Proceedings of the "Problems of Electromagnetic Ecology in Science, Industry and Education" Conference
Ulyanovsk, Russian Federation, October 11, 2010

Light Pollution Intensity Monitoring with Novel Multi-pixel Silicon Photon Detectors

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Abstract: Nowadays, numerous fields such as Environmental sciences, High Energy Physics, medical imaging devices, portable radiation detectors, portable light intensity monitors etc., require a robust, miniature, reliable and readily available photon detector that is stable in a variety of environments, such as the presence of strong magnetic fields or abrupt light lever changes. The recently available ~1mm^2 active area Multi-pixel Photon Counter (MPPC) sensors, produced by Hamamatsu Photonics, have been found to be reliable and an attractive choice for such applications.

The following sensor characteristics have been thoroughly tested by a number of different institutions: gain, dark noise, detection efficiency, reliability. These appear to be stable; in addition, the characteristic spread between numerous devices was assessed. Sensors with larger area are being developed for imaging and direct-to-scintillator coupling purposes.

1. Introduction

Nowadays, the reach of equipment that initially was developed for science, is starting to grow into the user field much faster than a decade ago or so. It seems that only couple of years back a conceptually new Geiger mode multi-pixel silicon photon detector was introduced, and now it's being adapted for usage in variety of fields and applications.

High sensitivity to low light levels (photon counting) yet ability to withstand daylight if accidentally exposed, insensitivity to strong magnetic fields and mechanical shocks, low operation voltage, ultra-low power consumption with high gain are the qualities that allow this detector to be used in the field applications and portable devices.

One of the possible applications is the portable light intensity detector for light pollution monitoring. Such devices could be placed in locations around an area in interest or be pointed to the sky or towards a range of objects. The recorded digital data of the change in light intensity may be collected to a centralized database for further processing.

The main purpose of this work is to show that Multi-pixel Photon Counter (MPPC) sensors are stable and reliable devices with output characteristics allowing the accurate light levels assessments.

2. Light Intensity Detector

The proposed device contains a single MPPC sensor in the light-tight environment with the aperture to control the light input level and optional focusing lens. The sample schematics and digitization scheme for this device are shown in Figure 1a and Figure 1b respectably.

