SILICON PHOTODIODE READOUT OF SCINTILLATORS
AND ASSOCIATED ELECTRONICS *

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ABSTRACT

The readout of scintillators by silicon photodiodes is reviewed. The use of photodiodes, rather than that of phototubes, is mandatory in modern particle physics detectors due to the presence of strong magnetic fields but such devices present also advantages in many other domains. After a reminder of photodiodes, scintillator and low-noise electronics characteristics the methods of using them together are described with special emphasis on the optimization of the signal-to-noise ratio.

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1. INTRODUCTION

The readout of inorganic scintillators by silicon photodiodes was first used nearly 30 years ago in space science [1] where the low power consumption of photodiodes and their long-term stability [2] was especially adequate. Some years later, scintillator-photodiode assemblies were investigated for nuclear physics applications like medium-energy charged particle detection [3] and low-energy γ -ray spectroscopy [4] but the field of application of such detectors stayed rather limited.

The situation changed about 10 years ago when several particle physics detector projects were demanding readout of big quantities of inorganic scintillators embedded in a high magnetic field (~ 1 T) excluding the use of phototubes. At that time several manufacturers had developed large area (≥ 1 cm²) PIN silicon photodiodes presenting high speed, low series resistance, low dark current and low junction capacitance resulting in low noise when used with state-of-the-art electronics. As a result, PIN photodiodes are now used extensively in electromagnetic calorimeters in particle physics detectors but also in many other fields like radiation monitoring, nuclear physics, etc.

In this paper, after a brief summary of photodiode, low-noise electronics and scintillator characteristics, some of the problems connected with the readout of scintillators by silicon photodiodes will be reviewed and some recent results in such applications will be given.

2. SILICON PHOTODIODES AND ASSOCIATED ELECTRONICS

For the readout of scintillators, PIN photodiodes in reversed bias operation are used. In this type of photodiode the wafer is made of high-resistivity (up to 8 k Ω ·cm), very pure n-type silicon also called intrinsic material. The p⁺ layer through which the light penetrates the diode is very thin and passivated by an oxide layer which also has an antireflective function.

This type of photodiode exhibits a great resistance to breakdown and can thus be operated with a reversed bias voltage. As a consequence, the junction can be fully depleted giving about 70 pF/cm² capacitance for a 200 μ m thick wafer. Also the response time is decreased to some nanoseconds. Finally, the response is linear over many decades of light intensity which is important to cover the dynamic energy range (up to 10⁵) of particle physics electromagnetic calorimeters.

Using high-quality bulk material and careful construction processes the dark current at ~ 20 V reversed bias voltage and at room temperature can be as low as 1 nA and the series resistance around 10 Ω . Nowadays, the most common photodiodes have a sensitive area of the order of 1 cm² but areas up to 8 cm² are available commercially.

Figure 1 shows the spectral response of a standard silicon photodiode [5]. The quantum efficiency is mainly determined by the light loss due to reflection at the diode surface and absorption in the p^+ , SiO_2 and other protective layers. Actually, the intrinsic quantum efficiency of silicon may be as high as 150% at short wavelengths due to double pair production by one photon [6]. The sensitivity may be extended to lower wavelengths (down to ~ 200 nm) by a special conception of these layers [6].

In modern detectors up to several 10^4 photodiodes may be used, very often in inaccessible locations. Thus the stability of operation and the reliability are important issues and a big effort was put into this field [5]. As a result, silicon photodiodes have now a very low failure rate.

Until recently, the radiation resistance of silicon photodiodes was sufficient since the scintillators themselves had usually much less radiation resistance. This may change with the operation of scintillator-photodiode assemblies around the future hadron colliders (LHC, SSC) where the radiation level may be several MRad/year.

