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Characterisation of Geiger-mode avalanche photodiodes for medical imaging applications

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Abstract

Recently developed multipixel Geiger-mode avalanche photodiodes (G-APDs) are very promising candidates for the detection of light in medical imaging instruments (e.g. positron emission tomography) as well as in high-energy physics experiments and astrophysical applications. G-APDs are especially well suited for morpho-functional imaging (multimodality PET/CT, SPECT/CT, PET/MRI, SPECT/MRI).

G-APDs have many advantages compared to conventional photosensors such as photomultiplier tubes because of their compact size, low-power consumption, high quantum efficiency and insensitivity to magnetic fields. Compared to avalanche photodiodes and PIN diodes, they are advantageous because of their high gain, reduced sensitivity to pick up and the so-called nuclear counter effect and lower noise. We present measurements of the basic G-APD characteristics: photon detection efficiency, gain, inter-cell crosstalk, dynamic range, recovery time and dark count rate.

Keywords: Avalanche photodiode; G-APD; SiPM; PET

1. Introduction

Multicell Geiger-mode avalanche photodiodes (G-APDs), able to detect single photons, have been developed in Russia. G-APDs are produced by means of a standard Metal–Oxide–Silicon (MOS) process that, as proven mass production technology, has the potential for low fabrication costs.

A G-APD is a matrix of identical micro cells with dimensions ranging typically from 7×7 to $100 \times 100\,\mu m^2$. Each cell operates as an independent photon counter in Geiger mode, e.g., when biased 10–20% above the breakdown voltage. A photon impinging on one of the cells can create free carriers that give rise to a Geiger-type discharge. Since every cell is connected to the bias voltage via an individual integrated resistor, this discharge is quenched when the cell's voltage drops below the breakdown voltage. After a short recovery time, the time needed for recharging, the cell is ready to detect the next photon. The cell is a binary device since the signal from a cell always has the same shape and amplitude.

The discharge currents from all cells are added on a common load resistor, therefore, the output signal of a G-APD is the sum of the signals from all the cells firing at the same time. Globally seen, the G-APD becomes an analog device. The high density of cells (100–10000 mm^{-2} are available) makes the response of a G-APD linear over a wide range of light intensities. Saturation effects do not set in until the flux of photons is comparable to the number of cells per unit area. In reality, the process is more complex because of the recovery time of the cells and the influence of dark counts.

In this work, we describe the operational characteristics of G-APDs. For details on the types of G-APDs see [1].

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2. G-APD characteristics

In Geiger mode the signal amplitudes A_i of the individual cells of a G-APD depend on the applied overvoltage and the cell capacitance C:

$$A_i \sim C \cdot \Delta V = C(V_{\text{bias}} - V_{\text{breakdown}}).$$

The G-APD gain can be as high as 10^7. When many cells fire at the same time the output amplitude is the sum of the standard pulses of the individual cells:

$$A = \sum A_i.$$

The photon detection efficiency (PDE) is wavelength dependent:

$$\text{PDE}(\lambda) = \text{QE}(\lambda)\varepsilon_{\text{Geiger}}\varepsilon_{\text{geometry}}$$

where QE(λ) is the quantum efficiency (typically 30–80%, wavelength dependent), $\varepsilon_{\text{Geiger}}$ is the probability for a carrier created in the active cell volume to initiate a Geiger-mode discharge and $\varepsilon_{\text{geometry}}$ is the so-called geometrical efficiency, that is the fraction of the total G-APD area occupied by active cell areas. The geometrical efficiency, limited by the dead area around each cell, depends on the construction and ranges typically between 20% and 60% of the total area.

In silicon free electrons have a higher probability to trigger a breakdown than holes. Therefore, the creation of free carriers in a front p-layer of the G-APD has the highest probability to initiate a discharge. Devices which are made of p-silicon on an n-substrate are sensitive to blue light which is absorbed in silicon within a fraction of a micrometer. In devices with n-silicon on a p-substrate either the holes generated in the front zone can initiate with low probability avalanche breakdowns or the light has to pass through the n-layer and generates an e–h pair in the underlying p-layer. Then the electron has again a high chance to start the breakdown. Only light with a wavelength longer than 500 nm has an absorption length of more than 1 μm, the typical thickness of the minimum layer of the high field zone. Consequently, the PDE peaks around 600 nm or higher.

In both types of G-APDs the maximal PDE can be higher than 40%. Shown in Fig. 1 are the measurements of the PDE for four wavelengths of a device with p-silicon on a n-substrate (from Hamamatsu Photonics).