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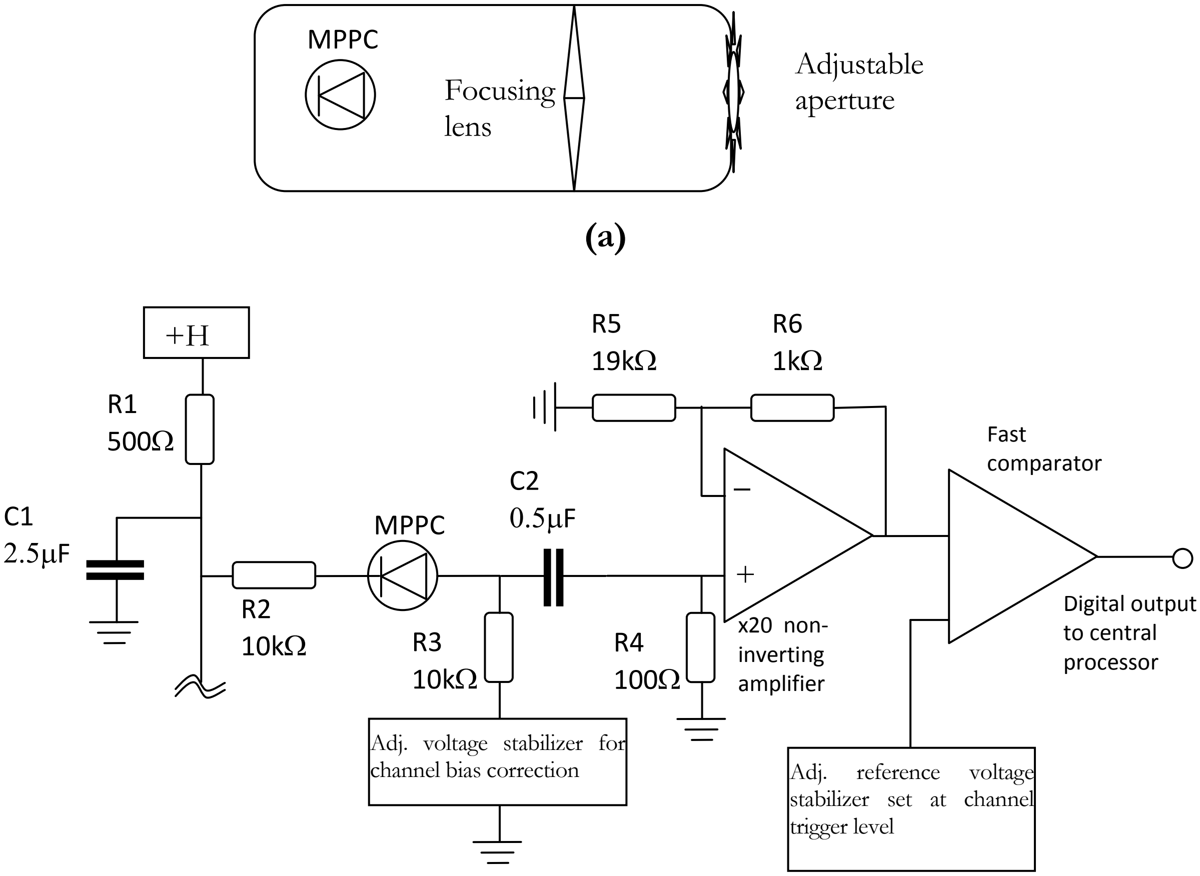


(a)

(b)

Figure 1. (a) - single MPPC sensor in the light-tight environment ;
(b) – Photosensor biasing and digitizing circuit schematic

The digital output from the comparator will be read by the processor and saved to the data storage media (solid state 'flash' memory) with a readout time stamp attached. Thus, later data can be reconstructed as the light intensity variation with time.

3. MPPC Photon Detector

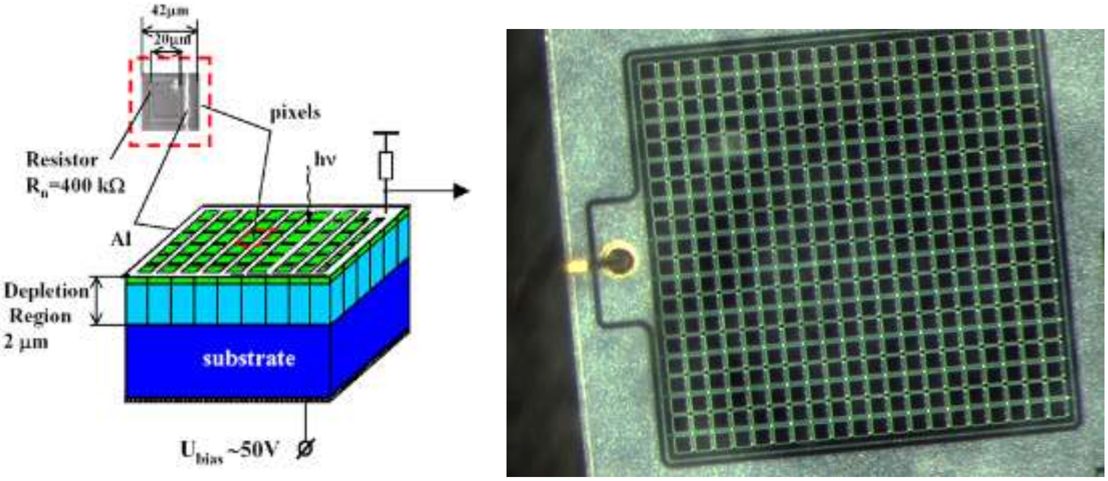
3.1 Geiger mode

Geiger mode is a runaway avalanche in Avalanche Photo Diode (APD). In this mode, detector will only indicate photon detection, not light amount. However, the APD gain can be drastically increased. To avoid the avalanche becoming self-sustaining, a limiting circuitry is introduced for an effect that is generally called quenching. Two types are defined: active and passive quenching.