Unlike phototubes, silicon photodiodes have high quantum efficiency (Fig. 1) but no internal amplification. As a consequence, the energy resolution at low energies will be determined by the electronic noise rather than by the photoelectron statistics. As will be seen later, one obtains between 10^3 and some 10^4 photoelectrons per MeV deposited in the scintillator. In order to obtain the best signal-to-noise ratio one uses a charge-sensitive preamplifier followed by a shaping amplifier characterized by a time constant τ [7]. Usually, the output of the shaping amplifier is a smooth unipolar pulse which peaks at time t_p and which amplitude is proportional to the charge delivered by the photodiode. The equivalent noise charge (ENC), expressed in units of number of electron-hole pairs, is a measurement for the equivalent charge fluctuations at the input of the preamplifier which would produce the observed noise at the output of the shaping amplifier. The complete equation for $(ENC)^2$ [7] reduces to the following expression if one omits the small $1/f$ noise contribution:

$$(ENC)^2 = a_1 (2 \cdot 10^4 \cdot \tau \cdot I_d + 10^3 \tau / R_p) + a_2 C^2 / g_m \cdot 1 / \tau$$

with τ = shaping time (in μs)

I_d = photodiode dark current (in nA)

R_p = total parallel resistance (in $G\Omega$)

C = total parallel capacitance (in pF)

g_m = FET transconductance (in S).

The values of a_1 and a_2 depend on the exact pulse shape and are of the order of 0.3 to 0.6 for normal unipolar pulses. For typical values ($\tau = 1 \mu\text{s}$, $I_d = 1 \text{ nA}$, $R_p = 0.1 \text{ G}\Omega$, $C = 100 \text{ pF}$, $g_m = 0.04 \text{ S}$) the noise is practically proportional to the total capacitance C . This is not true, of course, for shaping time constants $\tau \gg 1 \mu\text{s}$ but in practice one is limited to $\tau \sim 1 \mu\text{s}$ in order to avoid pulse pileup. In the above expression giving $(\text{ENC})^2$ the series resistance of the photodiode (some Ohms) is neglected in respect to the input impedance of the preamplifier. The presence of this series resistance increases the ENC by about 20% using a modern PIN photodiode.

In order to decrease the electronic noise one should decrease the total capacitance $C = C_{PD} + C_{PA}$ where C_{PD} is the junction capacitance of the photodiode and C_{PA} the input capacitance of the preamplifier (cabling and FET capacitance). C_{PA} is of the order of 30 pF if g_m is not too high and could be decreased using special techniques [8] but most of the gain could be obtained by decreasing C_{PD} . This capacitance is proportional to $1/d$ where d is the depletion depth. For the classical 200 μm thick wafer $C_{PD} \sim 70 \text{ pF/cm}^2$ at full depletion. Increasing the wafer thickness to 500 μm for example, a C_{PD} of $\sim 30 \text{ pF/cm}^2$ can be obtained but care must be taken so that the now much higher bias voltage necessary to obtain full depletion does not increase too much the dark current. For this purpose one has to use high resistivity material [9].

Another way to decrease dramatically the junction capacitance C_{PD} would be the use of drift photodiodes [8], [10]. Diode capacitances of some pF or less can be obtained at the expense of very long (μs) charge collection times. This type of photodiode is still in the development stage.

Finally, the use of silicon avalanche photodiodes would allow a large decrease in electronic noise while keeping the high quantum efficiency of silicon. These devices have internal avalanche gains of up to several hundred and can now be fabricated with large ($\sim 1 \text{ cm}^2$) areas [11]. The avalanche gain is strongly dependant of the bias voltage ($\sim 1 \text{ kV}$) and of the temperature. Also they are quite expensive for the moment. For all these reasons, they are not yet used routinely for the readout of large arrays of scintillators.

3. SCINTILLATORS

A scintillator is a transparent material where the energy deposited by charged particles gives rise to emission of light. Usually, the number of emitted photons is proportional to the energy deposited in the scintillator but deviations from proportionality are observed, e.g. for high ionization densities.

