Silicon photodetectors – the state of the art+

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The paper deals with recent achievements in the field of semiconductors detectors designed, developed, and fabricated at ITE. The properties of the PIN photodiode (sensitivity, dark current, spectral range, speed of response) are studied with regard to a kind of configuration, geometrical and technological parameters of the photodiode structure. The details of design and technology of an n^+-p-π-p^+ structure of silicon avalanche photodiodes are presented and the influence of technological parameters on most important parameters characterising APDs (avalanche noise current, gain) are thoroughly analysed. The use of APDs as counters of ultraweak signals and principles of APDs operation in a single counting mode in a passive quenching circuit are introduced. Characteristic parameters (dark and photoelectric count rates, probability of the detection) of the APDs developed at ITE are discussed and evaluated in the view of the devices application in the new mode.

1. Introduction

Since many years, silicon photodetectors such as phototransistors, photodiodes p-n (photocells), photodiodes p-i-n (PINs), avalanche photodiodes (APDs) and arrays made up of those elements have commonly been used for detection of visible (VIS) and near infrared (IR) radiation and recently of ultraviolet radiation (UV). This widespread utilisation is mainly due to the excellent performance parameters of these devices as well as to extremely well mastered epiplanar technology of silicon. Despite the fact that photodetectors have being produced for many years, the intensive development of design and technology of photodetectors, owning to the new emerging regions of their application, can be noticed recently. This development especially concerns such issues as:

– increasing a light-sensitive surface area of silicon APDs and PINs and at the same time decreasing their dark and noise currents

– designing and developing a new generation of APDs, optimised for VIS and UV radiation, with greater radiance immunity (immunity to γ radiation and particles) for applications in scintillation detectors of the X -ray and nuclear radiation .

– extending a spectral range of performance of silicon PINs towards shorter wavelengths (UV range) and strengthening their radiance immunity for the applications mentioned above.

– investigations into methods of detection of extremely weak optical signals by means of silicon APDs adapted to work in a new digital regime as counters of single photons. These studies consist in designing photodiodes capable to perform in this new mode of work and optimising their power supply system.

The studies mentioned above are in the focus of attention in many world leading research centres e.g. CERN, and firms such as EG&G (US, Canada) and HAMAMATSU (Japan) participate in them. These issues have also been the subject of researches carried out at ITE in statutory work – „Research into a new generation of semiconductor photodetectors" and KBN grants – project 8 S501 025 07 – accomplished in 1996 – "Investigations of APDs working in a single photon

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counting mode" and project 8 T119 037 13 – starting this year "Research on silicon APDs for applications in scintillation detectors for nuclear radiation".

The results of the mentioned above studies allowed to develop and implement into production the family of silicon avalanche photodiodes with the active area diameters of: 0.3 mm – BPYP 52, 0.5 mm – BPYP 54, 0.9 mm -BPYP 53, 1.5 mm – BPYP 58 and 3 mm – BPYP 59. The performance parameters of these APDs are as good as those which characterise the devices made by leading detector companies in the world. The team of researchers from ITE, who designed and manufactured the APDs, was conferred the title of MISTRZ TECHNIKI – WARSZAWA 1996 together with the first degree award given annually by NOT for the outstanding achievements in the field of technology. The APDs are fabricated on large scale, mainly for an American market.

2. Design, technology and properties of modern silicon avalanche photodiodes and PIN photodiodes.

2.1 PIN silicon photodiodes

In the photodetector structure of p^+-ν-n^+ configuration, which cross-section is shown in Fig 1, optical generation of carriers ought to take place in a space-charge region of the p-n junction. This region extends throughout the whole ν layer.

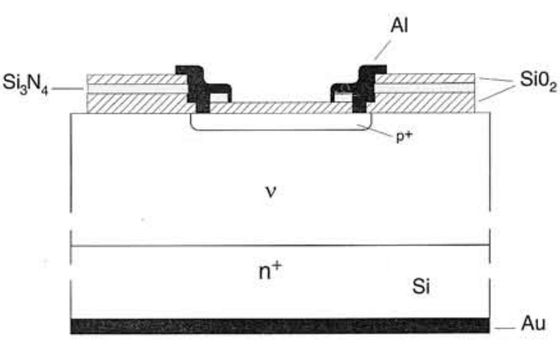

Fig. 1. Cross-section of the PIN photodiode structure with the p^+–ν-n^+ configuration.

The resistivity and thickness of this layer should be adjusted in such a way that at an assumed operational voltage (reverse bias) the whole thickness of the n layer was depleted and also that the strength of electric field was about 6×10^4 V/cm (2×10^4 V/cm – in the case of n^+-π-p^+ structures). The highly-doped p^+ region (diffused or implanted) is very thin (less than 1 μm) and is coated with the thin dielectric film (SiO_2 or Si_3N_4) which serves as an antireflection layer.

The n^+ region should be designed and made so that optically generated carriers could recombine there immediately thus didn't contribute to the photocurrent and also that the resistivity of this region and of the series contact was negligible. Described above requirements for the p-i-n structures can be realised by three different means:

– by using, as the material for production, a highly-resistive epitaxial layer deposited on a highly-doped substrate of the same type of conductivity.

– by using, as the material for production, a highly-resistive wafer with a highly-doped epitaxial layer grown on this wafer (so-called inverted epitaxy).

– by working out the structure from a highly-resistive monolithic material in which a highly doped region is formed by a diffusion technique or by diffusion and implanting technique.