Active quenching constituted an external circuit, typically a fast controller chip that cuts bias voltage to quickly stop the avalanche after its development is detected by the steep increase in current drawn by the photon detector. This is a fast and effective method, but it requires additional circuitry that normally is not on the photosensor itself.

Passive quenching typically is an internal to sensor high value resistor. As current drawn by the sensor will rise, the voltage drop over the resistor will reduce the total bias at the photosensor, thus quenching the avalanche. This method is slower than active quenching and produces an output with a longer, exponentially decaying, tail, but is cheaper and can be built into the device during the manufacturing process.

A typical multi-pixel silicon family photon detector has from ~100 to ~1600 pixels (1mm^2 models). Each pixel (typ. up to 100μm x 100μm) is an APD in limited Geiger mode, with passive quenching by surface film resistor (Figure 2). Since each pixel will avalanche with a single photon, then for low light levels with the single pixel occupancy (photon#/pixel#) less than 1, the total output of such multi-pixel detector will be proportional to incident light flux.



(a) **(b)**

Figure 2: (a) - Multi-pixel silicon family detector schematic [1];
(b) - S10361-050U MPPC magnified.

An incident photon, if absorbed, produces electron-hole pair. Accelerated by intense electric field within the pixel (typ. up to 10^6 V/m), either electron or hole, depending on the positive or negative biasing, can start avalanche in a pixel (pixel is said to 'fire').

Each pixel is passively quenched by means of a film resistor that is typically located on the device surface. As avalanche develops, rising current causes a voltage drop over resistor and reduces pixel bias below avalanche limit. This additionally protects the sensor from damage from high light levels.

The dark or uncorrelated, noise of this device is due to the thermally produced electron-hole pair can cause firing in the pixel. It has same output shape as from a detected single photon and is indistinguishable from it. In addition, there is a correlated noise produced by inter-pixel cross-talk within a single detector, and afterpulsing. Both will be discussed later.

3.2 MPPC Basic Characteristics

MPPC, or Multi-pixel Photon Counter, is one of the latest developments in the multi-pixel detector family by Hamamatsu [2]. The characteristics at 25°C of the MPPC photodiode, provided by the manufacturer, are summarized in Table 1. In addition, the temperature coefficient of breakdown voltage change is 50 mV/°C. The MPPC photograph under a microscope is in Figure 2b.

Table 1. Characteristics for S10361-050U MPPC

Number of pixels	Chip size	Active area	Pixel size	Pixel effective size	Geometric efficiency	Time resolution	Dark count rate	Gain typ.	Operating voltage
400	1.5 x 1.5 mm^2	1 x 1 mm^2	50 x 50 µm^2	38.1×38.8 µm^2	61.5%	220 ps	~5* 10^5 counts/sec	7·10^5	~70V[1]

3.3 Output PE Separation

Since MPPC is a multi-pixel device, with each pixel providing approximately equal output signal, the combined output of the MPPC exhibits a Photo Electron (PE) structure, such as in oscilloscope trace in Figure 3a [3]. Each line is traced when single pixel, or two or three fire at the same time. All testing is done at room temperature (~25°C) unless stated otherwise. A similar spectrum measured by Analog-to-Digital Converter (ADC) is in Figure 3b.

Figure 3b was obtained by flashing LED at low light level directly onto MPPC surface. The first peak is the pedestal, the second peak is a single fired pixel, with each subsequent peak representing an additional pixel fired. Here, several peaks are still clearly discernable, thus this photodetector feature can be used for the convenient calibration of the MPPC output.

