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Silicon photomultiplier and its possible applications

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Abstract

The Silicon Photomultiplier (SiPM) is a semiconductor device consisting of many photon microcounters ($10^3\,mm^{-2}$) positioned on a common Si substrate. SiPM operates in a limited Geiger mode and has single photoelectron gain (10^6) and photon detection efficiency (20%) similar to vacuum PMT. Main SiPM features are described and a number of examples of its possible applications are demonstrated, such as scintillator fiber readout, scintillator tiles + WLS readout, imaging Cherenkov counter timing. These SiPM applications are based on experimental test data and SiPM performance is compared with other photodetectors (PMT, APD, HPD, VLPC).

1. Silicon photomultiplier (SiPM) description and performance

The Silicon Photomultiplier (SiPM) is described in details in Ref. [1]. It is a multipixel silicon photodiode with a number of micropixels (typical size of 20–30 μm) joined together on common substrate and working on common load. The pixels are electrically decoupled from each other by polysilicon resistors (typical value of 500 kΩ) located on the same substrate. The operational bias voltage is 10–15% higher than the breakdown voltage, so each SiPM pixel operates in Geiger mode limited by individual resistor with a gain determined by the charge accumulated in pixel capacitance (typically 100 fF). Each pixel detects the carriers created by photon or MIPs or thermally with a "gain" about 10^6 independently on primary carrier number (for instance one photoelectron or a few hundred electrons created by MIP give rise to the same signal). Actually each SiPM pixel operates digitally as a binary device, but SiPM in whole is an analogue detector, which can measure the light intensity within the dynamic range of about $10^3\,mm^{-2}$.

We describe the performance of SiPM test batch with a depletion region of 2 μm and working bias voltage of about 50 V, consisting of 576 pixels, covering geometrically about 25% of total SiPM area of $1 \times 1\,mm^2$.

SiPM pulse height spectrum from low-intensity light flashes produced by light emission diode (LED) source is shown in Fig. 1a (room temperature) in comparison with the same spectra from Hibrid Photodiode (HPD) (room temperature) and Visible Light Photon Counter (VLPC) (temperature 6.5°K). One can conclude an excellent SiPM single photoelectron resolution (that means small pixel to pixel gain variation), and that the

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contribution to the SiPM excess noise factor (ENF) is expected to be very small. The electronics noise contribution can be estimated from pedestal width ($\leqslant 0.1$ electron). It is possible to distinguish each photoelectron pulse height even for more intensive light pulses with mean photoelectron (or fired pixel) number of 46 (see Fig. 1d).

In Fig. 2 one can see the comparison of photon detection efficiencies of vacuum and silicon devices. For PMT, APD and HPD the photon detection efficiency is actually quantum efficiency QE, whereas for SiPM it is less than that due to the "geometrical" efficiency $\varepsilon_{geometrical} = S_{sensitive}/S_{total}$. The SiPM photon detection efficiency is for a time being at the level of PMT QE for blue light and more for yellow–red region, that is important for some applications. In addition there is rather weak SiPM gain dependence on temperature and voltage which is shown in Table 1 in comparison with the same dependencies for APDs.

Due to very high gain the SiPM electronics noise is negligibly small (see above) and the main source of the noise is the dark rate. This rate is about 2 MHz at room temperature and it decreases to a few kHz at liquid nitrogen temperature.

The SiPM dynamic range is limited due to the finite number of pixels by the condition that the average number of photoelectrons per one pixel should be small enough ($\lesssim 1$).

The technologically possible density of pixel number is likely $(2–3) \times 10^3\,\text{mm}^{-2}$; therefore, it limits the SiPM dynamic range at the level of $(1–2) \times 10^3\,\text{mm}^{-2}$.