The first, from listed above, realisation is used in the case of designing very fast (t_r about 300 ps) photodiodes with small light-sensitive areas. In that case, the p^+-ν-n^+ as well as n^+-π-p^+ construction can be applied. An adopted thickness of the epitaxial layer (the highly-resistive region) usually doesn't exceed the value of 50 μm. The resistivity of this epitaxial layer is about several hundred Ωcm and the substrate resistivity is less than 0.01 Ωcm. The transit time of carriers in such photodiodes are much shorter than 1 ns and sensitivity at $\lambda = 850$ nm can exceed the value of 0.5 A/V. The small thickness of the epitaxial layer which is an advantage on the account of the transit time causes a relative increase in the value of capacitance per unit of a p-n junction area and that is why the diodes of this construction can have only the small light-sensitive area (less than 10 mm^2). These photodiodes are characterised by very low dark currents (lower than 1nA), low operating voltages (10-20 V), as well as the wide spectral range of operating (250 – 1050 nm). BPYP 42 and BPYP 43 photodiodes designed and manufactured at ITE are the examples of these kind of diodes.

The realisations nr 1 and 2 are applied for photodiodes with large light -sensitive areas (e.g.1 cm^2) . The thickness of highly-resistive region in the case of epitaxial layer usually is 100 – 200 μm, and for the construction in the monolithic material, 200 – 400 μm. The p^+-ν-n^+ as well as n^+-π-p^+ constructions are used, but better speed of response (at IR radiation) is obtained in the latter case (n^+-π-p^+), owning to the higher value of a drift velocity for electrons than holes. The configurations with the thick highly-resistive layer are used particularly for detection of radiation of the wavelengths near a long-wave absorption threshold (for $\lambda > 1000$ nm). In these configuration, the sensitivity obtained surpasses the value of 0.6 A/W at $\lambda =$ 900 nm and 0.2 A/W at $\lambda = 1060$ nm . In modern photodiodes of this type, the dark current for the bias voltage which ensures depletion of the highly-resistive layer is lower than 20 nA/cm^2 [1] . The examples of the current vs. voltage characteristics of the p^+-ν-n^+ photodiode with the 400 μm thick highly-resistive layer, worked out at ITE, are shown in Fig 2. Figures 3 and 4 demonstrate the C-V and spectral sensitivity characteristics, respectively. [2].

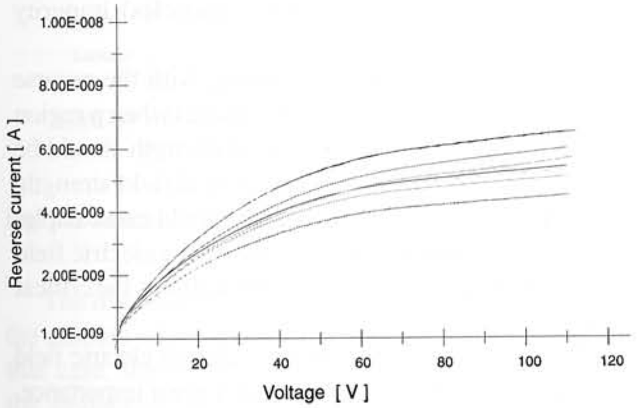

Fig. 2. Dark current vs bias voltage of PIN photodiodes with active area of 0.25 cm^2 and 400 μm – thick active region.

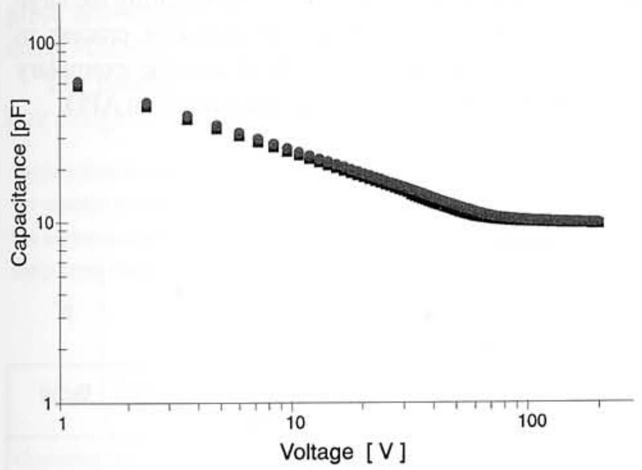

Fig. 3. Capacitance vs bias voltage of PIN photodiodes with active area of 0.25 cm^2 and 400 μm – thick active region.

The high sensitivity of a photodiode, especially one of the epiplanar variation, in an UV spectral range (0.1 A/W at $\lambda = 300$ nm) can be attained by optimising technology which consist in a special treatment of the surface and by conducting technological processes in such a way that the degradation of the surface won't take place. The example of the spectral sensitivity characteristic of such a photodiode fabricated at ITE is presented in Fig. 5 [1]

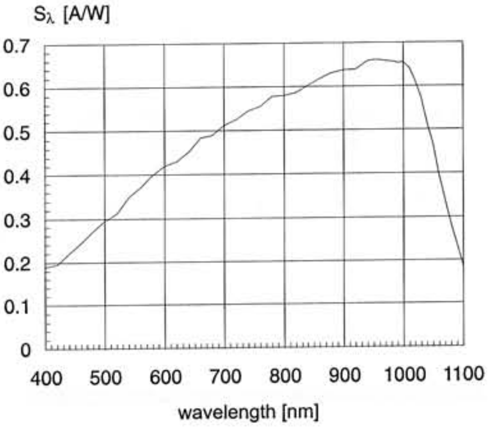

Fig. 4. Spectral response of PIN photodiode (thickness of active region – 400 μm).

