Semiconductor Detector Overview

Dieter Renker

Outline

- From Photomultiplier Tubes (PMTs) to Geiger-mode Avalanche Photodiodes (G-APDs)
- History of Solid State Single Photon Detectors
- Properties and Problems
- Applications and Choice of Paramaters
- Conclusion

From PMT to G-APD

PMTs have been developed during almost 100 years. The first photoelectric tube was produced by Elster and Geiter 1913. RCA made PMTs a commercial product in 1936. Single photons can be detected with PMTs.

The high price, the bulky shape and the sensitivity to magnetic fields of PMTs forced the search for alternatives.

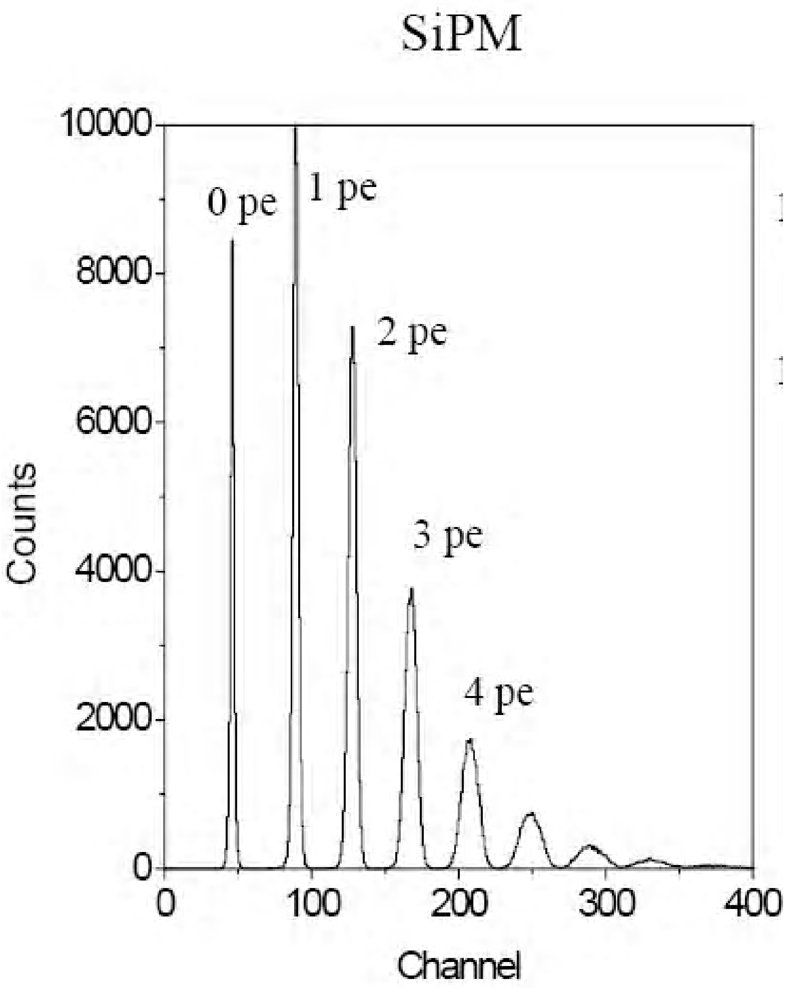
PIN photodiodes are very successful devices and are used in most big experiments in high energy physics (CLEO, L3, BELLE, BABAR, GLAST) but due to the noise of the neccesary amplifier the minimal detectable light pulses need to have several 100 photons.

Avalanche photodiodes have internal gain which improves the signal to noise ratio but still some 20 photons are needed for a detectable signal. The excess noise, the fluctuations of the avalanche multiplication limits the useful range of gain. CMS is the first big experiment that uses APD’s.

G-APDs can detect single photons. They have been developed and described since the beginning of this millennium.

From PMTs to G-APDs

Single photons clearly can be detected with G-APDs. The pulse height spectrum shows a resolution which is even better than what can be achieved with a hybrid photomultiplier.



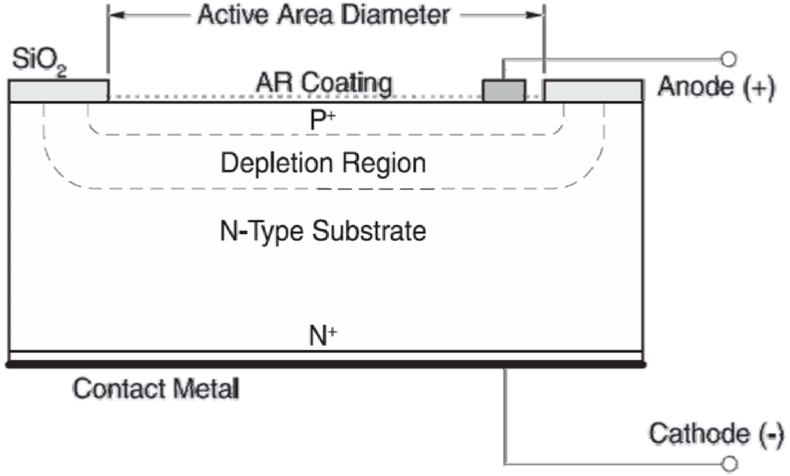
NIM A 504 (2003) 48

PIN photodiode

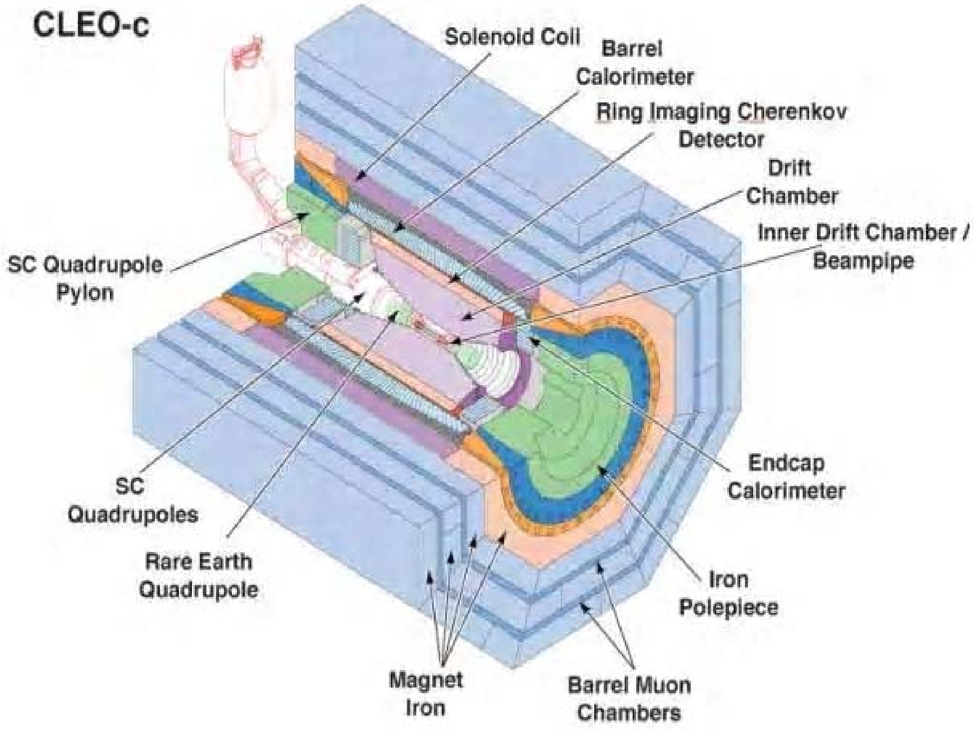
One of the simplest kind of photodiodes is the p-i-n photodiode in which an intrinsic piece of semiconductor is sandwiched between two heavily (oppositely) doped regions.

The two charge sheets (on the n+ and p+) sides produce a field which, even without an external field supplied, will tend to separate charges produced in the depleted region.

The separated charges will be swept to either terminal and be detected as a current provided that they are not recombined.



PIN photodiode



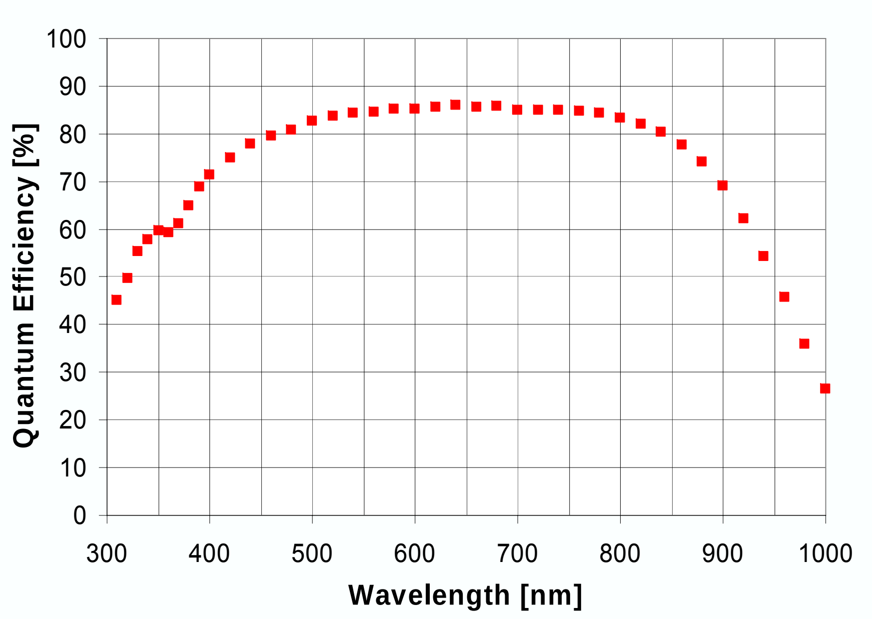
CLEO pioneered the use of CsI(Tl) crystals and PIN photodiodes in an electromagnetic calorimeter (7800 Crystals and 4 diodes/crystal).

The QE of PIN photodiodes matches the emission wavelength (550 nm) of CsI(Tl) better than PMT’s. It is ~80%.

Consequently the energy resolution is very good: <2% for 1 GeV γ’s.

The PIN photodiode is a very successful device – all B-factories use them and L3, GLAST …

PIN photodiode - Quantum efficiency



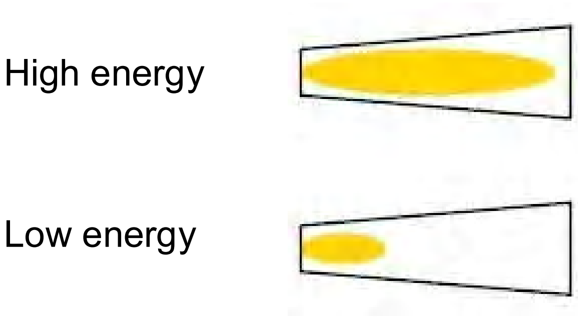
The QE in the UV region below 300 nm is still 20 to 30 %. With arsenic doping of the surface a QE of more than 50 % at 254 nm has been reported.