Table 1 lists some scintillators and their main characteristics. In order to absorb efficiently γ -rays the scintillator should present a short radiation length. This condition is fulfilled by most of the inorganic scintillators (crystals). Unfortunately, many of these crystals present long decay times.

Comparing the emission wavelengths of the scintillators of Table 1 with the photodiode sensitivity shown in Fig. 1 one sees that the scintillator CsI (Tl) is particularly well adapted for photodiode readout. It also has the highest light yield. For the fast inorganic scintillators BaF₂ and CsI, which emit in the UV region, special UV enhanced photodiodes [6] may be used but they could also be read out by wavelength shifters [12]. The light yield of the fast organic (plastic) scintillators is rather low but some of them present emission spectra well adapted to the silicon photodiode sensitivity.

4. SCINTILLATOR READOUT BY PHOTODIODES

In most cases one wants the best energy resolution, i.e. the lowest possible noise: one has to use the type of charge-sensitive electronics described in Section 2. Charge integration is particularly mandatory for the slow inorganic scintillators BGO and CsI (Tl). Of course, such devices present then very poor timing properties. The problem of timing with photodiode readout of scintillators will be examined at the end of this section.

4.1 Coupling of photodiodes to scintillators and light collection

In principle, the optical coupling of the photodiode to the scintillator is performed in the same way as in the phototube case using optical grease or glue. Usually, the photodiode sensitive surface is protected by a resin layer and no special precautions have to be taken. A big advantage of the photodiode is its small weight and its compactness thus avoiding any support structure. A special case is the scintillator BGO which presents an index of refraction of 2.1 and for which an optical coupling agent having an index of refraction intermediate between the BGO index (2.1), and the index of the resin layer of the photocathode (1.6), has not yet been found.

In order to collect the maximum light intensity, all faces of the scintillator not used for light readout should be polished and covered by a highly reflective layer as in the case of phototubes. Using appropriate materials, reflectivities up to 98%-99% can be reached [9]. For CsI (Tl) multiple layers of thin PTFE (Teflon) sheets give also good results.

4.2 Geometrical considerations

In many applications of photodiode readout of scintillators, the modules are arranged in large arrays, each scintillator being a long, but narrow crystal in order to obtain good γ -ray or particle absorption and also good spatial resolution (tower structure). Figure 2 shows a typical

situation. The only free surface to collect the scintillation light is the "back" area ($S \text{ cm}^2$). Usually, the area of one photodiode ($a \text{ cm}^2$) is smaller than S and the diode will collect a/S of the available photons at the back face.

Using n photodiodes (each with area $a \text{ cm}^2$) the number of photons collected will be increased roughly by a factor n , but the electronic noise (ENC) will also increase nearly by a factor n (see Section 2). As a consequence, the signal-to-noise ratio does hardly change ("Groom's theorem" [13]).

We have verified this effect using a 30 cm long CsI (Tl) crystal ($S \sim 36 \text{ cm}^2$) for n varying from 1 to 9. Figure 3 (open circles) shows that the noise-to-signal ratio (or the RMS noise expressed in equivalent energy deposit) is nearly independent of the number n of photodiodes (each had $a = 1 \text{ cm}^2$). Our electronic system ($\tau = 1 \mu\text{s}$) presented an $\text{ENC} = (140 + 3.3 C)$ electrons (C = external capacitance in pF), with $\text{ENC} = 230$ electrons at $C = 0$ pF. One can conclude that multiplying the number of photodiodes or using large area photodiodes does in general not improve considerably the signal-to-noise ratio which, even at low energies, determines the energy resolution rather than photoelectron statistics.

