New Approach to Solid State Photomultipliers

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***Abstract*—We present a new type of silicon photomultipliers that use Discrete Amplification (DA) for internal amplification of electrical signals in photodetectors. The method of Discrete Amplification is a new general approach to the detection of extra-weak electrical signals. The paper describes the main features of a DA photodetector including wide dynamic range at high PDE, wide and rather flat spectral curve from UV to red, fast response, high voltage and thermal stability.**

***Index Terms*—Semiconductor devices, Photomultipliers, Discrete Amplification, Photodetectors, Scintillation detectors**

I. Introduction

The USE of an overcritical (Geiger) avalanche process with negative feedback for proportional detection of an extra-low light signal was first proposed more than 10 years ago [1-3]. The work of several research groups [4-5] resulted in the development of the Geiger-mode APD matrix technology. Such devices are also called Silicon Photomultipliers (SiPM) or Solid-State Photomultipliers (SSPM).

This technology has significant advantages over conventional photodetectors and has generated interest in a number of application areas.

At the same time, photodetectors based on this approach have an intrinsic disadvantage of a photodetector matrix, that is, dead space between photosensitive cells. This leads to a trade-off between wide dynamic range, defined by the density of the cells, and high photon detection efficiency, limited by fill factor. In order to minimize light losses in dead spaces, one has to increase cell size and pitch, thus decreasing dynamic range (number of pixels on the whole device).

We propose the use of Discrete Amplification technology as a new way to create solid state photomultipliers with improved performance parameters..

The method of Discrete Amplification (DA) is a new general approach to internal amplification of extra-weak electrical signals. It can be used in different types of detectors.

In this approach, free charge carriers generated in semiconductor detector body through photoconversion or in some other way, are distributed among amplification channels of the built-in discrete amplifier, with no more than one electron per channel. Each amplification channel operates independently as a binary amplifier that transforms a signal charge carrier into a calibrated charge packet.

Combining calibrated charge packets from the fired channels produces a low-noise output signal from the DA-detector proportional to the number of primary signal electrons generated in the detector.

The necessary functional elements of a discrete amplifier are a signal distributor, a threshold avalanche multichannel electron amplifier, and a reader of amplified charge packets.

Numerous designs of discrete amplifiers and ways of their incorporation in a detector make the DA technology very flexible in that various types of DA detectors could be created to meet the requirements of a specific application.

Using the DA approach, a new silicon photomultiplier was developed. It provides wide-bandwidth analog detection of low-level light signals with high detection efficiency, wide dynamic range, and maximally flat spectral sensitivity curve in UV-red wavelength range.

This paper describes essential features and main parameters of the new DA photodetectors basing on measurement results.

II. Main Features of DA Photodetectors

A. Photodetector devices

The DA photodetectors contain imbedded dispersed discrete amplifiers to efficiently detect weak optical signal in analog and photon counting modes at wide spectral range.

Due to the special geometry optimization and design of amplifier channels and signal distributor, the photodetectors have all the advantages of the wide dynamic range, fast photoresponse, and good voltage ant thermal stability.

B. Wide and Flat Spectral Sensitivity Curve

Typical spectral sensitivity curve for DA photodetector is shown in Fig. 1.

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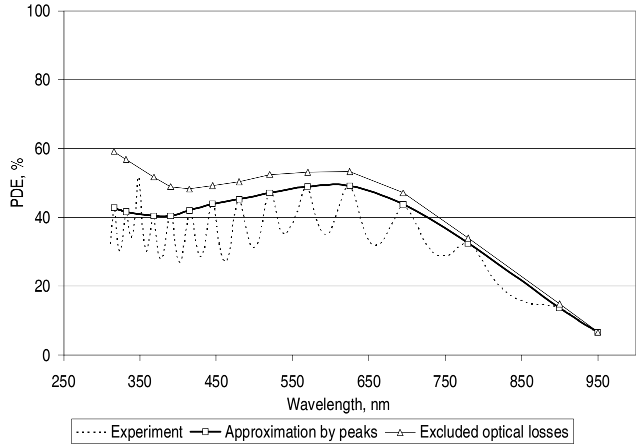

Fig. 1: Typical spectral sensitivity of photon detection efficiency (PDE) for a DA photodetector. The dotted curve with interference peaks corresponds to experimental results, squares to its approximation by the peaks, and triangles the curve with fully excluded optical loses.