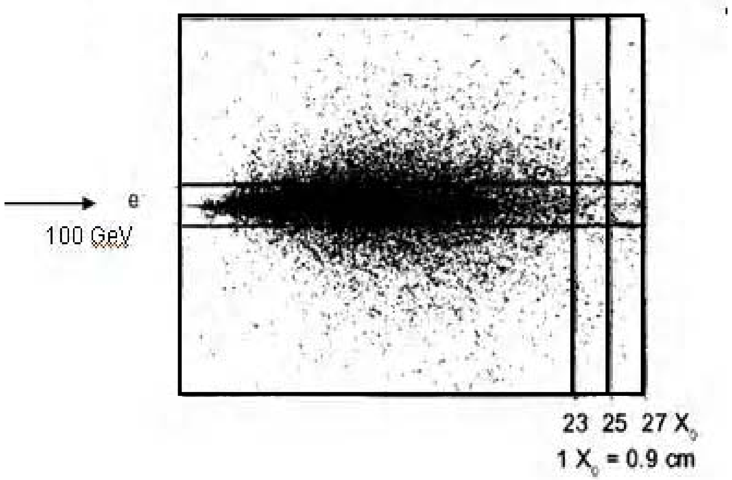
PIN photodiode – problems

- PIN photodiodes have no gain. The operation is very stable but they need a charge sensitive amplifier which makes the signal rise time slow and introduces noise to the system (C_{PIN} ~80 pF/cm^2). Calorimeters made of materials with low light yield (pure CsI in KTeV and Čerenkov calorimeters with lead glass) cannot use PIN photodiodes.

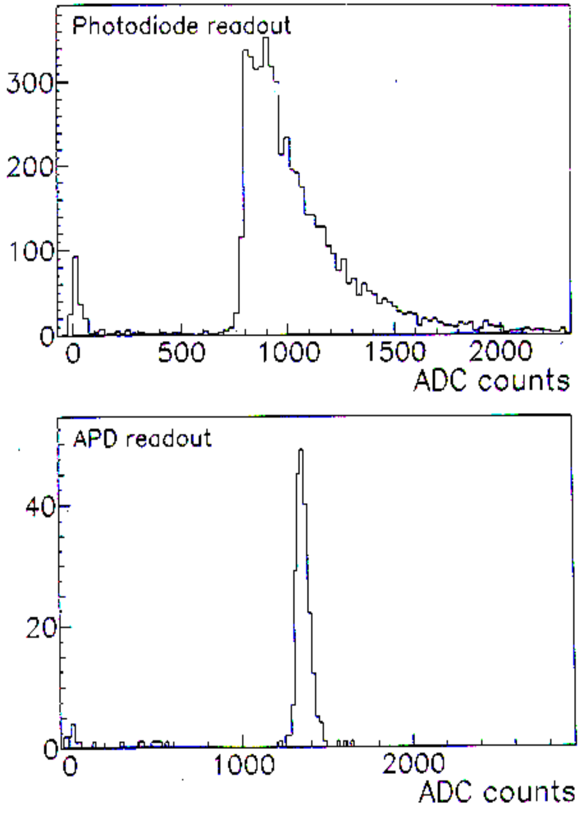
- The full thickness of the PIN photodiodes (300 μm) is sensitive. Charged particles (e.g. e^+ and e^-) which leak out at the rear end of the crystals and pass the diode produce an unwanted addition to the signal. A MIP creates some 100 electron-hole pairs per micron in silicon. This makes 30.000 electron-hole pairs which fake ~6 MeV additional energy in a CsI(Tl) calorimeter (Nuclear Counter Effect).

PIN photodiode – nuclear counter effect





Each dot stands for an energy deposition of more than 10 keV



80 GeV e^- beam in a 18 cm long $PbWO_4$ crystal

Basic APD Structure (CMS version)

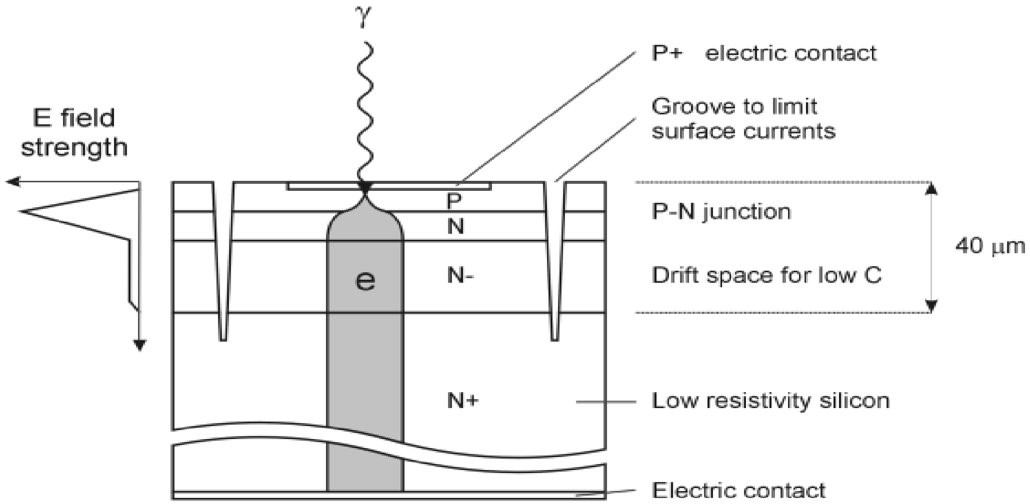


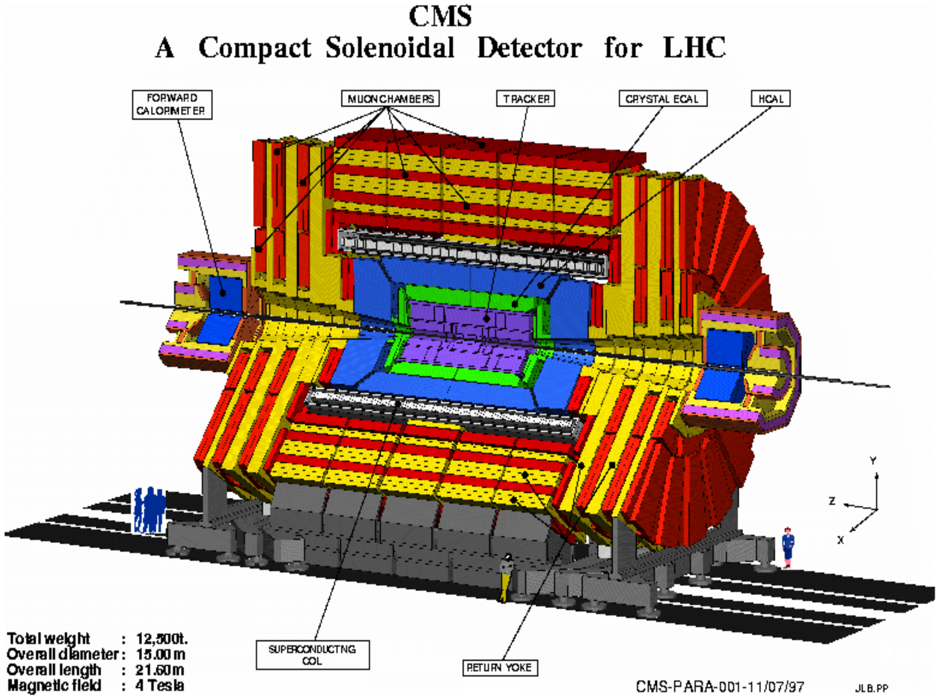
Photo-conversion electrons from the thin p-layer induce avalanche amplification at the p-n junction.

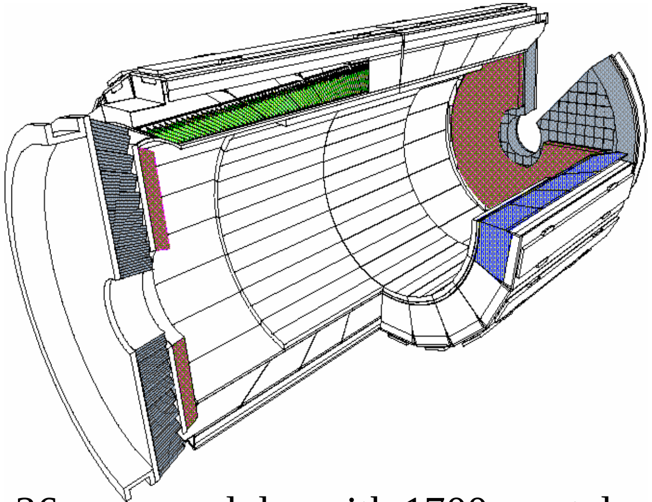
Electrons created by ionising particles traversing the bulk are not amplified.

→ $d_{eff} \sim 6\ \mu m$

50 times smaller than in a PIN diode.

APDs in the CMS ECAL

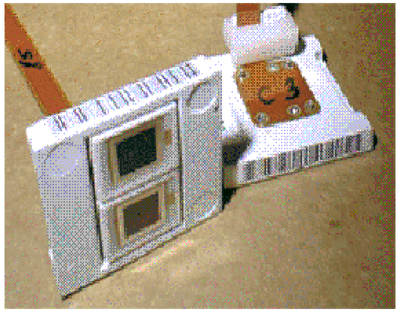


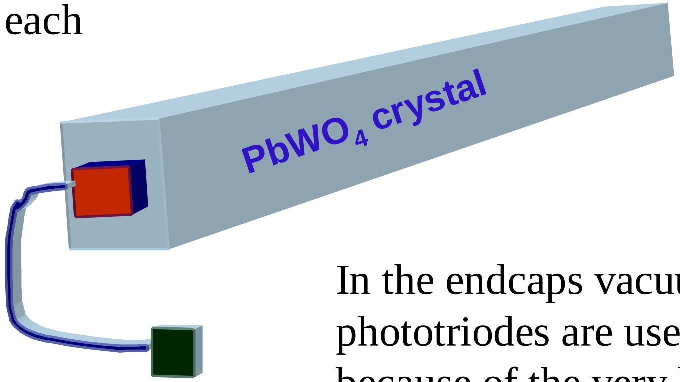


36 supermodules with 1700 crystals each

2 APD’s/crystal

→ 122.400 APD’s





In the endcaps vacuum phototriodes are used because of the very high radiation levels.

