TESTING THE SILICON PHOTOMULTIPLIER FOR IONIZATION PROFILE MONITOR*

S. Barabin, D. Liakin, A. Orlov, ITEP, Moscow, Russia
P. Forck, T. Giacomini, GSI, Darmstadt, Germany

Abstract

A new kind of photonic device is proposed to be used in the fast operating mode of the ionization profile monitor. A silicon photomultiplier device combines the advantages of photomultipliers and solid-state photo detectors. It provides high sensitivity, wide optical spectrum response, high bandwidth and absence of 1/f noise component. Those parameters are critical in the IPM with fast readout feature, which is under development by GSI in collaboration with ITEP, COSY, MSU and CRYRING laboratories. First investigations were made to obtain detailed parameters of silicon photomultiplier. A testing layout and resulting performance data are presented in this publication.

INTRODUCTION

To provide a non destructive beam profile measurement at modern ion synchrotrons and storage rings our collaboration is developing a Ionization Profile Monitor (IPM) [1,2]. It will cover wide range of beam intensities and dimensions with high spatial resolution and high timing performance operating on turn-by-turn basis. In IPMs an electrostatic field accelerates the products of the beam and residual gas ions collisions towards a Micro Channel Plate (MCP). Secondary electrons, produced in MCP, hit a phosphor screen, where they produce a light spots. In the fast mode of operation of the IPM time evolution of the beam profile will be sliced with 10 profiles/μs record speed. For that we foresee a readout with a resolution of 1mm by a 100-channel avalanche photodiode array or multi-anode photomultiplier, which register light intensity distribution over the phosphor screen. In this paper we presented new type of photodetector – Silicon Photomultiplier (SiPM), which can substitute other photodetector types in fast readout system.

A SiPM [3,4] is a multi-pitch silicon photodiode with a number of micro-cells (typical size of 20–30 μm) joined together on common substrate and working on common load. The operational bias voltage is 10–15% higher than the breakdown voltage, so each SiPM pixel operates in Geiger mode with avalanche current limited by individual polysilicon resistor located on the same substrate, with a gain determined by the charge accumulated within pixel capacitance. Each pixel multiplies the carriers created by photon or thermally by a factor about 10^6, the value close to that of photomultiplier. Actually, each SiPM pixel operates as a binary device, but SiPM upon the whole is an analogue detector, which can measure the light intensity within the dynamic range, determined by a finite number of pixels (~10^3/mm^2).

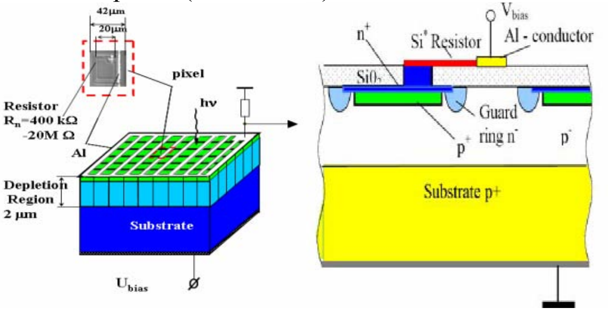

Figure 1: Schematic view of SiPM.

SiPM have the following features that allow to use it in RGM: high gain (~10^6), same as in photomultiplier (PMT) but much larger than on Avalanche Photodiodes (APD) (~10^2) with Photon Detection Efficiency (PDE) same as for a PMT (~16%) with respect to the phosphor screen wavelength (470nm); photon counting capability; low electronic noise; very good time resolution (≤100 ps); short recovery time; good temperature and voltage stability (much better than for APD); insensitivity to magnetic field ; low bias voltage (~50V) (comparable to PMT's ~1kV); compactness and robustness; low cost and simplicity of measurement system.

TESTING LAYOUT AND MEASUREMENT PROCESS

For obtaining the working characteristics of SiPM for our conditions and defining optimal parameters for the measurements, we explore main characteristics of SiPM.

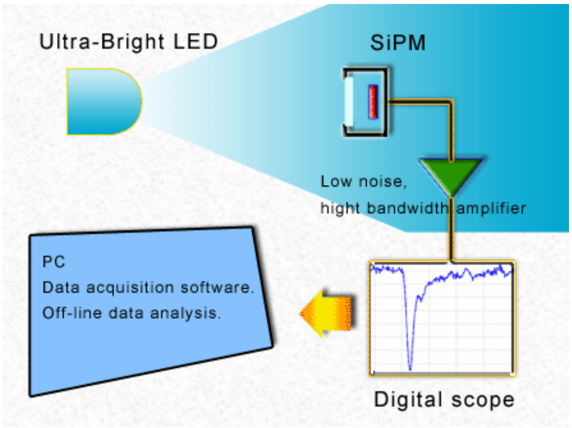

Figure 2: Testing Layout.