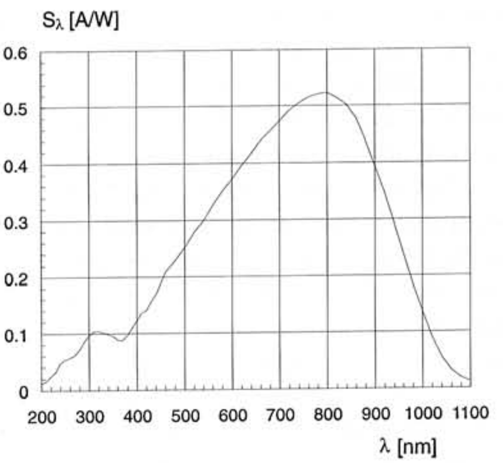

Fig. 5. Spectral response of PIN photodiode (UV-version).

2.2 Silicon avalanche photodiodes.

An n^+-p-π-p^+ structure is a characteristic configuration for modern avalanche photodiodes (APDs). An epiplanar structure of APDs of this configuration, designed at ITE, optimised for detection of the 700-900 nm wavelength radiation will be discussed. (Fig 6)

An initial material for working out the photodiode is Si wafer with a π type epitaxial layer ($\rho_\pi = 200 - 250$ Ωcm, x_π = 30-35 μm) on a p^+ substrate of <111> crystallographic orientation.

The choice of conductivity type of the highly-resistive layer (π type) ensures higher participation of electrons than holes in the process of IR radiation detection in APDs. This event is of an advantage on the account of performance speed as well as "avalanche" parameters (noise and gain) of an APD.

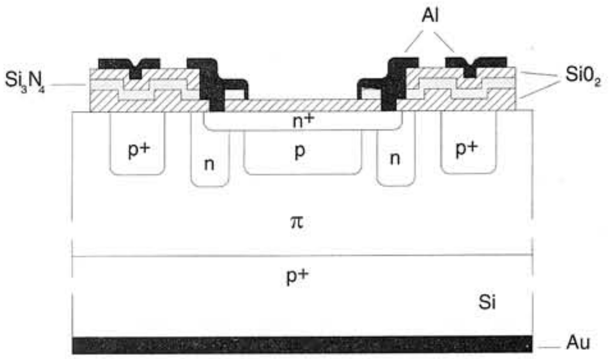

Fig. 6. Cross-section of the avalanche photodiode structure developed at ITE.

The chosen thickness of highly-resistive layer: 30-35 μm (the actual thickness of this region after technological processes is reduced about 5 μm because of boron diffusion from the substrate during thermal processes) secures the high primary (without gain) sensitivity 0.5 A/W at $\lambda = 850$ nm and the high speed of performance (about 300 ps for photodiodes with an active area diameter not greater than 0.3 mm.).

The selection of resistivity for the π-type region is the consequence of technological and design demands. That is, the lower is resistivity of this region, the easier is the reproducible way of its formation and lesser its degradation in thermal processes.

The n-type guard ring is provided by pre-diffusion of phosphorus from a $POCI_3$ source followed by re-diffusion that takes place during a thermal treatment of the active region ($N_s = 5 \times 10^{20}$ cm^{-3}, $x_j = 7$μm). This ring constitutes the region under the contact.

The p^+-type channel stopper is made by implanting and then re-diffusing boron (re-diffusing is mutual for p^+ and p regions; $N_s > 10^{18}$ cm^{-3}, $x_p = 4.5$ mm). The purpose of this stopper is to limit the propagation of space charge on the interface between SiO_2 and highly-resistive π-type Si

The 150 nm thick SiO_2 antireflection layer (optimised for $\lambda = 850$nm) covers the photodiode active region.

The active (photosensitive, avalanche) region constitutes the central region with the n^+-p hyper-abrupt junction obtained by arsenic diffusion from amorphous silicon (doped with As during the deposition process) to the p-type area previously formed by boron implantation followed by boron re-diffusion.

The parameters of the n^+-p junction in particular its depth and distribution of boron concentration determine the most important features of a photodiode structure. This depth should be as small as possible so that to minimise the participation of holes in detection process.

The parameters of an active (p) section should, first of all, ensure the optimum electric field distribution in the photodiode structure biased by a voltage close to the value of its avalanche breakdown voltage.

In the avalanche region, a field strength ought to be greater than the critical one (which attains a value ranging from 2×10^5 to 5×10^5 V/cm, depending on the design). In the highly-resistive region, this strength shouldn't be below 2×10^4 V/cm but not higher than 6×10^4 V/cm so that to avoid likeable local breakdowns at places where defects or atom (particles) impurity inclusions occur.

While biasing such a photodiode with the reverse voltage equal the reach-through voltage (when p region reaches π region), the electric field strength should be a few percentage lower than the critical field strength. Further increase of the bias voltage should cause depletion of the p region and an increase of the electric field strength in the avalanche region till it attains the critical value.

The choice of the maximum value of electric field strength in the active area is also of a great importance. The lower is this value, the higher is the ratio of ionisation coefficients of electrons to that of holes in silicon and hence lower avalanche noise and higher gain. The avalanche noise can be minimised by ensuring the large participation of electrons in the detection process in avalanche photodiodes. Fig 7 illustrates the exemplary impurity distribution in an n^+-p junction of an APD.