The dotted curve represents photon detection efficiency (sensitivity) measured by the photocurrent method. It should be noted that the result can be somewhat affected by neglecting cross-talk and afterpulsing.

The oscillations visible on the curve are caused by optical interference due to the lack of anti-reflective coating in the prototypes. The solid line with square markers is a crude approximation of the spectral sensitivity (fitted through its spectral maxima). The purpose of this approximation is to eliminate the optical losses due to the lack of anti-reflective coating. The curve with triangular markers corresponds to the more precise extraction of optical losses based on simulations and represents the spectral response of the photodetector with an ideal antireflection coating.

The nearly flat region of the spectral response curve is in the range between 300 nm and 600 nm. Some increase in spectral sensitivity at wavelengths shorter than 350 nm is most likely caused by the quantum yield increase in silicon (that is, more than one electron-hole pair being generated by a single UV photon). While direct measurements at shorter wavelengths have not been performed, in accordance with simulation results the curve is extendable into shorter wavelengths without significant drop of sensitivity if proper antireflection coating is used.

We conclude that the use of DA technology allows the development of photodetectors with a wide and rather flat spectral sensitivity curve between 300 nm and 600 nm that is unusual for the most silicon devices.

C. Wide Dynamic Range at High Fill Factor.

An important advantage of DA technology is its ability to provide a high density of micro-pixels (wide dynamic range) while preserving high photon detection efficiency (PDE). As illustrated in Fig. 3, the reason for this is a much higher fill-factor than is achievable in conventional Geiger-mode APD arrays.

1) Fill Factor

Fill-factor (FF) or geometric factor is the ratio of a detector's photosensitive area to its total active area (including "dead" or non-transparent areas). It has the most influence on photon detection efficiency and defines the upper limit of its optimization.

2) Photon Detection Efficiency (PDE)

Photon detection efficiency is the probability that a single photon will cause a detectable output pulse. In devices utilizing the mechanism of Discrete Amplification, the detection process can be considered as a sequence of stages, and PDE is then calculated as the product of the efficiencies of these stages and the Fill-Factor (FF):

-- Optical efficiency, $P_{opt}(\lambda)$, is the probability that a photon is not lost (reflected or absorbed) while penetrating the semiconductor. Optical efficiency is a function of wavelength λ;

-- Photoconversion efficiency, $\eta(\lambda)$, is the probability of the photon being converted into a photoelectron in the semiconductor;

-- Collection efficiency, $Pc(\lambda)$, is the probability that the photoelectron is transported to one of the amplification channels;

-- Amplifier channel detection efficiency, $Pd(V)$, is the probability that the photoelectron that has reached an amplification channel is amplified to a detectable level. This efficiency is a function of bias voltage V. In other words, this efficiency can be presented as a function of "overvoltage" (excess of bias voltage over the avalanche breakdown value).

The photon detection efficiency is then determined as

$$\mathrm{PDE}(\lambda, V) = \mathrm{FF}\cdot P_{opt}(\lambda)\,\eta(\lambda)\,P_c(\lambda)\,P_d(V) \qquad (1)$$

PDE is a function of two variables – wavelength λ and bias voltage (or overvoltage) V.

The typical experimental dependence of PDE on overvoltage is shown in Fig. 2.

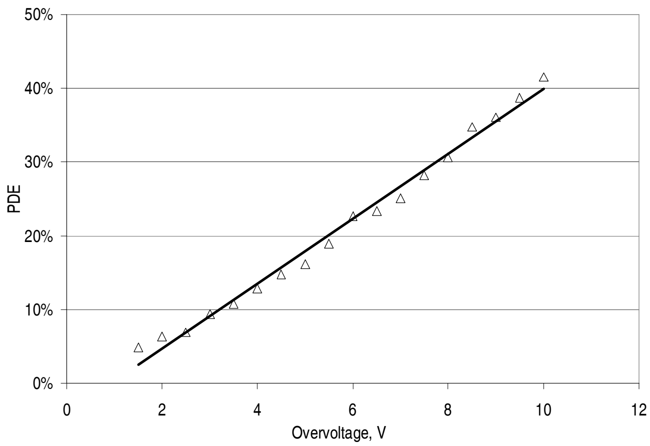

Fig.2: Typical dependence of PDE on overvoltage (excess of bias voltage over the avalanche breakdown value) for the DA photodetector measured by the photocurrent method (LED at 468 nm).