The testing layout includes the SiPM (1 mm^2, 576 pixels) and a 3mm Ultra-Bright light emitting diode

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(LED) with matched emission spectrum. These devices were located 160mm opposite each other in a dark box, with black matted inner walls to negligible reflections from the walls and protect the SiPM from outer light. A reverse voltage to SiPM was supplied by regulated voltage source (0-60V); the LED current could be established in the 0..20mA range; the output of the SiPM was connected to the 50Ohm-matched transmitting line, loaded with an input impedance of a 43 dB gain wideband amplifier; the output voltage was acquired by a digital scope TDS3052 and stored as a set of multiple waveforms in a data file for further analysis with a PC.

The output signal from SiPM is a time-distributed set of peaks from certain pixels, fired by photons or thermally. Fall time of peaks is defined by the carrier drift velocity (~10^5 m/s) in the pixel depletion region (2 µm), rise time – by resistance and capacitance of pitch elements, and the amplitude of the signal is proportional to overvoltage multiplied by the ratio of load and quenching resistors. The typical SiPM output is shown in Fig.3. The investigations consist mainly of analyzing of characteristics of that peaks.

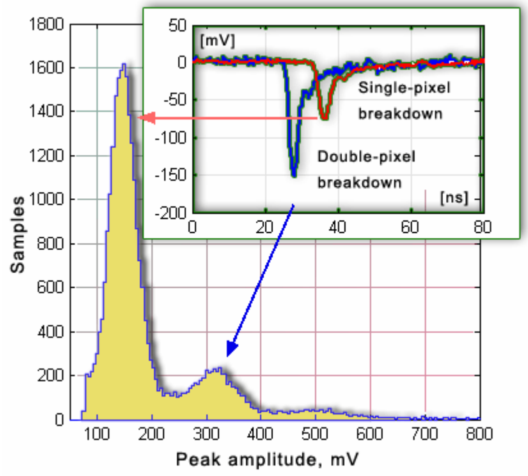

Figure 3: Amplitude spectrum and pixel impulse.

MEASUREMENT RESULTS

Photon Counting Measurement Characteristics

The amplitude spectrum of the output peaks is used as a basis for detailed investigations. The spectrums are obtained by collecting the digitized data waveforms within 1ms observation time. The amplitude spectrum is shown in Fig.3. As we can see from this figure, single, double and triple photoelectron peaks are clearly visible and pixel-to-pixel gain variation and electronic noise (pedestal width) are small.

Next exploration is made to measure SiPM single-pixel gain, that we obtain by measuring amplitude spectrum with different reverse voltages and determine the parameters from it amplitudes of the first maximum of the spectrum.

The gain of a single-pixel mode is determined by the charge accumulated within pixel and proportional to overvoltage on SiPM above breakdown voltage, as we see in Fig.4. From this figure we define breakdown voltage equal 43V. Determining the average area of single pixel impulse, we can obtain gain for one photoelectron.

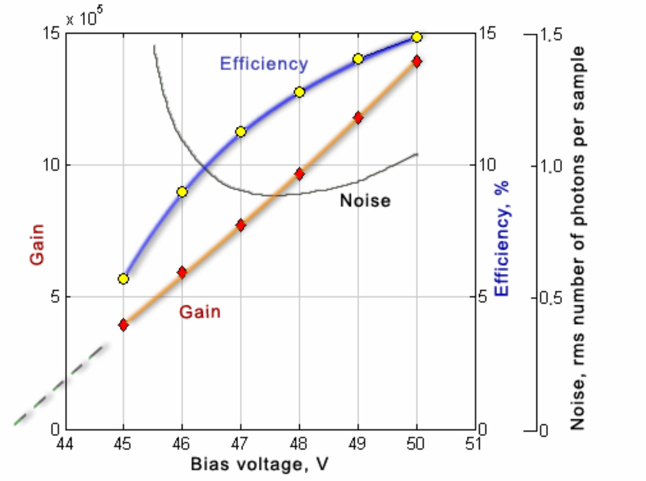

Figure 4: One pixel gain, detection efficiency and input noise.

SiPM's Noise

SiPM's output noise includes the following major parts: electronic noise, pixel-to-pixel gain variation (determined by variation of pixel capacitance) and dark-rate noise.

The discrete nature of the incoming signal leads to additional shot noise which can't be eliminate by increasing of incoming photons rate, because of the SiPM saturation effect, and rms value of that noise is equal to square root of fired pixels.

An equivalent output noise of the electronics for the current test layout is approximately 4mV rms for 500 MHz frequency band, defined basically by thermal noise of load resistor and is negligibly small in comparing to single peak amplitude value.