4.3 Use of wavelength shifters

For scintillator areas $S \gg 10 \text{ cm}^2$ the signal-to-noise ratio may be improved by the use of a wavelength shifter (also called fluorescent flux concentrator) [14,15]. The lower insert of Fig. 3 shows such an arrangement. The wavelength shifter covers the whole surface S and is read out by one or several rectangular photodiodes glued on its edges (the free edges are covered with white reflective paint). The wavelength shifter, usually lucite with some dye, is designed to have its absorption spectrum centred on the peak of the emission spectrum of the scintillator. The efficiency of the wavelength shifter, i.e. the number of secondary photons reaching the photodiode relative to the number of scintillation photons leaving the surface S , is of the order of 10% [14].

Using such an arrangement, the RMS noise (in keV) of our CsI (Tl) module decreased down to 250 keV (full circle in Fig. 3). The efficiency of the wavelength shifter was in this case around 7% and the number of photoelectrons per MeV around 1800. It should be noticed that in the case of a small CsI (Tl) crystal (some cm^3), directly coupled to a photodiode, the number of photoelectrons per MeV can reach $\sim 3 \times 10^4$ [9].

4.4 Timing with photodiodes

In the preceding subsections, charge-sensitive electronics with microsecond shaping was assumed in order to obtain the lowest noise figure. If one wants also timing properties, two cases have to be distinguished.

4.4.1 Timing with slow inorganic scintillators

The decay time constants of such scintillators are in the microsecond range (see Table 1). For these scintillators, like BGO or CsI (Tl), charge-sensitive electronics is mandatory since the total charge delivered by the photodiode is spread over a large time interval. The rise time of the output pulse of the charge-sensitive preamplifier will then be equal to the decay time of the scintillator, i.e. in the microsecond range. A constant fraction discriminator adapted to such long rise times should then be used. The time resolution obtainable with such a set-up depends on the signal-to-noise ratio in a classical way.

4.4.2 Timing with fast scintillators

Silicon photodiode readout of fast, inorganic scintillators (BaF_2 , pure CsI) is not very well investigated mainly because they emit in the UV region (see Table 1). This situation may change with the arrival of the future hadron colliders (LHC, SSC), where timing in the nanosecond range is required. Due to the large energy deposits the signal-to-noise ratio may be adequate even using fast electronics but the high radiation level will probably exclude silicon as the photodiode material and may be replaced by GaAs for example.

Organic (plastic) scintillators are mainly used to detect minimum ionizing particles (MIP). A MIP traversing 1 cm of plastic scintillator deposits 2 MeV of energy corresponding to approximately 10^4 photons. Photoelectron yields between 2.5 and 5×10^3 per cm have been observed [16,17]. Using conventional slow charge-sensitive electronics, signal-to-noise ratios between 5 and 10 were obtained. Usually, for operation of plastic scintillators, a timing information much better than the one obtainable with the above-mentioned slow electronics is necessary. Fast electronics (low-noise current amplifier) used with one photodiode (~ 70 pF) presents a RMS noise of about 2.5×10^3 electrons [18], i.e. the signal-to-noise ratio becomes very poor. As a consequence, silicon photodiodes seem not to be used for the readout of plastic scintillators for MIP detection. Avalanche photodiodes may be usable in this application, since gain stability is not essential here, if mass production lowers the price of such devices to an acceptable level.

In conclusion, the timing properties of silicon photodiode read out of scintillators are rather poor and are far from reaching those obtainable with phototubes.

5. EXAMPLES OF APPLICATION OF PHOTODIODE READOUT OF SCINTILLATORS

Scintillator-photodiode assemblies are now routinely used from very low to very high energy applications. Only some typical examples are given here.

5.1 Low-energy domain (~ 1 MeV)

CsI (Tl) scintillator-photodiode assemblies allow the construction of very compact gamma-ray probes with an energy resolution comparable to the one obtained with phototubes. For example, for the 661 keV line of ^{137}Cs a FWHM energy resolution of 8% is achievable [19]. Positron emission tomography may also be an interesting field of application using BGO crystals, especially when cooling of the crystal-photodiode-FET assembly is applied [20]. Silicon avalanche diodes are also interesting devices once their price decreases to an acceptable level for this application which involves a high number of photodiodes. The combination of stable and low-mass photodiodes with CsI (Tl) crystals which are only slightly hygroscopic and can thus be machined easily to any shape gives rise to promising prospects for application in low-level spectroscopy [21].

