

Silicon Photomultiplier for Laser Detection of Objects in the Near Area Vehicle Environment

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ABSTRACT

In the last decade great developments have been achieved in detection of single photons. They were mainly driven by research on subatomic particles at CERN. However, for automotive, medical and sensor applications Hamamatsu Photonics K. K. invented Multi Pixel Photon Counters (MPPCs). The MPPC is a Silicon Photomultiplier (SiPM) containing lots of Geiger-mode Avalanche Photodiodes (G-APD) connected in parallel combining them to a light sensor. The numerous G-APDs are also called pixels. In the Geiger-mode, not just electrons but also holes lead to the creation of an avalanche. Thus, the sensitivity is improved. Their low bias voltage, high gain and excellent photon counting capability make them more and more suitable for sensor applications. In this paper we want to discuss the properties of the 1600 pixel MPPC, create an equivalent circuit diagram and reflect on the benefits of them in sensors for transportation systems.

Keywords: Multi Pixel Photon Counter, Geiger-mode, impact ionization, equivalent circuit diagram.

1. INTRODUCTION

Distance control and speed measurement are getting more and more important in automotive systems. Applications have been achieved with radar-based technics, which are emitting electromagnetic waves in the micro- and millimetre-wave range. Photodiodes and photomultipliers are getting more and more smaller. Thus, these devices get more and more efficient in order to integrate them into transportation systems. A Light Detection and Ranging (LIDAR) Adaptive Cruise Control (ACC) was commercialized for the first time in Japan in 1995. However, in Germany and the USA a RADAR-based ACC-System has been preferred. Nowadays LADAR, mostly realized with a LASER and SiPM, is used for 3D-Imaging in automotive systems. Novel transportation systems, like the Personal Rapid Transit system (PRT) at London Airport Heathrow drive electrically and autonomous. The guidance is realized with optical Time of Flight (TOF) sensors, which control the pods driving between the curbs. These sensors are mainly equipped with Avalanche-Photodiodes (APD) as optical receivers. Unfortunately these sensors suffer from long range detection and grey value shift. In contrast the MPPC overcome this problem.

2. BASICS IN PHOTON DETECTION

A pn-photodiode is able to detect a photon, if its energy E_{phot} is high enough to overcome the band gap ($E_{\text{phot}} > 1.1$ eV in case of silicon). At reversed biased pn-photodiodes the photon is absorbed and an electron-hole pair is generated. At the pn-junction exists a high electric field due to the depletion region and the reverse voltage. This electric field influences the electron-hole pair and thus the electron drifts to the *anode* and the hole drift to the *cathode* of the voltage source. The result is a photocurrent flow. Not every incident photon creates an electron-hole pair. Some photons get lost due to reflection and some generated electrons and holes get captured by acceptors and donors. The ratio of the amount of generated electrons and the amount of incident photons specify the quantum efficiency.

3. THE SILICON PHOTOMULTIPLIER

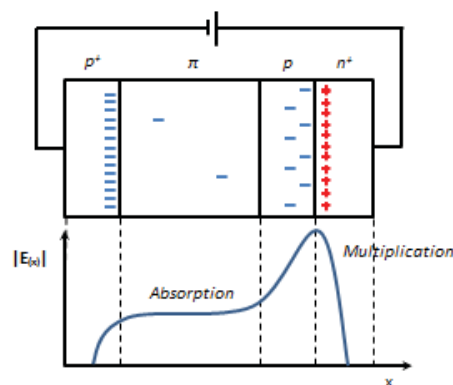


Figure 1. Layer structure of a pixel and its electric field strength curve.