3.4 Cross-talk, Afterpulsing and Dark Noise

MPPC output has the following features that arise from its multi-pixel structure and avalanche amplification scheme. These are cross-talk between pixels and the afterpulse of the pixel. Cross-talk occurs when, from a firing from signal detection or dark noise pixel, an electron or recombination photon reaches some neighboring pixel and causes it to fire effectively simultaneously. The probability of cross-talk acts as additional amplification is a sense, however, needs to be understood for accurate energy output calibration.

Afterpulse is the same pixel firing shortly after it had fired due to signal detected, dark noise or cross-talk. In majority, this is due to the electrons that get trapped on impurities and structure defects in the pixel structure and can cause an avalanche later. Typical lifetime of such trap states is from several ns to few 100ns. A pixel needs a recovery time after firing so that it can support full avalanche. If afterpulse occurs before that time, the output will be of partial amplitude. Afterpulse, in turn, can cause crosstalk.

This is illustrated with a simple and visual way for cross-talk and afterpulse check in presented in Figure 4. ~100x amplifier was used. This is a graph of average dark noise frequency (averaged over a minute) for different biases at different threshold values of the discriminator (of scalar/counter). Each plateau length is the amplitude of single PE, the slope at the ends of plateaus shows the effects of afterpulsing (otherwise it would be almost vertical with slight slope due to pixel to pixel output variations). Ratios between frequencies of each plateau give the rate of the cross-talk. Note that for some high noise sensors (~1MHz), the accidental coincidence of different pixels with dark noise may be significant.

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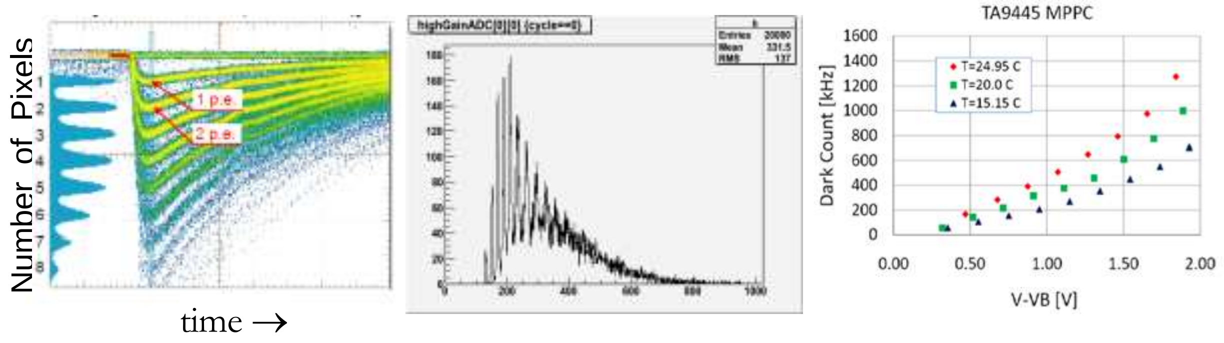
[1] The value varies from sensor to sensor

In addition, the dependence of the dark noise on bias voltage and temperature was measured at threshold of 05.PE[4]. The result is presented in Figure 3c.



(a) **(b)** **(c)**

Figure 3. (a) - MPPC output PE spectrum [3]; (b) - MPPC PE output using ADC; (c) - Dark noise vs. bias and temperature. VB here denotes breakdown voltage [4].

