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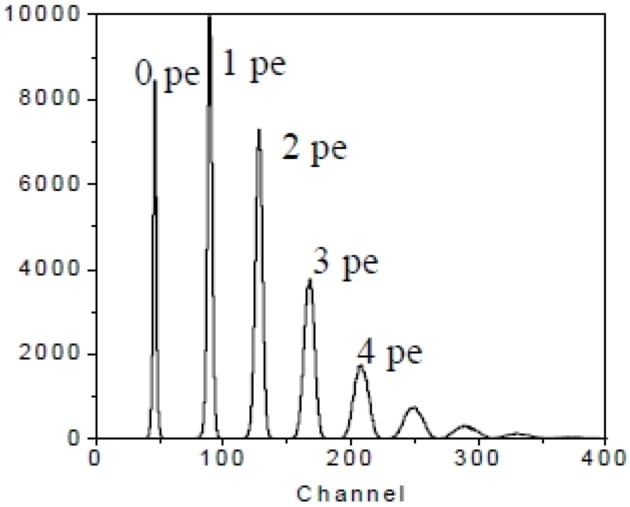

Geiger-mode avalanche photo diodes: status and future

Dieter Renker

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Outline

Principle of operation

Gain and saturation

Dark count rate

Crosstalk

Afterpulses

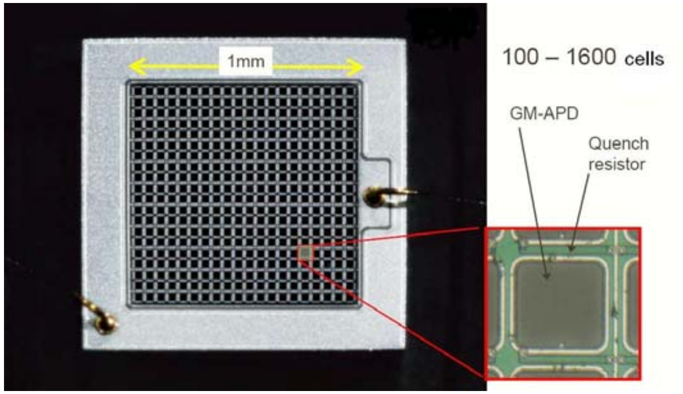
Time resolution

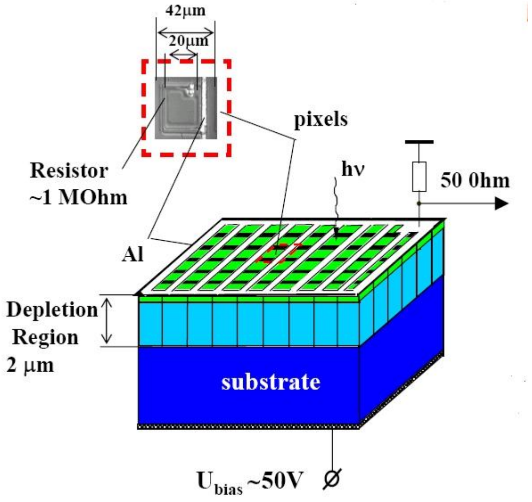
Photon detection efficiency

Where do we stand ?

What can we expect in the near future ?

Geiger-mode APD: principle of operation





NIM A 504 (2003) 48

- Each cell is reverse biased above breakdown
- Selfquenching of the Geiger breakdown by individual serial resistors
- Sensitive to single photons
- High gain up to 10^7
- Number of cells 100 to 40,000 / mm^2
- Recovery of cells after breakdown 5 to 1000 ns

High gain

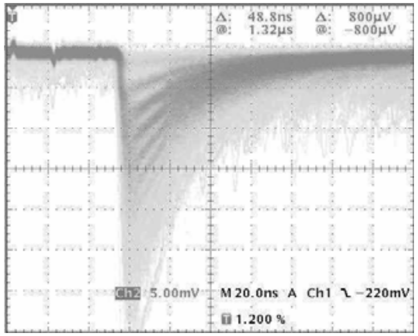
G-APDs produce a standard signal when any of the cells goes to breakdown. The amplitude A_i is proportional to the capacitance of the cell divided by the electron charge times the overvoltage.

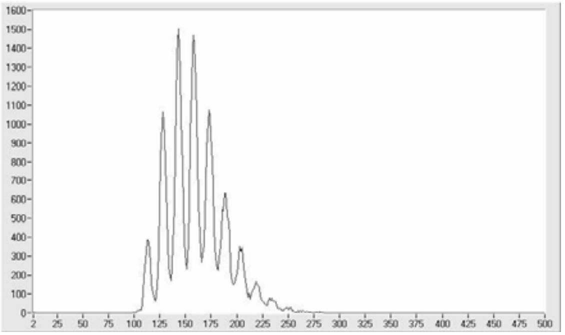
$A_i \sim C/q \bullet (V - V_b)$ $(V - V_b)$ we call "overvoltage"

V is the operating bias voltage and V_b is the breakdown voltage.

When many cells are fired at the same time, the output is the sum of the standard pulses.

$A = \sum A_i$ The summing makes the device analog again.





Oscilloscope picture of the signal from a G-APD (Hamamatsu 1-53-1A-1) recorded without amplifier (a) and the corresponding pulse height spectrum (b).

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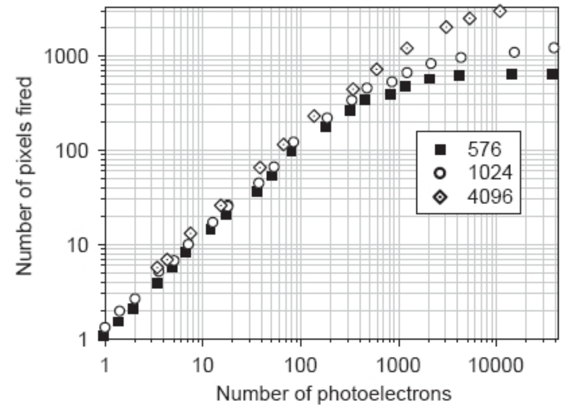
Saturation

The output signal is proportional to the number of fired cells as long as the number of photons in a pulse (N_{photon}) times the photo detection efficiency PDE is significantly smaller than the number of cells N_{total}.

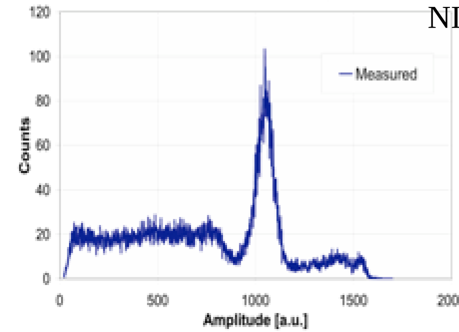
$$A \approx N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

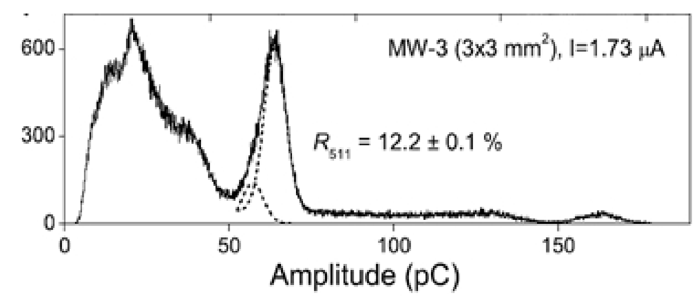
2 or more photons in 1 cell look exactly like 1 single photon.

When 50% of the cells fire the deviation from linearity is 20%.



NIMA 540 (2005) 368



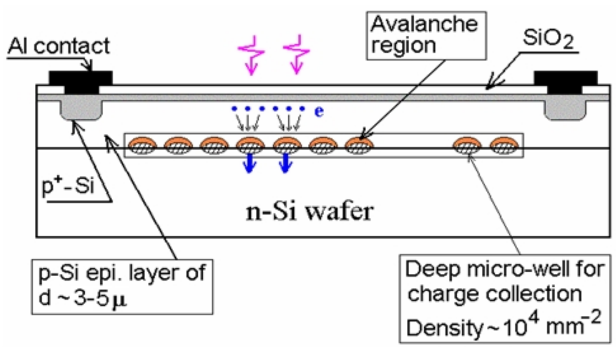


G-APD from CPTA/Photonique with ~400 cells/mm^2 and from Zecotek with 15’000 cells/mm^2.