G-APDs have a limited dynamic range due to the finite number of cells:

$$N_{\text{firedcells}} = N_{\text{total}}(1 - \exp(-N_{\text{photon}}\text{PDE}/N_{\text{total}}))$$

where N_{photon} is the number of impinging photons and Photon Detection Efficiency (PDE) of the G-APD. The average number of photoelectrons per cell should be less than 50%. The finite number of cells N_{total} results in a deviation from linearity of the G-APD signals with increase in light intensity (Fig. 2). State of the art crystals (LSO, LuAP, LYSO, LaBr) used in PET detectors are very efficient scintillators and emit typically

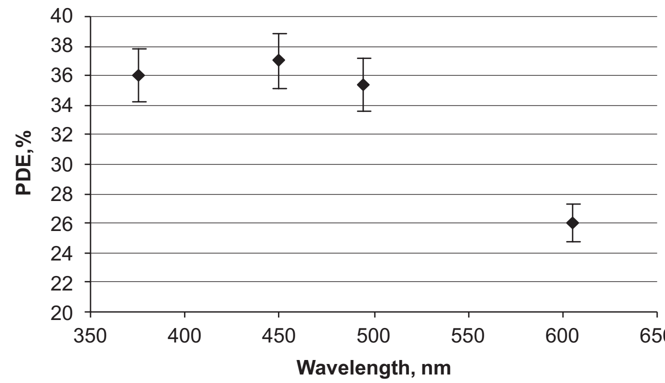

Fig. 1. Photon Detection Efficiency at 4 wavelengths for a Hamamatsu G-APD (cell size is $70 \times 70\,\mu m^2$, pitch 100 μm).

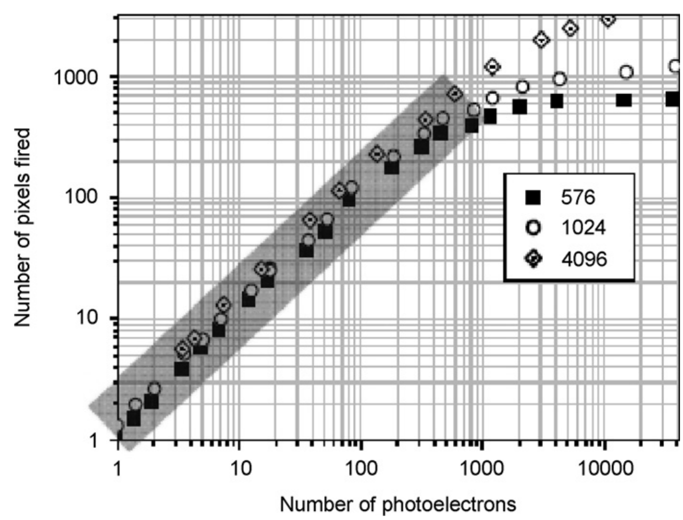

Fig. 2. The saturation effect of G-APDs with different numbers of cells [2].

15–25,000 photons/511 keV.[1] Only G-APDs with more than 1000 cells/mm^2 and a sufficiently large area should be used for the readout in PET.

G-APDs produce dark counts with a rate that can exceed 1 MHz/mm^2. These dark counts are initiated by thermal generation or field-assisted generation (tunneling) of free carriers. The first and dominant effect can be reduced by cooling. The rate decreases in first order by a factor of 2 for every 8°C, but some types of G-APDs show big deviations from this behavior. The dark count signals correspond not always only to a single electron signal, but because of cell-to-cell crosstalk, quite large amplitudes can sometimes occur (see discussion below).

The high dark count rate is a concern when light flashes of very low intensity or even single photons have to be detected. However, this is not the case in PET applications.

[1]Only a fraction of this light can be collected at one end of a typical crystal configuration of a PET detector module. In addition the limited PDE has to be taken into account. Thus a signal between a few hundreds and a few 1000 photoelectrons is expected.

The count rate falls dramatically with an increase in threshold of the readout electronic. At a threshold which corresponds to five photoelectrons—still extremely low in PET applications where several hundred photoelectrons are produced by the 511 keV X-rays—the rate is down to several 10 counts/s, as shown in Fig. 3.

In general, reverse biased silicon diodes emit light when they are operated in Geiger mode. The photon emission rate is 2.9×10^{-5} photons with an energy higher than 1.14 eV per carrier crossing the p–n junction [3]. Photons emitted by a cell could travel to a neighboring cell and trigger a breakdown there. This effect leads to photon-assisted crosstalk between the cells and has a small but not negligible contribution to the G-APD output signals.

Avalanche fluctuations of APDs operated in linear mode (with a bias voltage below the breakdown voltage) cause an excess noise factor that is bigger than 2. The excess noise factor of G-APDs is very small and could eventually be one, since the cells act as individual photon counters without fluctuations in the signals. Crosstalk effects are statistical and increase the excess noise factor to a value between 1.1 and 1.2.

During the avalanche multiplication, a very local process, very high-plasma temperatures can be reached and, in turn, photons can be generated (a few for a gain of 10^5). There is a concern that these photons could travel inside the silicon (or even retransmitting and reflecting materials, such as the case of small crystals), where they may be reflected and may trigger the breakdown of additional cells. This was tested by mounting directly in front of a G-APD a diffuse Teflon block acting as an additional reflector for photons escaping towards the front side. Fig. 4 shows the pulse height spectrum of dark counts. A breakdown of a single cell causes the peak at channel 70. The higher peaks are generated when 2, 3 or more cells fire at the same time due to the optical cross talk. With the particular G-APD used in this test the probability that cells fired was 19% without the reflector and the probability went up to 24% when the reflector was mounted. The difference of 5% was caused by photons generated in the breakdown G-APD which were reflected and have triggered an additional breakdown in another cell.