APD Impact on Energy Resolution

ECAL energy resolution:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

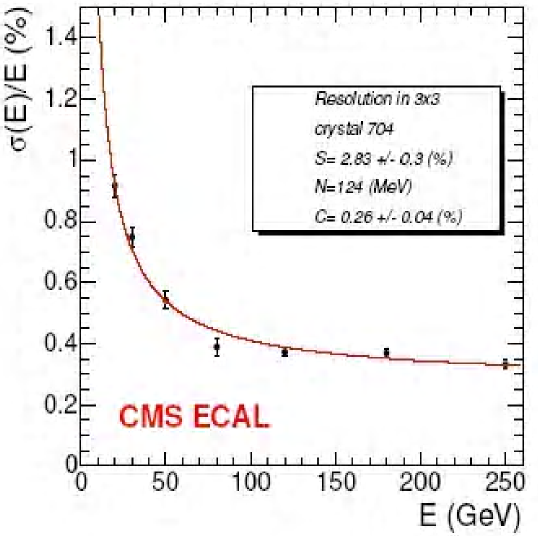
CMS design goal : *a* ~ 3%, *b* ~ 0.5%, *c* ~ 200 MeV

APD contributions to:

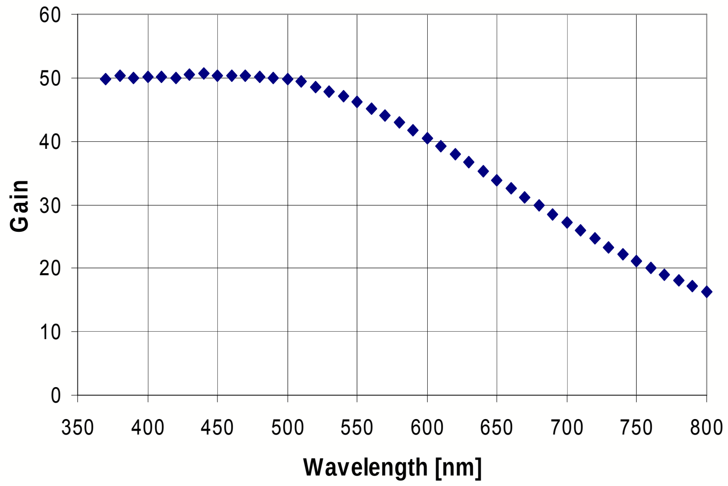
a: photo statistics (area, QE) and avalanche fluctuations (excess noise factor)

b: stability (gain sensitivity to voltage and temperature variation, aging and radiation damage)

c: noise (capacitance, serial resistance and dark current)

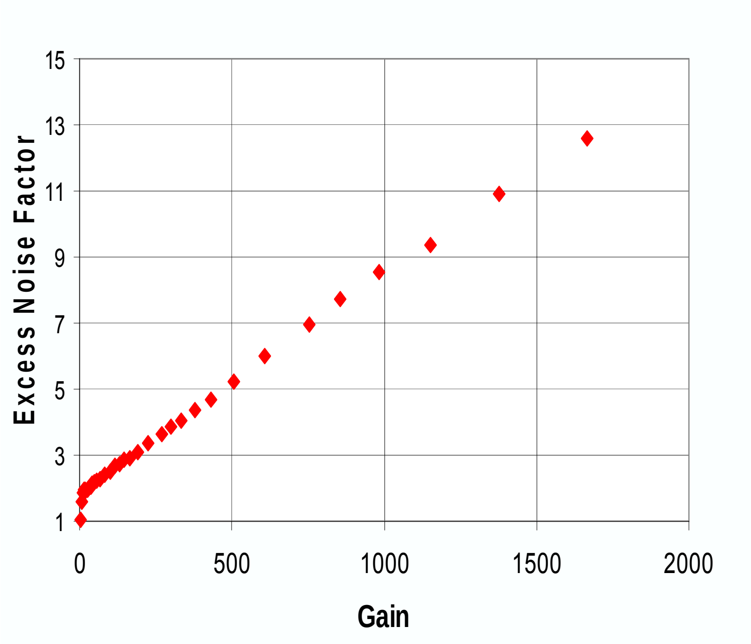


Gain x QE



The absorption length for light in silicon increases with the wavelength. Therefore photons with wavelengths longer than 500 nm create electron-hole pairs in or even behind the high field of the p-n junction and the avalanche multiplication is reduced.

Excess Noise Factor



$F(\langle M \rangle) = \langle M^2 \rangle / \langle M \rangle^2$

$F = k_{eff} \bullet M + (2-1/M) \bullet (1-k_{eff})$

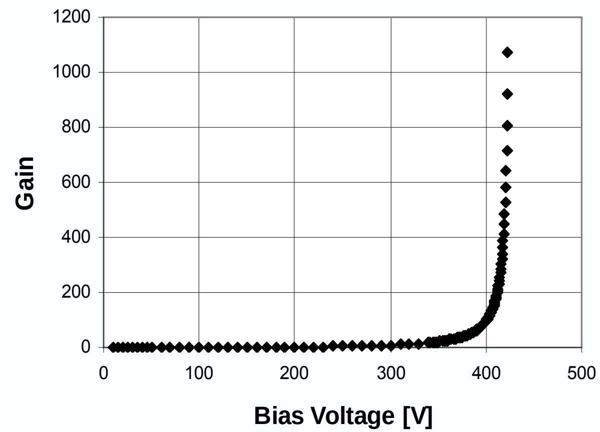
for $M > 10$: $F = 2 + k_{eff} \bullet M$

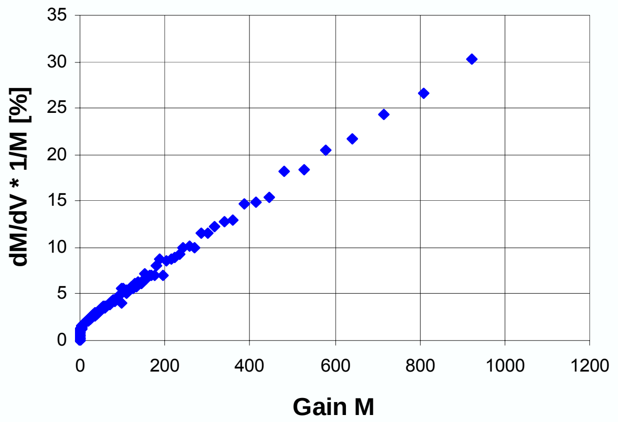
$k_{eff} \approx k = \beta / \alpha$

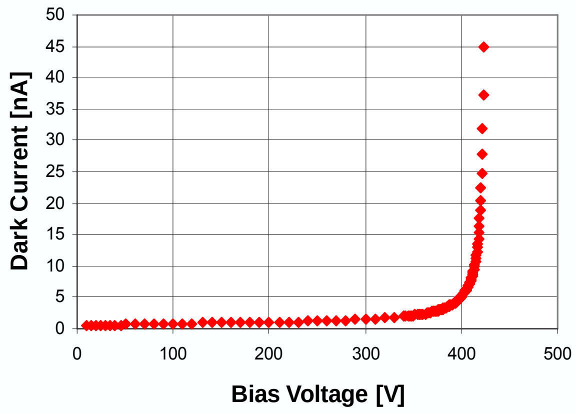
α and β are the ionization coefficients for electrons and holes

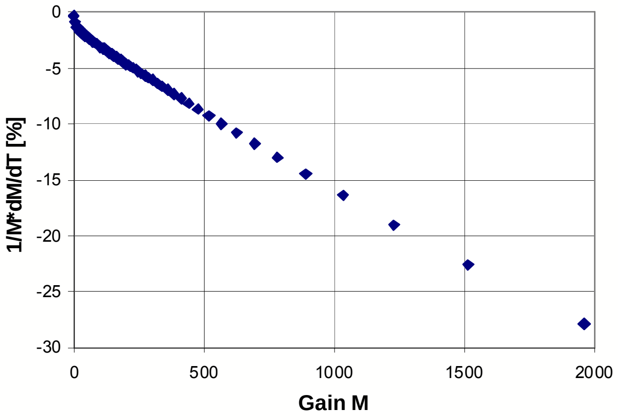
$\alpha >> \beta$

Gain and Dark Current of a 5x5 mm^2 APD from Hamamatsu







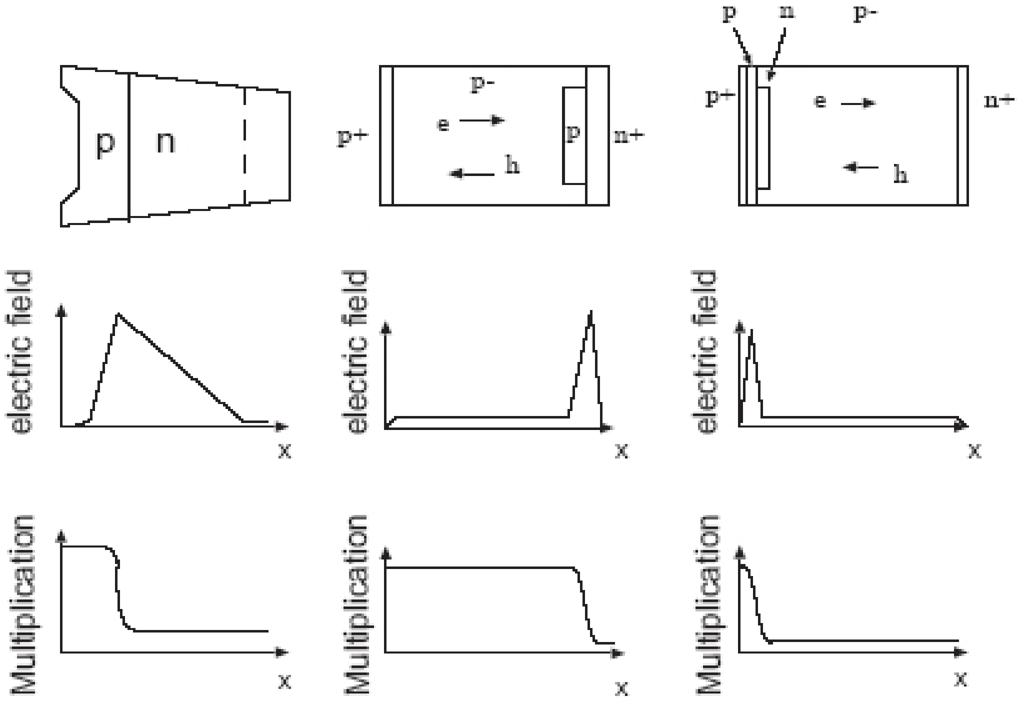


Other Types of Avalanche Photodiodes

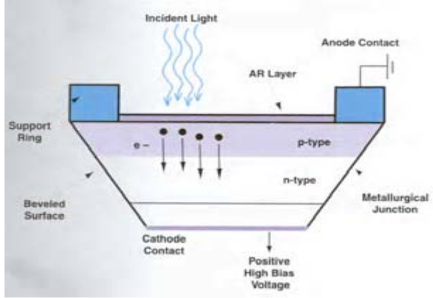
Beveled edge
API, RMD

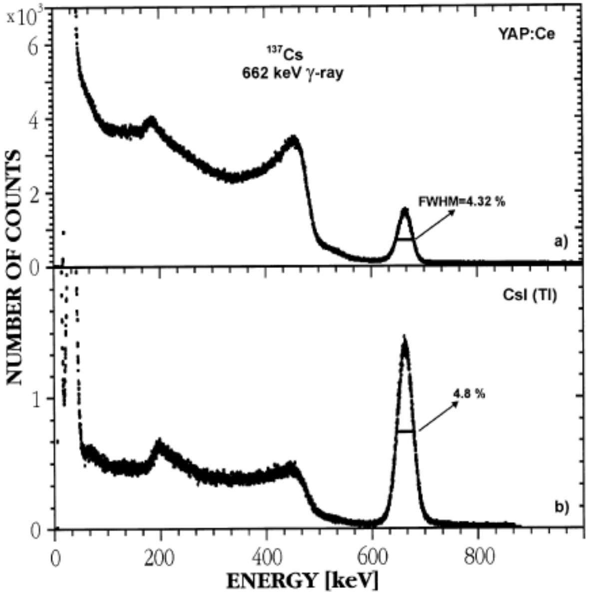
Reach through
Hamamatsu,
Silicon Sensor

Reverse
PerkinElmer,
Hamamatsu



APD with Beveled Edge





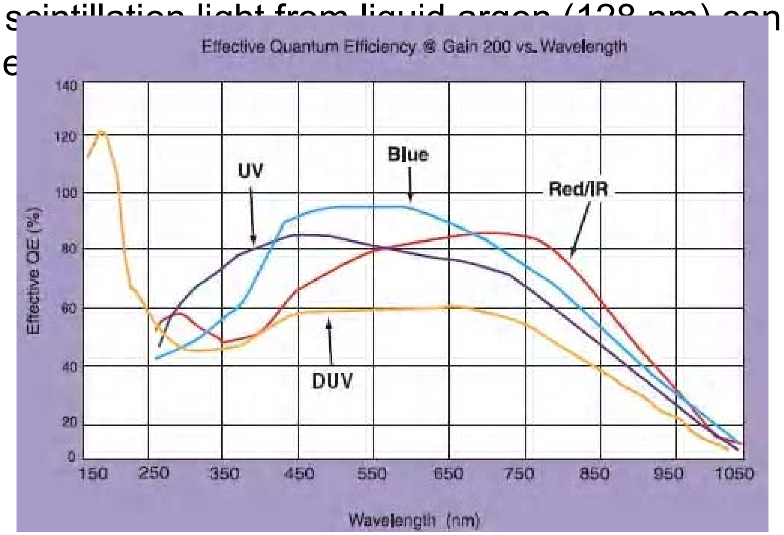
From M. Moszynski et al., NIM A 442 (2000)

Advanced Photonix Inc. (API) were the first to bring a large area APD on the market. They call it **LAAPD**.