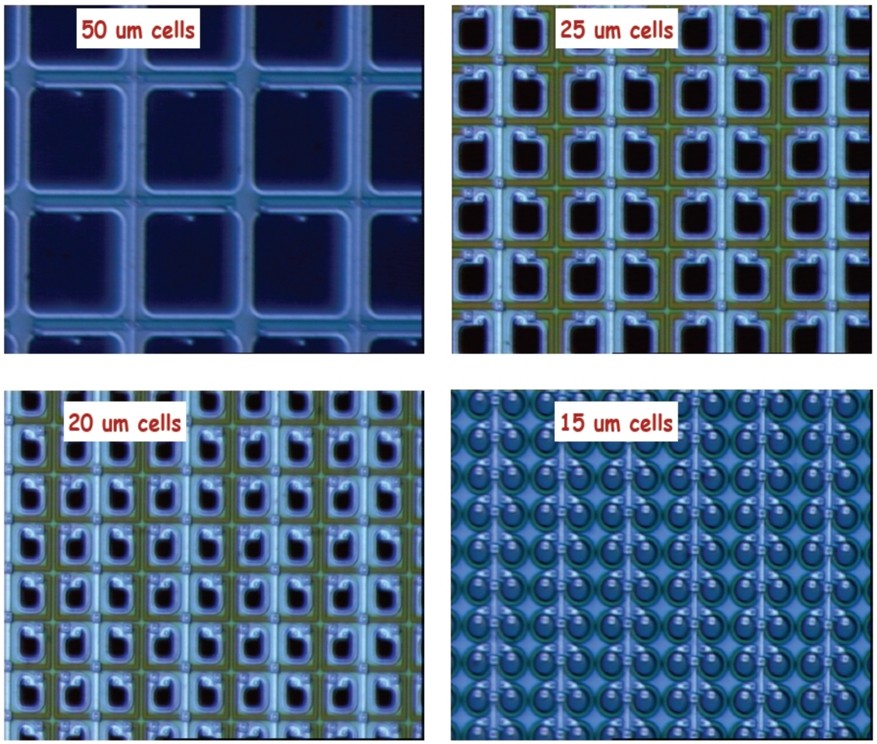
Saturation: solutions

Zecotek (Singapure) produces devices with 15,000 and 40,000 cells/mm^2.

The structure is different:

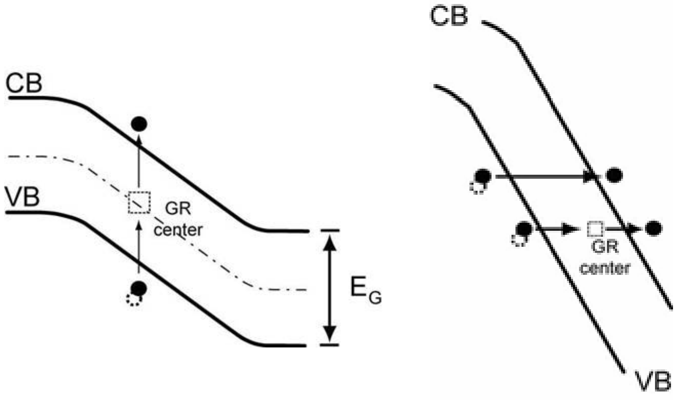


G-APDs from Hamamatsu have up to 4,500 cells/mm^2

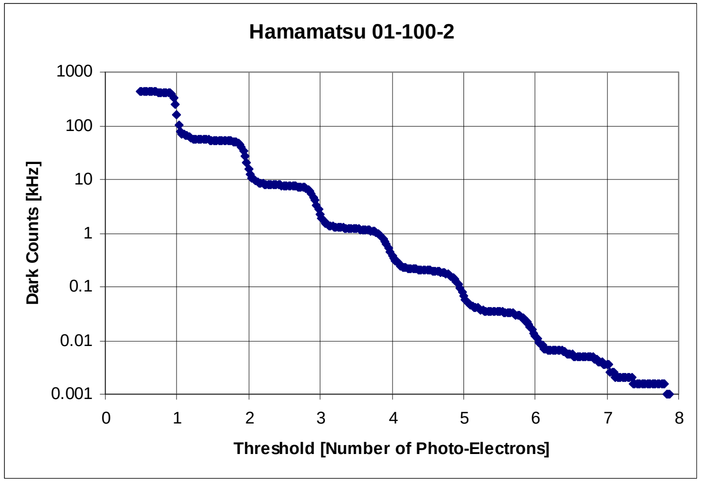


Dark count rate

A breakdown can be triggered by an incoming photon or by any generation of free carriers. The latter produces dark counts with a rate of 100 kHz to several MHz per mm^2 at 25°C when the threshold is set to half of the one photon amplitude.



Breakdown events initiated by thermally generated free carriers can be reduced by cooling (factor 2 reduction of the dark counts every 8°C) and by a smaller electric field (lower gain).



Field-assisted generation (tunneling) is a relative small effect. It can only be reduced by a smaller electric field (lower gain).

The dark count rate falls rapidly with increasing threshold with steps that depend on the crosstalk probability (~12% for the G-APD shown)

Dark count rate reduction

Dark counts are in most cases no problem:

- When the threshold is set to a couple of photo electrons the rate is low.
- In IACTs the rate only needs to be lower than the night sky background which amounts to 20-40·10^6 photons/mm^2·sr.

H. Daudet (PerkinElmer) has an idea which will allow to reducte the dark count rate by a factor of 10 to 100.

Let's see.

Optical crosstalk

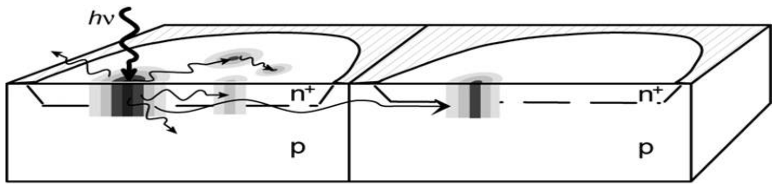
Hot-Carrier Luminescence:

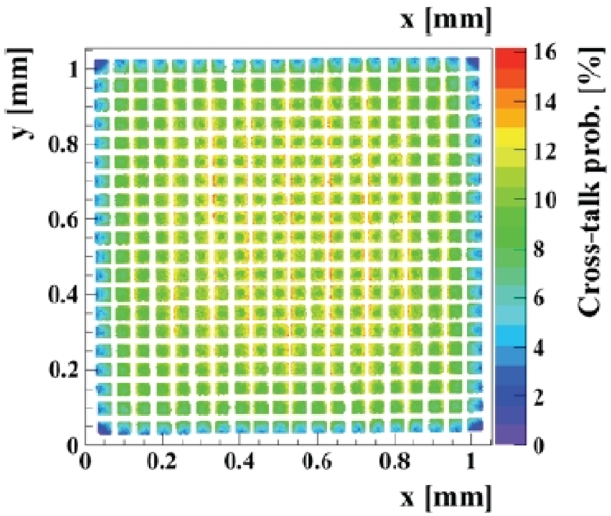
10^5 carriers in an avalanche breakdown emit in average 3 photons with an energy higher than 1.14 eV. (A. Lacaita et al, IEEE TED (1993))

When these photons travel to a neighboring cell they can trigger a breakdown there.

Optical crosstalk acts like avalanche fluctuations in a normal APD. It is a stochastic process. We get an excess noise factor (F = 1 + crosstalk probability)

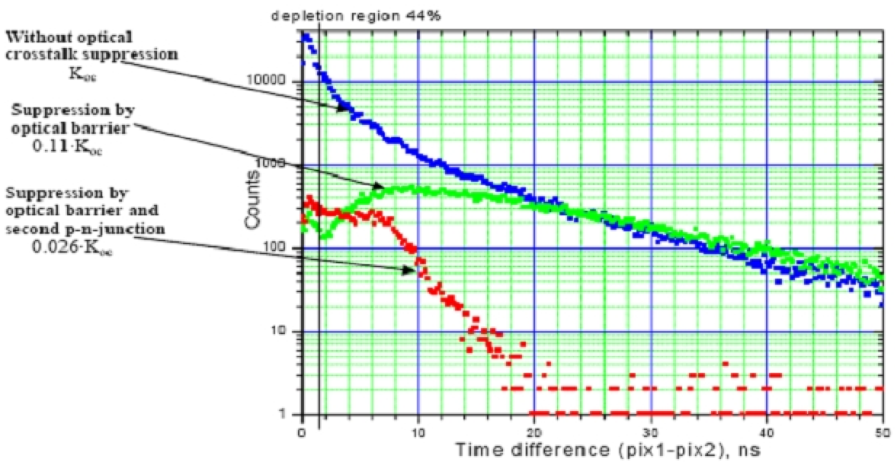
$$F = 1 + \frac{\sigma_M^2}{M^2}$$

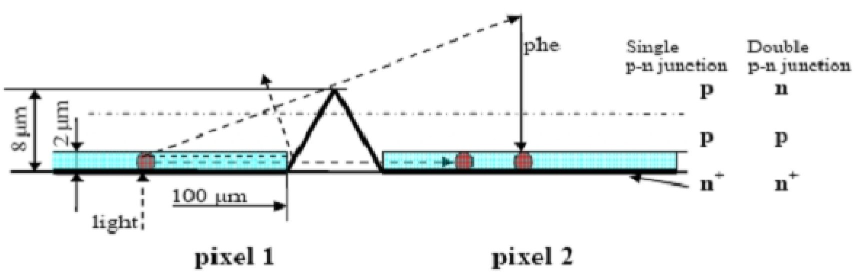




A. Tadday, 22.02.2010, SiPM Workshop DESY Hamburg

Crosstalk: solutions





Optical crosstalk between two separate pixels

Additional suppression:

• High doping concentration ~10^{19} in between pixels - free carrier absorption of OC light (~1000 nm) *(I.Reshet al. Optic Express 16(12)2008)*

• Absorption of OC light (~1000 nm) in Si damaged by ion implantation (*Patent pending*)

R. Mirzoyan, SiPM for CTA SST

Crosstalk suppression: results

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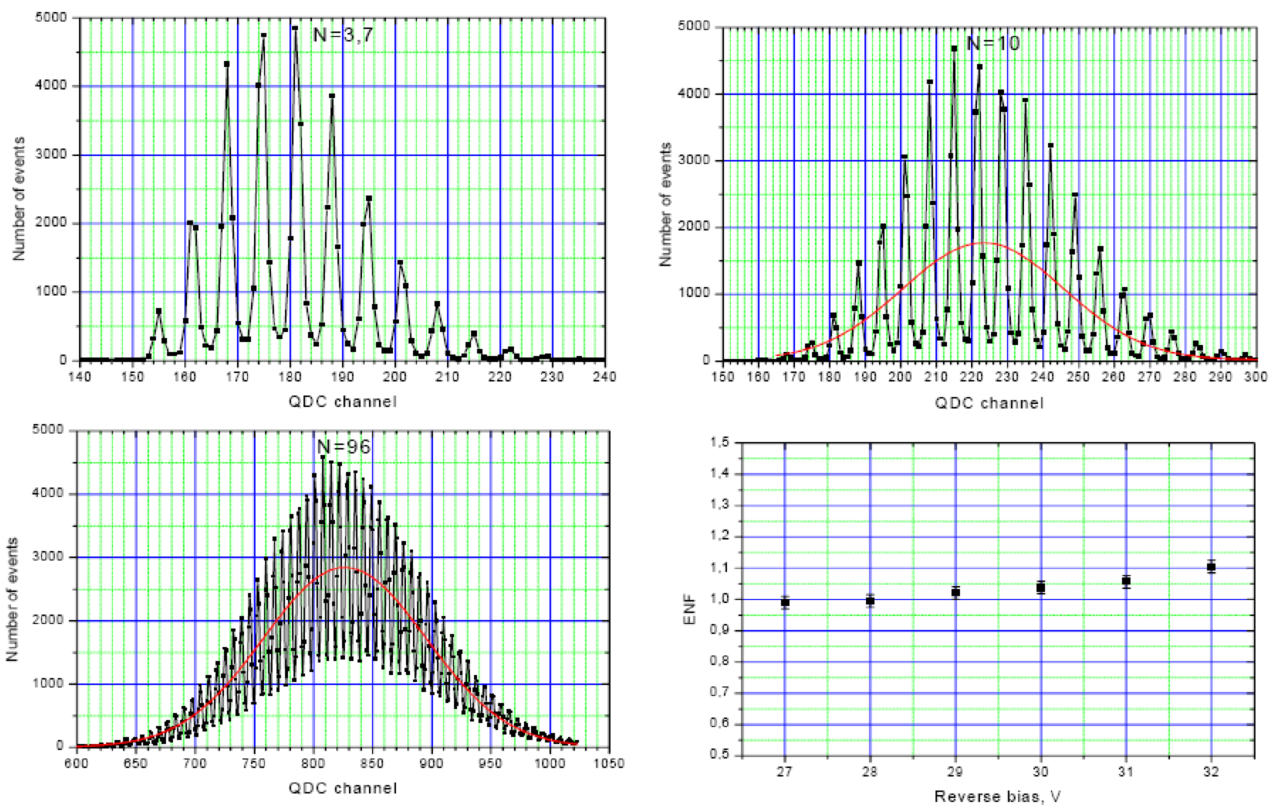
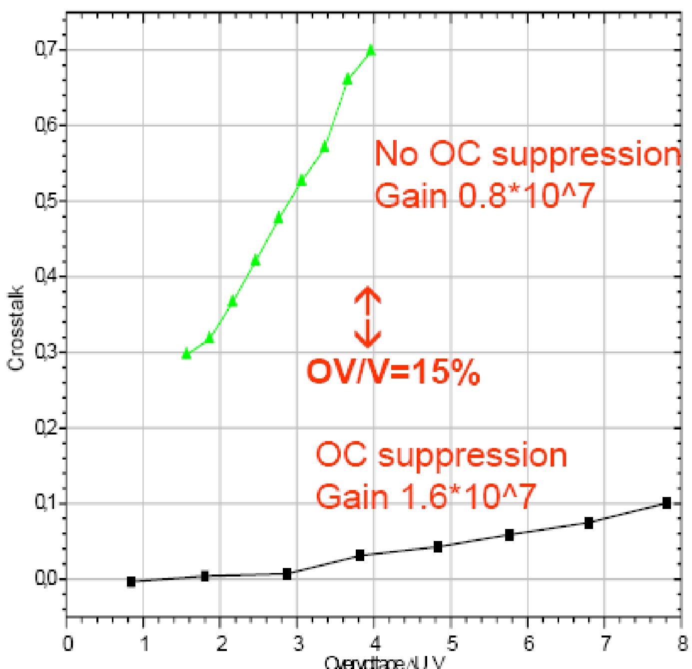
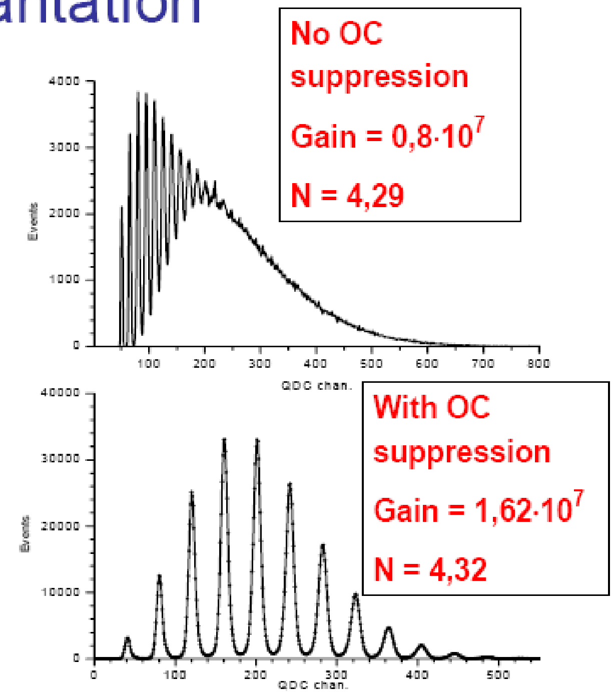
G-APD with cross-talk suppression: World record of ultra-fast light sensors in amplitude resolution (R. Mirzoyan, SiPM for CTA SST)



Crosstalk suppression: results

Prompt OC suppression using Si damaged by ion implantation

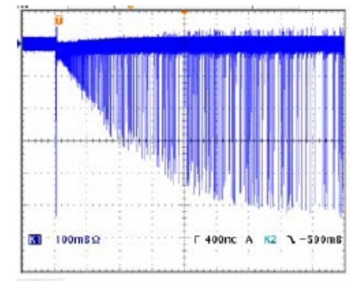




SiPM 1x1 mm^2

10-Jun-2010 B.Dolgoshein Silicon PM 27

Afterpulses

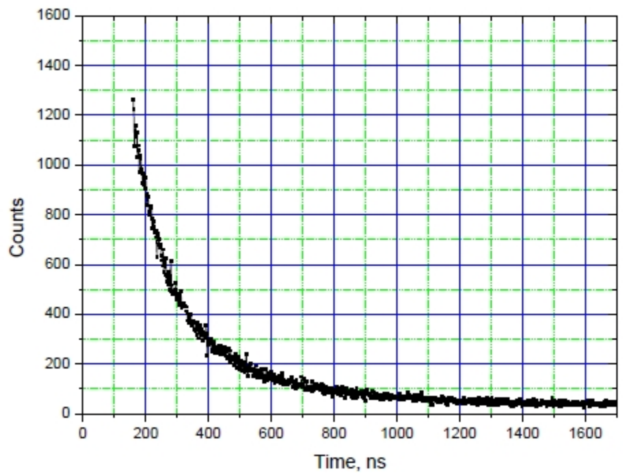


In the silicon volume, where a breakdown happened, a plasma with high temperatures (few thousand degree C) is formed and deep lying traps in the silicon are filled. Carrier trapping and delayed release causes afterpulses during a period of several 100 nanoseconds after a breakdown.

The probability for afterpuses increases with higher overvoltage (higher gain).

A recovery time ~.5 us is needed for AP suppression down to a level of ~1-2%. This can be achieved by a proper choice of the quenching resistor ($\tau=C_{cell}\cdot R_q$).

Some devices (e.g. from Hamamatsu) have very short recovery times (5 ns). This helps to increase the dynamic range in calorimetry.