5.2 Medium energy (~ 100 MeV) physics

In the nuclear physics domain (heavy ion physics, photonuclear reactions, etc.) scintillator-photodiode assemblies are mainly used in large arrays for the detection of charged particles. For example, using $25 \times 25 \times 30 \text{ mm}^3$ CsI (Tl) crystals, each read out by a $10 \times 20 \text{ mm}^2$ silicon photodiode, a RMS noise figure of 400 electrons was obtained (3 μs shaping time constant) [22]. This corresponds to an energy resolution of 80 keV FWHM. A special characteristic of CsI (Tl) is the relation between scintillation decay time and ionization density allowing pulse shape discrimination of light particles (p, d, t, α , etc.) [23]. One can also use the photodiode, which measures the light of a CsI (Tl) crystal, as a dE/dx detector obtaining thus a simple and compact charged particle telescope [24].

In the medium energy particle physics domain scintillator-photodiode assemblies are mainly used in 4π electromagnetic calorimeters (in a high magnetic field) to detect photons in the energy range from ~ 10 MeV to some GeV. Two of such detectors are now in operation.

The CLEO-2 electromagnetic calorimeter [25] is composed of ~ 8000 CsI (Tl) crystals each of 30 cm length and $\sim 5 \times 5 \text{ cm}^2$ cross-section. Each crystal is read out by four 1 cm^2 photodiodes for redundancy. The average RMS noise per module is of the order of 0.6 MeV.

The Crystal Barrel electromagnetic calorimeter [26] is composed of 1380 CsI (Tl) crystals of similar size as those of CLEO-2. Each crystal is read out by one rectangular ($3 \times 30 \text{ mm}^2$) photodiode via a wavelength shifter as explained in Section 4.3. The average noise per module is 400 electrons (equivalent to 220 keV). The energy resolution for photons between 20 MeV and 1 GeV is $\sigma(E)/E = 2.5\% \times [E (\text{GeV})]^{-0.25}$.

Several such calorimeters are planned for the future B and τ/charm factories.

5.3 High-energy ($>> 1$ GeV) particle physics

The L3 electromagnetic calorimeter is composed of ~ 12000 BGO crystals each of 24 cm length and $\sim 3 \times 3$ cm² cross-section. Each crystal is read out by two 1.5 cm² silicon photodiodes. The RMS noise per module is of the order of 1 MeV. The electron (or photon) energy resolution $\sigma(E)/E$ is $\sim 0.5\%$ for $E > 10$ GeV but is still 5.6% at $E = 100$ MeV [27].

For the use as a high-resolution electromagnetic calorimeter at the future hadron colliders (LHC, SSC), several research and development programs are in progress to find a scintillator-photodiode combination presenting high speed and high radiation resistance (several 10^6 Rad/year).

6. OUTLOOK

Silicon photodiodes are now used routinely and in big quantities to read out scintillators in many physics domains. This tendency will certainly continue, especially since silicon photodiodes have now reached a plateau concerning excellent performances and reasonable price. On the other hand, the noise problem on the low-energy border and the timing and radiation-resistance problems on the high-energy border, forces physicists and engineers to look for new types of photodiodes.

