Silicon Photomultipliers for PET Scanners

Vinod K. Madan
Model Institute of Engineering and Technology, Jammu
Email: klvkmadan@gmail.com

Abstract

Silicon photomultipliers (SiPMs) are the current state-of-the-art technology for detecting optical photons produced by 511 kev annihilation gamma rays in scintillators in positron emission tomography (PET) scanners or PET based multi-modality simultaneous scanners like PET and magnetic resonance imaging (MRI). Since decades photomultiplier tubes (PMTs) have been the workhorse for gamma ray based systems for various applications, and have been used in PET systems too. This paper describes evolution of technology from PMTs to SiPMs, principle of avalanche photodiodes (APDs) and development of SiPMs and its advantages, its application to PET and recently introduced simultaneous PET-MRI systems, and future of this technology.

Introduction

In PET scanners detection of optical photons produced by 511 kev annihilation gamma rays in scintillators, PMTs have been used for more than two decades. PMTs have been the workhorse in gamma ray based system since over 70 years. It has been used in wide-range of applications like nuclear medical, high energy physics, astrophysics, and industrial applications. PMTs have been used since decades in nuclear medical systems like in single photon emission tomography (SPECT) and also in PET scanners.

The PMTs have advantages like high gain (~10^6 to 10^7), fast response time (~picoseconds), good collection efficiency (~80%), and large dynamic range (~10^6). Their disadvantages are vacuum technology, bulky, small quantum efficiency (~26 %) in blue region, and are affected by high magnetic field. With the advancement of technology, avalanche photodiodes (APDs) were developed and found to be useful for use with scintillators. APDs overcame several drawbacks of PMTs like high quantum efficiency, compact solid state structure, and insensitivity to magnetic field. However this is offset by inferior signal-to-noise ratio and timing properties. With the further advancement of technology SiPMs were developed, and they combined many of the advantages of PMTs and APDs. SiPMs have high gain, excellent timing properties and are insensitive to magnetic fields, and they are suitable for PET and PET-MRI simultaneous scanners.

This paper describes a single APD in linear and Geiger mode, and evolution of SiPMs. It describes characteristics of SiPMs, and their advantages and applications for PET scanners and simultaneous PET-MRI scanners.

Avalanche Photodiode

The desired characteristics of an APD are low dark noise, broad spectral range and wide frequency response, a gain on the order of 10^6 or more, and low cost. APD provides internal signal gain. However one of the key parameters to consider when selecting an APD is the detector spectral noise; either detector noise limited at low power levels, or photon shot noise limited at higher powers. As an APD is designed to be operated under a reverse bias, sensitivity at low light levels will be limited by the shot noise and the APD's leakage current.

An APD can be operated in linear mode or in Geiger mode. It has applications in both modes. In the linear mode operation, the APD is useful for applications requiring high sensitivity and fast response times like laser range finders, fast receiver modules for data communications, high speed laser scanner (2D bar code reader), speed gun, ceilometers (cloud height measurement), PET Scanner, and particle detection.

In Geiger mode it is biased above its breakdown voltage, has a large current, and it provides a very high gain on the order of 10^5 to 10^6.

Silicon Photomultiplier

A SiPM array consists of parallel connection of many identical SiPM cells as depicted in Fig. 1(a), and Fig. 1 (b) depicts an APD operating in Geiger mode, and a quenching resistor. The detection window of the APD is kept smaller than the active region, as certain amount of area is used for connecting metal wire. The shape of the active region is kept with rounded corners. This helps in suppression of unwanted edge breakdown at sharp corners due to high electric field there. For quenching use of polysilicon strips resistors are usually used, and their values are on the order of 100 kΩ for effective quenching of avalanche current.

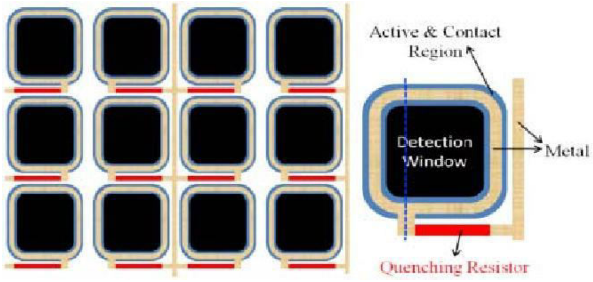

Fig. 1. (a) SiPM Array (b) Single Cell

APD gain has an exponential dependence on the applied electric field strength. The field increases with increasing bias voltage. It causes the gain to increase rapidly because of avalanche action until it reaches a typically breakdown value on the order of 400kV/cm. Photoelectrons generated near the surface by blue light initiate impact ionization when they enter the high E-field region because of energy gain along the path.

