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New pixellated avalanche photodiodes with remarkable properties for cosmic ray experiments

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We report on progress with a new class of pixellated avalanche photodiode offering remarkable properties including low noise, very high quantum efficiency across the visible spectrum, low bias voltage requirements, extremely simple requirements for support electronics, and extremely fast response. We have already used these devices for scintillator readout and considered their application for fluorescence and Čerenkov imaging as replacements for photomultipliers. We describe their design and operation and contrast them to conventional photodetectors in a variety of applications.

1. Introduction

Significant progress has been made in the development of avalanche photodiodes over the last few years, and these solid state devices may well start to replace photomultipliers in many applications. While there is a complex "zoology" of these devices with many possible variations, just as there is for photomultipliers, the basic concept is always the same: arrange for a sufficiently electric field in a photodiode in order that carriers produced by the absorption of photons gain enough energy to release more carriers (produces an avalanche) so that a gain greater than one is provided in the device itself.

Such an approach offers several advantages, not the least of which is the possibility of very high quantum efficiencies. Unlike the situation with traditional vacuum tube devices, one can arrange for a very high probability of photon absorption. After that the gain mechanism takes place locally without the need for a liberated charge carrier to be transported to some remote place to be amplified. In addition, one can have a reach into longer wavelengths where photocathodes (if they exist at all!) are often of very low quantum efficiency and poor stability.

A number of other incidental advantages are immediately offered by a move to the solid state: devices are compact, use little power and can be made more inexpensively. They are far more mechanically robust than their vacuum tube counterparts, tolerant of exposure to bright light even while biased, largely insensitive to even very high magnetic fields (up to several Tesla at least), very easy to bias, and can offer very fast response times. A drawback is a higher intrinsic dark count rate but in applications where gated operation is possible this need not be a serious problem.

Traditionally one can think of two modes of operation of an APD. The first is a (approximately) linear mode where gain is moderate (several tens). One then expects a current to be produced which is more or less proportional to the intensity of the incident light (number of photons) but which will vary exponentially with the voltage, thus requiring very careful power supply regulation. [1]

The second is a highly nonlinear mode termed "Geiger" operation where the gain is so high that one can think of it as essentially infinite: an incident photon triggers a very large avalanche which makes it possible to think of the diode as acting as a light-activated switch. In this case power supply regulation is much less of an

[1] Actually the situation is a little more subtle with an added complication arising from the fact that the gain itself may not be the same from photon to photon depending on such random factors as where the photon is absorbed, and one speaks of an "excess noise factor", but a detailed discussion of this is beyond the scope of this short article.

issue, but one then loses the ability to determine the number of incident photons within the time window of the avalanche and its quenching and the recovery of the device. Naturally there is significant deadtime incurred by the need for quenching and the recharging of the intrinsic capacitance of the device.

A new approach, which is the topic of this paper, is to combine these modes of operation in a novel device structure[1]. While there are many subtleties in the fabrication, the basic idea is simple: divide the active area of the APD into a large number of independent individual cells ("pixels") all connected in parallel. Now bias the device for Geiger mode operation and think of each pixel as a tiny light-activated switch. If n photons are incident and n is small compared to the number of pixels, it is unlikely that 2 or more photons will hit the same pixel, so the current produced will be n times that produced if one pixel is hit - in other words, the operation is linear, even though each pixel acts as an absolute "yes/no" Geiger mode APD. Since each pixel is small, response time and recovery time can be very short, and the effective capacitance involved which needs to be recharged is also very small. Timing resolutions of tens of picoseconds are readily achievable. A recent commercial devices we have used is available from Photonique, SA in Switzerland[2].

Space precludes anywhere near the information that we would like to convey in this conference, but the following pictures give some idea of the type of performance possible, and we refer the interested reader to the website [2] for more information and detailed data sheets. The field is growing rapidly with new devices specialized for various applications appearing every few months, so the time is right for thinking about applications.