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REFERENCES

- [1] A.J. Tuzzolino, J. Appl. Phys. 33 (1962) 148.
- [2] A.J. Tuzzolino, Nucl. Instr. and Meth. 204 (1982) 161.
- [3] N.G. Blamires, Nucl. Instr. and Meth. 24 (1963) 441.
J.E. Bateman, Nucl. Instr. and Meth. 67 (1969) 93; Nucl. Instr. and Meth. 71 (1969) 261.
- [4] G. Keil, Nucl. Instr. and Meth. 66 (1968) 167.
- [5] K. Yamamoto et al., Nucl. Instr. and Meth. A253 (1987) 542.
- [6] T.E. Hansen, Nucl. Instr. and Meth. A235 (1985) 249.
- [7] W.J. Willis et al., Nucl. Instr. and Meth. 120 (1974) 221.
V. Radeka, IEEE Trans. Nucl. Sci. NS-21 (1974) 51.
- [8] G. Bertuccio et al., Contribution to this Workshop (1991).
- [9] S. Gunji et al., Nucl. Instr. and Meth. A295 (1990) 400.
- [10] B.S. Avset et al., Nucl. Instr. and Meth. A288 (1990) 131.
- [11] R. Farrel et al., Nucl. Instr. and Meth. A288 (1990) 137.
- [12] J. Giehl et al., Nucl. Instr. and Meth. A263 (1988) 392.
- [13] D.E. Groom, Nucl. Instr. and Meth. 219 (1984) 141.
- [14] G. Keil, Nucl. Instr. and Meth. 87 (1970) 111.
- [15] E. Lorenz, suggested to us the use and the type of wavelength shifter adapted for the readout of CsI (Tl).
- [16] D. Hall et al., Nucl. Instr. and Meth. A245 (1986) 344.
- [17] B. Mouëllic, private communication (1991).
- [18] P. Jarron et al., Nucl. Instr. and Meth. 226 (1984) 156.
- [19] Specification sheet, Eurorad.
- [20] S.E. Derenzo, Nucl. Instr. and Meth. 219 (1984) 117.
- [21] V. Kilgus et al., Nucl. Instr. and Meth. A297 (1990) 425.
- [22] J.R.M. Annand et al., Nucl. Instr. and Meth. A292 (1990) 129.
- [23] P. Kreutz et al., Nucl. Instr. and Meth. A260 (1987) 120.
- [24] G. Pasquali et al., Nucl. Instr. and Meth. A301 (1991) 101.
- [25] C. Bebek, Nucl. Instr. and Meth. A265 (1988) 258.
- [26] E. Aker et al., The Crystal Barrel Spectrometer at LEAR (in preparation).
- [27] M. Schneegans, Nucl. Instr. and Meth. A257 (1987) 528.

Table 1

Main properties of some scintillators

Scintillator	NaI (Tl)	BGO	CsI (Tl)	CsI	BaF ₂	NE 108	NE 110	BC 430
Nature	--	--	Crystal	--	--	--	Plastic	
Hygroscopic	Yes	No	slightly	No	No	--	No	--
Density (g/cm ³)	3.7	7.13	4.41	4.88	4.88	--	~1	--
Radiation length (cm)	2.59	1.12	1.86	2.03	2.03	--	42	--
dE/dx for MIP (MeV/cm)	4.85	9.2	5.6	6.5	6.5	--	1.95	--
Peak emission (nm)	420	480	550	305	220/305	535	434	580
Refractive index	1.85	2.1	1.8	1.5	1.5	--	~1.6	--
Light yield (phot./MeV)	4·10 ⁴	~8·10 ³	5·10 ⁴	~2·10 ³	~2/6·10 ³	~10 ⁴	~10 ⁴	7.6·10 ³
Decay time (ns)	230	300	~900 a)	10	0.6/600	1.5	3.3	17

a) CsI (Tl) has two decay times: fast = 0.4-0.8 μs depending on ionization density, slow = some μs.

Figure captions

- Fig. 1 : Spectral response of a typical silicon photodiode [5].
- Fig. 2 : Typical geometry for photodiode readout of long and narrow scintillators arranged in an array.
- Fig. 3 : Noise-to-signal ratio (or RMS noise expressed in equivalent energy) of two types of photodiode readout; open circles: photodiodes glued directly to the scintillator (upper insert); closed circle: light readout via a wavelength shifter and one rectangular photodiode (lower insert).

Fig. 1

Fig. 2

Fig. 3