Fig. 2 depicts V-I characteristics of an APD including that in Geiger mode. For bias voltage above 10 to 20% breakdown voltage (V_{BD}), the device goes into Geiger mode and works as a logical device. However count rate is limited in this mode because of dead time.

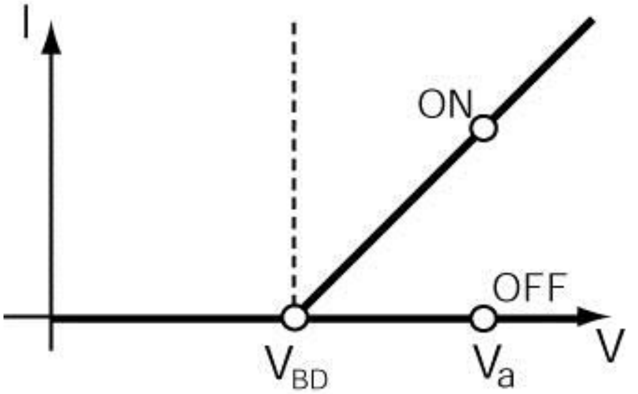

Fig. 2. V-I Characteristics of an APD

The Geiger mode has number of advantages including large output logical signal. It has high immunity to noise, high sensitivity to a single photon, good temperature stability, and low sensitivity to drift of bias voltage because the signal produced is logical, operating voltage less than 100 V, insensitive to magnetic field and that makes it suitable for multimodality imaging like PET-MRI.

The SiPM consists of an array of cells where each cell is an APD operating in Geiger mode. The number of cells is on the order of 100 to over 2000. All cells are connected in parallel, and we get a summed signal. The dynamic range depends on number of cells.

The disadvantages of SiPMs is high dark current and optical cross talk produced by emission of photons in SiPM cells. Dark current can be reduced by limiting thermally agitated carriers by cooling of devices, and tunneling can be reduced by reduction of operating voltage. There are many ways of reducing cross talk like operating in a low bias voltage or optically isolating cells. This provides challenge to researchers to overcome limitations and enhance performance of SiPMs.

Many research laboratories and companies are working to enhance performance of SiPMs. For example KETEK GmbH has developed SiPMs with ultra-low crosstalk down from 17% to 3%.

It may be mentioned that other notable research laboratories and companies are SensL, Ireland; Max-Planck Semiconductor Lab, Munich; MEPhI/Pulsar Enterprise, Moscow; Center of Perspective Technology and Apparatus CPTA, Moscow; JINR (Dubna)/Micron Enterprise; and HAMAMATSU.

Conclusion

This paper describes evolution of SiPMs from PMTs. SiPMs are the current state-of-the-art technology for detecting optical photons produced by 511 kev annihilation gamma rays in scintillators in PET and PET-MRI scanners. It describes its principle, characteristics, and challenges to researchers to enhance performance.

However the development of SiPM technology in India with performance at par with those developed by advanced research laboratories and multinational companies in the world is too a challenge. It is hoped that the HWC2015 conference will provide a forum to discuss and meet the challenge and in a few years India would be commercially producing advanced level SiPMs.

References

1. Fei Sun, Ning Duan, and Guo-Qiang Lo, “Highly Efficient Silicon Photomultiplier for Positron Emission Tomography Application,” International Journal of Medical, Health, Biomedical, Bioengineering and Pharmaceutical Engineering vol,7, no. 9, pp 241-243, 2013.

2. V.K. Madan, “Silicon Photomultipliers: An Emerging Technology for Gamma Counting,” Lecture delivered at BARC, Mumbai on December 12, 2012 (Invited).

3. Silicon photomultipliers ideal for PET/MRI, August 28, 2014. (http://medicalphysicsweb.org/cws/article/research/58345).

4. KETEK GmbH, Munich, Germany (Nov 2014).

5. York Haemischa et. al. “Fully Digital Arrays of Silicon Photomultipliers (dSiPM) – a Scalable Alternative to Vacuum Photomultiplier Tubes (PMT)” Physics Procedia, volume 37, pp 1546–1560, 2012.