This APD has the “bevelled edge” structure (reduction of the surface current). It has a very uniform internal field due to a neutron transmutation doping process (^{30}Si → P).

Probably this is the best available device. At least the best energy resolution has been achieved with this APD.

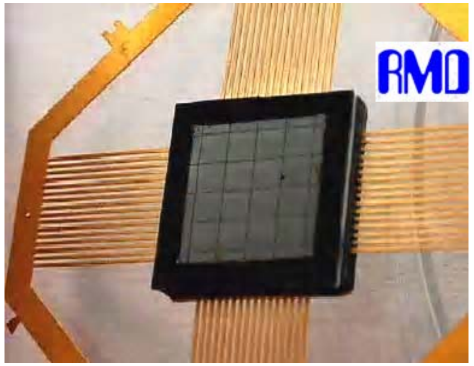
The scintillation light from liquid argon (128 nm) can be de

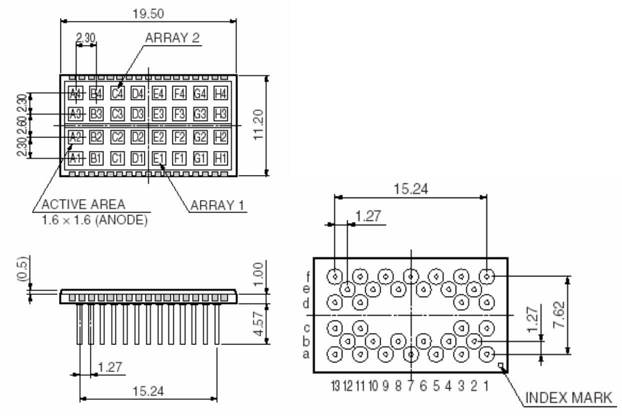


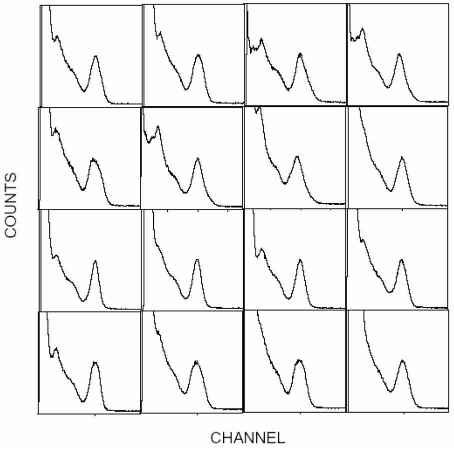
Avalanche photodiode: Arrays

HAMAMATSU

Monolithic arrays of APDs can be produced with a very good fill factor.







16 CsI(Tl) crystal coupled to the array and illuminated by a ^{22}Na source

History of Solid State Single Photon Detectors

Pioneering work was done in the nineteen sixties in the **RCA** company (R.J. McIntyre) and in the **Shockley** research laboratory (R.H. Haitz).

The famous paper „Multiplication Noise in Uniform Avalanche Diodes“ by McIntyre appeared 1966 (IEEE Trans. Electron Devices 13 (1966))

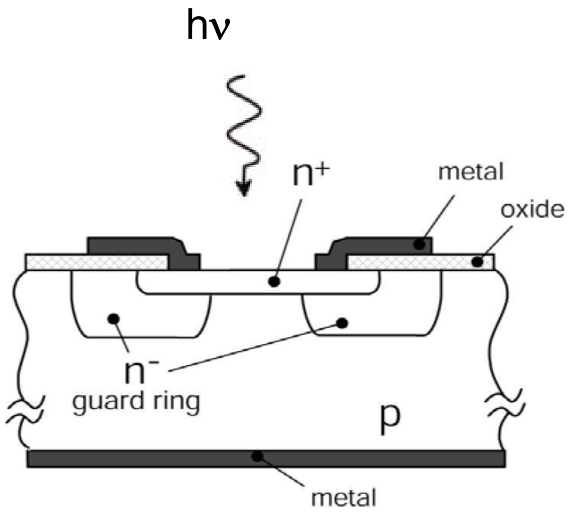
APD‘s in linear- and in Geiger-mode were in the sixties and early seventies a very active field of experimental and theoretical research.

A model of the behaviour of APD‘s operated in Geiger-mode was developed and experimentally verified with test structures.

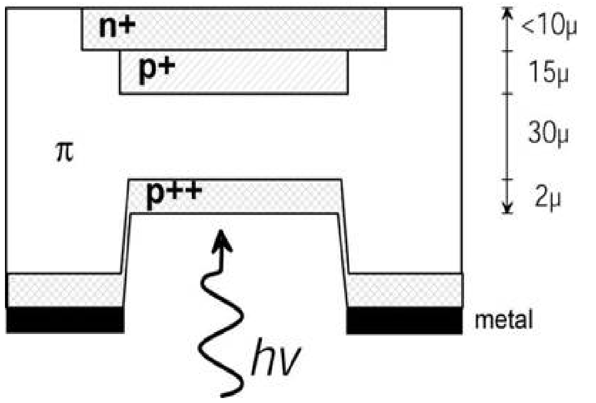
The performance of the first devices was not very good but single photons have been seen and with improving technology the development was leading to the Single Photon Avalanche Diode (SPAD) and to the SLIK™ structure produced by Perkin-Elmer (a device with 1 mm diameter was in the seventies a commercial product of RCA).

History of Solid State Single Photon Detectors

The first 2 silicon single photon detectors were fabricated by Haitz and by McIntyre. Both had to be operated in Geiger-mode with a bias voltage several volts higher than the breakdown voltage.



planar diode (Haitz)



reach-through diode (McIntyre)

History of Solid State Single Photon Detectors

With the early devices the quenching of the breakdown was done passively.

When the current fluctuations happens to go to zero the breakdown stops and needs a new triggering event to start again.

The devices were slow and the maximal count rate was smaller than 100 kHz. This is still true for state of the art devices nowadays.

Only the development of active quenching circuits allows high count rates of > 1 MHz and provides a short deadtime (S. Cova, M. Ghioni, A. Lotito, F. Zappa, Politecnico di Milano).

All these SPAD‘s and the SLIK™ devices are small with a diameter of less than 200 μm.

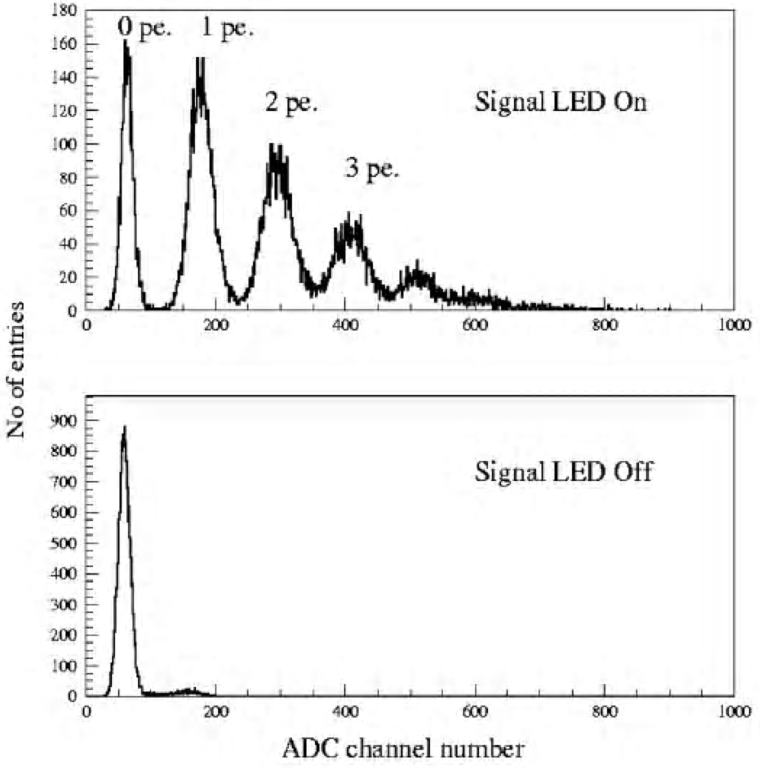
History of Solid State Single Photon Detectors

Stapelbroek et al. developed 1987 the **Solid State PhotoMultiplier** (**SSPM**) in the Rockwell International Science Center. This is an APD with very high donor concentration which creates an impurity band 50 meV below the conducting band.

Later this device was modified to be less sensitive to infrared light and is now called **Visible Light Photon Counter** (**VLPC**).

The small band gap forces an operation at very low temperatures of few degree Kelvin.

The tracker of DØ utilizes scintillating fibers and VLPC's.



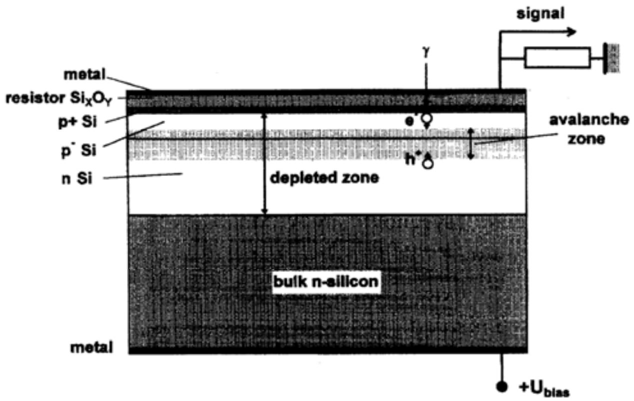
A Bross et al., NIM A 477 (2002) 172

History of Solid State Single Photon Detectors

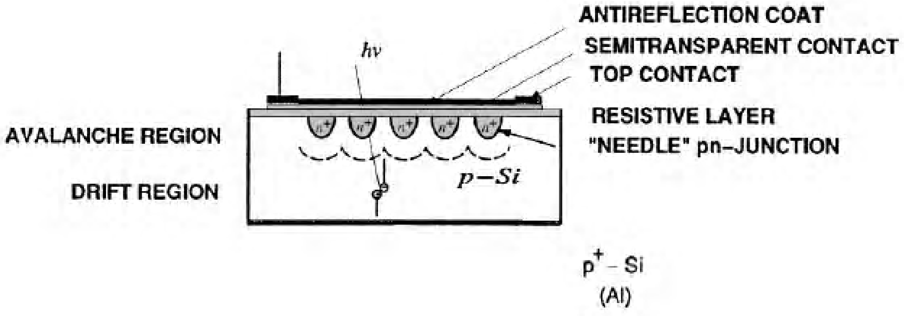
Around 1990 the **MRS** (Metal- Resistor-Semiconductor) APD‘s were invented in Russia.