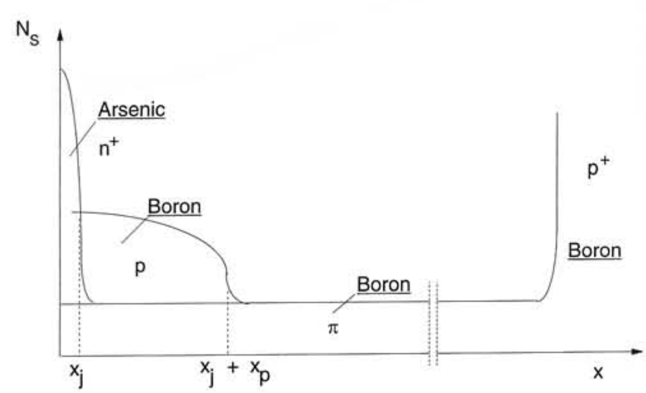

Fig. 7. Distribution of dopants in active region of APDs.

The resultant number of electrically active atoms of the acceptor impurity (boron) in the active region should be chosen so that to ensure formation of electric field strength distribution shown in fig 8 (curve 1), as well as an optimum value of the maximum strength of this field in the n^+-p junction. The examples of incorrect distributions (curves 2 and 3) are also displayed in fig 8.

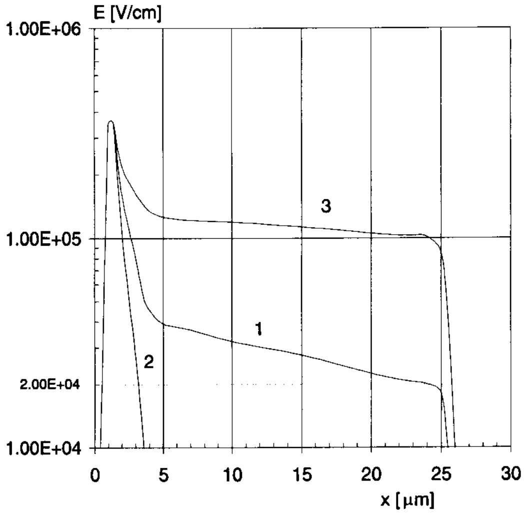

Fig. 8. Distribution of the electric field in APD active region.

The distribution illustrated by curve 2 occurs when the amount of boron in the active area is too large. In that case, the junction breaks down prematurely and the avalanche breakdown voltage V_{BR} is not higher than 50 V.

In the case represented by the curve 3, the amount of boron is too small, so the avalanche event takes place also in the highly-resistive area; and the breakdown voltages reach the values higher than 300 V.

The parameters of the n^+-p junction for the structure designed at ITE ought to have values as follows:

the junction depth	$x_j = 0.42$ µm
the arsenic surface concentration	$N_s = 6 \times 10^{19}$ cm^{-3}
the boron surface concentration optimum	optimum
the p layer thickness	optimum

The surface parameters, it means dimensions of the separate areas of photodiode structures are determined by appropriate photolitographic masks. These parameters are chosen so that electric field strength was lower than critical one in all, but avalanche, junction regions of a structure biased by the voltage near the avalanche breakdown voltage. At the same time, the layout of the structure cannot be too much expanded considering the necessity to minimise the electric capacitance and dark current. The photodiode structure is "sealed" with the ~ 100 nm Si_3N_4 layer. Aluminium and gold provide contacts to the n type region and p type substrate, respectively.

APDs of the discussed design are characterised by the reach-through breakdown voltage of the p region V_{RT} = 48–52 V and the operating voltage typically in the range of 180–200 V (the catalogue values: 130–280 V) at which noise currents I_N, at gain of 100, attain values as follows; 0.07 pA/Hz$^{1/2}$ for the 0.3 mm-diameter APDs, 0.12 pA/Hz$^{1/2}$ for the 0.5 mm, 0.3 pA/Hz$^{1/2}$ for the 0.9 mm, 0.45 pA/Hz$^{1/2}$ for the 1.5 mm, and 1.4 pA/Hz$^{1/2}$ for the 3 mm- diameter APDs. The avalanche breakdown voltage are usually 10 V higher.

The basic parameters of the avalanche photodiodes developed at ITE [3], [4] are compiled in Tab. 1.

The example of bias voltage dependence of gain and noise current for BPYP 59 photodiode (3mm diameter of the light-sensitive area) is illustrated in Fig 9. The bias voltage dependence of noise current for APDs with the different diameters of light-sensitive area are shown in Fig 10.

3. Further investigations on silicon photodiodes

As it was mentioned in the introduction, the extensive studies into a new generation of silicon APDs

Table 1. Typical parameters of silicon avalanche photodiodes developed at ITE.

Parameter	Symbol	Units	BPYP 52 0.3 mm	BPYP 54 0.5 mm	BPYP 53 0.9 mm	BPYP 58 1.5 mm	BPYP 59 3 mm	Test conditions*
Operating Voltage	V_R	V	180 ÷ 220 (min.130 ÷ max. 280)					λ = 850 nm
Temperature Coefficient of V_R	α_{TR}	V/°C	0.75					
Sensitivity	S_λ	A/W	50					λ = 850 nm
Noise Current	I_N	pA/Hz$^{1/2}$	0.07	0.12	0.3	0.45	1.5	$P_\lambda = 0$
Noise Equivalent Power	NEP	fW/Hz$^{1/2}$	1.4	2.4	6	9	30	λ = 850 nm
Excess Noise Factor	F(M)		4					λ = 850 nm
Dark Current	I_0	nA	0.7	1.2	2.2	5	12	$P_\lambda = 0$
Capacitance	C_{tot}	pF	1.7	3	7	12	40	$P_\lambda = 0$
* **Test conditions**: V_R for the gain M = 100; t_{amb} = 22°C								