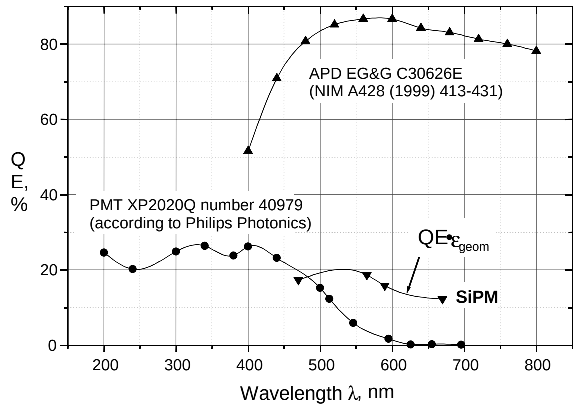

Fig. 2. Comparison of photon detection efficiencies for PMT [4], APD [5] and SiPM.

Table 1
The change of the temperature and bias voltage needed for a gain variation of 1%

Photodetector	ΔT	$\Delta V/V$
APD EG&G C30626E[a]	0.15°	$0.4\,V/400\,V = 10^{-3}$
APD Hamamatsu S5345[a]	0.3°	$0.04\,V/300\,V = 1.5 \times 10^{-4}$
SiPM ($M = 2 \times 10^6$)	2.5°	$0.05\,V/50\,V = 10^{-3}$

[a] For the gain $M = 100$ [5].

2. Experimental studies of the possible SiPM applications: comparison with other photodetectors

2.1. Scintillator fiber detector

The relativistic particle detection by means of scintillation fiber has been studied at room

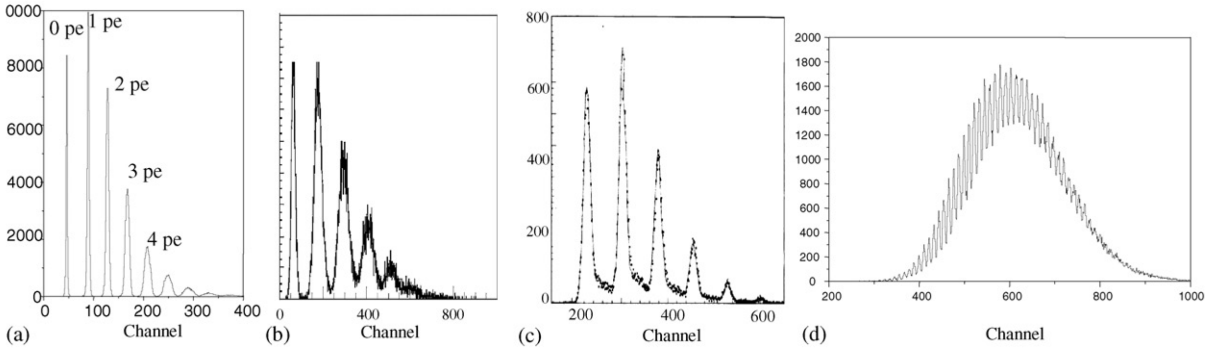

Fig. 1. SiPM (a) photon counting capability compared to VLPC [2] (b) and HPD [3] (c). SiPM pulse height spectrum (d) for more intensive light burst with mean number of photoelectrons 46.