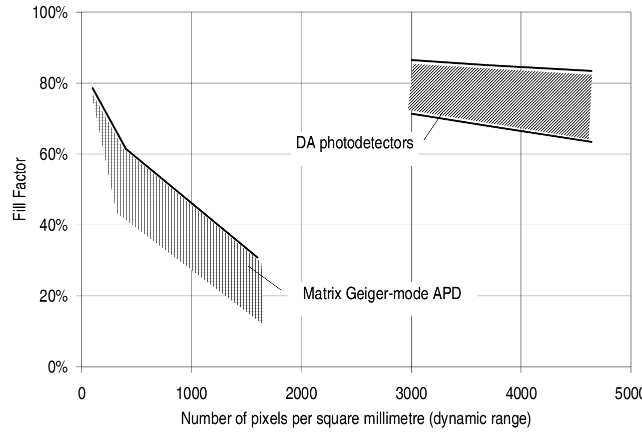

Fig. 3: Typical ranges of fill-factor and dynamic range for the DA photodetectors and Geiger-mode APD arrays.

3) Dynamic range

In the analog mode, when the signal amplitude is within the dynamic range of a detector, its output amplitude is proportional to the number of incident photons in the pulse (the number of fired amplifier channels). As the input signal increases, the photodetector starts to saturate as the output signal amplitude cannot exceed the number of channels multiplied by the Single-Electron Response (SER) amplitude of a channel.

Analog detection requires that photoelectrons simultaneously generated by a short light pulse be distributed over the amplifier channels in such a way that no more than one photoelectron hits a channel at the same time. Thus, the total number of amplifier channels defines the upper limit of the detector's dynamic range for very short light pulses.

In order to increase the dynamic range of a detector with a given active area, it is necessary to increase the density of channels (micro-pixels for arrays of Geiger-mode APDs), which, in turn, leads to a decrease in the fill-factor (PDE). This trade-off between PDE and dynamic range is a limitation of both the described technology and that of the traditional arrays of Geiger-mode APDs. However, as shown in Fig. 3, the DA technology provides this trade-off at a high PDE for a given level of dynamic range.

The ability to simultaneously achieve high values of photodetection efficiency and dynamic range is a significant advantage of the technology over the traditional approach of using arrays of Geiger-mode APDs.

For short pulses, dynamic range is simply a function of the number of micro-pixels. In the more general case of detecting longer light pulses, dynamic range is also dependent on the reset time of fired micro-pixels because the same micro-pixel might be fired more than once over the duration of the pulse.

D. Fast Response Time and. Good Timing Resolution

Fast response time of a photodetector is an important requirement of many applications, especially those involving measurements within a narrow time gate. The DA technology provides very fast time response as well as high Gain – Bandwidth product, which is a prerequisite for the high-speed detection of low-level signals. Single-Electron Response (SER) pulse as an output of a 1 mm active area diameter DA photodetector is shown in Fig. 4; its response time is approximately 1.3 ns FWHM at the gain level of 2.8 x 10^5.

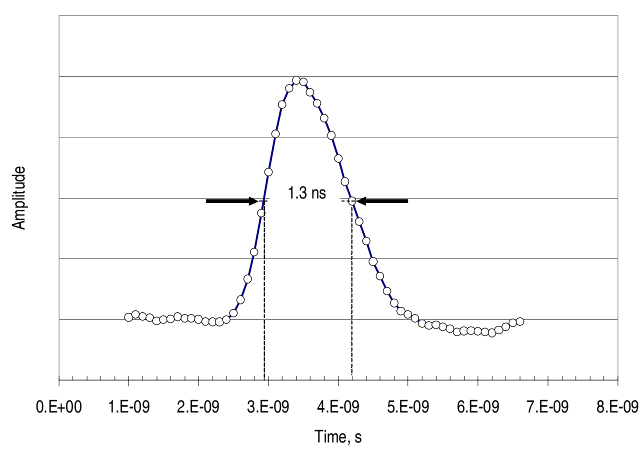

Fig. 4: Shape of Single Electron Response (averaged) for a 1 mm diameter active area device.