The same principle of photon detection is used by SiPM similar in an APD. However, it is designed to produce a high electric field. Fig. 1 shows the layer structure of a SiPM pixel and its electric field strength curve:

The pixel is set up with $p^+-\pi-p-n^+$ layers, where p^+ is a highly doped p-layer, n is a normal doped n-layer, π is a slightly doped p-layer (intrinsic layer) and n^+ a highly doped n-layer. Therefore, applying a reverse bias voltage two regions will be achieved: The *absorption* and the *multiplication region*. The electric field reaches from the positively charged donors in the n^+ -layer to the negatively charged acceptors in the p^+ -layer. Its maximum is located directly at the $p-n^+$ -junction. The absorption region is spread over the π -layer, where an incident photon generates an electron-hole pair. The electric field influences the

electron-hole pair and makes it drift towards the reversed charged layers. Due to the high electric field, the electron is accelerated to high speed. Reaching the p-n⁺-junction, the high speed electron has impacts with the atoms in the lattice. The kinetic energy is sufficiently high to ionize the lattice atom and contribute a further electron. This electron is also able to collide with further lattice atoms and carries on the effect of *impact ionization*. A single generated electron can create a large number of electrons (*avalanche of electrons*) which is expressed by a photocurrent pulse.

3.1 Geiger-mode

As described the Si-Photomultiplier is designed to produce a high electric field. Moreover, it is also designed to be reversed biased with a higher amount of the negative *breakdown voltage*. This mode of operation is called *Geiger-mode*. In this case, the electric field in the semiconductor is now high enough to accelerate not exclusively electrons, but also holes. Thus, even holes get a sufficient high kinetic energy to enhance the impact ionization process. In silicon, impact ionization coefficients for electrons α_n are higher than for holes α_p ($\alpha_n > \alpha_p$). Therefore, electrons contribute stronger than holes in the creation of a charge carrier avalanche. However, due to the Geiger-mode, the charge carrier avalanche spread out in two ways, which finally leads to a higher number of charge carriers and a higher gain. Due to the break through behaviour and the self-preservation of the avalanche the current continuous, even if there is no additional photon. Therefore, this light independent current has to be quenched. This can be done in an active or passive manner. *Active quenching* controls the photocurrent and reduces it when necessary. Therefore, additional electronic components are necessary. *Passive quenching* is the easiest way to stop the undesirable current. Hence, a *quenching resistor* is integrated in serial with each G-APD. Thus, the current is reduced by producing a voltage drop and thus decreasing the reverse voltage at the G-APDs. To estimate the quenching resistor R_Q , the forward current-voltage characteristics has to be investigated.

3.2 Quenching resistor

Like every pn-junction diode the MPPC shows a typical forward voltage driven behaviour. Due to the reduction of the depletion zone by exceeding the diffusion voltage, the conductivity of the diode is increasing. This is caused by a decrease of the differential resistance, while the quenching resistor R_Q becomes more and more dominant. In order to describe the electrical model and the qualitative current profile, the determination of the quenching resistor R_Q is necessary, see the following results:

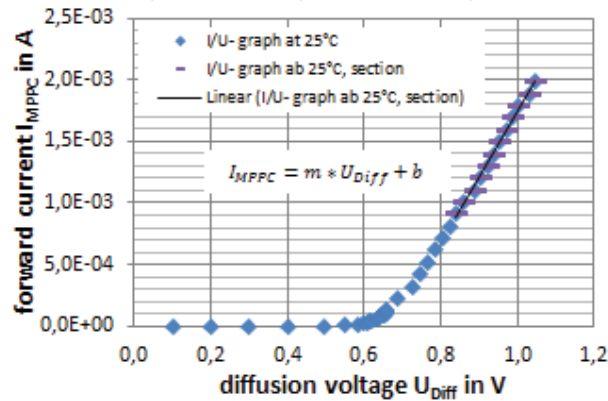


Table 1. Quenching resistor values at different ambient temperatures.

Ambient temperature in °C	Quenching resistor in kΩ
-5	346,89
5	334,14
15	310,44
25	300,54
35	285,56
55	260,33
85	227,27

Figure 2. Forward characteristic graph for estimating the quenching resistor R_Q .

Figure 2 shows the forward behaviour at 25°C. Thus, for the slope m and the y-axis intercept b can be found: $m = 0,0053238 \text{ A/V}$ and $b = 0,003584 \text{ A}$. The determination of the quenching resistor R_Q is possible with using the graph in Fig. 2 – results see Tab. 1.

3.3 Gain

As mentioned, a single generated electron is able to create a large number of electrons, which is expressed by a photocurrent pulse. The gain can be expressed as the amount of the charge carriers Q of this pulse. Figure 3 shows the gain G versus the overvoltage ($U_{MPPC} - U_{Br}$), where U_{Br} is the breakthrough voltage.

