Spectral dependence of main parameters of ITE silicon avalanche photodiodes

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ABSTRACT

New applications for avalanche photodiodes (APDs), as in systems using visible radiation, have prompted the need for the evaluation of detection properties of ITE APDs in the 400 ÷ 700 nm spectral range.
The paper presents the method and results of studies on the spectral dependence of the gain, dark and noise currents, sensitivity and excess noise factor of ITE APDs. The studies have shown that ITE APDs optimised for the near infrared radiation (800 ÷ 850 nm) can be effectively applied in the detection of radiation above the 500 nm wavelength.

Keywords: silicon avalanche photodiode, spectral dependence

1. INTRODUCTION

New applications of silicon avalanche photodiodes, foremost in scintillation detection of nuclear radiation, have brought about the need for their characterisation in the visible and ultraviolet range of radiation that is emitted by known scintillating materials.
Silicon avalanche photodiodes for scintillation detection are being used in many experiments in physics of high-energy particles, in medicine, etc. Also, the development of new techniques for monitoring environment or for controlling food processing has renewed the interest in avalanche photodiodes that can co-operate with short-wave radiation sources [1-6].
In the present work, the method and results of the study on the spectral dependence of the basic properties of silicon avalanche photodiodes developed and fabricated at the ITE are discussed. A reach-through structure of these photodiodes is optimised for the detection at wavelengths of λ = 800 – 850 nm.
The study was conducted in the 400 – 1000 nm spectral region. The properties of APDs in the spectral region of 400 –700 nm (the visible radiation) were compared with those in the region of near infrared radiation. This research enabled to determine the spectral range in which ITE avalanche photodiodes attain good detection properties.
New ITE avalanche photodiodes, with the 5 mm diameter active area, were subjected to the examination. The selected results were compared to the results obtained for the 1.5 and 3 mm diameter ITE avalanche photodiodes.
The spectral characteristics of the following parameters were examined;

- gain of photoelectric current - M
- photodiode noise current - I_N
- excess noise factor - F.

The knowledge of spectral dependence of the gain (at I_N= cons.) and of the noise current - I_N (for M = cons.) enables to determine:

- a spectral characteristic of the total sensitivity of an avalanche photodiode $S_\lambda = S_{\lambda 0} \times M$, where $S_{\lambda 0}$ is the primary photoelectric sensitivity (M = 1) conditioned by a quantum efficiency of the photoelectric phenomenon, in similar way as sensitivity of PIN photodiodes.
- a value of NEP (NEP = I_N/S_λ) at λ = cons.

An excess noise factor is also a very important parameter of avalanche photodiodes since it determines the noise brought by the avalanche phenomenon.
The design and technology of avalanche photodiode should ensure a high gain, low noise current, low excess noise factor of a photodiode in a wide spectral range of detection.
An avalanche photodiode made in silicon - the material in which the ionising coefficients of electrons are always higher than the ionising coefficients of holes - should be designed in such a way as to ensure that mainly optically generated electrons would take part in the avalanche processes. The multiplication of optically generated holes significantly worsens the quality of silicon avalanche photodiode parameters, especially it decreases the value of gain and increases an excess noise factor. At the same time, the magnitude of electric field shouldn't be higher than 3.5×10^5 V/cm in order to ensure the small ratio of hole to electron ionising coefficients [7]. To fulfil these requirements, the optical generation of carriers should take place in p type region (most often of the high resistivity) adjacent to the p-n avalanche region, in which the electrons

moving towards the p-type layer are multiplied. For the avalanche photodiodes with the given design, the spectral range of operation is conditioned by the number of optically generated electrons in a total photoelectric current moving into the avalanche region.
In the ITE silicon avalanche photodiodes, participation of holes in a primary photoelectric current is negligible for the spectral region of $\lambda > 800$ nm. The lesser the wavelength, the larger is the participation of optically generated holes in the avalanche phenomenon within the photodiode structure.