B. Dolgoshein, Imaging 2010, Stockholm

Afterpulses

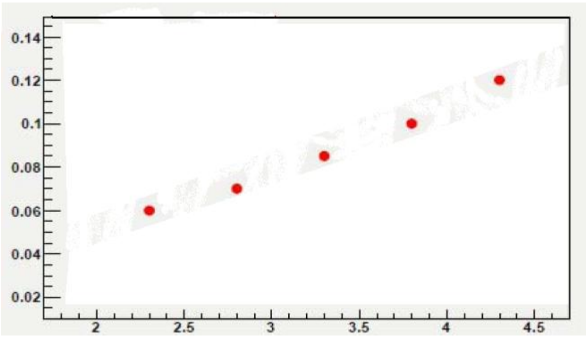
Afterpulses appear with a decay time constant of about 100 ns at the one pe level (only increased by cross talk).

This is different compared to the behaviour of PMs which produce large afterpulses with amplitudes of tens of pe's at a well defined delay.

High operating voltage (high gain)

increases the number of afterpulses.

Afterpulse probability

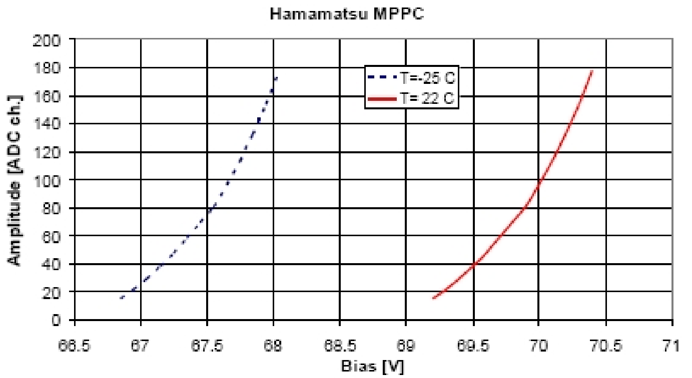


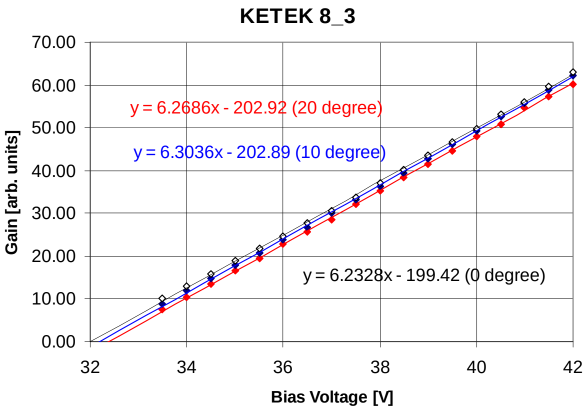
H. Otono, PD07

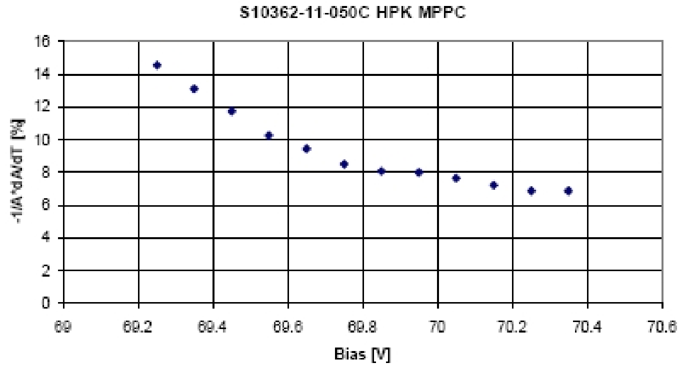
Overvoltage [V]

Stability

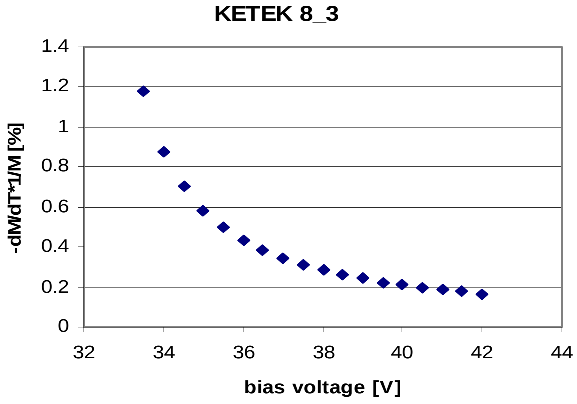
The breakdown voltage and by this the gain varies with the temperature (phonon interactions). With a large range of overvoltages the effect can be minimized.







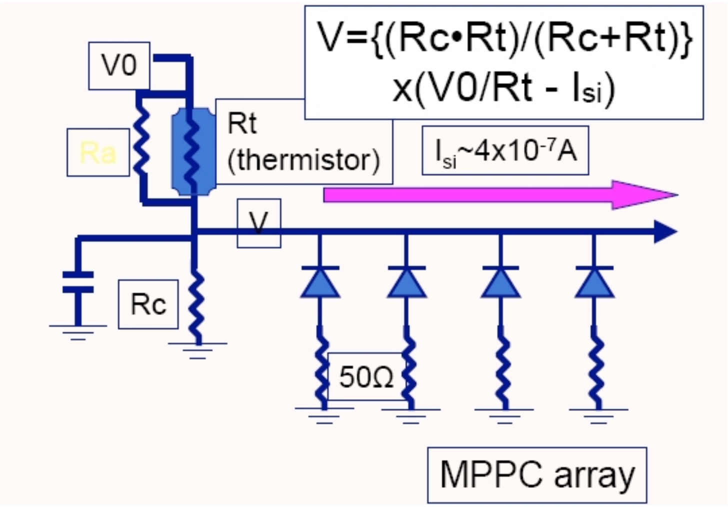
Y. Musienko PoS(PD07)012

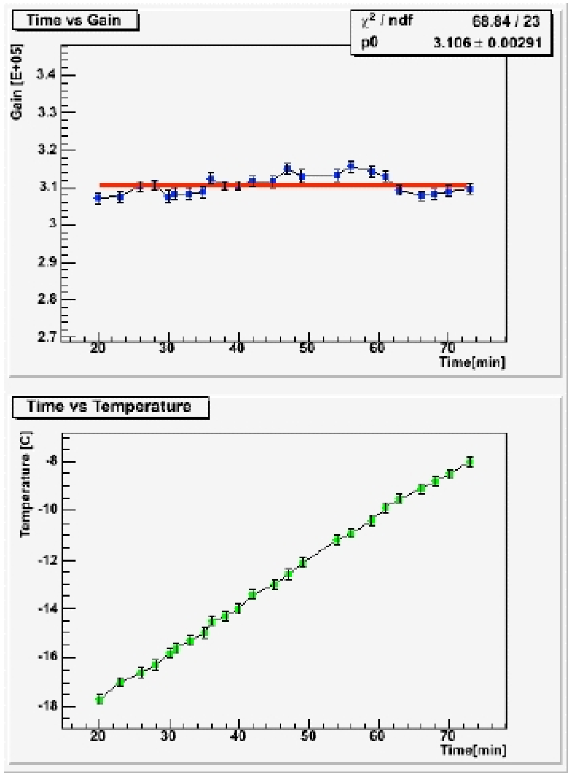


Stability

The problem of temperature dependence can easily be solved by regulating the bias voltage even when G-APDs with a large coefficient are used.

The simplest way is to use a thermistor:





Gain: +/- 0.1 %/degree C

H. Miyamoto, TIPP09

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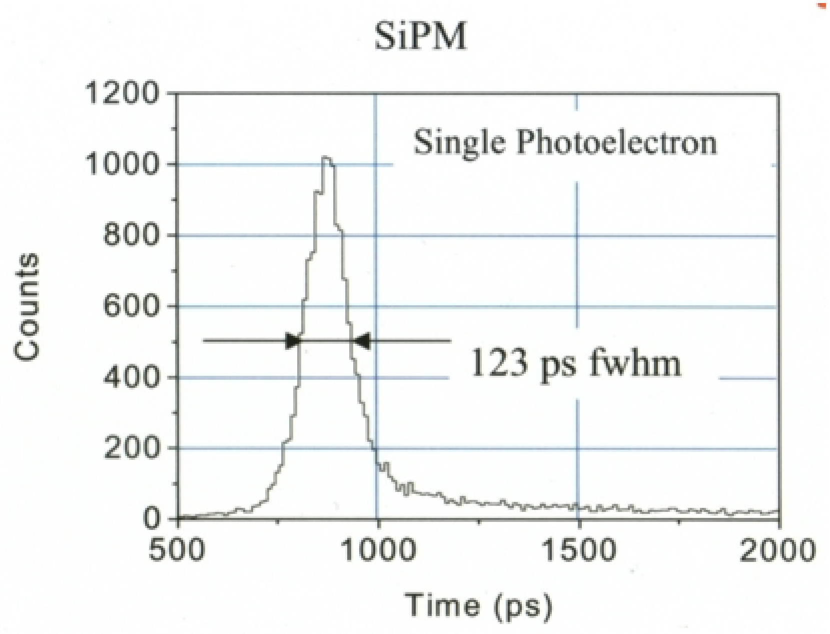
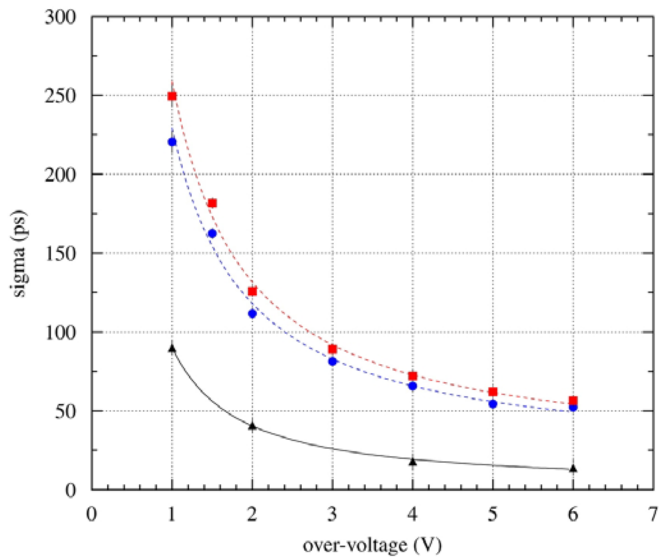
Time resolution

Excellent time resolution can be achieved when the G-APDs are operated at high overvoltage.