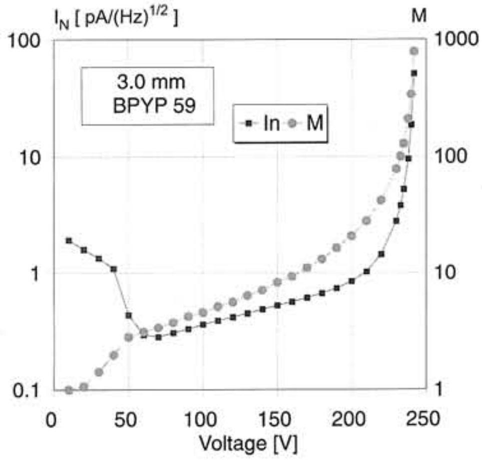

Fig. 9. Gain and noise current vs bias voltage of the 3 mm-diameter APD.

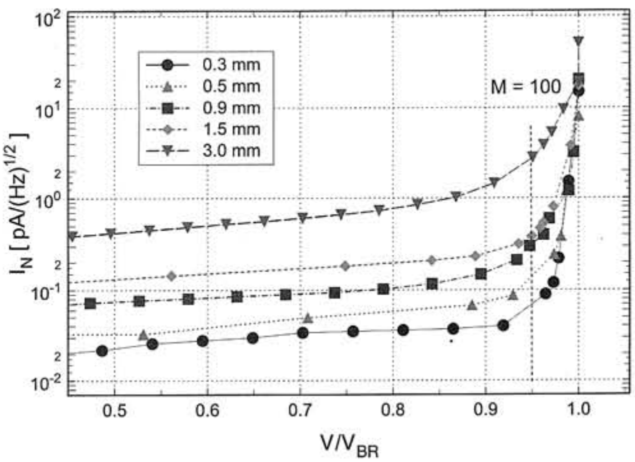

Fig. 10. Noise currents vs normalised bias voltage of five different types of APDs.

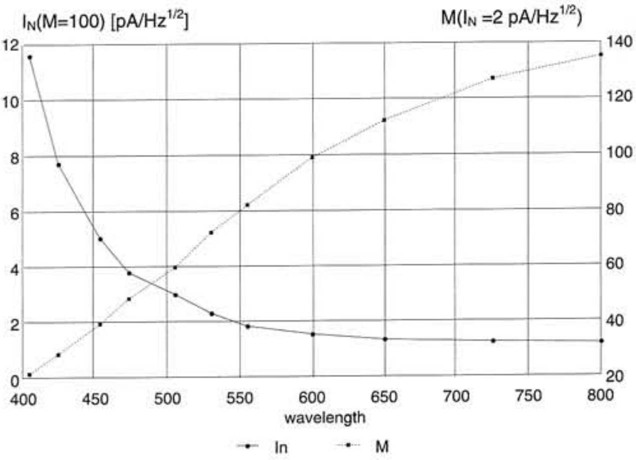

Fig. 11. Noise current (at gain M = 100) and gain (at noise current $I_N = 2$ pA/Hz$^{1/2}$) vs wawelength (the 3 mm diameter APD).

sensitive in an UV spectral range are being conducted at present. While some increase of quantum efficiency of p-i-n photodiodes as well as the primary sensitivity of APDs are attainable by optimising their design and technology, to obtain good "avalanche" parameters, it means the high gain and low noise, in the present configuration of APDs is not possible because of the fact that the short-wavelength radiation is absorbed mostly in the n-type region which causes that the holes predominate in photocurrent.

In fig 11, there is shown an example of the spectral dependence of noise currents at the gain of M = 100 and that of the gain at the noise current of $I_N = 2$ pA/Hz$^{1/2}$ for the 3mm (BPYP 59) avalanche photodiodes, discussed in the previous section in this article. To obtain good avalanche parameters for the radiation below the 400 nm wavelength there is a need of complete change into the configuration of the APDs structure in such a way that the absorption could take place in an p-type region. Such work has been carried out in HAMAMATSU as well as in EG&G firms and ITE has been working in this field too.

The second essential issue, concerning prospective applications of APDs in scintillation detectors, is solving the problem of radiance immunity. CERN co-ordinates studies, on a world scale, into this issue. ITE participates in them.

4. Silicon avalanche photodiodes working as counters of single photons

4.1 Principle of APDs operation in a single photon counting mode

Even though APDs working in analog regime are the most sensitive semiconductor detectors in this mode, they don't allow detection of very weak optical signals ($P_\lambda < 10^{-14}$ W, that corresponds to the numbers of photons per second less than 40 000 at $\lambda = 830$ nm)

At present, photomultipliers, working in a single counting mode, are most often used for detection of the radiation of $P_\lambda < 10^{-14}$ W

Avalanche photodiodes working in a new mode, as single photons counters (the alternative terms: Geiger mode, triggering mode, switching mode, digital mode, impulse mode) have come to be semiconductor photodetectors which compete successfully with photomultipliers, and are even better, especially for so called "spot" detection (the flux of radiation focused into the small spot) and for wavelengths of $\lambda > 600$ nm.