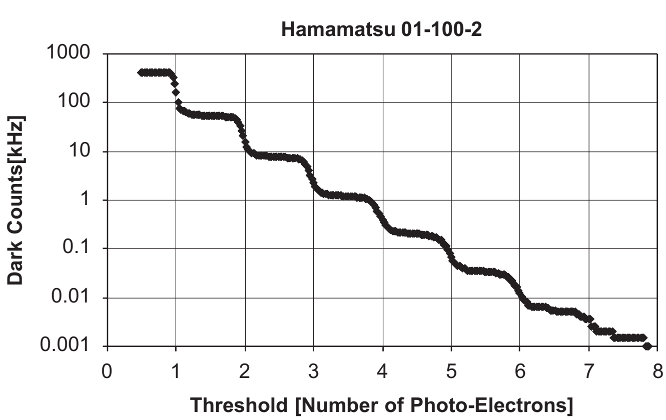

Fig. 3. Dark count rate of the Hamamatsu G-APD (cell size is $70\times70\,\mu m^2$, pitch 100 μm) for different threshold levels.

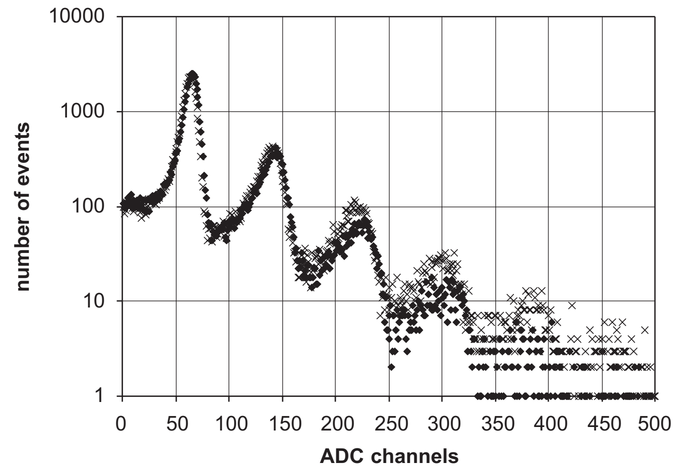

Fig. 4. The crosstalk of the G-APD SSPM_050701GR-TO18 from Photonique without (■) and with a Teflon reflector (×).

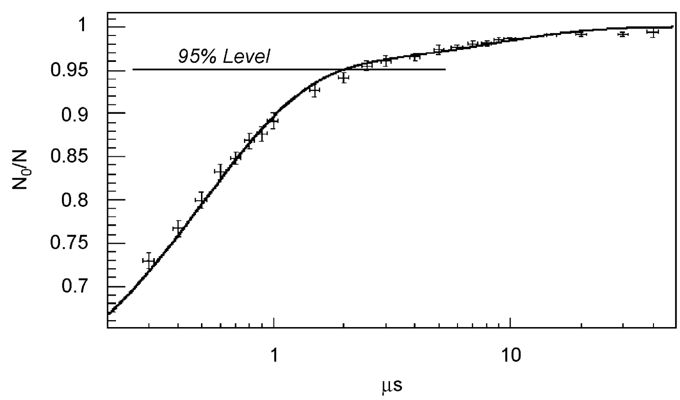

Fig. 5. Recovery time of a Hamamatsu G-APD with a cell size of $20\times25\,\mu m^2$ on a pitch of 50 μm.

After the breakdown of any cell has been quenched by a voltage drop in the individual resistor some time is needed to fully recharge the cell. We define the recovery time of a G-APD as the recharge time needed for subsequent breakdowns to have signals at the level of 95% of the amplitude of an breakdowns without a preceding breakdown, as shown in Fig. 5. The recovery process depends mostly on the cell size (capacitance) and the individual resistor of the G-APD. G-APDs have recovery times from dozens of nanoseconds up to several hundreds of microseconds [4]. When too many of the cells are in the recovery phase at the same time the saturation effect mentioned earlier should be enhanced.

G-APDs suited for PET need to have many cells of small size. In case the recovery time is below 1 μs, a count rate per module of more than 1 MHz will be possible. The probability to find a cell in the recovery phase after a dark count will be below 1 per mille at any given time.

3. Summary

The relatively high photon detection efficiency, the insensitivity to magnetic fields and to ionising particles passing the silicon chip, the compactness and low sensitivity to pickup make G-APDs a good candidate for medical imaging applications. Apparent disadvantages such a dark count rates, crosstalk and recovery time are negligible in medical application.

Acknowledgment

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