Includes the contribution of the laser (40 ps) and the electronics (60 ps) ⇒ 100 ps FWHM for the SiPM G-APD from MEPhI/Pulsar

NIMA 504 (2003) 48

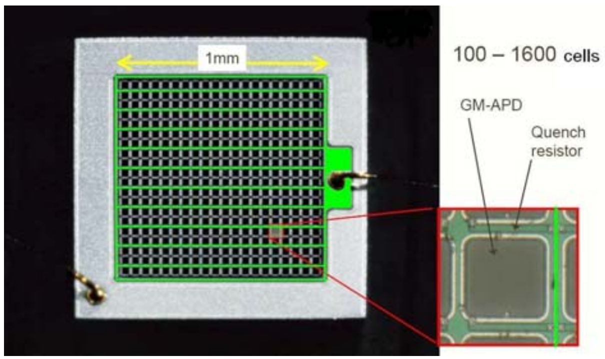
Time resolution for single photons with λ= 400 nm ● and λ=800 nm ● as a function of overvoltage. G-APD from FBK-irst

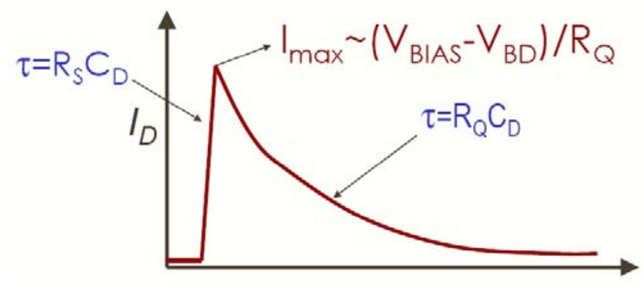
▲ show the contribution of electronic noise

NIMA 581 (2007) 461

Pulse shape

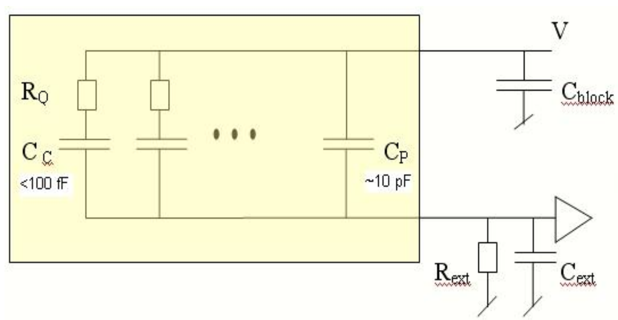
For the best timing we need with small parasitic capacitance (G-APD design) and a low impedance amplifier (our problem)

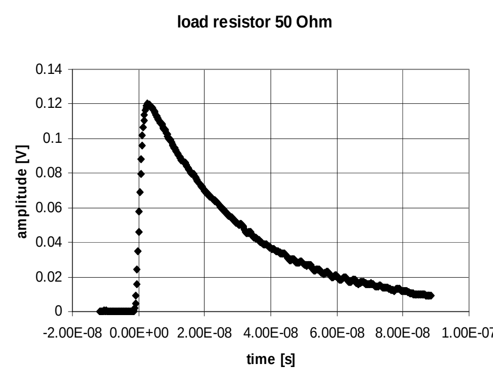


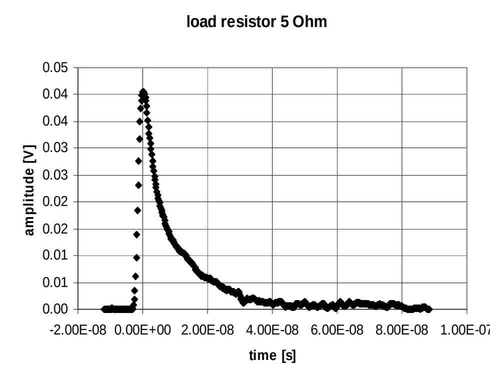


The usual interpretation of the pulse shape

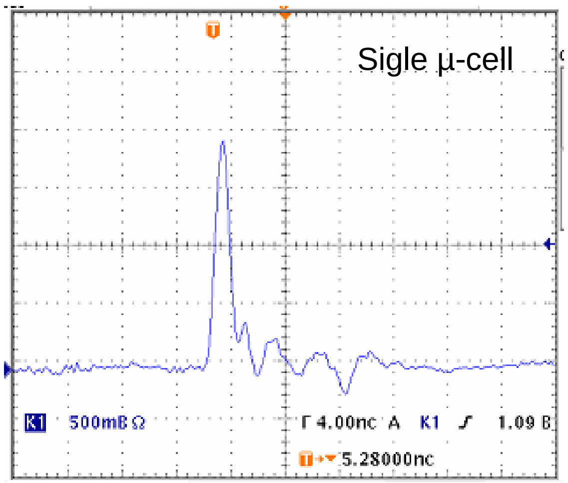
Simple equivalent circuit:

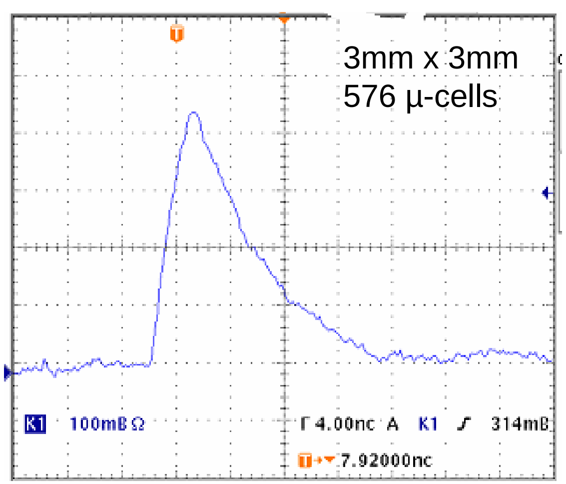






Pulse width depends on the SiPM chip size



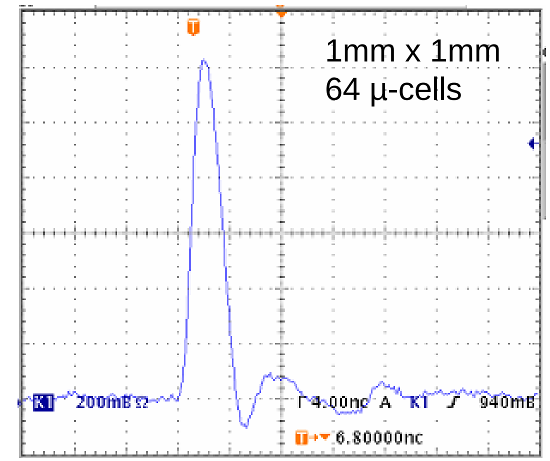


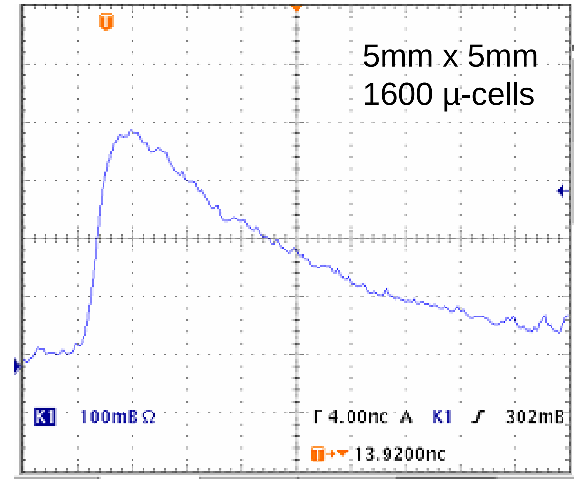
A single ph.e. pulse shape for different SiPMs