APDs are able to work as photon counters when a bias voltage of a photodiode is set slightly above an avalanche breakdown voltage (V_{BR}) and the photodiode is biased in a circuit (Fig 12) containing, in

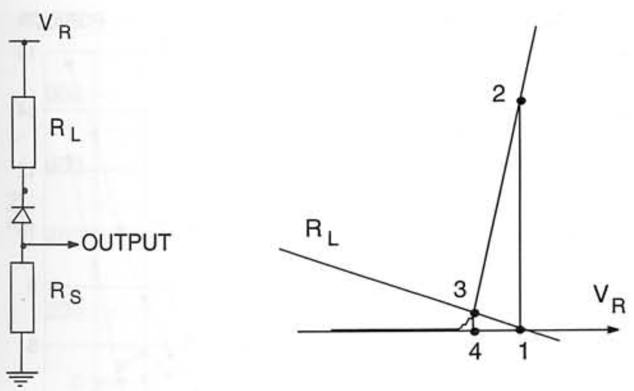

Fig. 12. Principle of the operation of APDs in the passive quenching circuit.

its simplest version (passive quenching) a limiting resistor R_L (typically R_L 100kΩ) and an output resistor R_S (typically R_S =100 Ω).

The R_L resistor limits a self-sustaining avalanche current generated in the photodiode biased by the voltage that exceeds V_{BR} .The photodiode is in a "stand by state" (point 1 in Fig 12). Then, a single photon incident onto and absorbed in the active area generates an avalanche of carriers (electron-hole pairs) – transition from point 1 to 2. The current caused by the avalanche flows through the external circuit (transition from point 2 to 3) until the avalanche is quenched in consequence of the discharge of diode junction capacitance and circuit stray capacitance (transition from point 3 to 4). As the result, the voltage on the photodiode drops to the value of $V_R \approx V_{BR}$. This way the current generated by the absorbed photon is registered on the resistor R_S as the voltage pulse. The photodiode is ready to detect next photon after a certain time (dead time) which is required for recharging the photodiode to the original voltage $V_R= V_{BR} + \Delta V$ (point 1). However, in an over-biased photodiode, which is in the stand by state, an avalanche can also be triggered by thermally generated charge carriers. In this case so called dark pulses appear in the external circuit. Their numbers per time unit, called the dark count rate (DCR), depend on properties of an initial silicon material and technology of diode manufacture. The fewer there are the centres generating the free charge carriers in the space charge area, the fewer numbers of the "dark" pulses occur, and the photodiode is better suited for a single photon counting.

In order to decrease the "dead time" (to accelerate the process of transition from the photon detecting state to the stand by state) active quenching circuits are applied.[4]

4.2 Basic parameters of avalanche photodiodes working in a single photon counting mode.

The method of characterising APDs working in a single photon counting mode consists in measuring following parameters:

– dark count rate DCR – a number of pulses per second generated in a photodiode that is not illuminated

– photon count rate PCR – a number of photoelectric pulses per second, PCR = TCR – DCR.

The above parameters are mainly a function of over-biased voltage detn. ΔV_R ($\Delta V_R = V_R - V_{BR}$) and of operating temperature. A photon count rate substantially depends on a dark count rate.

PCR measurements enable to determine the probability of photon detection, which is defined as the ratio of numbers of photoelectric pulses to numbers of photons incident onto a photodiode, detn. P_{dp}

$$PCR = N_\lambda \times P_{dp}$$

N_λ – a number of photons incident on a photodiode during 1 second defined by the equation:

$$N_\lambda = P_\lambda/h\nu = 5.03 \times 10^{15} \times \lambda \times P_\lambda$$

where:

P_λ – radiation power in W
$h\nu$ – photon energy
λ – wavelength in nm

The photon detection probability is the product of quantum efficiency of radiation detection η_λ determined in an analog mode and the probability of triggering the avalanche by an optically generated charge carrier (electron or hole)

The values of PCR, DCR, ΔV_R measured for the photon detection probability of P_{dp} = 5 % are most frequently used to characterise APDs. Additionally, a dead time is an important parameter, its value essentially depends on a kind of photodiode supply circuit defined in section 4.1.

The other important application parameters are a signal-to-noise ratio dent. S/N and a noise equivalent power NEP, determined for integrating time of 1 s:

$$\frac{S}{N} = \frac{PCR}{\sqrt{2DCR}}; \quad NEP = \frac{\sqrt{2DCR}}{P_{dp}} h\nu$$

4.3 Properties of APDs working in a single counting mode.

The properties of APDs working in a single photon counting mode will be illustrated taking as the example BPYP 52 photodiodes developed at ITE. The investigation was carried out using the passive quenching circuit (R_S = 10 kΩ, R_L = 100kΩ)

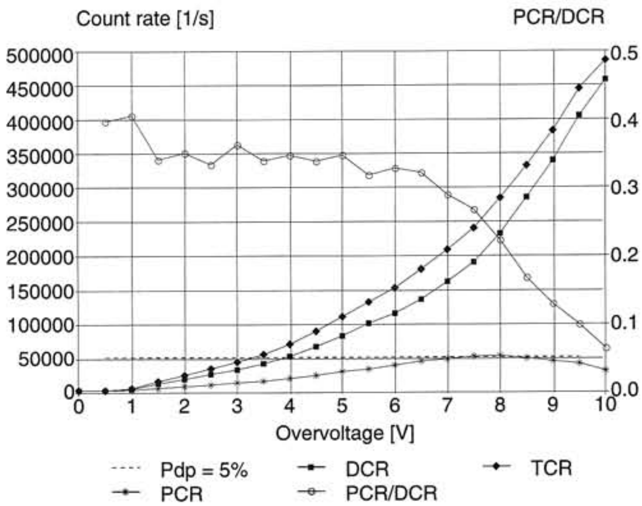

Fig. 13. Over-voltage (ΔV_R) dependence of dark count rate DCR, total count rate TCR, photon count rate PCR and PCR/DCR ratio at λ = 812 nm, P_λ = 0.24 pW and t = 0°C. Dashed line indicates the value of photon count rate at which photon detection probability (P_{dp}) equals 5%.