2. THE DESCRIPTION OF THE ITE AVALANCHE PHOTODIODE DESIGN

A family of silicon avalanche photodiodes (APDs) with an active surface area of the 0.3, 0.5, 0.9, 1.5, 3, and 5mm diameters has been designed and developed at the Institute of Electron Technology (ITE) Warsaw, Poland. These photodiodes were optimised for the detection of near-infrared radiation at the wavelengths of 800 – 850 nm [8].
The epiplanar structure of these avalanche photodiodes is of an n^+-p-π-p^+ type with an n^+-p hyper-abrupt junction in the central region of structure (see fig. 1)

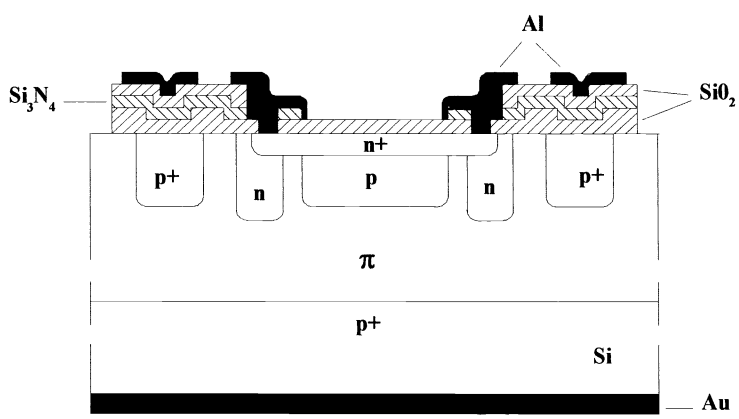

Fig.1 Cross-section of the avalanche photodiode structure developed at the ITE

The 4 μm thick, p-type region, which is inside the 30 – 35 μm thick, highly resistive, π type epi-layer, is formed by boron implantation and then its re-diffusion. The n^+ type region is made by the arsenic diffusion from amorphous silicon (doped in situ). The active area (avalanche, photosensitive) is surrounded by the n type, under-contact ring and by p^+ channel stopper ring. The photosensitive surface of photodiode is covered with a SiO_2 antireflection layer.
The ITE avalanche photodiodes with the type of structure described above, in the optimal spectral range of 800 ÷ 850 nm have high gains M > 100 at low noise current (I_N<2 pA/Hz$^{1/2}$), small excess noise factors (F ≈ 4 at M = 100). The values of these parameters are achieved at relative low operating voltages, typically 180- 220 V.
Also, these APDs are characterised by high speed of performance; for example, the rise time is 4.5 ns for photodiode of the 3 mm diameter and 12 ns for the 5 mm photodiode.

3. RESEARCH METHODS AND OBTAINED RESULTS

Research was conducted in the electronic set-up shown in Fig. 2.
The noise current (root-mean-square value) is measured using a selective nanovoltmetr with a preamplifier (f = 12 kHz, Δf = 150 Hz). A halogen bulb with focusing optics and a set of interference filters make up a radiation source. An avalanche photodiode is protected against the background radiation and is kept at a stabilised temperature.
On the condition that the excess noise factor doesn't depend on what sort of carriers are multiplied, those generated optically or thermally, the total noise current I_{NT} of the avalanche photodiode (multiplied shot noise current), in reference to the unit energy band width (1 Hz), can be calculated from following formula:

$$I_{NT} = \sqrt{\left[2q\left(I_{PO} + I_{OB}\right)M^2 F(M) + I_{OS}\right]} \qquad (1)$$

where q - charge of electron, I_{PO} - primary photocurrent I_{OB} - primary bulk dark current I_{OS} - surface dark current.