A very thin metal layer (Ti,~ 0.01 μm) and a layer of SiC or Si_XO_Y with a resistivity of 30 to 80 MΩcm limits the Geiger breakdown by a local reduction of the electric field.

The technolgy is difficult because all parameters need to be controlled very precisely.



Antich et al., NIM A 389 (1997) 491



Saveliev and Golovin, NIM A 442 (2000) 223

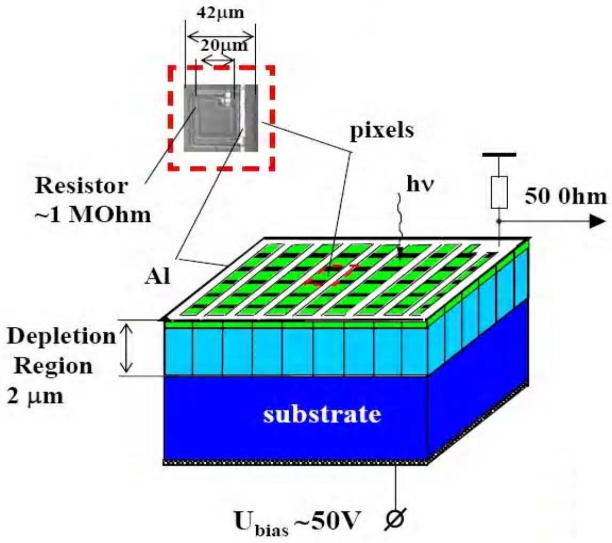
Geiger-mode APD

A normal large area APD could be operated in Geiger mode but it would never recover after a breakdown which was initiated by a photon or a thermally generated free carrier.

Way out:

Subdivide the APD structure into many cells and connect them all in parallel via an individual limiting resistor. The G-APD is born.

The technology is simple. It is a standard MOS (Metal-Oxide-Silicon) process and promises to be cheap. An educated guess is a price of 1 $ per mm^2.



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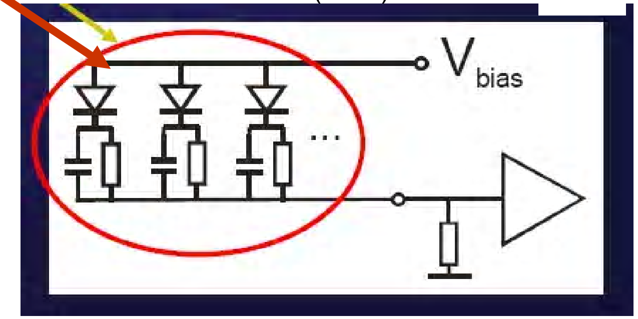
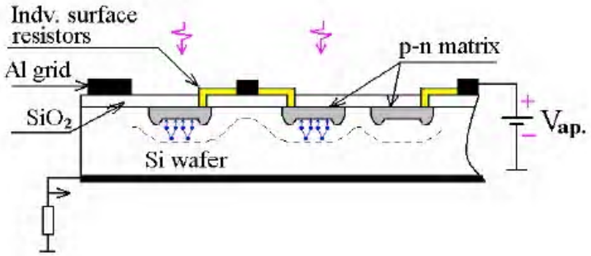


Design

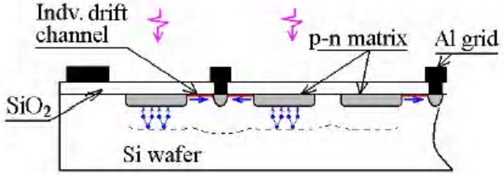
Several designs are possible. Most of the G-APDs are of the type shown on top.

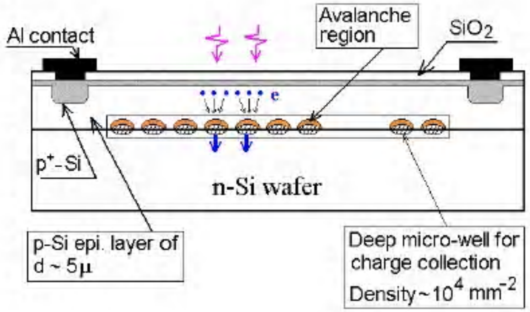
The number of cells in the G-APDs ranges from 100 cells/mm^2 to 10.000 cells/mm^2.

The sketches are taken from Zair Sadygov‘s presentation in Beaune 2005. Zair Sadygov, JINR, Dubna and Victor Golovin, CPTA, Moscow have been the key persons in the development of G-APDs.




The first AMPD sample of vers.1, 10x10 pixel/mm²






0.75mm•0.75mm


2.8mm•2.8mm

High Gain

G-APDs behave like PMTs and some people call them Silicon Photomultiplier, SiPM.

The gain is in the range of 10^5 to 10^7. Single photons produce a signal of several millivolts on a 50 Ohm load. No or at most a simple amplifier is needed.

Pickup noise is no more a concern (no shielding).

There is no nuclear counter effect – even a heavily ionizing particle produces a signal which is not bigger than that of a photon.

Since there are no avalanche fluctuations (as we have in APDs) the excess noise factor is very small, could eventually be one.

Grooms theorem (the resolution of an assembly of a scintillator and a semiconductor photodetector is independent of the area of the detector) is no more valid.

Binary Device

Single photons clearly can be detected with G-APDs.

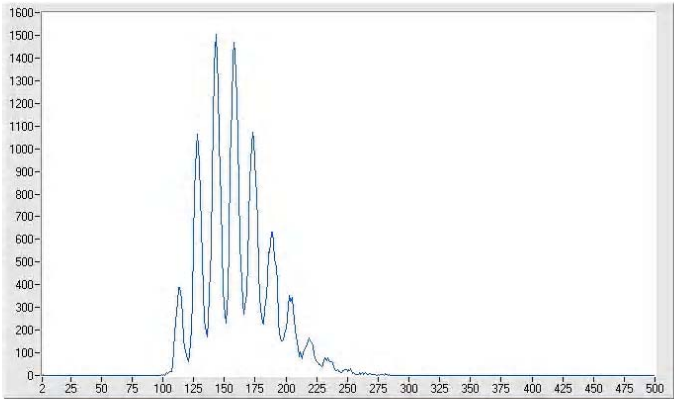
G-APDs produce a standard signal when any of the cells goes to breakdown. The amplitude A_i is proportional to the capacitance of the cell times the overvoltage.

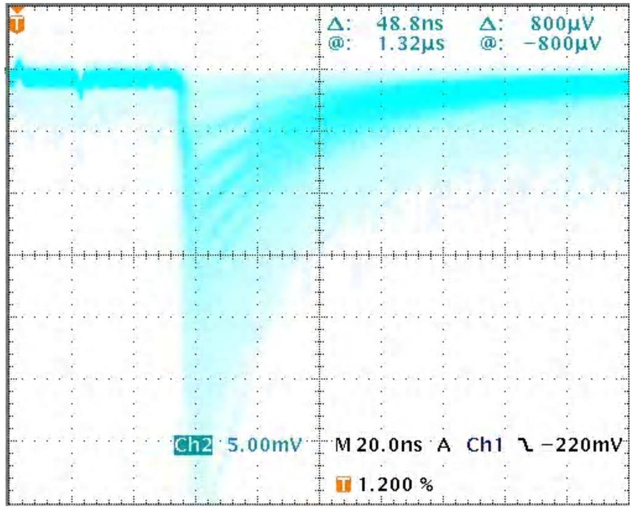
$$A_i \sim C \cdot (V - V_b)$$

When many cells fire at the same time the output is the sum of the standard pulses

$$A = \sum A_i$$

The summing makes the device analog again.



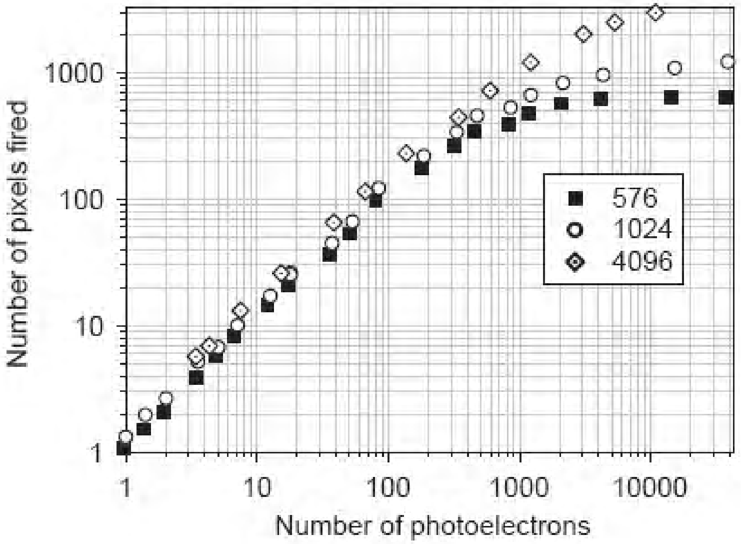


Hamamatsu 1-53-1A-1, cell size 70 x 70 µm

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 photodetection efficiency PDE is significantly smaller than the number of

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



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%.

Dark Counts

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.

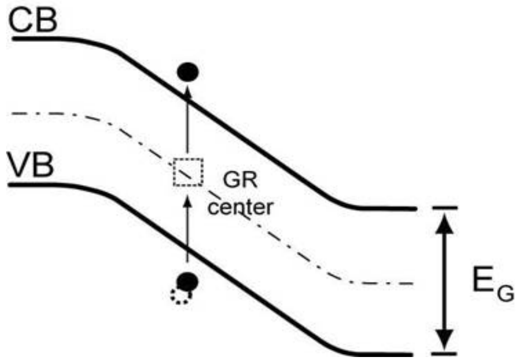
Thermally generated free carriers can be reduced by cooling (factor 2 reduction of the dark counts every 8°C) and by a smaller electric field (lower gain).

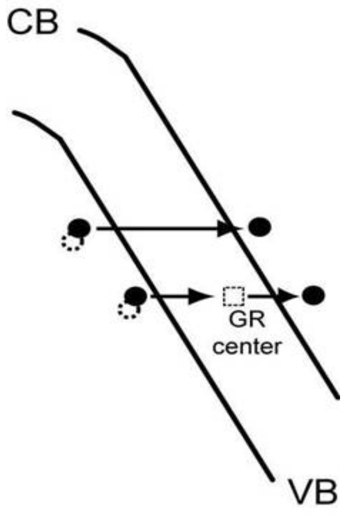
Field-assisted generation (tunneling) can only be reduced by a smaller electric field (lower gain).

→

Reduce the number of generation-recombination centers in the G-APD production process.