Timing resolution of single photon detected pulses (transit time spread or jitter) is shown in Fig. 5. The time axis corresponds to the instant when the detected signal crosses the discriminator level (set at 50% of Single Electron Response pulse amplitude). The Y-axis corresponds to the number of events with the same arrival time. It can be seen that the timing resolution, evaluated as the TTS distribution FWHM, does not exceed 300 ps.

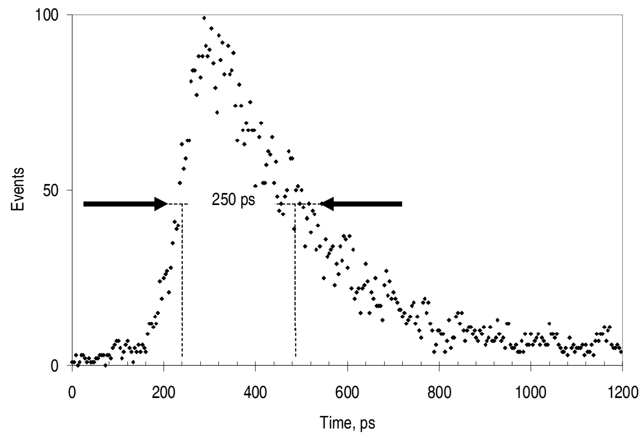

Fig. 5: Transit time spread histogram for the detection of the 60 ps single photon laser pulse (440 nm) .

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E. Low Excess Noise

The mechanism of Discrete Amplification, the foundation of DA technology, is almost noiseless due to the binary type of amplification in separate channels, with a very small dispersion of their output values. Excess Noise Factor (ENF), which measures avalanche amplification noise, is typically less than 1.05 at room temperature for the DA photodetector, and values even less than 1.005 have been recorded. Such ultra-low excess noise level is less than observed in the operation of even the best cryogenic single photon detectors. The low ENF and multi-channel design of the photodetector provide the ability to count the number of photons in an individual signal pulse with very high accuracy. Fig. 6 shows how clearly signals of N and N+1 photoelectrons are resolved. This feature is not possible even in the best PMTs because their ENF is much worse (1.3 and greater).

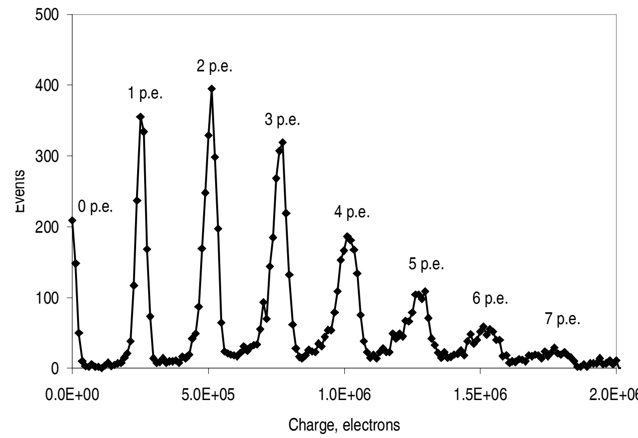

Fig. 6: Output charge distribution histogram for the detection of a 60 ps few-photon repetitive laser pulse (440 nm). Corresponding number of detected photoelectrons (p.e.) is labeled at histogram peaks.

F. High Voltage and Thermal Stability

An important advantage of DA photodetectors is its voltage and thermal stability. It allows the development of large detector arrays that would use a single power source, with array elements having only very minor variations of basic parameters at the same voltage.

The dependence of gain on overvoltage for various DAPD designs is shown in Fig. 7 in comparison with that of typical arrays of Geiger-mode APDs. The lower slope and higher overvoltage range demonstrate better voltage stability of DAPDs, which minimizes the requirements for power supply stabilization. In addition, the flexibility of DA technology allows one to change the slope angles considerably by altering properties of amplification channels. This feature enables optimization of the DAPD design to benefit a wide range of application areas.

