Preliminary test measurements of SPAD array

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Abstract: This is a progress report on preliminary test measurements aimed to evaluate the performance of new single photon avalanche diodes (SPAD) developed by ST Microelectronics. Various samples with different dimensions (from 10 to 100 µm diameter) and two 5X5 arrays (20 and 40 microns) are manufactured by STM; some of them have been characterized. A brief description of the device and of its main characteristics (dark, quantum efficiency and linearity) are presented.

Key words: SPAD, detector, photon counting, quantum efficiency

1. THE SINGLE PHOTON AVALANCHE DIODE

SPAD is a p-n junction working at polarisation voltages above the breakdown. In this operative condition a couple hole-electron generated in the depletion layer causes an avalanche, measurable as a current. The diode works as a single photon detector in Geiger mode, with an infinite gain.

The current flows in the diode until the drive circuit, called the active quenching circuit (AQC), turns off the polarisation for a dead time and restores it. In this way the SPAD is ready for another event. Turn off time is named *hold off* time and this chosen time depends on the quality of the SPAD. *Figure 2* shows the block diagram of the quenching circuit.

The quality of SPAD is evaluated by quantum efficiency (QE) and dark current. *Figure 1* shows the structure of the last generation SPAD and of the array.

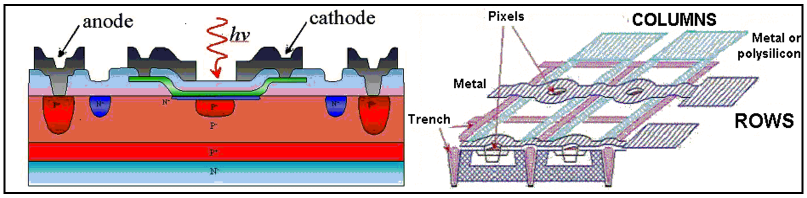

Figure 1. structures of device [left] and array [right]

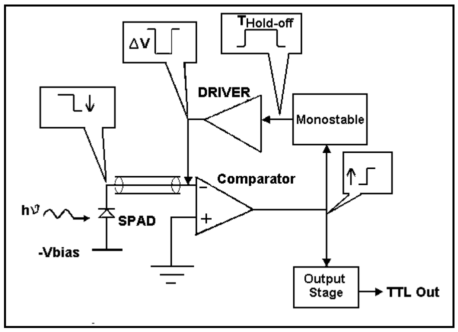

Figure 2. Active–Quenching Circuit Block Diagram

1.1 Quantum efficiency

The SPAD quantum efficiency, measured in the range 350-1050 nm, can be comparable to that of a typical silicon based detector and shows a peak of about 60% at 550 nm for 100 µm diameter devices. We measured the QE at different polarization voltages and the result is that the QE increases at the same time as the polarization voltage. The instrumental apparatus used for the quantum efficiency measurement was designed at the Catania Astrophysical Observatory. The system is a modified version of a previous system, already operating for CCD's QE measurements. The first module, which accommodates an optical system, is made up of mirrors and diaphragms, whose purpose is to have the beam emitted by the radiation source matching the f/5.4 focal ratio of the monochromator. The parallel beam, emitted by the xenon lamp, is intercepted by a flat mirror and focused on the slit by the second parabolic mirror. Finally, between the two mirrors there is a filter wheel that holds interference filters, band pass filters and long pass filters. Their purpose is to filter out the second order and/or to cut down the contribution of the stray light.

The second module along the radiation beam path is the monochromator (model VM504 manufactured by the Acton Research Corporation). It has a Czerny-Turner configuration with a focal length of 0.39 m and an aperture ratio of f=5.4. The monochromator is equipped with three 1200 g/mm ruled gratings to cover more efficiently the whole spectral range. The entrance and exit slits were both 500 µm wide and 1 cm long.