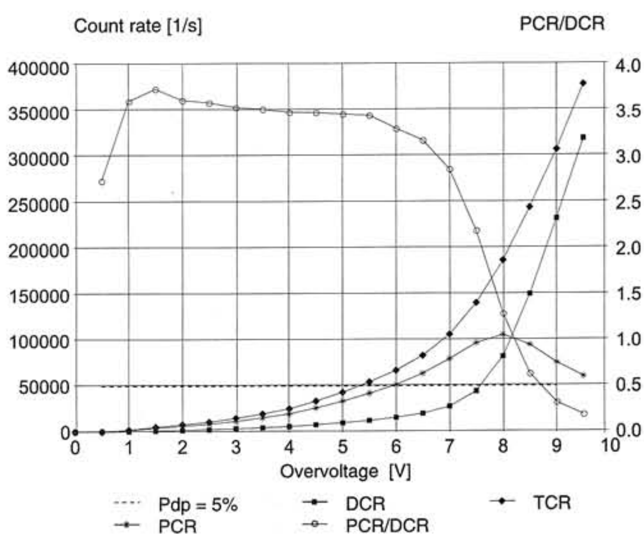

Fig. 14. Over-voltage (ΔV_R) dependence of dark count rate DCR, total count rate TCR, photon count rate PCR and PCR/DCR ratio at λ = 812 nm, P_λ = 0.24 pW and t = –25°C. Dashed line indicates the value of photon count rate at which photon detection probability (P_{dp}) equals 5%.

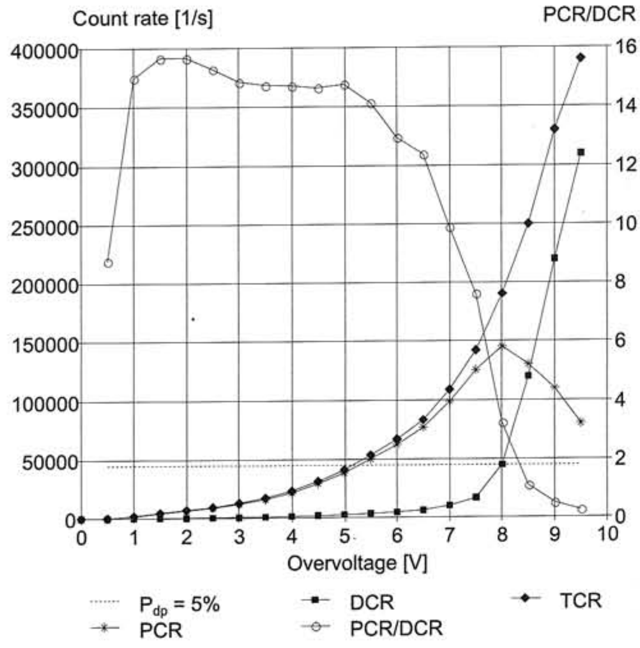

Fig. 15. Over-voltage (ΔV_R) dependence of dark count rate DCR, total count rate TCR, photon count rate PCR and PCR/DCR ratio at λ = 812 nm, P_λ = 0.24 pW and t = –40°C. Dashed line indicates the value of photon count rate at which photon detection probability (P_{dp}) equals 5%.

The examples of over-biased voltage dependence of: the dark count rate DCR, photon count rate PCR, PCR/ DCR ratio, photon detection probability P_{dp}, signal-to-noise ratio S/N, and the noise equivalent power NEP all measured at temperatures; t = 0°C, –25°C and –40°C at the wavelength of λ = 812 nm and P_λ = 0.24 nW are shown in Fig 13, 14, 15, 16, 17, and 18.

The temperature dependencies of the DCR and

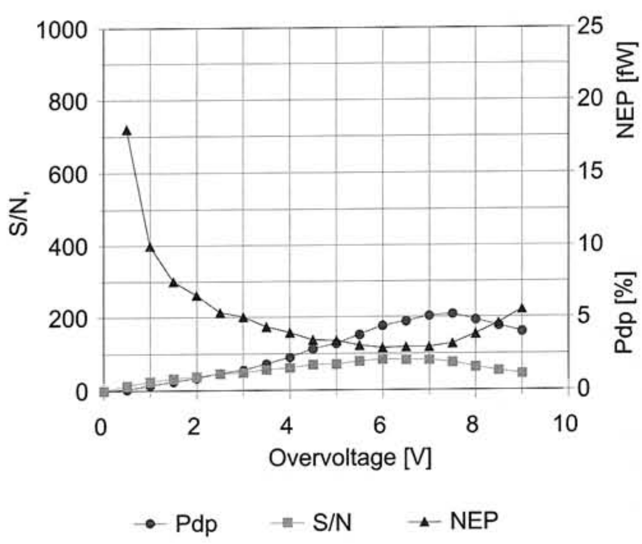

Fig. 16. Typical over-voltage dependence of the signal to noise ratio S/N, noise equivalent power NEP and photon detection probability P_{dp} at 0°C temperature.