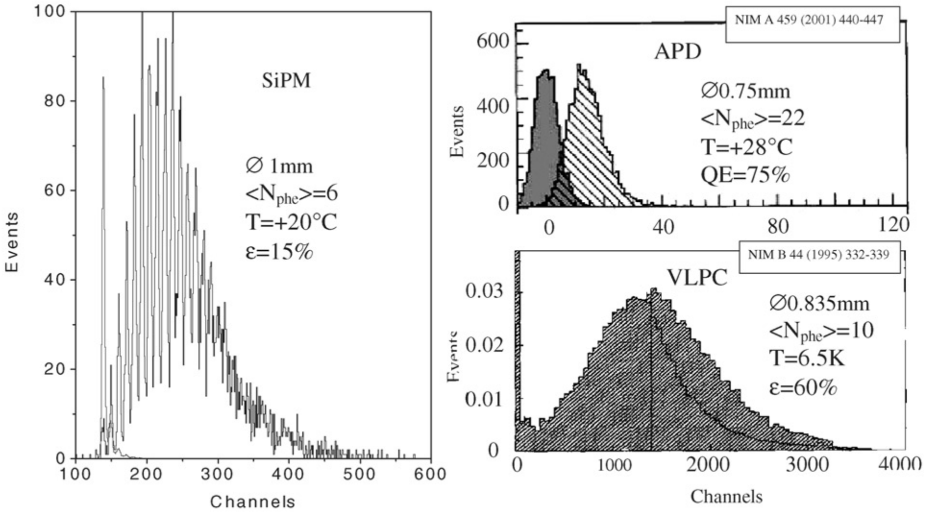

Fig. 3. SiPM application for sci fiber MIP detection (at room temperature): comparison with APD [6] (room temperature) and VLPC [7] (6.5°K).

temperature using Sr^{90} β-source and multicladding Kuraray sci fiber SCSF-3HF (1500)M with core diameter 0.94 mm, emission peak at 530 nm, decay time 7 ns and 1/e length >4.5 m.

The results of the measurements are shown in Fig. 3 together with the results obtained in the similar measurements with APD [6] (gain 115, room temperature) and VLPC [7] (gain 2×10^4, $T = 6.5°$K).

SiPM signal-to-noise ratio at room temperature looks almost as good as in VLPC case ($T = 6.5°$K) and much better than APD (room temperature) — because of the absence of electronics noise, negligible contribution of surface leakage current and low ENF.

2.2. Plastic scintillator + WLS shifter readout

The plastic scintillator with wavelength shifter (WLS) readout is very attractive in case of the necessity to readout a very large number of scintillators with a small room available and also the need to perform in high magnetic field.

We have carried out the test measurements with plastic scintillator + WLS readout[1] using SiPM. Fig. 4 shows the test results for plastic scintillator $5 \times 5\,cm^2$ and 5 mm thickness for minimum ionizing particles (pion beam 1 GeV). For optical readout we used the fiber with 1 mm diameter and WLS ($\lambda = 494$ nm) with the length of 1.5 m. The WLS fiber was positioned in the groove in plastic body, one end of fiber was covered by aluminized mirror in order to increase the light collection, the other one was connected to SiPM. The results for SiPM readout (Fig. 4a) are compared with the similar results where the PMT was used for scintillation light detection for the same scintillator–WLS system (Fig. 4b). We can see that the SiPM signal-to-noise ratio for the MIP detection looks as good as PMT.

We have estimated the possibility of tile scintillator + WLS fiber readout by SiPM, considering as an example the Hadron Tile Calorimeter for TESLA experiment [8]. The dynamic range of Hadron Tile Calorimeter for one tile + $1\,mm^2$ SiPM readout element is determined by the ratio of max signal (high-energy jet) to min signal (MIP) and estimated to be of about 100 and requires the SiPM with the number of pixels more than 1500–2000 mm^{-2}. Moreover, the safe MIP detection is needed for calibration purposes. Fig. 4c shows the results of beam test

[1] Scintillator + WLS fiber was provided by ITEP.