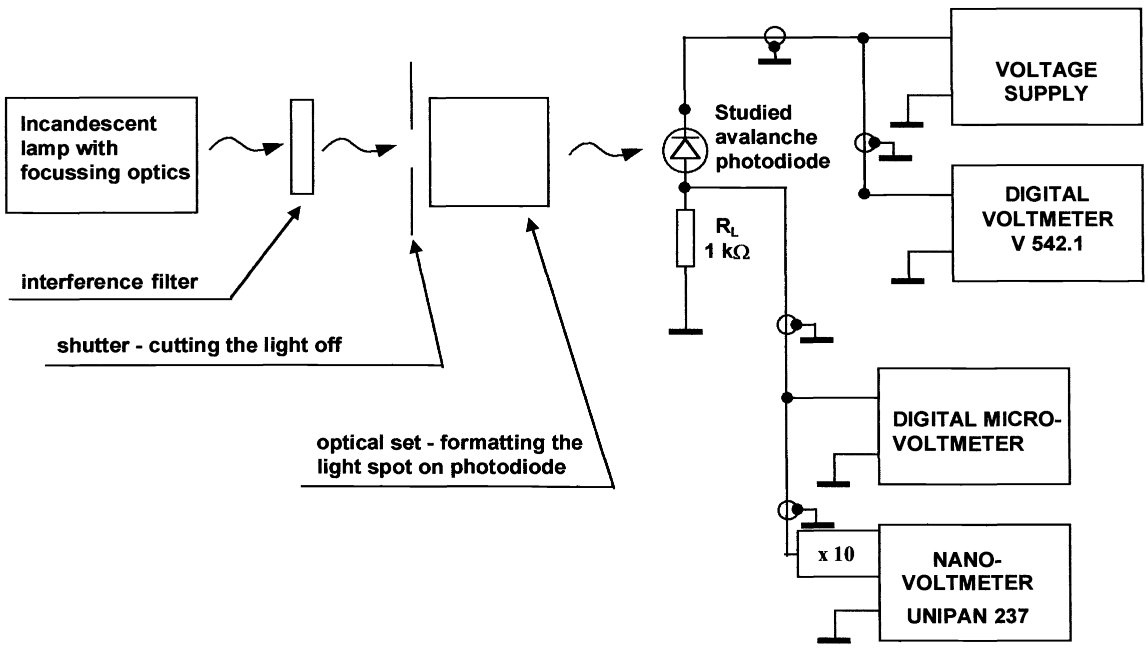

Fig 2 Block diagram of the set-up for the gain M, noise current I_N and excess noise factor F measurements

The noise features of avalanche photodiodes are well characterised by the spectral density of photodiode "dark" noise current, called the photodiode noise current, and its value is given in the equation 2.

$$I_N = \sqrt{2q\left(I_{OB}M^2F(M) + I_{OS}\right)} \qquad (2)$$

The next important parameter of avalanche photodiodes is the excess noise factor F (M) = M^x that characterises the avalanche noises. For silicon photodiodes, the value of x very often equals 0.2 ÷ 0.5 hence, for example, at M = 100: the value of F factor ranges from 2.5 to 10 [7].
The F factor is very often determined by the ratio of (equation 3) measured noise power of a real photodiode photocurrent (I_{NP}^2) to a "hypothetical" noise power of an ideal photodiode photocurrent ($2qI_{P0}M^2\Delta f$). The ideal photodiode is such a device where the avalanche process doesn't bring in (excess) noise.

$$F(M) = \frac{I_{NP}^{\;2}}{2qI_{PO}M^2\Delta f} \qquad (3)$$

The photocurrent should be high enough so the dark current could be neglected (see equation 1)
In Fig 3, there are spectral functions of noise current I_N at gain M = 100 and of gain for the fixed value of noise current I_N = 2 pA/Hz$^{1/2}$ for the 1.5; 3 and 5 mm diameter photodiodes
As it is seen in Fig 3, ITE avalanche photodiodes have the noise current below 2 pA/Hz$^{1/2}$ and the gain higher than 100 for the wavelengths above 500 nm. The larger the photodiode diameter, the lower the gain at a given level of the noise current. It is illustrated by spectral characteristics of sensitivity, shown in Fig 4, for the 1.5, 3, and 5 mm diameter photodiodes that were measured at I_N = 2 pA/Hz$^{1/2}$.
The spectral dependence of the excess noise factor F for the 5 mm diameter photodiodes (for different values of gain M) and the F versus gain dependence for different wavelengths of radiation are presented in Figs 5 and 6.
The lesser a wavelength, the higher an F factor. It results from bigger participation of holes in the process of detection of short-wave radiation that goes in ITE avalanche photodiodes.
The values of excess noise factor F of the 5 mm diameter avalanche photodiodes for different wavelength are in the table 1. In the table 1, the gains and wavelengths where F < 3 and F < 4 are marked. It is the range of gains and wavelengths in which the photodiodes achieve very good detection characteristics.

