Study of Pixellated High Gain Avalanche Photodiodes for Single Photon Detection

Y.Musienko[a,*)], D.Renker [b)], S.Reucroft [a)], J.Swain[a,**)].

[a)] Dept. of Physics, Northeastern University, Boston, MA 02115, USA

[b)] Paul Scherrer Institute, Villigen, 5232, Switzerland

[*)] on leave from INR (Moscow)

[**)]corresponding author: John.Swain@cern.ch

Abstract

We report here on preliminary investigations into the performance of two novel pixellated avalanche photodiode devices which are capable of single photon counting at very high gain.

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1. Introduction

This paper reports on preliminary studies of two novel, pixellated avalanche photodiode (APD) detectors. These are operated in something close to Geiger mode, in that they have very high gain and give a simple "yes/no" signal in response to an incident photon. Avalanches are usually restricted to single pixels so that they do not spread throughout the whole device. The pixellation then makes the devices resemble arrays of a large number of individual APDs electrically connected in parallel.

They are from two Russian producers[1,2]: CPTA (1 mm^2 active area), and INR/JINR (0.5 mm^2 active area). Both these devices are "micro-pixellated", with 1370 (CPTA) and 10000 pixels per mm^2 (INR/JINR). References [1] and [2] give more details on the structures of these APDs.

2. Gain vs. Voltage

Rather remarkably for these devices, gain is a linearly rising function of voltage. The charge when one pixel is hit by an incident photon is the product of the overvoltage (the voltage in excess of breakdown voltage) applied and the pixel capacitance (including whatever stray capacitances are present). Typical gains are ~30,000 for INR/JINR APD, ~350,000 for CPTA APD (see figure 1). These differences in gain are primarily due to pixel capacitance, as the possible range of over-voltage which can be applied is rather restricted. The maximum over-

voltage, which can be applied to the APDs is limited by self-heating effects, and probably also by photo-ionization effects where photons produced by an avalanche

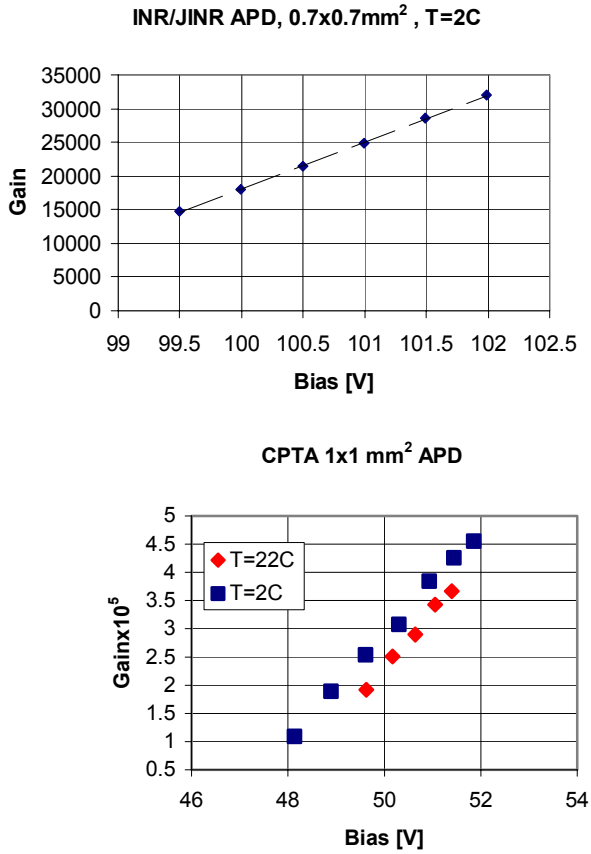

Fig. 1: Gain vs. voltage curves for INR/JINR and CPTA APD`s

in one pixel can fire neighbouring pixels, increasing the current drawn and raising the temperature of the APD.

3. Single Electron Resolution

The single electron resolution is quite good for all the devices studied, and lies in the range of 5% to 20% for reasonable gains (see figure 2).

4. Photon Detection Efficiency

Photon detection efficiency is the probability that an incident photon will create a detectable signal. Not

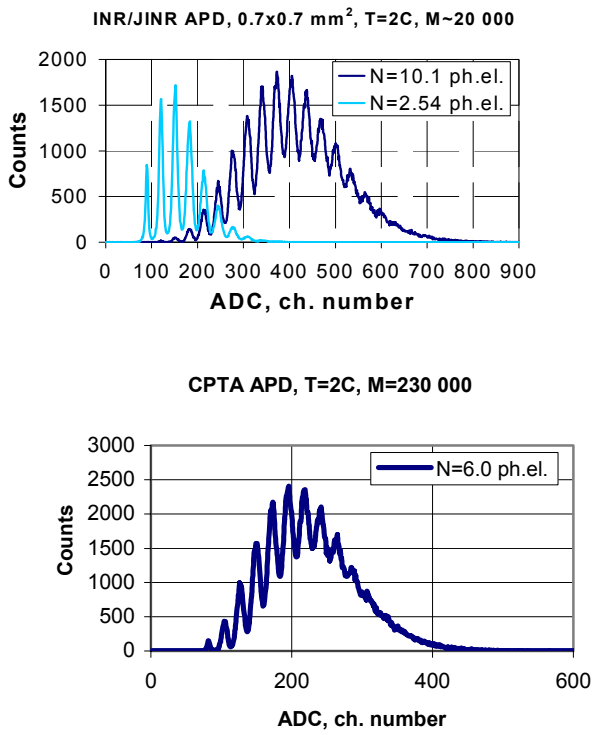

Fig. 2: INR/JINR and CPTA APD pulse height spectra for small amplitude light pulses

all the photons reaching the APD can be detected. Some are reflected at the surface, while others are absorbed in dead parts of the APD, or in regions where the electric field is so low that no avalanche is initiated, or an avalanche fails to develop. There is clearly room for improvement in these areas.