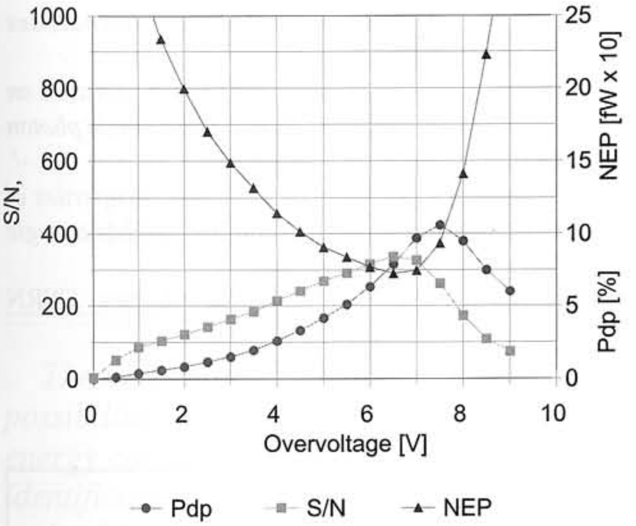

Fig. 17. Typical over-voltage dependence of the signal to noise ratio S/N, noise equivalent power NEP and photon detection probability P_{dp} at –25°C temperature.

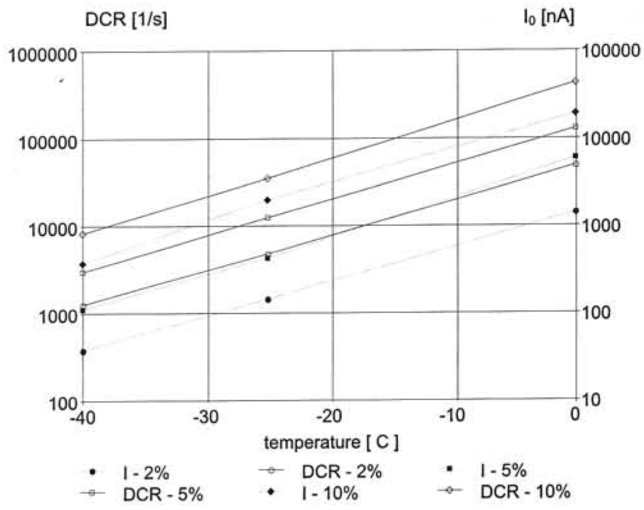

Fig. 19. Temperature dependence of dark current I_0 and dark count rate DCR at voltages which correspond to the photon detection probability of 2, 5, 10%.

dark current are in Fig 19 while in Fig 20 the quantum efficiency – measured in an analog mode, and the probability of triggering the avalanche versus radiation wavelengths are demonstrated.

As it can be seen, BPYP 52 photodiodes achieve good properties in a single photon counting mode at temperatures below 0°C. At the ambient temperature the value of DCR is too high.

The further research aimed to bettering the technology of APDs working in a single photon counting mode will be carried out in order to decrease, as much as possible, dark count rate which in turn may enable to increase the probability of photon detection thus will make possible for APDs, developped at ITE, work as photon counters at the ambient temperature. The thermoelectric modules containing photon counting APDs will be developed and implemented for production in near future.

Acknowledgements

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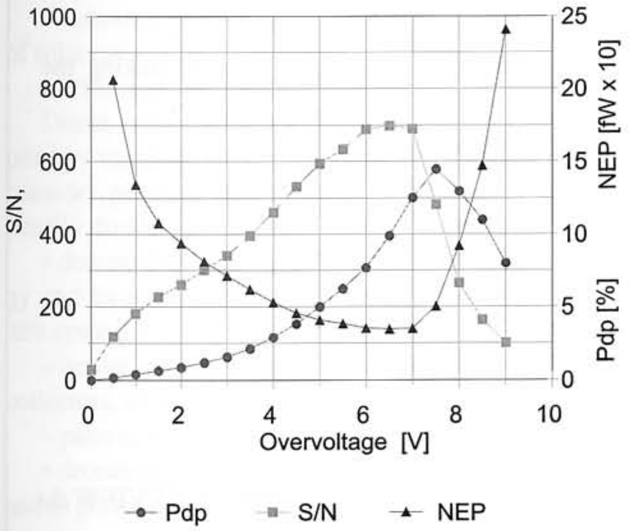

Fig. 18. Typical over-voltage dependence of the signal to noise ratio S/N, noise equivalent power NEP and photon detection probability P_{dp} at –40°C temperature.

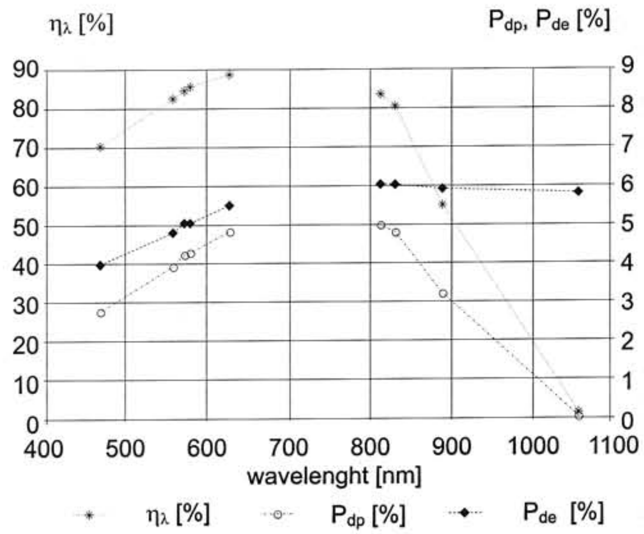

Fig. 20. Quantum efficiency $\eta\lambda$, photon detection probability P_{dp} and probability of trigeringg the avalanche P_{de} versus radiation wavelenght.

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