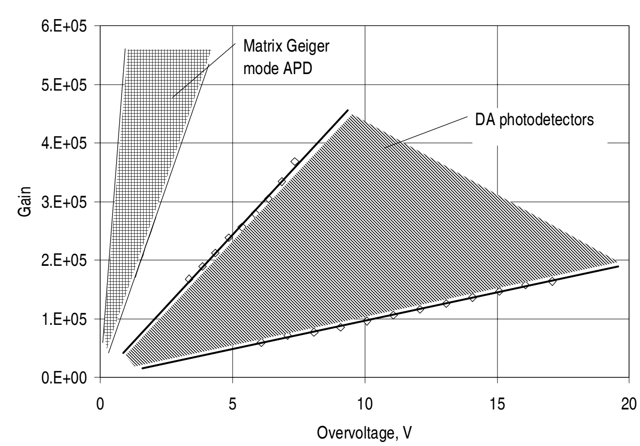

Fig. 7: Dependence of gain on overvoltage for DAPDs and arrays of Geiger-mode APDs.

Dependence of performance parameters on temperature is another important practical consideration. In addition to the lower degree of dependence of gain on overvoltage, DA photodetectors also have better thermal stability. This is clearly seen on Table 1, which shows temperature coefficients of reverse bias voltage, gain, and PDE. Thermal stability of gain and PDE for DAPDs is several times better than is typical for arrays of Geiger-mode APDs.

TABLE I
GAIN, PDE, AND OVERVOLTAGE VARIATION AS A FUNCTION OF TEMPERATURE

Parameter	Definition	Unit	Typical value
Temperature coefficient of operating bias ***V***	$\frac{dV}{dT}$	mV/˚C	20 - 30
Temperature coefficient of Gain	$\frac{d(\mathrm{Gain})}{dT \cdot \mathrm{Gain}}$	%/˚C	0.1 - 0.5
Temperature coefficient of PDE	$\frac{d(\mathrm{PDE})}{dT \cdot \mathrm{PDE}}$	%/˚C	0.1 - 0.6
Overvoltage range	$V - V_{br}$	V	7 - 20

III. APPLICATIONS

Highly sensitive, fast silicon photodetectors based on the DA technology can be utilized in numerous applications and open up new application areas [6-8]. Some of the advantages of DA photodetectors over vacuum tube based detectors are higher detection efficiency over a wide spectral range, robustness, small size, low operating voltage, better excess noise factor, insensitivity to magnetic fields, ease of integrating readout and application-specific electronics on the same chip, and the ability to create multi-element photodetector arrays.

The flexibility of the unique DA approach enables a level of application-specific customization and performance parameter optimization not possible using the traditional silicon photomultiplier technology.

The presented DA photodetectors, with the threshold sensitivity of a few photons, have spectral response over a wide range, from UV to near-IR, with a flat spectral curve between 300 nm and 600 nm, high photon detection efficiency, and wide dynamic range. High energy resolution, coupled with excellent timing resolution, makes these devices a natural photodetector option for many applications where scintillators are utilized. Combined with good voltage and thermal stability, these characteristics make the detectors an attractive choice for medical imaging applications such as PET and CT scanners, high energy physics experiments, X-ray spectral fluorescence analyzers, and other applications.

A high level of customization of solid-state photomultipliers and the degree of performance parameter optimization is possible with the use of DA technology.

The features of the presented DA Photodetector make it an attractive choice for the development of single- and multi-element detection systems in medical imaging, nuclear science, and high-energy physics.

IV. CONCLUSION

A wide-spectral silicon photodetector was developed using new DA approach to internal amplification. It allows wide-bandwidth analog detection of low-level light signals ranging from one photon to several thousands of photons.

This new type of a solid state photomultiplier, the DA photodetector, has some important advantages. It has a wide dynamic range at high photon detection efficiency that appears to be a persistent problem for traditional arrays of Geiger APDs. It also has notably better spectral sensitivity, which includes a wide and relatively flat spectral curve. Fast photoresponse, and in particular short fall time, is another distinguishing feature of the DA photodetector. In addition, it is important to note very good voltage and thermal stability of the photodetector.

These performance advantages of the DA photodetectors as a new solid photomultiplier generation can be interesting and useful for developing radiation imaging systems and different scintillator radiation detectors as well as a number of other applications.

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