If the region with a strong electric field is thin, there can also be a significant probability that electrons (or holes) traverse this region without multiplication, or with reduced multiplication leading to a signal which is below the

electronics threshold to constitute a count.

Figure 3 shows the photon detection efficiency (PDE) as a function of wavelength for two APDs, both measured at room temperature. For the CPTA device,

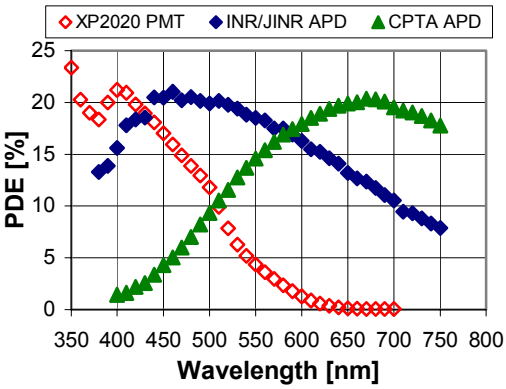

Fig. 3: Photon detection efficiency vs. wavelength measured with INR/JINR APD (PDE of XP2020 PM is shown for comparison)

the low wavelength effects are due the "inverse" (n+p) APD structure.

Electrons created by blue and UV light do not pass through the high electric field region. Holes do make it, but they have low ionization coefficients and they are less likely to initiate an avalanche than electrons.

The INR/JINR APD has p+pn structure (similar to the structure of Hamamatsu S8148 APD reported on elsewhere in this issue [3]), and has high PDE at short wavelength, exceeding that of a Phillips XP2020 PMT for the wavelengths between 430 and 800 nm (see figure 3). The PDE of these APDs increases with the applied over-voltage due to the higher electric field in the avalanche region, as is shown in figure 4.

As mentioned earlier, however, the overvoltage cannot be made arbitrarily large without causing overheating. In addition, the increased heating increases the noise rate. Higher PDE probably can be reached at temperatures below 0C .

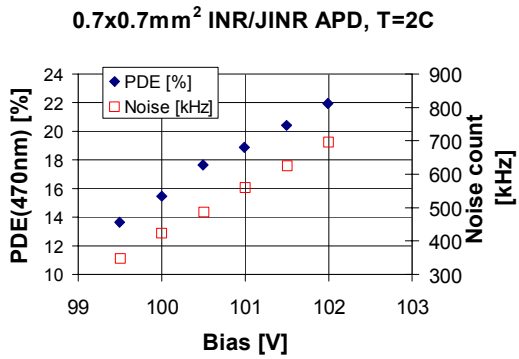

Fig. 4: Photon detection efficiency and noise count vs. bias for INR/JINR APD

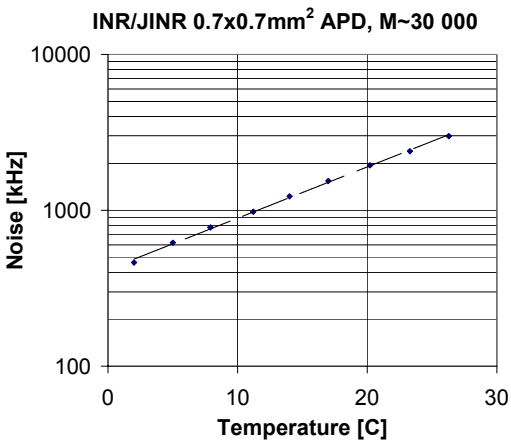

Fig. 5: Noise count vs. temperature measured with INR/JINR APD

5 Noise and Dark Count Rate

Noise and the attendant dark count rate is a function of both APD temperature and gain (which is set by the operating voltage). For both the devices reported on here, it is

measured to be 2-4 MHz/mm^2 at room temperature. It decreases approximately exponentially with decreasing temperature, as shown in figure 5.

6 Possible Improvements

Several possible improvements can be envisioned for these devices. One approach would be to reduce the dead area between pixels.

For the CPTA APD, a change in structure of the avalanche region from n+p to p+pn should improve sensitivity at shorter wavelengths.

Optical cross-talk between the pixels should be reduced, and pixel gain should be optimized. Here lower gains are preferable as they should lead to less self-heating and lower noise. Better pixel separation and smaller gain (smaller pixel capacitance) should allow higher over-voltages and thus higher PDEs. Avalanche region optimization (favouring a wide and smooth pn-junction) should increase avalanche probability, also raising PDE.

Clearly, any dead region in front of the pn-junction should be reduced and an antireflection coating may also offer significant improvements in PDE.

7 Conclusion

Despite the many possibilities to improve these devices, they already offer impressive performance with rather modest support electronics due to their high gains, and quite good detection efficiencies (15 - 20%). Even at room temperature, single photon counting is possible with very simple associated electronics. The excellent temperature and voltage stability of the gain makes much of the electronics traditionally needed to support stable APD operation unnecessary. The devices show great promise for many future applications.

References:

[1] Sadygov, Z. *et al.,* 2003, *Nucl. Instr. and Meth.*, **A504**, 301.

[2] Bondarenko, G. *et al.,* 2000, *Nucl. Instr. and Meth.*, **A442**, 187.

[3] Dorokhov, A. *et al*., 2003, this issue.