All tested devices had µ-cell size of 100µm x 100µm

Operated under gain: 10^7

R. Mirzoyan, SiPM for CTA SST



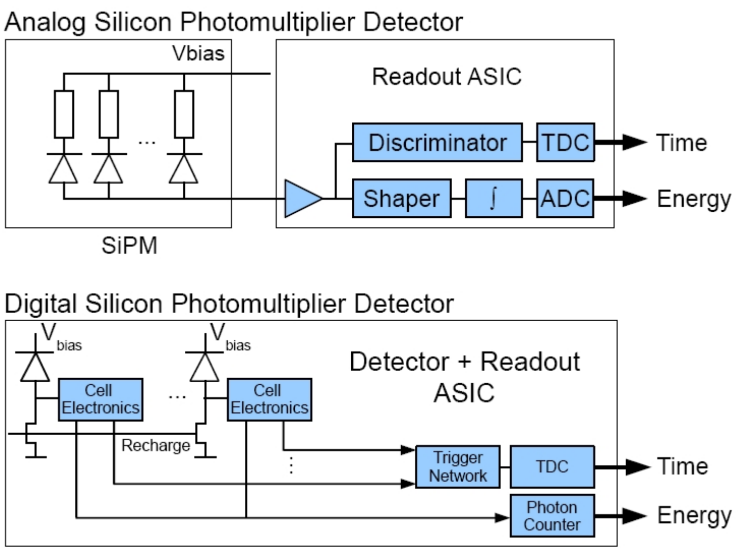


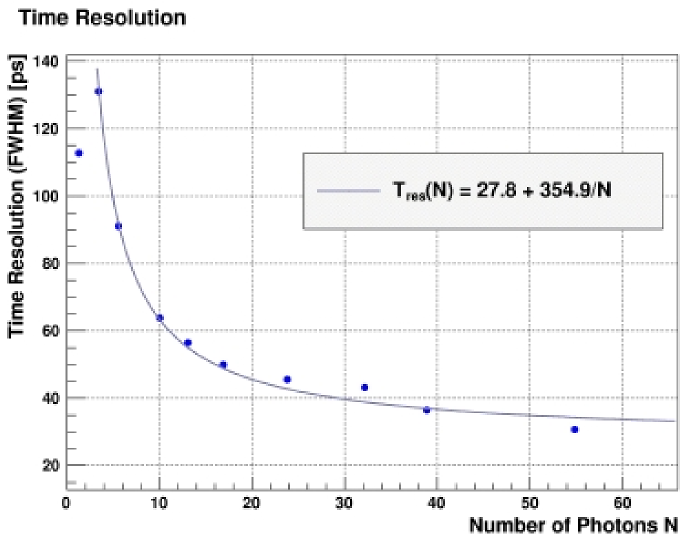
Timing: PHILIPS SiPM

Connecting each individual cell to a readout electronic chain should consequently result in the best possible time resolution

PHILIPS

Digital SiPM – The Concept





- Sensor triggered by attenuated laser pulses at first photon level
- Laser pulse width: 36ps FWHM, λ = 410nm
- Contribution to time resolution (FWHM):

  SPAD: 54ps, trigger network: 110ps, TDC: 20ps

- Trigger network skew currently limits the timing resolution
- Manual fine-tuning of the trigger network will reduce the skew

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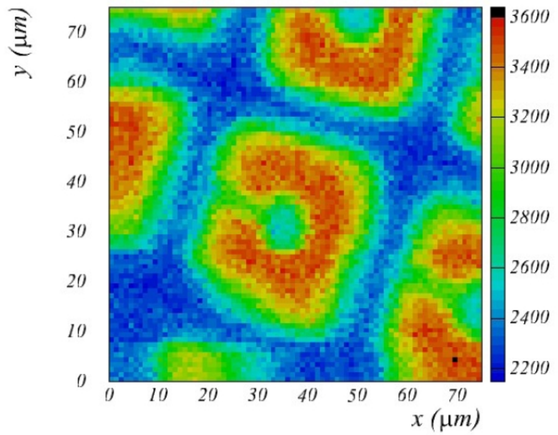
Photon Detection Efficiency (PDE)

The photon detection efficiency (PDE) is the product of quantum efficiency of the active area (QE), a geometric factor (ε, ratio of sensitiv to total area) and the probability that an incoming photon triggers a breakdown ($P_{trigger}$)

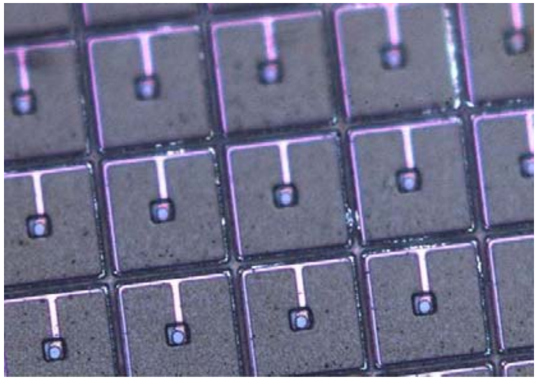
$$PDE = QE \cdot \varepsilon \cdot P_{trigger}$$

The QE is maximal 80 to 90% depending on the wavelength.

ε, the geometric factor has not been optimized by all producers. Best is now Hamamatsu with ~80% for the device S10362-33-100C



P. Križan, Light07



SSPM_0606BG4MM from Photonique/CPTA

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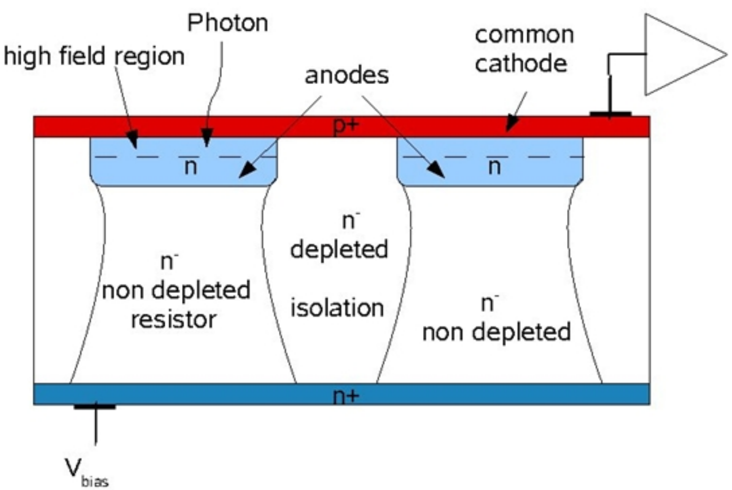
SiMPI: G-APD with bulk integrated quench resistors from MPI-HLL

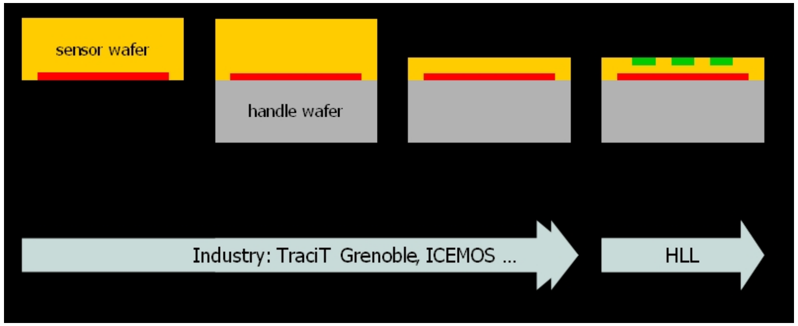
geometric factor ~75 % - no resistor on the surface → PDE ~ 60 %

free entrance window for light, no metal necessary within the array

allows engineering of the entrance window

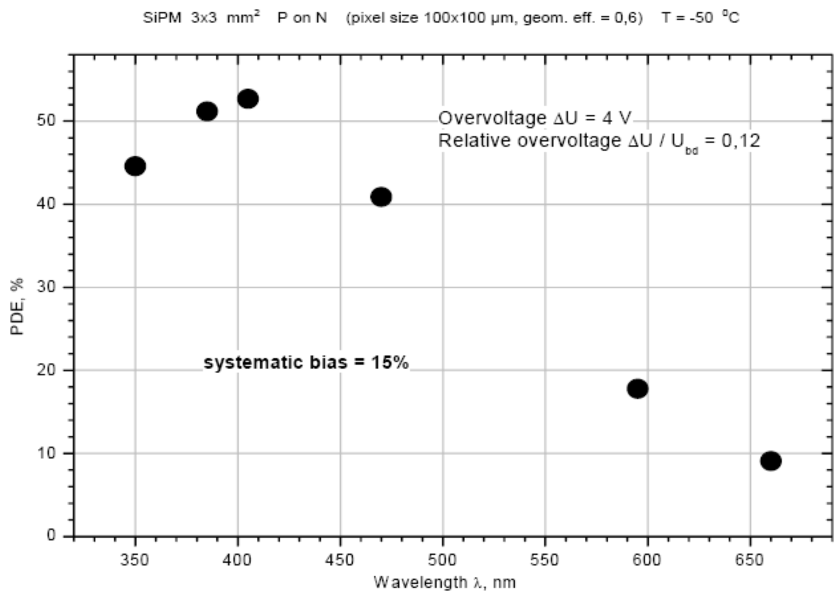
improved radiation hardness – no lateral high field regions on the surface

