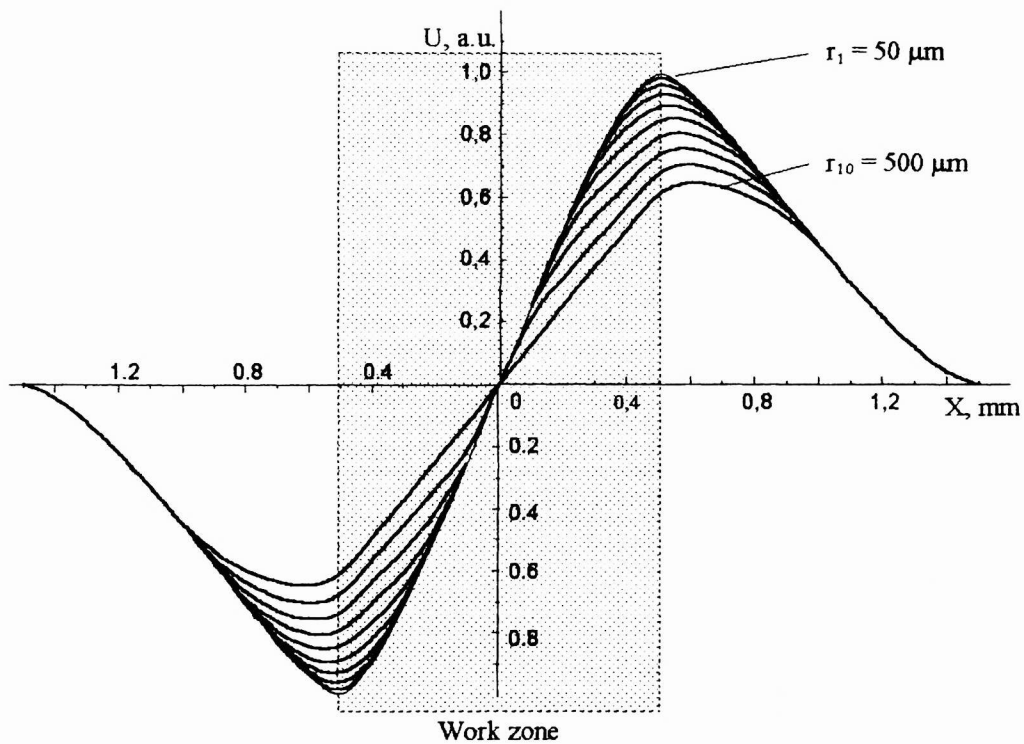


Fig.6. Evolution of coordinate characteristic depending on central detector radius.

A manufactured quadrant-detector encapsulated in capsule TO-5 is illustrated in Fig.7 and its main parameters are presented in the table.

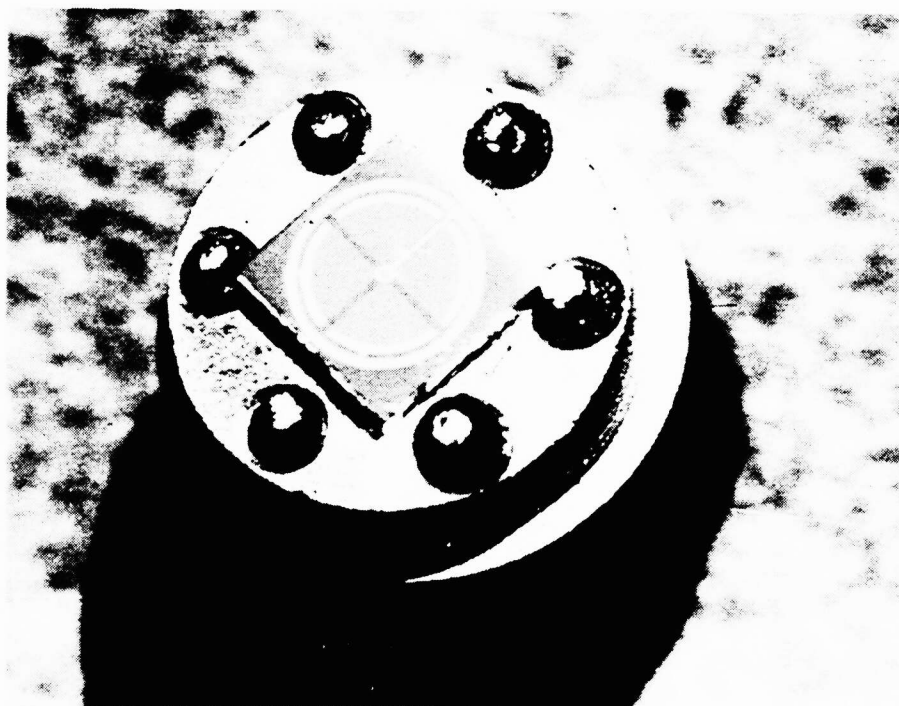


Fig.7. Quadrant - detector.

No.	Parameters	Value
1	Chip dimensions, mm × mm	3 × 3
2	Diameter of photodiode quadrant-detector, mm	2.6
3	Radius of photosensible sectors (R_0), mm	1
4	Diameter of central photodetector (d), μm	200
5	Width of protective peripheric ring, μm	150
6	Width of metal contacts: of quadrant, μm of central detector, μm	100 50
7	Width of SiO_2 separative strips, μm	100; 50
8	Radiation wavelength in maximum photosensitivity (λ_{max}), μm	1.06
9	Semiwidth of photosensitivity spectrum ($\Delta\lambda$), nm	< 100
10	Absolute sensibility ($S_{\lambda_{\text{max}}}$), A/W	0.57
11	Quantum efficiency (η), %	60
12	Own capacity of a quadrant photosensible sector (C_0^h), pF	190
13	One sector capacity for reverse voltage $U_{\text{rev}} = 1.5 \text{ V}$ (C_0^h), pF	145
14	Own capacity of central detector (C_0^v), pF	4
15	Own capacity of central detector for $U_{\text{rev}} = 1.5 \text{ V}$ (C_0^v), pF	1.5
16	Abruptness of coordinate characteristic (K), $\text{V}\cdot\text{W}^{-1}\cdot\text{mm}^{-1}$	$8\cdot 10^3$

4. CONCLUSIONS

A new device called selective quadrant-detector with large functional possibilities was realized for the first time. It can successfully work in two regimes: detection of high frequency ($f > 1 \text{ GHz}$) optic signals, of small duration ($t \leq 1 \text{ ns}$) unitary signals and coordinate determination. It has coordinate characteristic abruptness $K = 8\cdot 10^3 \text{ V}\cdot\text{W}^{-1}\cdot\text{mm}^{-1}$, absolute spectral sensibility $S_{\lambda=1.06} = 0.57 \text{ A/W}$ and photosensitivity spectrum semiwidth $\Delta\lambda \leq 100 \text{ nm}$.

5. REFERENCES

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