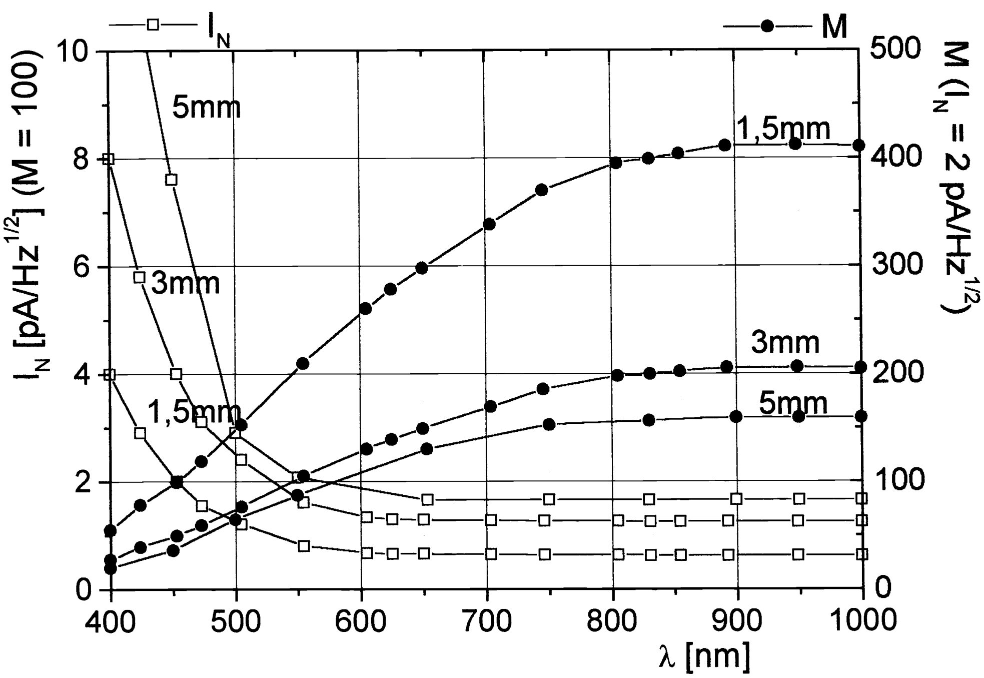

Fig 3 The example of spectral dependence of noise current I_N at gain M = 100 and of gain M for noise current $I_N = 2\ pA/Hz^{1/2}$ of the 1.5; 3 and 5 mm diameter photodiodes.