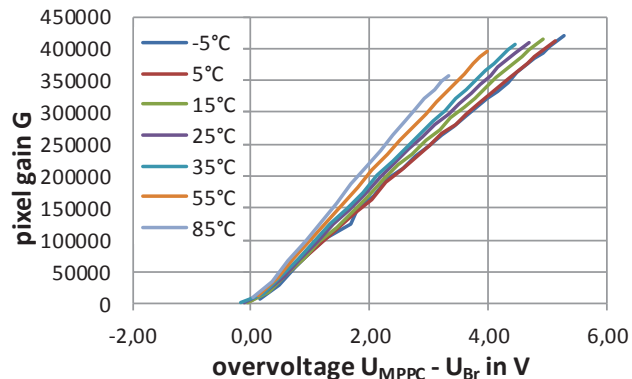


Figure 3. Gain G with dependence of the overvoltage.

Gain values have been determined up to 400000 by an overvoltage of 4 – 5 V. Figure 3 shows the gain versus an increasing overvoltage. Variations of the gain G versus ambient temperature at constant overvoltage can be interpreted as the dependence of the pixel capacitance C_{Pixel} on the ambient temperature [1]. Nevertheless, with increasing temperature, the atoms in the crystal lattice tend to vibrate stronger. Thus, the hit probability of the charge carriers with the atoms increases due to the decrease of the free path length. The accelerated carrier energy is not high enough. Therefore it is difficult for the impact ionization to occur [2]. To obtain a stable pixel gain, a reverse bias voltage control is necessary, in order to compensate the temperature influence. The breakdown voltage is temperature dependent and therefore has to be investigated, see Fig. 4.

The temperature drift amounts to 56.5 mV/°C, which is a smaller value compared to the temperature drift of conventional silicon APDs (140 mV/°C, see [3]).

3.4 Pixel Capacitance

To describe the MPPC correctly the determination of the depletion layer capacitance is necessary. Since the gain G can be expressed by

$$\frac{C_{\text{Pixel}}(U_{\text{Pixel}} - U_{\text{Br}})}{N_{\text{Pixel}} e}, \quad (1)$$

the depletion layer capacitance C_{Pixel} can be calculated. See Fig. 5 for results.

3.5 Equivalent circuit diagram

By the determination of the quenching resistor R_Q , the breakdown voltage U_{Br} and the depletion layer capacitance C_{Pixel} , a construction of the *equivalent circuit diagram* is possible. Thus, we are able to describe the MPPC behaviour. Figure 6 shows the simplified equivalent circuit diagram:

The values of the circuit elements have been determined at 25°C, where R_B is the series resistance of the microplasma in the avalanche [4]. The button simulates an incident photon.

Figure 7 shows the current-time profile of a pixel breakthrough when an incident photon causes an avalanche.

The current profile can be divided into two sections: the *rising* and the *falling edge*. Regarding the equivalent circuit diagram, the rising and falling edge can be described with the following formulas:

$$I_{\text{max}} \approx \frac{U_{\text{MPPC}} - U_{\text{Br}}}{R_Q + R_B}, \quad (2)$$

$$\text{rising edge} \approx I_{\text{max}} \left(1 - \exp\left(-\frac{t - t_0}{R_B \cdot C_{\text{Pixel}}}\right) \right), \quad (3)$$

$$\text{falling edge} \approx I_{\text{max}} \cdot \exp\left(-\frac{t - t_1}{R_Q \cdot C_{\text{Pixel}}}\right). \quad (4)$$

The entire pulse fall time is approximately $5 \cdot \tau_{\text{fall}} = 5 \cdot R_Q \cdot C_{\text{Pixel}}$. The recovery time, which is determined by the time constant τ_{fall} , is about 4.29 ns at 25°C. During this time no further incident photon can be detected. Therefore, the fall time would be about 21.45 ns. The recovery time is voltage independent, but depends on the quenching resistance and in particular on the depletion layer