Figure 1 shows individual photon peaks measured (ADC channel number along the x-axis) with one of the newer Photonique devices biased at $U = 43$ V with mild cooling to -28C. Similar operation is also possible at room tem

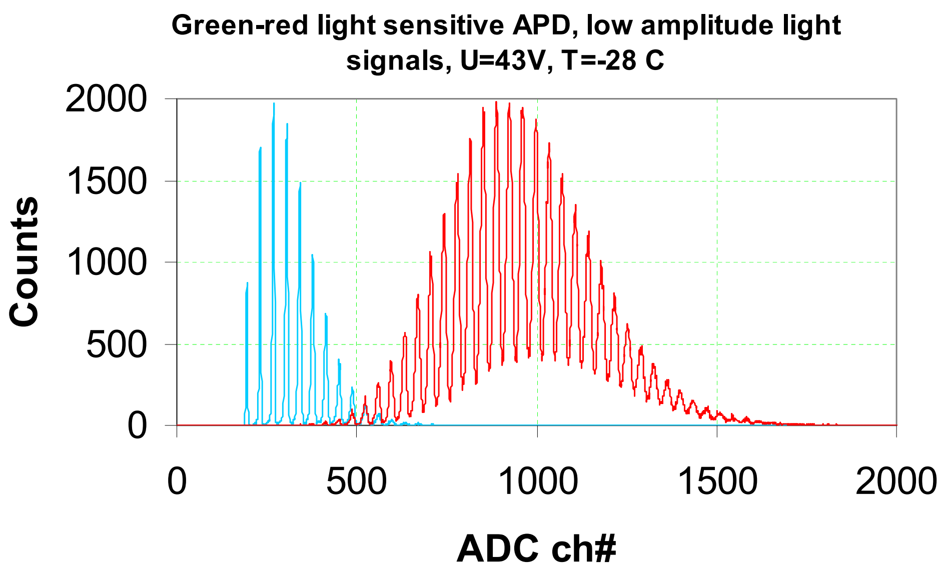

Figure 1. ADC spectra showing individual photon peaks from LED pulses. The envelope is the expected Poisson distribution, but the ability to discriminate between various discrete, small numbers of photons is striking!

Figure 2 is a picture of the device showing the pixellated structure.

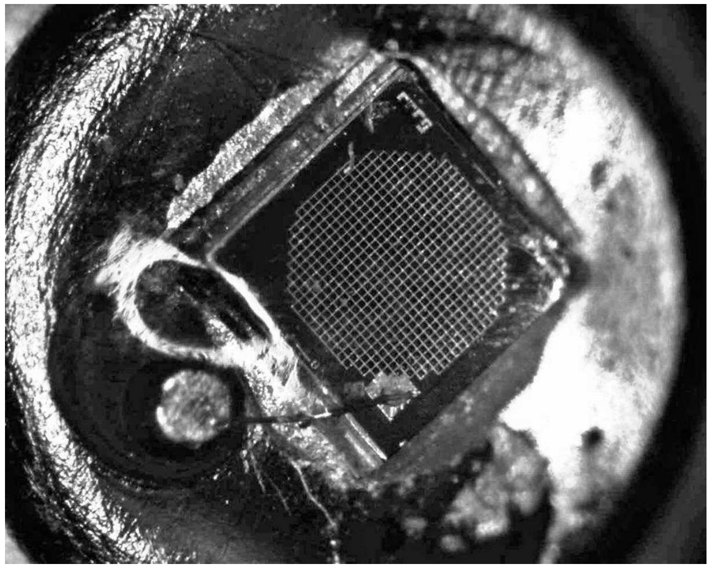

Figure 2. Photograph of the pixellated device structure. Sensitive area is 1mm×1mm with 556 pixels.

Figures 3 and 4 show photon detection efficiency as a function of wavelength and gain as a function of voltage.