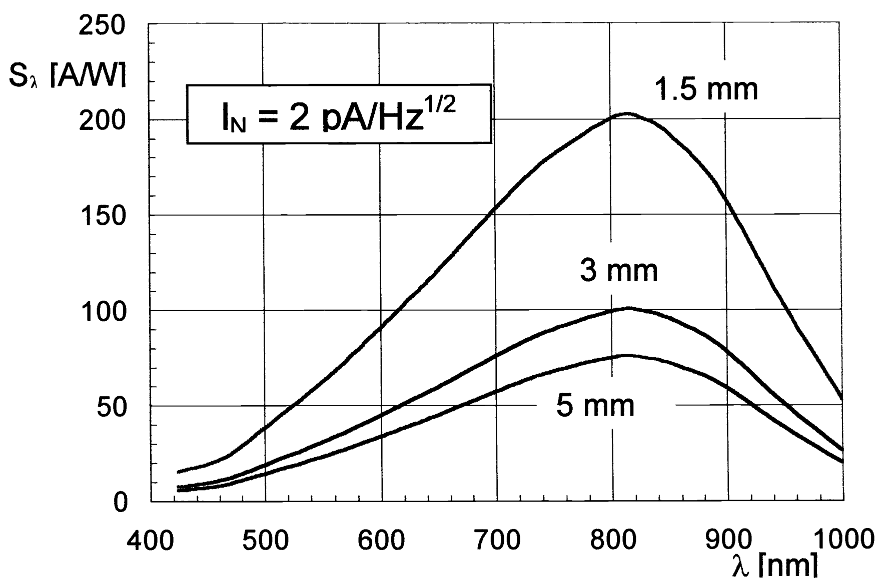

Fig. 4 The example of spectral characteristics of sensitivity for the 1.5; 3 and 5 mm diameter photodiodes (measured at $I_N = 2\ pA/Hz^{1/2}$).

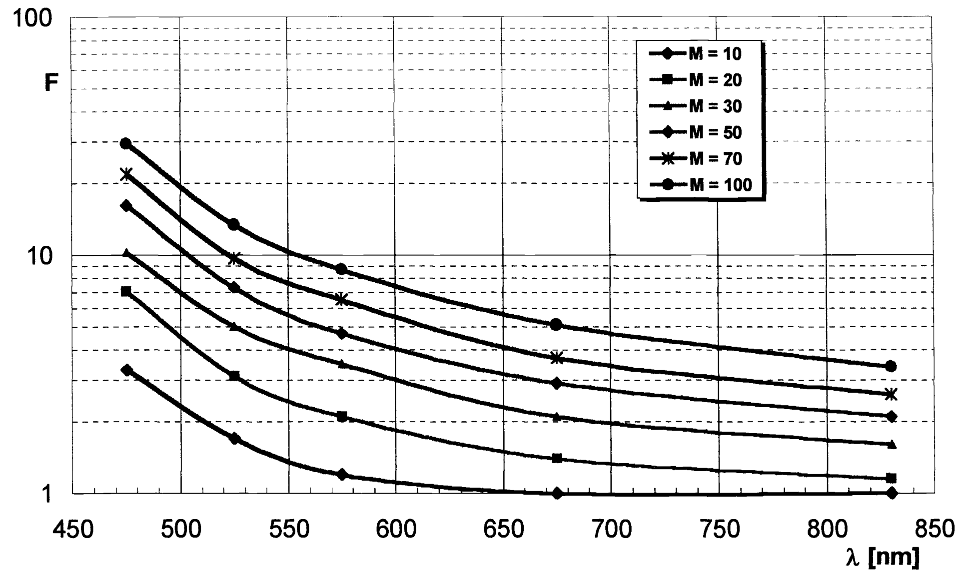

Fig. 5 An example of the spectral dependence of the excess noise factor F for different gains. The 5 mm diameter silicon avalanche photodiode.