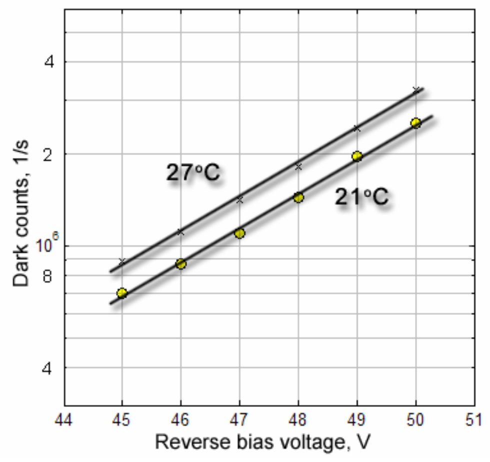

Figure 5: Dark rate.

The gain variation may be found by analyzing of the first maximum of the amplitude spectrum for a set of voltages. It was found that the relative variation of the gain is equal for all cases approximately 13%, and consequently, excess noise factor (ENF), responsible to pixel-to-pixel gain variation ENF=1+ σ^2/S^2 is 1.016, where S and σ are single pixel signal and its dispersion, respectively

The dark noise, which originates from the carriers created thermally in the sensitive volume and also due to the effect of high electric current is a main source of noise. Dark rate increases exponentially with voltage, as shown in Fig.5. For a reverse voltage of 5V above the breakdown in the 500MHz frequency band the dark current produces approximately 15mV rms noise. It may be shown that in the time domain dark current produces in average about 1 count per 100ns of binning time.

Fortunately, main noise factor decrease with temperature, as it is shown in Fig.5. In fact, 6°C cooling decreases the dark count noise approximately by 20%

Photon Detection Efficiency and Optimal Operating Conditions for Best s/n Ratio

The SiPM's PDE is $\varepsilon = QE \times \varepsilon_G \times Apixels/Atotal$, where *QE* is the quantum efficiency, *Apixels/Atotal* is the so-called geometrical efficiency that is fraction of total SiPM area occupied by the active pixel area and ε_G is probability of Geiger-mode discharge.

The PDE depends on overvoltage ΔV, because of probability of Geiger mode discharge is overvoltage dependent. We measure PDE by counting the number of pixels fired by photons, emitted from LED during 1ms time. Knowing the incident light power on the SiPM surface, we can evaluate the PDE value from the data shown in Fig.4.

Signal/noise ratio is voltage dependent due to the numerous factors. Voltage decreasing proportionally lowers the gain and rise electronics part of noise; It also decreases the PDE; on other hand voltage increasing increases the dark current component of the noise.

Taking into account the testing results shown in Fig.4 we estimate the optimal operational conditions for SiPM in IPM applications. It was found that the highest s/n ratio is achieved with 47.5V bias voltage.

Dynamic Range

The dynamic range of the SiPM is defined by the limited number and fixed recovery time of the pixels. We measure the dynamic range by determination amplitude of signals from SiPM with different light fluxes from LED to SiPM. The resulting curve for transmission coefficient in linear operation mode with 10MHz bandwidth is shown in Fig.6. Note, that saturated number of pixels is higher than the number of pixels in SiPM, because each pixel could be fired more than once in 100 ns time.

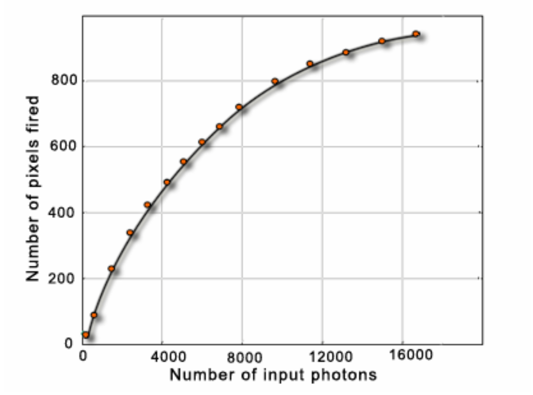

Figure 6: Dynamic range.

CONCLUSIONS

The presented test results shows good performance of SiPM in IPM applications. High gain, low operating voltage and good manufacturability lead to certain advantages in comparing to photomultipliers and traditional silicon photodetectors. The multipitch structure of the SiPM allows to use it in linear and photon counting modes. Relatively high dark count rate is not a problem for the fast readout mode of IPM operation due to the sufficient input signal power.

SiPMs can be easily integrated into multielement modules with good form-factor parameter.

The SiPM is a modern technique and in near future we can expect devices with better characteristics, such as dynamic range (by increasing number of pixels in device), and PDE (by increasing of effective photosensitive area of SiPM). Also some manufacturers already offer cooled devices for low-noise applications [5].

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