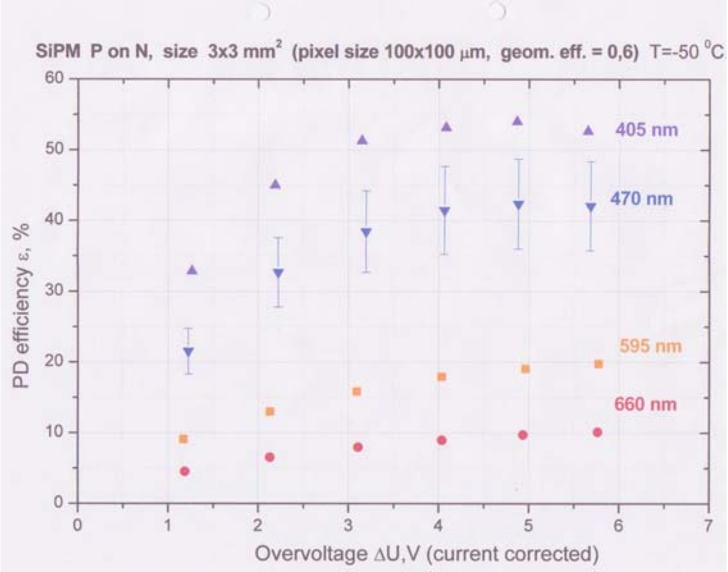




Photon detection efficiency

PDE ,SiPM p on n,3x3 mm^2,
OV/V=12% +OC suppression





Test-product of PerkinElmer, to become soon commercial product

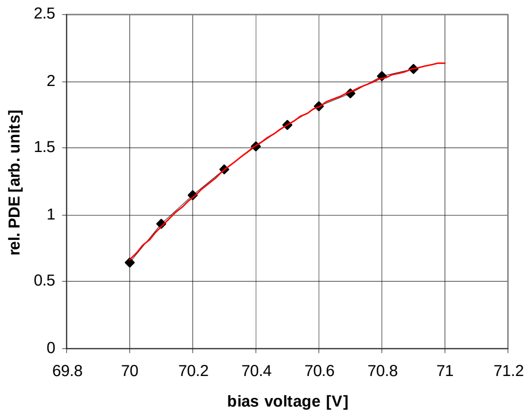
$PDE = QE(\sim 85\%) \cdot \varepsilon\mathbf{(60\%)} \cdot P_{trigger}$

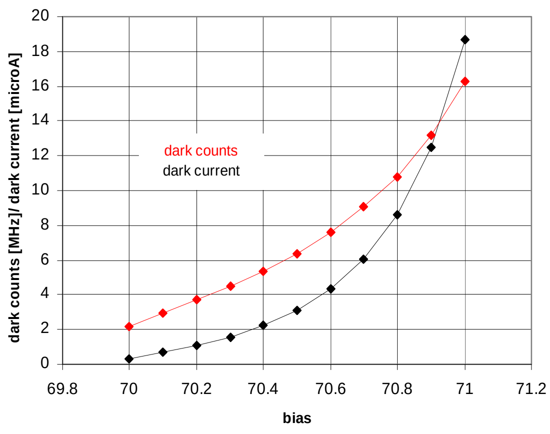
$\Rightarrow P_{trigger} = 1$

R. Mirzoyan, SiPM for CTA SST

PDE

Hamamatsu devices don’t reach unity breakdown probability:





The PDE is therefore well below the limit of PDE = QE(~85%) · ε**(80%)** ~ 65%

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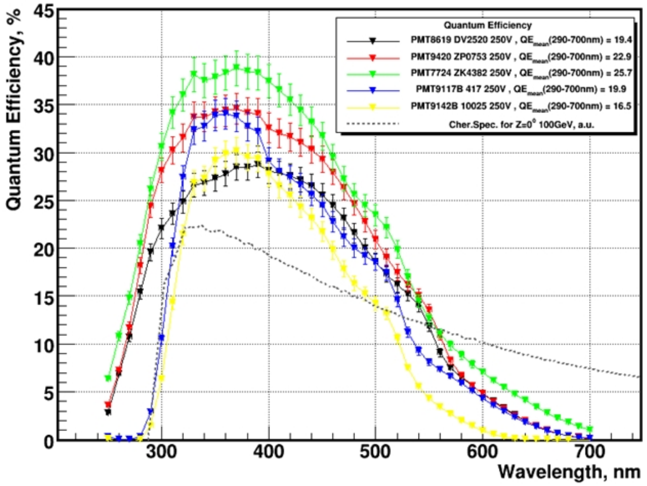
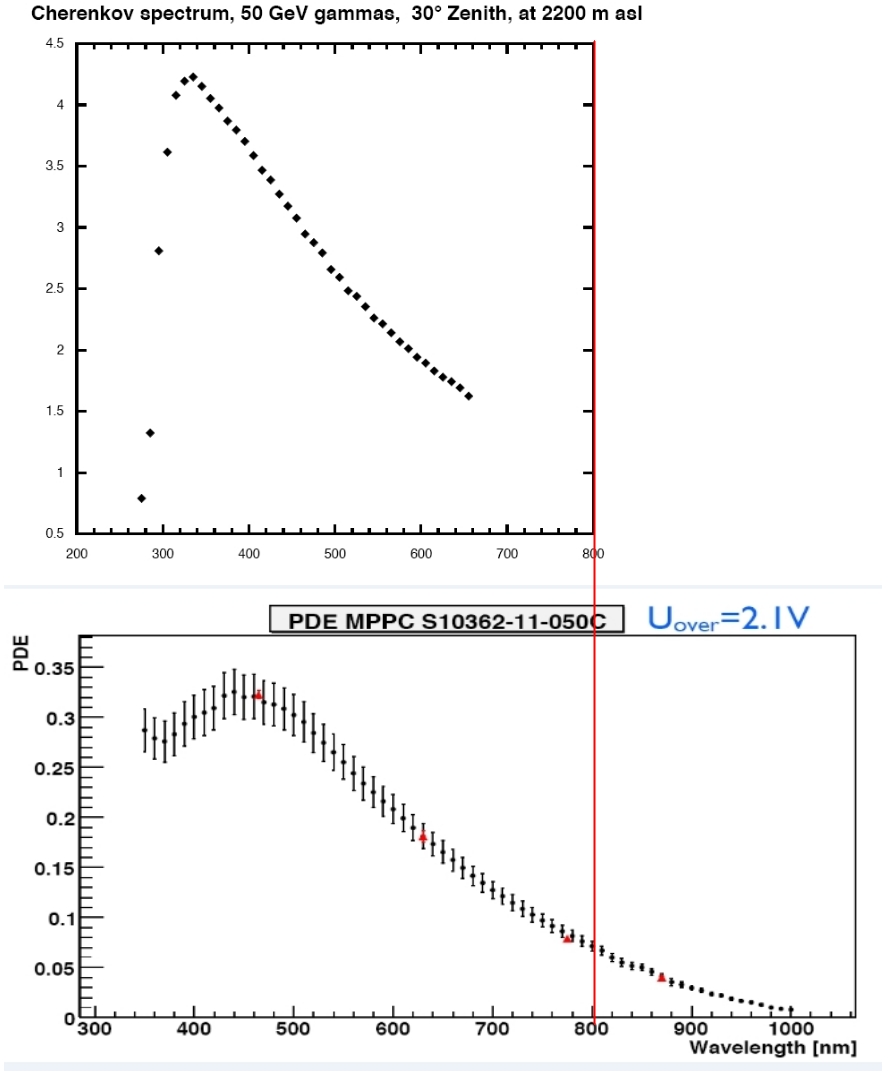
PDE for IACT