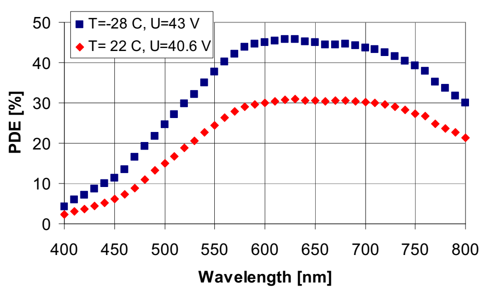

Figure 3. Photon detection efficiency as a function of wavelength for a pixellated Geiger mode APD shown for temperatures of 22 C (bias U= 40.6V) and -28 C (bias U= 43V.

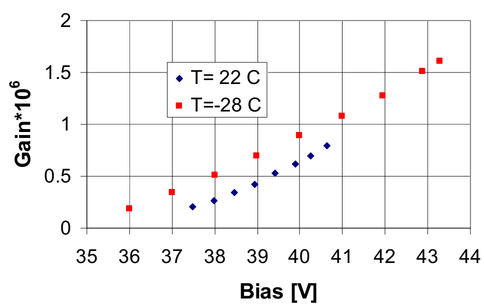

Figure 4. APD gain as a function of voltage shown for temperatures of 22C and -28C.

Figure 5 shows a test setup to compare PMT and APD readouts of the same signal from a real scintillator [4] with the results shown in figure 6.

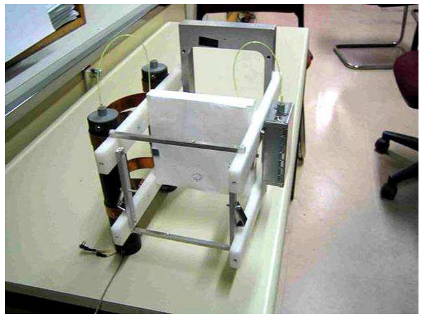

Figure 5. Scintillator (150mm×150mm×15mm from Kharkov, Ukraine with 1mm diameter Y11 wavelength shifter), exposed to 20 GeV muons at room temperature (22C) read out with a pixellated Geiger mode APD and PMT to produce the adjacent plots.

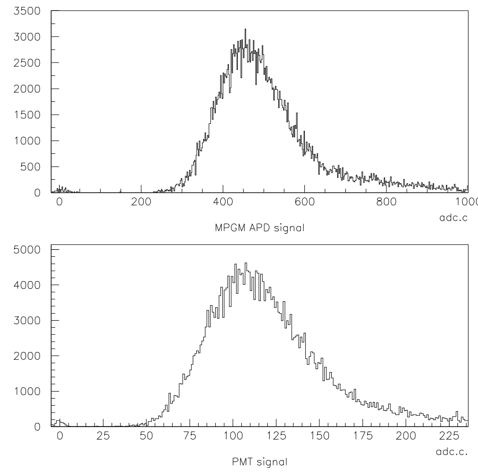

Figure 6. Upper plot shows spectra for APD readout (40 photoelectrons), with lower plot using Philips XP2961 green-extended PMT (26 photoelectrons)

2. Summary

A novel pixellated structure for avalanche photodiodes promises to make these devices extremely attractive for a wide range of applications. We have already used these to replace a linear mode APD in a simple scintillator-based cosmic ray detector[3] and in this paper exhibited superior performance to a PMT in reading out muons signal from a scintillator. In addition to applications in reading out scintillators, these devices offer great promise in the detection of atmospheric fluorescence and Čerenkov radiation. Space precludes a more detailed discussion, but the graphics should speak for themselves!

References

[1] Bondarenko, G. et al., Nucl. Instr. and Meth. **A504**, 301 (2000).
[2] Commercial devices are available from Photonique, SA. See `http:www.photonique.ch`
[3] Swain, J. et al., “SCROD: A new approach to large school based cosmic ray experiments”
[4] E. Guschin et al., “Multi-pixel Geiger-mode avalanche photodiodes with high quantum efficiency and low excess noise factor”, Proceedings of the 4^{th} International Conference on New Developments in Photodetection, June 19–24, Beaune, France (in press).