After being dispersed the radiation beam enters an integrating sphere, where the SPAD and a NIST calibrated photodiode are mounted. The acquisition system reads, at the same time, the counts of the SPAD and the current measured by a calibrated photodiode.

To measure the QE of SPADs of different active area (10,20, 50 and 100 µm), we first measured the breakdown voltage of each device and chose the polarization voltage value 10% and 20% above this value.

Typical breakdown voltages are from 30 to 40 volts and depend on the diameter of the devices. The results of QE measurements show an increase of efficiency when the diameter increases. This result is unexpected because the QE measurements are normalized by area. One hypothesis is that there is a small area around the pixel with poor sensitivity, due to the non-perfect fabrication process and the effect becomes negligible for devices with larger area.

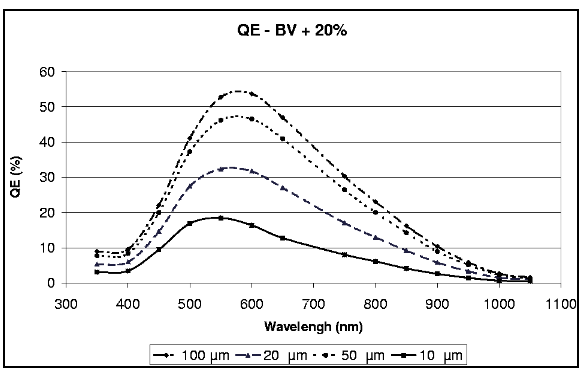

Figure 3. Quantum efficiency at polarization voltage 20% above the breakdown voltage

1.2 Dark counts

Two effects can produce dark counts: thermal generation and afterpulsing. The first effect increases with the bias voltage because the higher electric field increases the probability of avalanche and the depletion volume. The second effect depends on the following phenomena: during the avalanche, some carrier can be trapped in the depletion layer and released after a time delay. If this time delay is greater then hold-off time, the carrier generates an avalanche named afterpulsing. For this reason, to eliminate the afterpulsing effect, the hold-off time had to increase although this reduces the rate of acquisition. Both causes of dark counts depend on the defects in the depletion volume and can be reduced with a cleaner fabrication process. Dark counts are measured at 20°C, with a hold-off time of 360 nsec that diminishes the afterpulsing effect. *Table 1* shows the dark counts for a last generation 20 µm SPAD.

Table 1. Dark Counts of 20 µm SPAD at 20°C

Bias Voltage [V]	QE [%] @ 550 nm	Dark Counts
36.87	12.96	6.2
40	18.25	8.2
41	19.82	12.2
42	21.64	10.4
43	21.10	14.8
44	22.75	18

1.3 Linearity

The linearity is measured using a standard method, consisting of illuminating the detectors at different signal levels with a uniform source of illumination. In *Table 2* the deviation of linearity is shown.

Photodiode (pA)	Spad (count)	QE (%)	Deviation from linearity
1072	6650	22.526	1.003
911	5650	22.521	1.003
467	2850	22.161	0.987
122	760	22.621	1.007

Table 2 - Linearity of 50 µm SPAD

1.4 Conclusions and future developments

The SPAD quantum efficiency, measured in the range 350-1050, can be comparable to that of a typical silicon based detector, shows a peak of about 60 % at 550 nm for 100 µm diameter devices and increases with the bias voltages, due to the increase of the electric field.

The QE increases with the active area. This can depend on the presence of a small area around the pixel with poor sensitivity, due to the non-perfect fabrication process. The effect becomes negligible for devices with larger area. New methods to investigate this effect and to eliminate it is under study.

The dark current at room temperature (20 ºC) and the linearity are satisfactory.

Two arrays of 5 X 5 elements, with pixel size 20 and 40 µm of diameter, was developed by STM and a series of measures are scheduled in the next weeks.

A new active quenching circuit, to allow array readout, is under development.

A smart controller to drive the array and provide all necessary circuitry to acquire the image is under study.