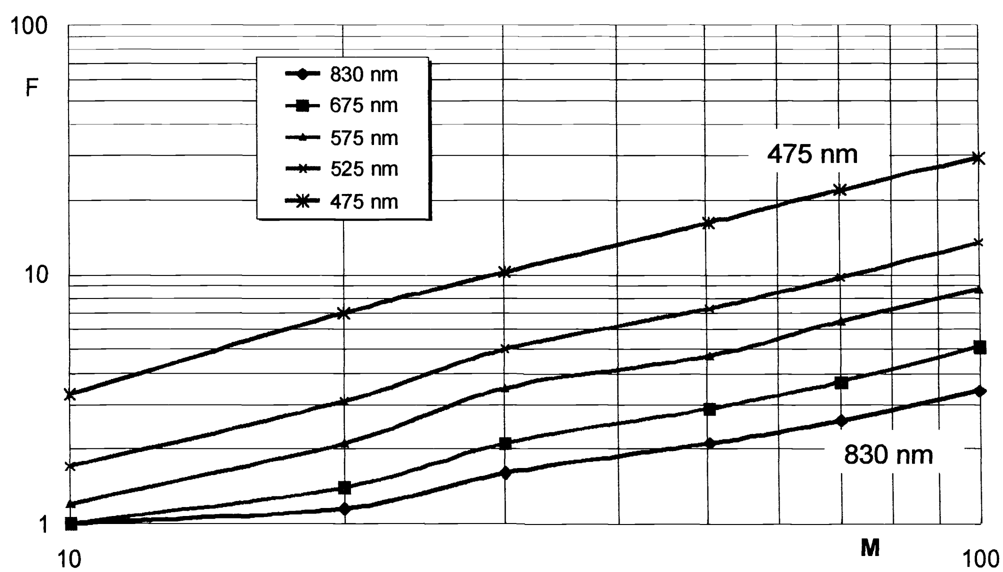

Fig. 6 An example of the excess noise factor F versus gain for different wavelengths. The 5 mm diameter silicon avalanche photodiode.

Tabl. 1 Values of excess noise factor F for the 5mm avalanche photodiode

M↓ λ =	830nm	675nm	575nm	525nm	475nm
10	1	1	1.2	1.7	3.3
20	1.15	1.4	2.1	3.1	7
30	1.6	2.1	3.5	5	10.2
50	2.1	2.9	4.7	7.3	16.1
70	2.6	3.7	6.5	9.7	21.8
100	3.4	5.1	8.7	13.4	29.3

4. SUMMARY

The avalanche photodiodes of very good parameters at λ = 800 - 850 nm were designed and developed at ITE. The new potential applications for these photodiodes, especially in scintillation detection of nuclear radiation, have led to the study of these photodiodes in the short-wave (visible) range of optical radiation spectrum. To this end, the special measurement methods and sets were adapted. The measurements of following spectral characteristics were done; the photodiode noise current I_N (at M = cons.), the gain M and the excess noise factor F in function of the wavelength in the spectral range of 400 - 1000 nm. All these studies were done for avalanche photodiodes designed and developed at ITE including the newest photodiode of the 5mm diameter.

The presented results of noise and gain measurements enabled to determine the values of these parameters and to compare them with the values obtained for the optimal spectral range of operation for these photodiodes (800 – 850 nm)

For example, at the wavelength 550 nm the noise current I_N at M = 100 for the 5 mm diameter avalanche photodiode is close to the value of 2 pA/Hz$^{1/2}$. For the 3 mm diameter photodiode the I_N is about 1,8 pA/Hz$^{1/2}$, and for the 1.5 mm diameter photodiode this value is below 1 pA/Hz$^{1/2}$. The value of gain at this wavelength for I_N = 2 pA/Hz$^{1/2}$ are three-fold lower than at λ = 800 - 850 nm.

The spectral characteristics of sensitivity shown in fig 3 enabled to determine, for each given wavelength, the absolute sensitivity of studied photodiodes, for the gain corresponding to I_N = 2 pA/Hz$^{1/2}$.

At λ = 550 nm, the 5mm diameter photodiodes sensitivity is typically above 20 A/W, for the 3mm diameter photodiodes this sensitivity is about 30 A/W, and for the 1.5 mm diameter photodiode this value is about 60 A/W.

The results of the excess noise factor F measurements of the 5 mm diameter photodiodes enabled to find out maximum gain for different wavelengths of radiation at which this factor doesn't exceed the value of 4 ($F \leq 4$ ensures a good detection properties).

The conclusions from the F studies of the 5 mm photodiodes are valid for the photodiodes of smaller diameters.

The conducted studies have shown that ITE avalanche photodiodes can be applied for detection of radiation in the 500 - 1000 nm range. In spectral range of 550 to 1000 nm they achieve good parameters and in the range of 600 ÷ 950 nm very good ones.

5. ACKNOWLEDGEMENTS

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