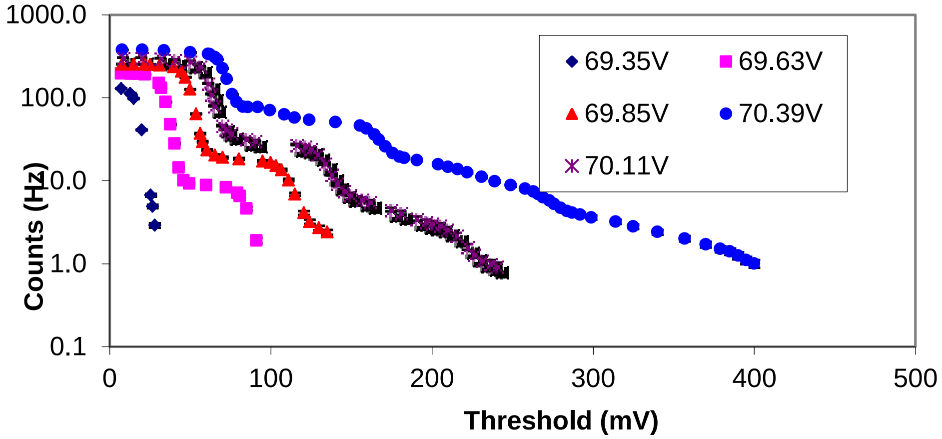
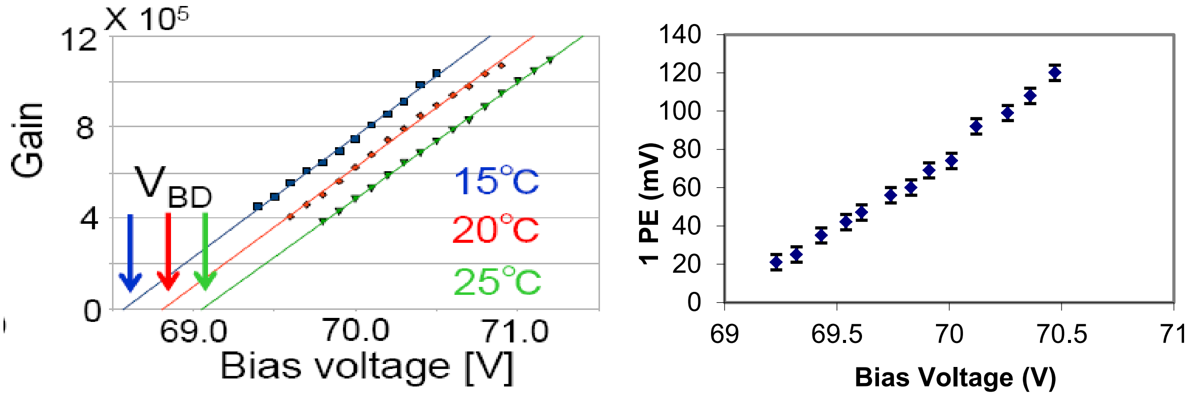


Figure 4. MPPC average noise rate vs. bias and threshold.



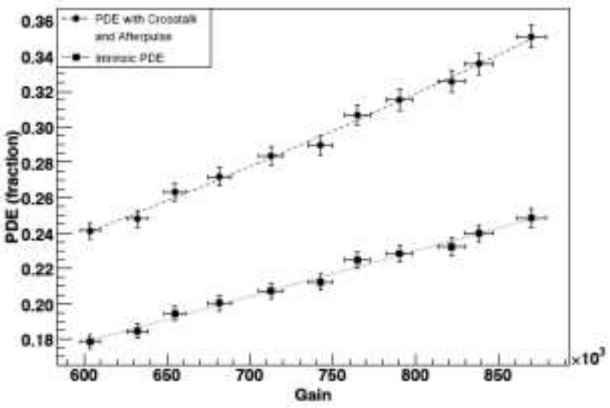
(a) **(b)**

Figure 5. (a) - MPPC Gain vs. Bias and Temperature[4]; (b) - MPPC single PE amplitude vs. Bias.