QE of state of the art PMTs

R. Mirzoyan, SiPM for CTA SST

G-APDs have at long wavelength still a good PDE

What counts is $\int ChI(\lambda)\cdot PDE(\lambda)$

FACT = First G-APD Cherenkov Telescope for TeV Gamma Astronomy

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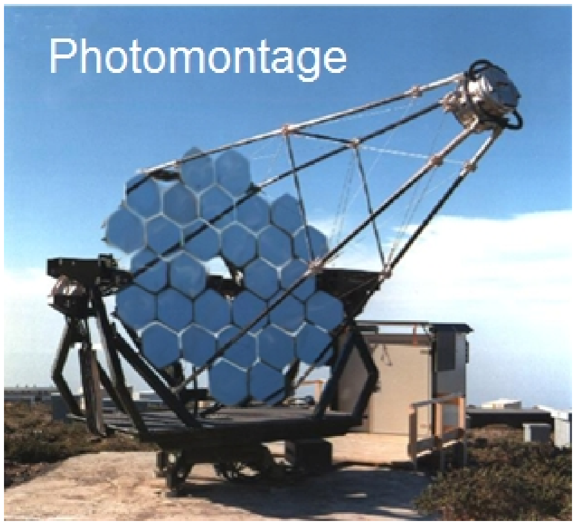
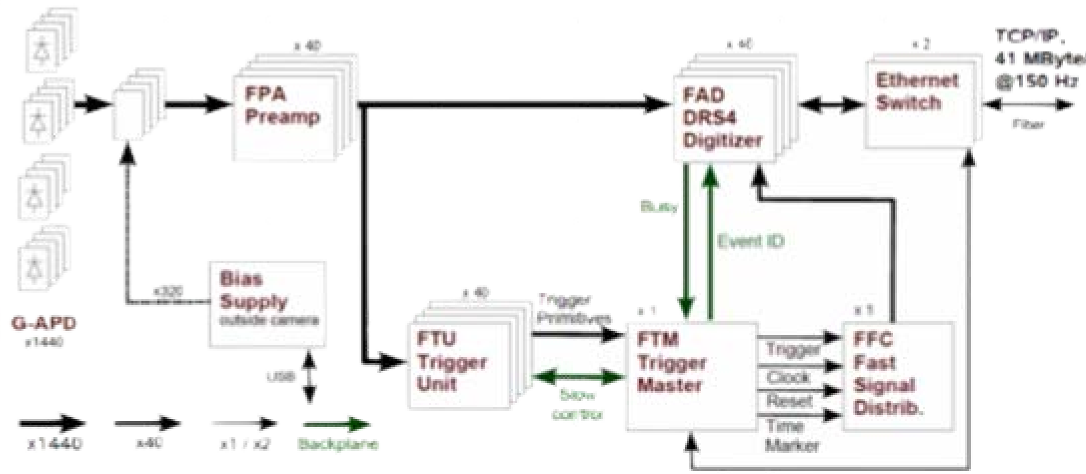
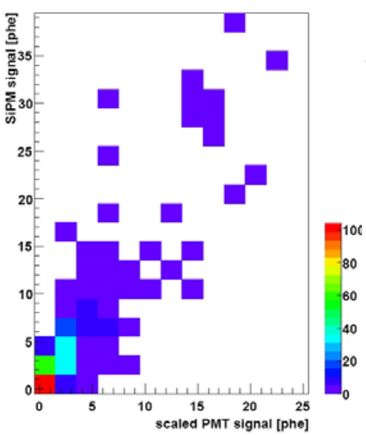
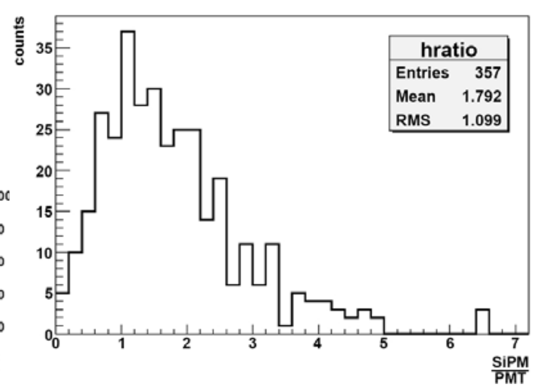
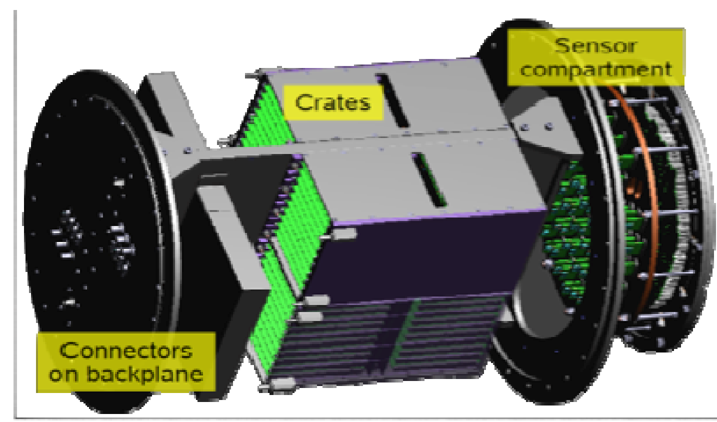
TU Dortmund, EPF Lausanne,
U Würzburg, ETH Zürich











More Properties

There are more features which are not mentioned yet:

G-APDs work at low bias voltage (~50 V),

have low power consumption (< 50 $\mu W/mm^2$),

are insensitive to magnetic fields up to 7 T,

are compact, rugged and show no aging,

tolerate accidental illumination,

cheap because they are produced in a standard MOS process – **not yet!**

List of producers (incomplete)

Since 1989 many G-APD structures were developed by different developers:

- CPTA/Photonique (Moscow/Geneva)
- Zecotek (Singapore)
- MEPhI/Pulsar (Moscow)
- PerkinElmer (Montreal, Canada)
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL (Cork, Ireland)
- RMD (Boston, USA)
- MPI Semiconductor Laboratory (Munich, Germany)
- KETEK (Munich, Germany)
- FBK-irst (Trento, Italy)
- STMicroelectronics (Italy)
- ……

Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, SPM, DAPD, PPD, G-APD

Where do we stand?

Significant progress in the development of G-APDs over the last 2-3 years:

High PDE of 30-50% for blue light (PerkinElmer, Hamamatsu, Zecotek, KETEK)

Reduction of dark count at room temperature to <300 kHz/mm^2 (PerkinElmer, Hamamastu, Zecotek)

Low crosstalk <1-3% (PerkinElmer, CPTA/Photonique, STMicroelectronics)

Low temperature coefficient of <0.3%/C (PerkinElmer, CPTA/Photonique, KETEK)

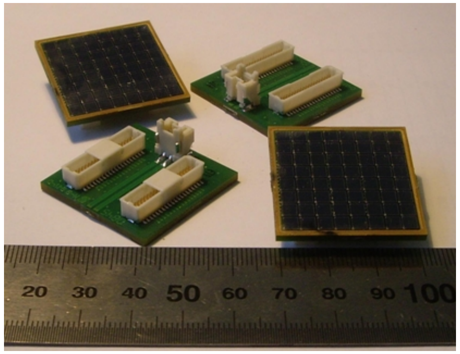
Fast timing ~50 ps (RMS) for single photons (all)

Large dynamic range with 5 000 – 40 000 cells/mm^2 (Hamamatsu, Zecotek)

Large area of 3x3 mm^2 (PerkinElmer, CPTA/Photonique, Hamamatsu, FBK, SensL, Zecotek, KETEK, STMicroelectronics…)

Future

The development of G-APDs is ongoing. What can we expect in the next 2 to 3 years?



PDE >60% for 350-650 nm light

dark count rate <100 kHz/mm^2 at room temperature

optical crosstalk <1%

active area >100mm^2

high DUV light sensitivity (PDE@128 nm ~20-40%)

G-APD arrays:6x6, 8x8 ...

very fast position sensitive detectors operated in Geiger mode

radiation hard G-APDs -up to $10^{14} \div 10^{15}$ n/cm^2 (new materials: diamond?, GaAs?, SiC?, GaN? …)

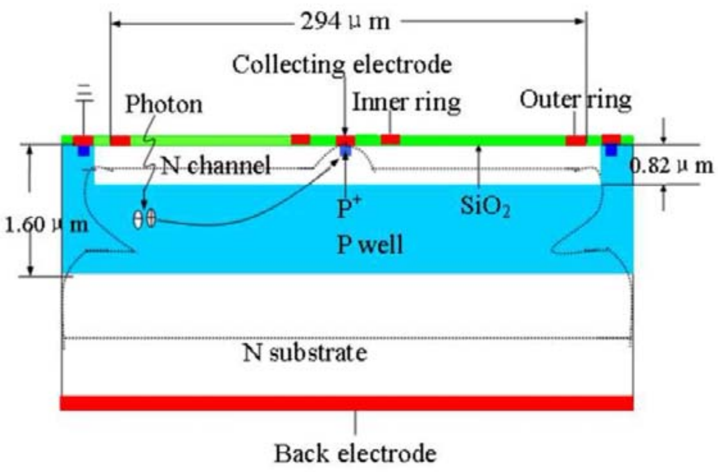
production cost ~1$/mm^2

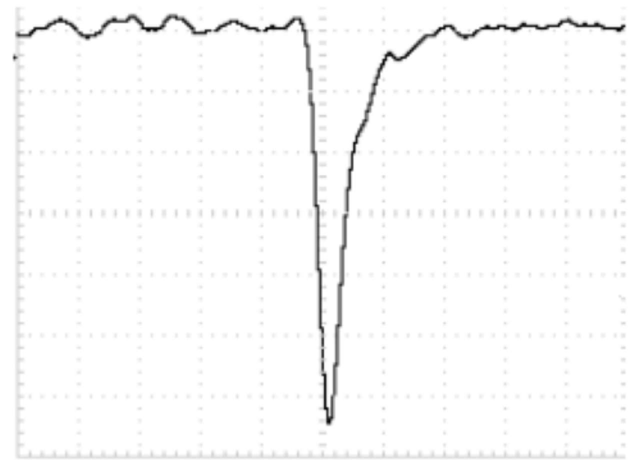
Front illuminated G-APD from Beijing

combination of drift diode and G-APD

small capacitance of the amplification structure

simple CMOS process





G. Wu et al., Demonstration of an avalanche drift detector with front illumination, NIMA