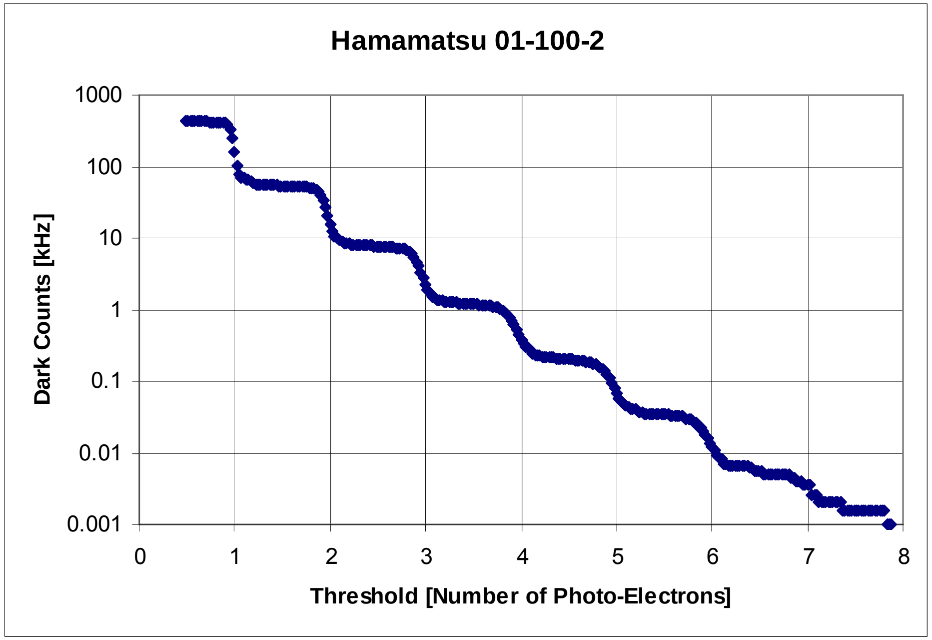
In an environment with high levels of radiation we expect a considerable increase of the dark counts.





Dark Counts

The dark count rate falls rapidly with increasing threshold:



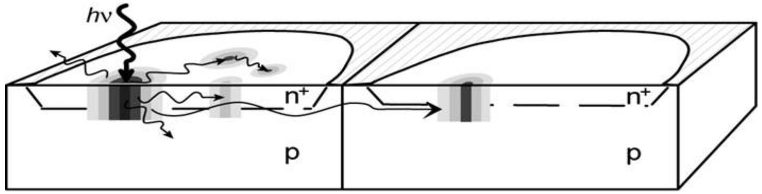
Crosstalk

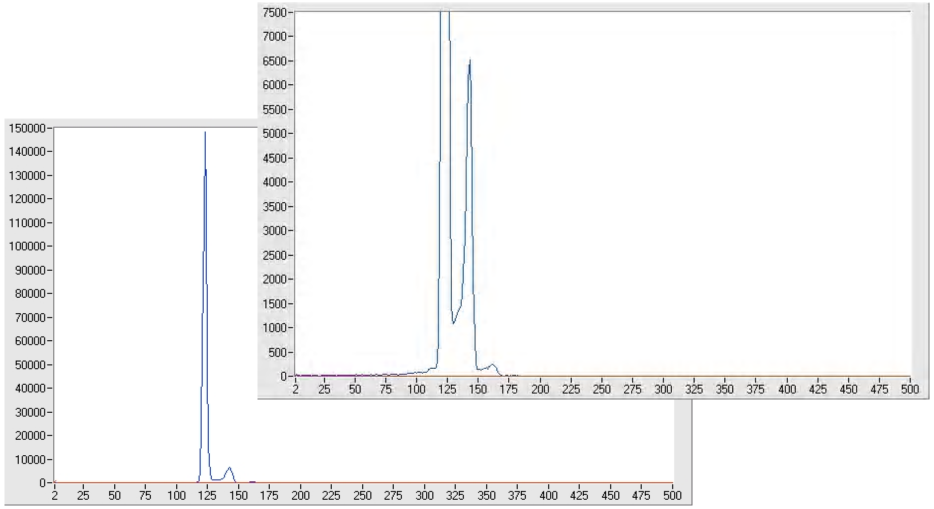
Hot-Carrier Luminescence:

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.

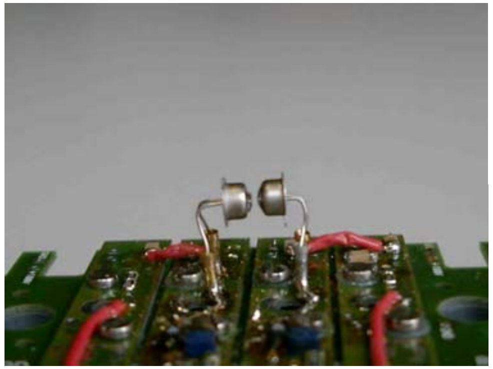
Optical crosstalk acts like avalanche fluctuations in a normal APD. It is a stochastic process. We get the excess noise factor back.





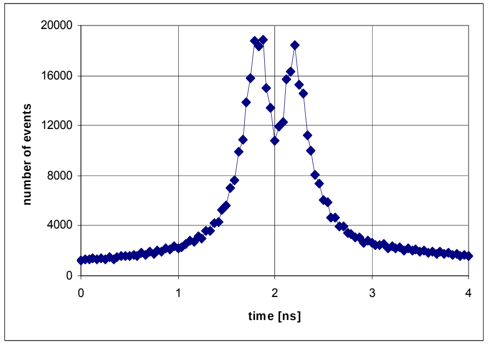
Hamamatsu 1-53-1A-1, cell size 70 x 70 μm

Luminescence and Cross Talk

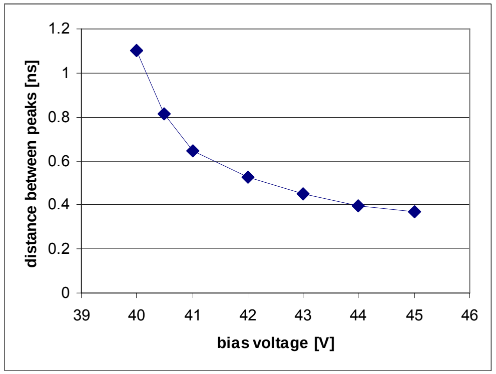


2 G-APDs (from V. Golovin) were mounted face to face.

A dark count from the left G-APD started a TDC, the right stopped it. When the left fired first the time is running left to right in the spectrum, when the right was first, the time runs right to left.



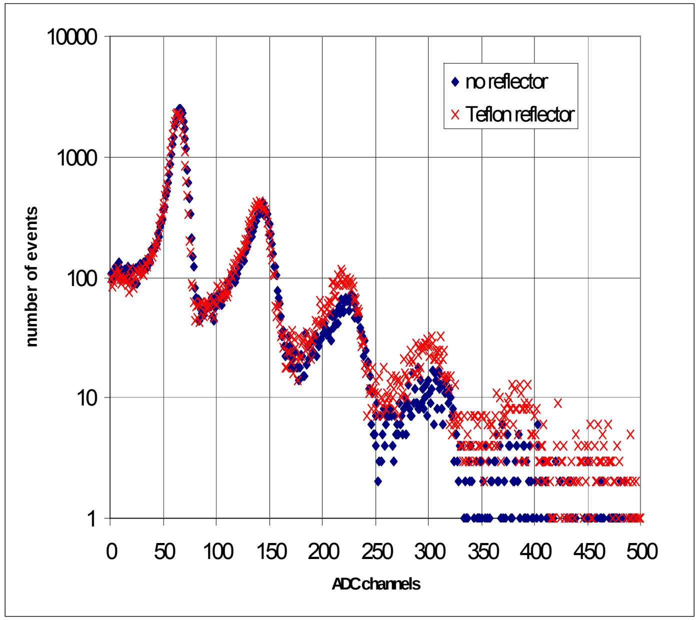
It takes 200 ps and more between the appearance of a signal in one G-APD (formation of a micro-plasma, relaxation of electrons that have been lifted in the plasma to high bands) and an output signal in the other G-APD.



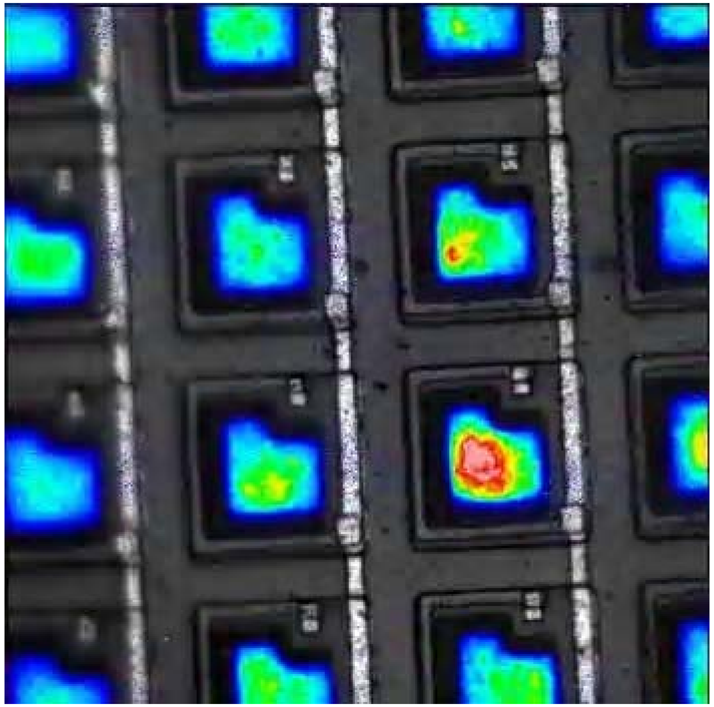
Luminescence and Cross Talk

A diffuse reflector (Teflon) was mounted in front of an G-APD from Golovin in order to simulate the emission into a fiber and reflection of the light at the other end of the fiber.

The peak from dark counts with internal cross talk (2 cells fire) was enhanced by 4% by reflected photons.



Microscopic picture of light emission



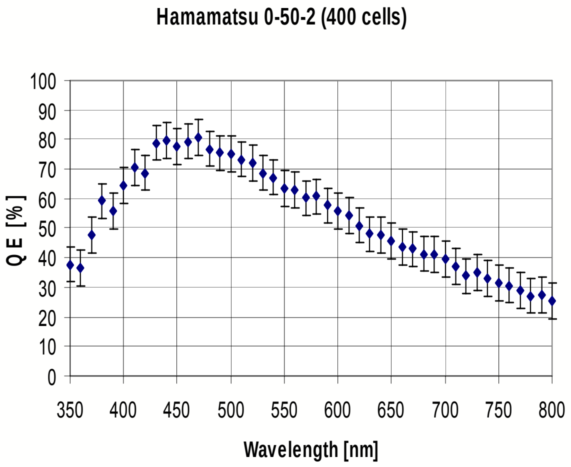
Photon Detection Efficiency

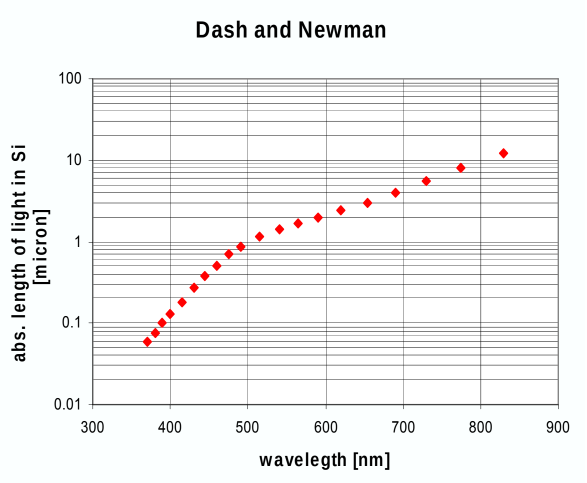
The photon detection efficiency (PDE) is the product of quantum efficiency of the active area (QE), a geometric factor (ε, ratio of sensitiv to total area) and the probability that an incoming photon triggers a breakdown ($P_{trigger}$)

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

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

The QE peaks in a relative narrow range of wavelengths because the sensitive layer of silicon is very thin (in the case shown the p^+ layer is 0.8 μm thick)





Photon Detection Efficiency

The triggering probability depends on the position where the primary electron-hole pair is generated and it depends on the overvoltage. High gain operation is favoured.