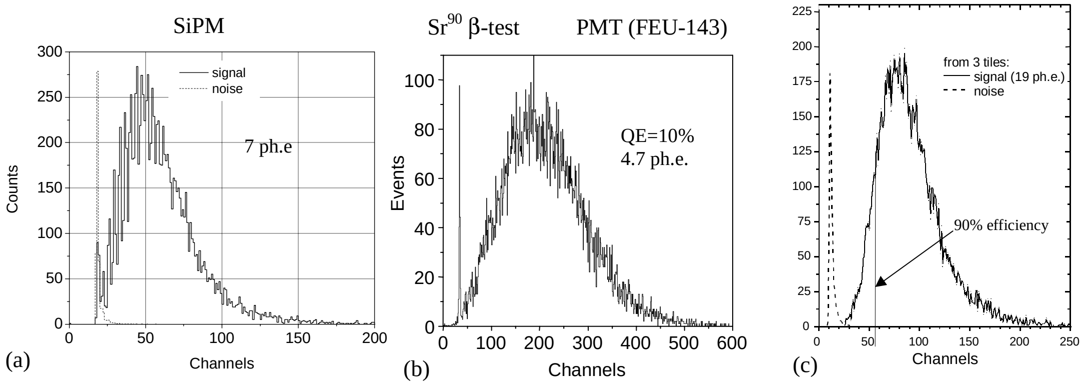

Fig. 4. SiPM application for scintillator and wavelength shifter readout. MIP particle detection is shown using one $5 \times 5 \times 0.5\,\mathrm{mm}^3$ sci tile and SiPM (a) or PMT (b) and the setup with three cells each consisting of tile + SiPM (c).

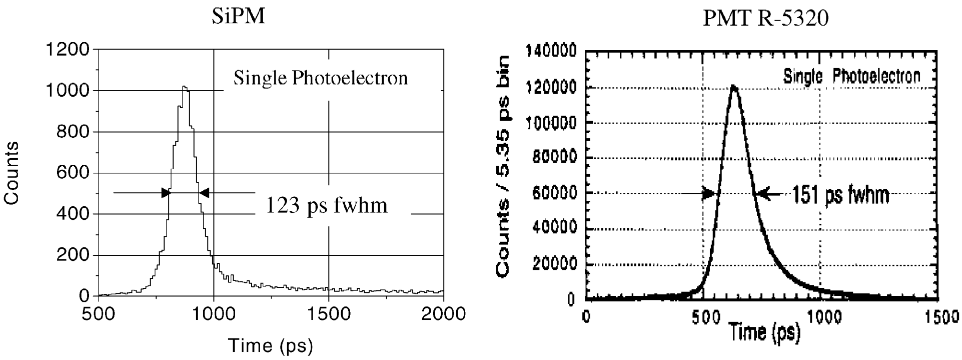

Fig. 5. Single photoelectron timing resolution for SiPM and PMT [11].

(pion beam 1 GeV) for three tiles cell (tile size $5 \times 5 \times 0.5\,\mathrm{cm}^3$ with 1 mm WLS fiber + SiPM). One can see a very good signal-to-noise ratio (noise probability at the level less than 10^{-6} for 90% MIP efficiency at room temperature).

2.3. *SiPM application for imaging Cherenkov counters*

The SiPM is intrinsically very fast due to very small width of depletion region and extremely short Geiger-type discharge (a few hundreds picoseconds). Therefore, the subnanosecond timing of SiPM together with the other features such as insensitivity to magnetic field, single photoelectron detection with a good S/N ratio (see Fig. 1), good photon detection efficiency in the wide spectral range (Fig. 2) and position-sensitive ($1\,\mathrm{mm}^2$) capability look very promising for the application in the field of modern imaging Cherenkov detectors such as DIRC [9] and Time of Propagation (TOP) Cherenkov detector (upgrade of BELLE [10]).

Timing by SiPM has been studied using very fast red laser diode ($\lambda = 670\,\mathrm{nm}$, light pulse of 40 ps FWHM). Fig. 5 demonstrates the single photoelectron (single pixel) timing for very low-intensity laser pulse. For comparison, one can see the timing resolution of one out of the best PMT (FWHM = 151 ps [11]). The single photoelectron timing, including the laser pulse width and contribution of the electronics is 123 ps (FWHM). The intrinsic single photoelectron timing resolution of SiPM after substraction of laser and electronics contributions is FWHM $\simeq$ 100 ps (or 50 ps rms).

3. Conclusions

The R&D studies of SiPM show that after the tuning of some its parameters (photon efficiency, gain, timing, dynamic range, etc.) one can consider the SiPM as a very promising photodetector for a number of applications.

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