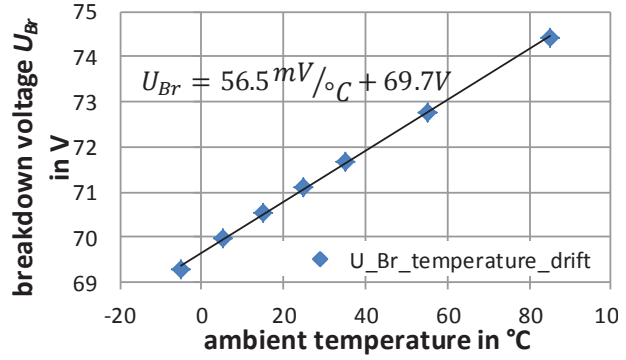


Figure 4. Temperature drift of breakdown voltage U_{Br} .

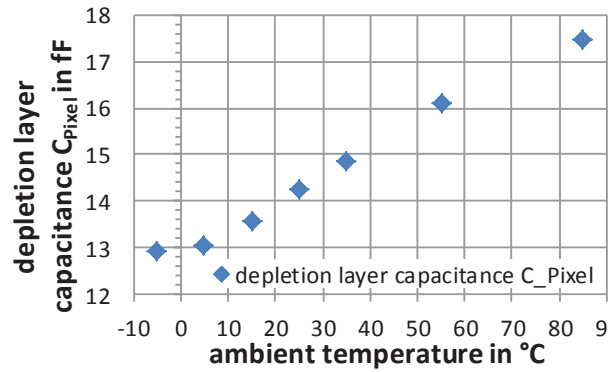


Figure 5. Depletion layer capacitance C_{Pixel} at different ambient temperatures.

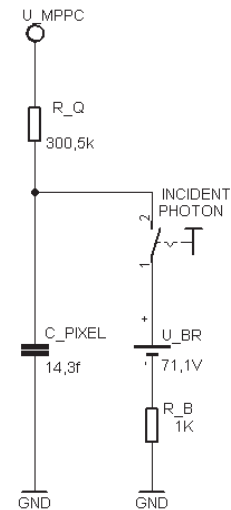


Figure 6. Equivalent circuit diagram of a pixel.

capacitance. Thus, Si-Photomultipliers with larger pixels show a longer recovery time. More details about the recovery time can be found in [5] and [6].

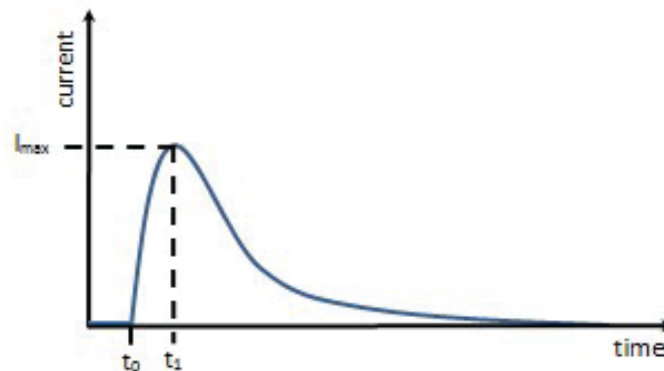


Figure 7. Qualitative current profile to describe mathematically the behaviour of a pixel.

4. CONCLUSIONS

The MPPC shows in many ways benefits and offers new possibilities in automotive, medical and sensor applications. In comparison with a conventional APD, we achieve a higher gain up to 400000 at lower supply voltages of about 70 – 80 V. Applying the MPPC in the Geiger-mode, we achieve a greater avalanche, caused by an additional involvement of holes concerning the impact ionization. But then unfortunately, we suffer from an extension of the fall time. Nevertheless, we still have the advantage of an extraordinary large dynamic range for automotive, medical and sensor applications. The achieved rise time is 1 – 2 ns and the recovery time is 4 – 5 ns. Therefore, bandwidth values of more than 100 MHz can be achieved. Equipping Time of Flight (TOF) sensors with 1600 pixel MPPCs, we achieve a higher measurement distance compared to the use of a conventional APD. Thus, the initial distance of 6 m can be improved to nearly 10 m, using a 90% backscatter reference card. Moreover, the distance deviation is lowered from 1.5% to 0.1% of the measurement range, comparing a 90% with an 18% backscatter reference card.

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