Electrons have in silicon a better chance to trigger a breakdown than holes. Therefore a conversion in the p+ layer has the highest probability.

A material other than silicon in which the holes have a higher mobility and higher ionization coefficient like GaAs could have a very high trigger probabilty.

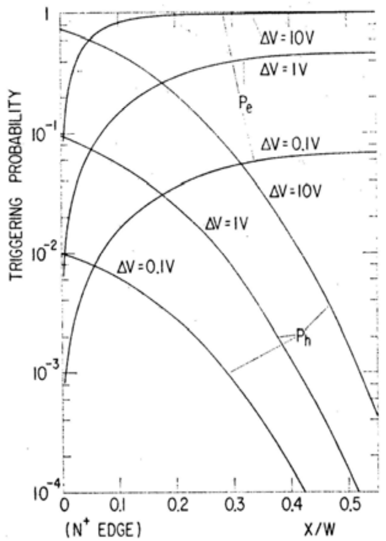


Fig. 4. The triggering probabilities P_e and P_h of an n⁺-p diode at several voltages above breakdown. $P_e(x, \Delta V)$ is the probability that an electron starting at position x will trigger an avalanche in a diode that is biased ΔV V above breakdown. $P_h(x, \Delta V)$ is the similar probability for holes.

W.G. Oldham et al., IEEE TED 19, No 9 (1972)

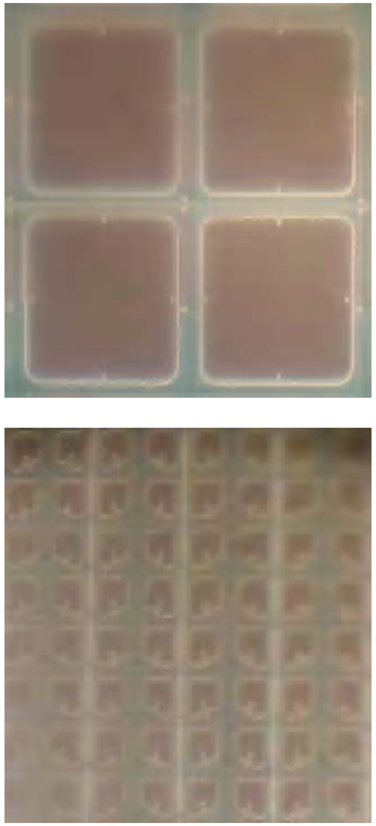
Photon Detection Efficiency

The geometric factor ε needs to be optimized depending on the application.

Since some space is needed between the cells for the individual resistors and is needed to reduce the optical crosstalk the best filling can be achieved with a small number of big cells.

In a camera for air Cherenkov telescopes the best possible PDE is wanted. Since the number of photons is small big cells are suitable and a geometric factor of 60% and more is possible.

LSO crystals for PET produce many photons and several thousands can be collected at the endface of the crystals. In order to avoid saturation the number of cells needs to be big and the cells small. The geometric factor will be in the range of 30 to 40%.

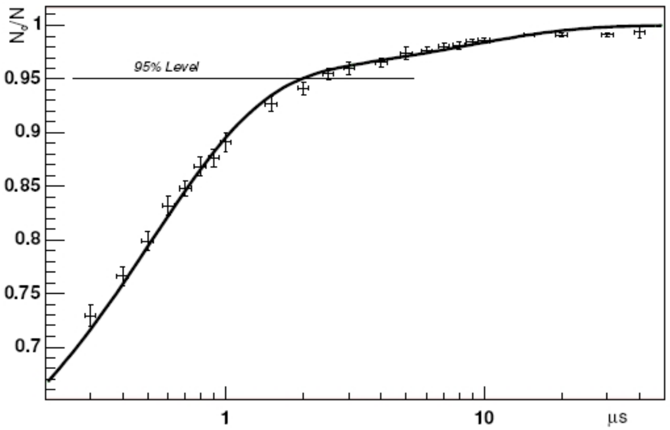


Microscopic view of G-APD‘s produced by Hamamatsu with 100x100 and 25x25 μm^2 cells

Recovery Time

The time needed to recharge a cell after a breakdown has been quenched depends mostly on the cell size (capacity) and the individual resistor (RC).

Afterpulses can prolong the recovery time because the recharging starts anew. Can be reduced by low gain operation.

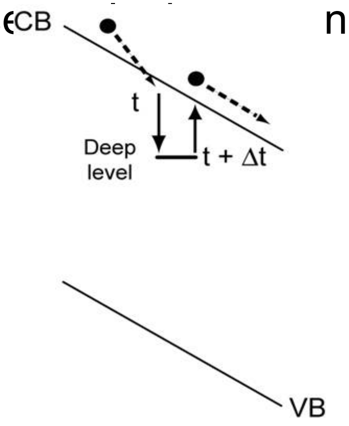


Some G-APDs need microseconds after a breakdown until the amplitude of a second signal reaches 95% of the first signal. Smallest values for G-APDs with small cells and small resistors.

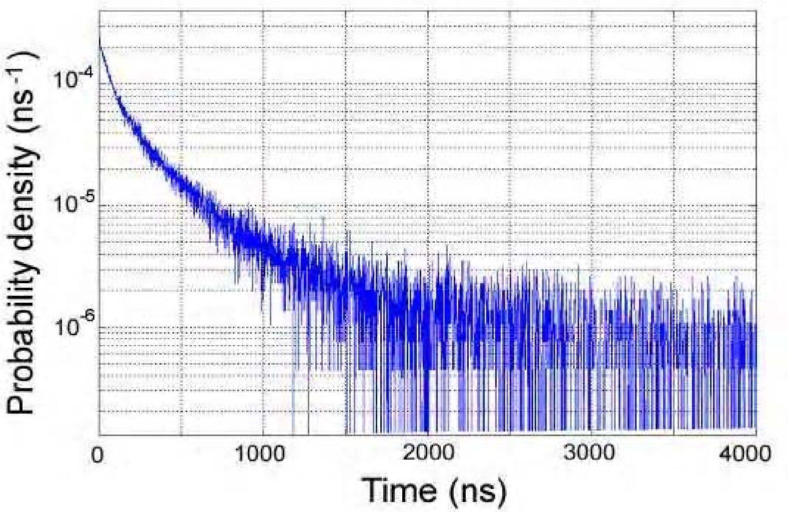
Polysilicon resistors are used up to now which change their value with the temperature. Therefore there is a strong dependence of the recovery time on the temperature. → Go to a metal alloy with high resistivity like FeCr.

G-APDs: Afterpulses

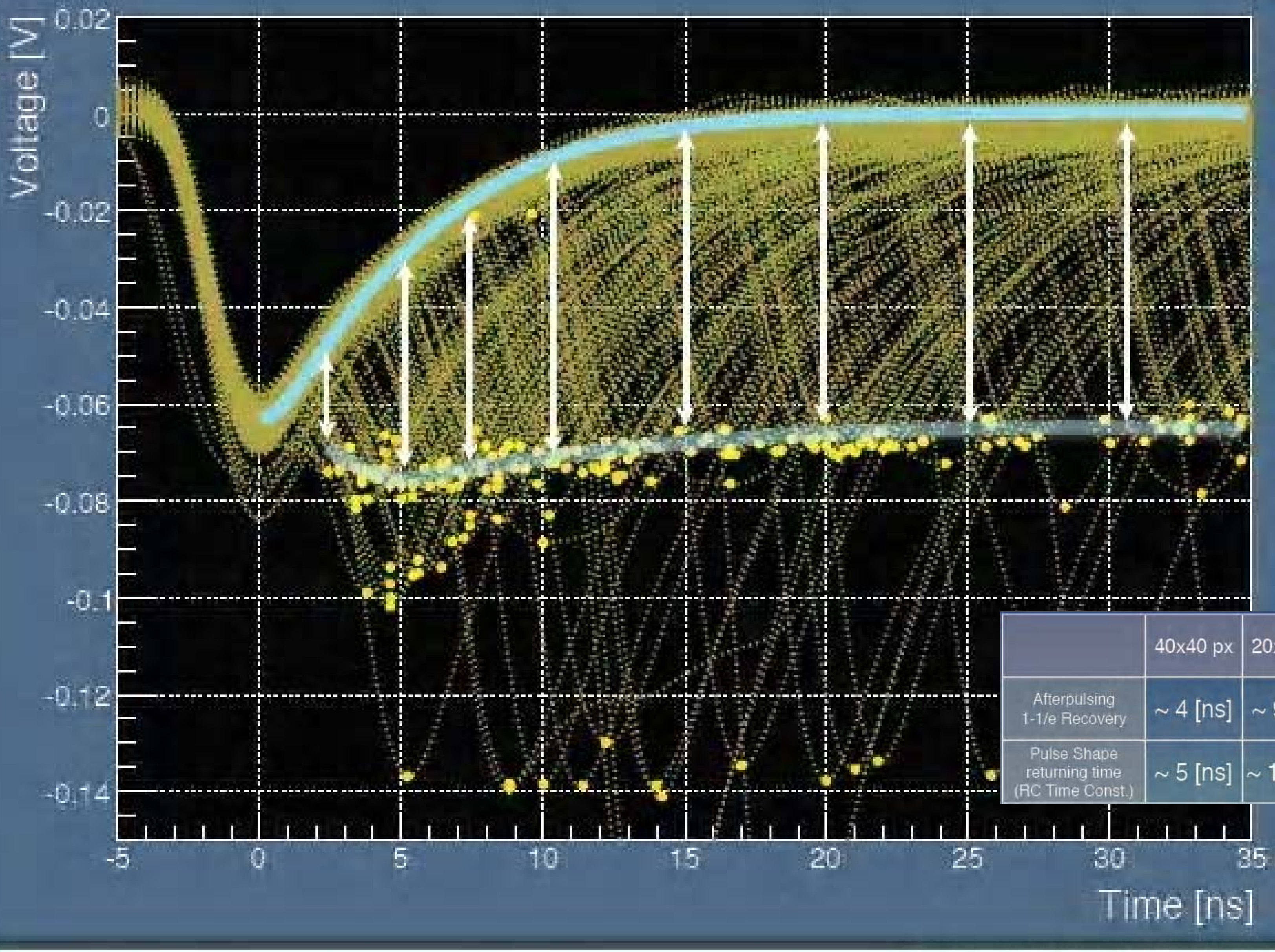
Carrier trapping and delayed release causes afterpulses during a period of se nds.



Afterpulses with short delay contribute little because the cells are not fully recharged but have an effect on the recovery time because the recharging starts anew.