3.5 MPPC Gain and PDE

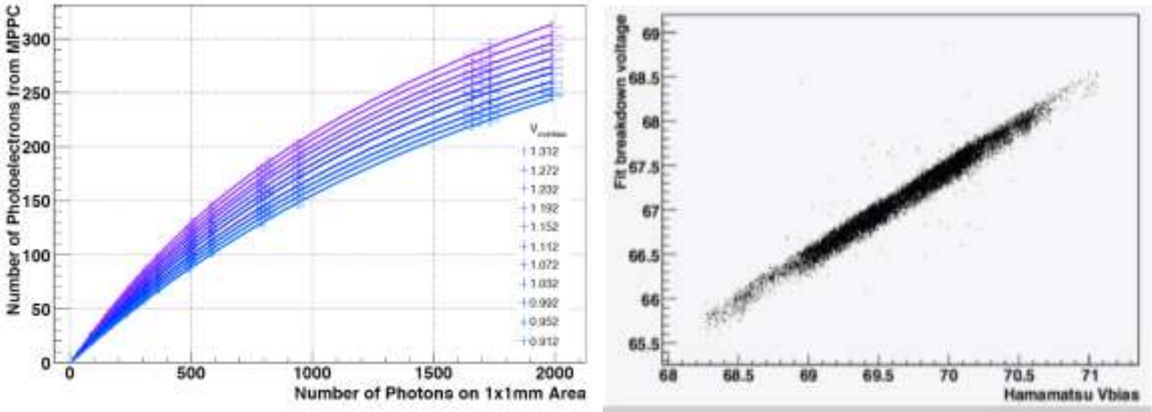
The photosensor gain and Photon Detection Efficiency (PDE) dependence on temperate and biasing voltage were studied. The dependence of gain on bias and temperature is shown in Figure 5a [4]. The temperature coefficient of bias change with T used was 50mV/°C.

Amplitude of a single PE, using ~100x amplifier, was measured for various biases (Figure 5b). Figure 6a [4] is the PDE of the sensor vs. gain at 470nm (that is linear with bias voltage). The bottom and top lines in the figure illustrates the difference of the apparent from intrinsic PDE caused the effects of cross-talk and afterpulsing. Thus, afterpulse and cross-talk act to increase the apparent sensor output. No noticeable change of PDE with temperate has been observed [4]. With bias, the dark noise rate grows, so it's not practical to use these sensors at the upper bound of the operating range. In addition, as bias increases, the PDE, cross-talk and afterpulse increase as well (Figure 6b).



(a) **(b)**

Figure 6. (a) - PDE vs. MPPC gain [4]; (b) - Signal amplitude in PE vs. biasing voltage.



(a) **(b)**

Figure 7. (a) - output vs. applied signal for a range of biasing voltages [4];
(b) - MPPC operating voltage spread for ~11k sensors [5].

The MPPC has a limited number of pixels. As it is assumed that the incoming photons spread equally over sensor surface, and each pixel's output doesn't increase if more than one photon is detected at the same time (or before pixel recovers). This non-linearity of the output to the applied signal vs. bias is illustrated in Figure 7a [4] (for 400 pixel device).

3.6 MPPC Large Scale Deployment

For P0D-T2K project, ~11k MPPC were ordered and tested [5]. This testing involved: obtaining ADC spectra using LED before installation into the detector, dark noise after installation, radioactive source signal during each module scanning, and dark noise testing. During initial testing, approximately 14 sensors were found to be bad, 2 with damaged surface. Four more sensors were replaced for various reasons after final testing. Figure 7b is the spread of operating bias between all P0D sensors [5]. The bias values used are the manufacturer recommended ones.

3.7 Multi-pixel detector testing

Besides tests done on MPPC, rigorous testing of similar sensors from other manufacturers was performed outside of this project. These included 1MRad irradiation, alignment with fiber and performance in 9T magnetic field [6].

4. Conclusion

Overall, MPPC sensors are found to be reliable and an attractive choice for field applications, especially in portable devices with limited power and high voltage shielding. Sensor characteristics such as gain, dark noise, PDE appear stable over time and under irradiation and magnetic field. Long term dependability and failure rate, currently very promising, are to be determined from MPPC lasting performance in numerous applications.

Currently, sensors with larger area are being developed. Other applications for such sensors include medical imaging devices, portable detectors, security systems and other possibilities.

References

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