From S. Cova et al., Evolution and Prospect of Single-Photon Avalanche Diodes and Quenching Circuits (NIST Workshop on Single Photon Detectors 2003)



	40x40 px	20x20 px	10x10 px
Afterpulsing 1-1/e Recovery	~ 4 [ns]	~ 9 [ns]	~ 33 [ns]
Pulse Shape returning time (RC Time Const.)	~ 5 [ns]	~ 11 [ns]	~ 35 [ns]

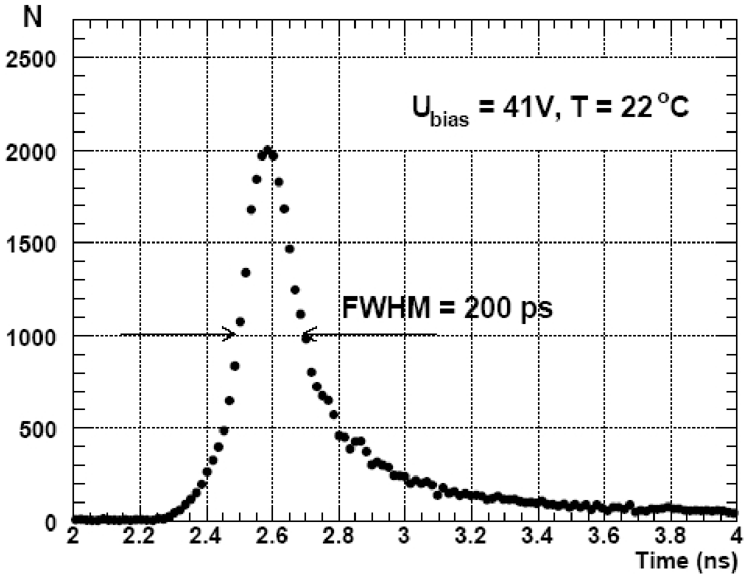
Timing

The active layers of silicon are very thin (1 to 2 μm), the avalanche breakdown process is fast and the signal amplitude is big. We can therefore expect very good timing properties even for single photons.

Fluctuations in the avalanche are mainly due to a lateral spreading by diffusion and by the photons emitted in the avalanche.

A. Lacaita et al., Apl. Phys. Letters 62 (1992) A. Lacaita et al., Apl. Phys. Letters 57 (1990)

High overvoltage (high gain) improves the time resolution.



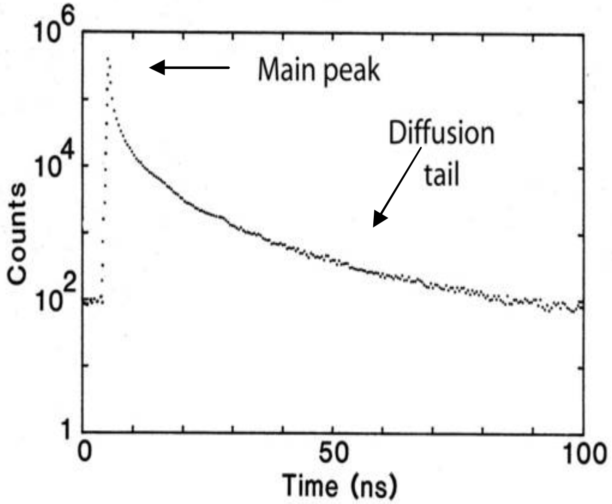
Contribution from the laser is 37 ps FWHM

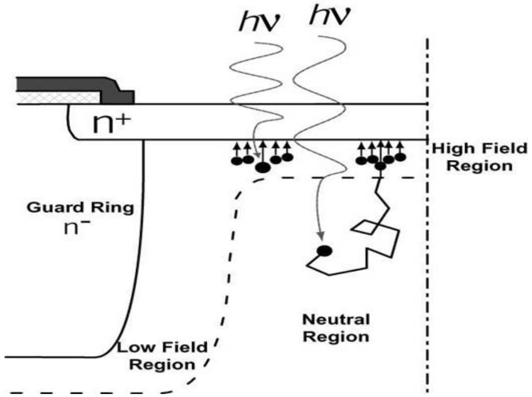
taken from physics/0606037

Timing

Carriers created in field free regions have to travel by diffusion. It can take several tens of nanoseconds until they reach a region with field and trigger a breakdown.

At low gain the lateral spreading of the depleted volume can be incomplete and can enhance the diffusion tail.

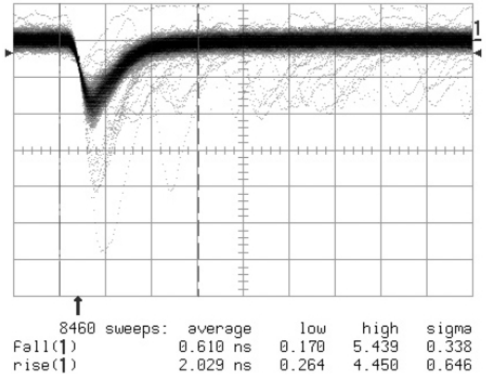




Pictures from S. Cova et al., Evolution and Prospect of Single-Photon Avalanche Diodes and Quenching Circuits (NIST Workshop on Single Photon Detectors 2003)

Signal rise and decay time

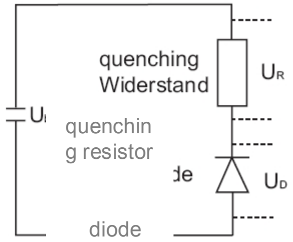
Rise time 0.6 ns



```
      8460 sweeps:  average      low     high    sigma
Fall(1)              0.610 ns   0.170   5.439   0.338
rise(1)              2.029 ns   0.264   4.450   0.646
```

Hor. Scale 2 ns/div, vert. Scale 10 mV/div

Fall time depends on the cell size (capacity) and the serial resistor



$$U_{bias} = U_R + U_D$$

$$U_R(t) = R \cdot i(t)$$

$$Q(t) = C \cdot U_D(t) \Rightarrow i(t) \cdot \frac{\partial U_D(t)}{\partial t}$$

$$U_{bias} - U_D(t) = R \cdot i(t) = R \cdot C \cdot \frac{\partial U_D(t)}{\partial t}$$

Solution of this diffential equation is

$$U_D = \alpha \cdot e^{-\frac{t}{RC}} + U_{bias}$$

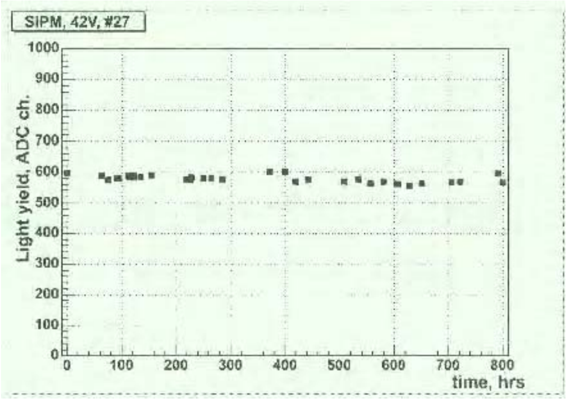
$$U_R(0) = U_{bias} - U_{breakdown}$$

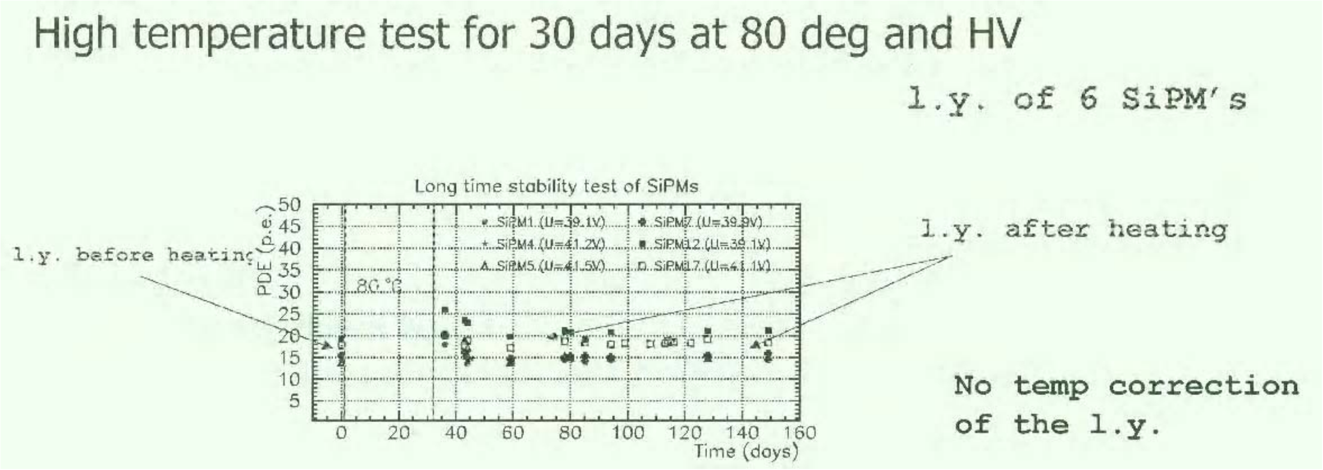
$t = 0$ at signal maximum

$$U_D = (U_{bias} - U_{breakdown}) \cdot e^{\boxed{-\frac{t}{RC}}} + U_{bias}$$

Long Term Stability

The stability of the light yield of G-APDs from V. Golovin was tested by Y. Kudenko and co-workers (INR, Moscow) including an accelerated aging with very promising results.





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 μW/mm^2),
- are insensitive to magnetic fields up to 15 T,
- are compact, rugged and show no aging,
- tolerate accidental illumination,
- cheap because they are produced in a standard MOS process

Choice of Paramaters

Many different designs are possible:

- Semiconductor material – PDE, wavelength
- p-silicon on a n-substrate – highest detection efficiency for blue light
- n-silicon on a p-substrate – highest detection efficiency for green light
- Thickness of the layers – range of wavelength, crosstalk
- Doping concentrations – operating voltage and its range
- Impurities and crystal defects – dark counts, afterpulses
- Area of the cells – gain, geometric factor, dynamic range, recovery time
- Value of the resistors – recovery time, count rate/cell
- Type of resistors – temperature dependence
- Optical cell isolation (groove) – crosstalk

Where to go shopping

There is competition. Currently there are 7 producers:

- Center of Perspective Technology and Apparatus (CPTA), Moscow, Russia
- MePhi/Pulsar Enterprise, Moscow, Russia
- SensL, Blackrock, Ireland
- JINR/Micron Enterprise, Dubna and Zelenograd, Russia
- Zecotek, Vancouver, Canada
- Hamamatsu, Hamamatsu City, Japan
- RMD, Boston, USA

and developments in several institutes:

- Max-Planck Semiconductor Lab, Munich, Germany
- Center for Scientific and Technological Research of Trento, Italy

Summary

Solid state photo sensors are the best choice for the detection of light when there is a magnetic field and/or when space and power consumption are limited.

The PIN photodiodes are the simplest, cheapest and most reliable sensors. They are utilized in many big experiments in high energy physics and operate since many years without any problem.

APD’s are well suited for applications which require high sensitivity and a fast response. Due to their small nuclear counter effect and the internal gain they have a clear advantage over conventional PIN diodes in calorimetry with a low level of light (PbWO4). Geiger-mode APDs will take over in many applications but there are still some fields where APDs are the best choice because of their high dynamic range.

When single photons need to be detected with very short resolving times, a domain where up to now only photomultiplier tubes could be used, the Geiger-mode APD’s promise to perform very well. Their high PDE makes them in some applications even superior to PMT’s. In addition they allow the construction of cost effective detectors because they will be cheap due to the standard CMOS production process and because they need only simple electronic circuits, no shielding, little space and have low power consumption.