Silicon Photomultipliers

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PAUL SCHERRER INSTITUT

Name: SiPM?

- SiPM (Silicon PhotoMultiplier) inherently wrong, it is a photoelectron multiplier
- MPGM APD (Multipixel Geiger-mode Avalanche PhotoDiode)
- AMPD (Avalanche Micro-pixel PhotoDiode)
- SSPM (Solid State PhotoMultiplier) – already in use
- G-APD (Geiger-mode Avalanche PhotoDiode)
- GMPD (Geiger-Mode PhotoDiode)
- DPPD (Digital Pixel PhotoDiode)
- MCPC (MicroCell Photon Counter)
- MAD (Multicell Avalanche Diode)

And a definition: a SiPM is made of many small APD‘s which are connected in parallel. I call the whole device a pixel and the small APD‘s a cell.

Outline

- From PM to SiPM in High Energy Physics
- History of Solid State Single Photon Detectors
- Properties and Problems
- Applications and Choice of Paramaters
- Conclusion

From PM to SiPM

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

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

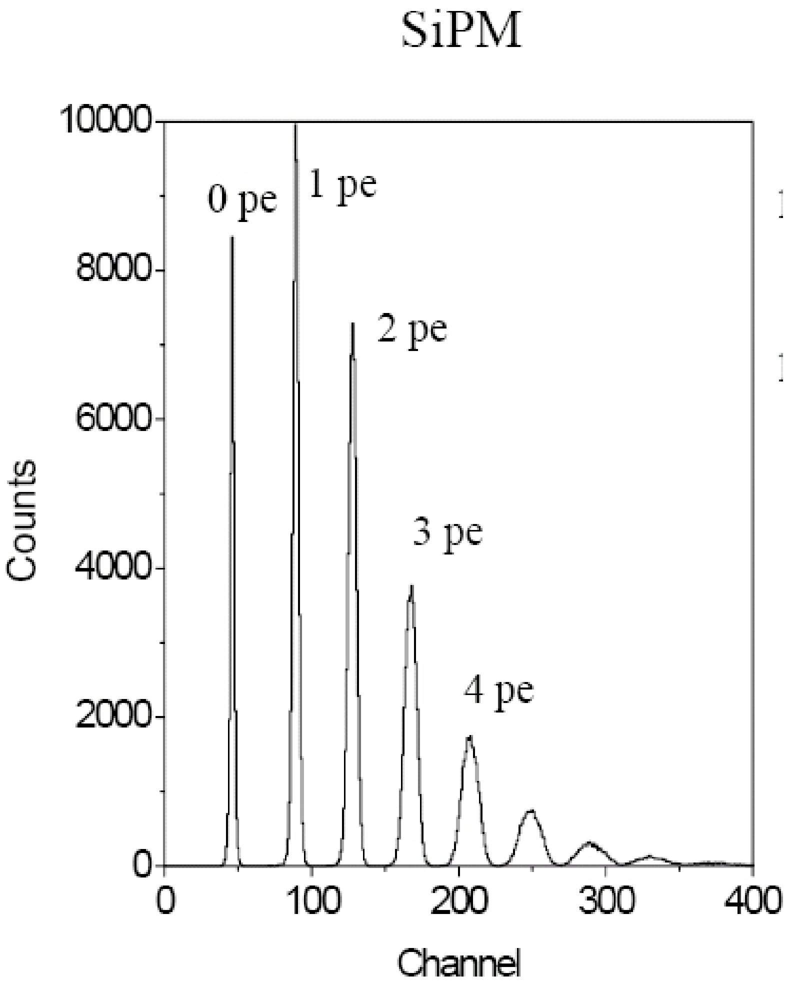
PIN photodiodes are very successful devices and are used in most big experiments in high energy physics (CLEO, L3, BELLE, BABAR, GLAST) but due to the noise of the neccesary amplifier the minimal detectable light pulses need to have several 100 photons.

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.

SiPM‘s can detect single photons. They have been developed and described since the beginning of this millennium (patent of Z. Sadygov 1996). 3 years ago B. Dolgoshein presented their properties and possible applications here in Beaune.

From PM to SiPM

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



Picture taken from B. Dolgoshein‘s presentation in Beaune 2002
(NIM A 504 (2003) 48)

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))

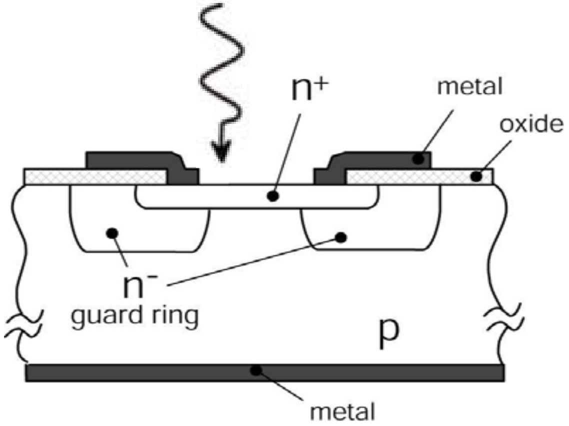
APD‘s in linear- and in Geiger-mode were in the sixties and early seventies a very active field of experimental and theoretical research.

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

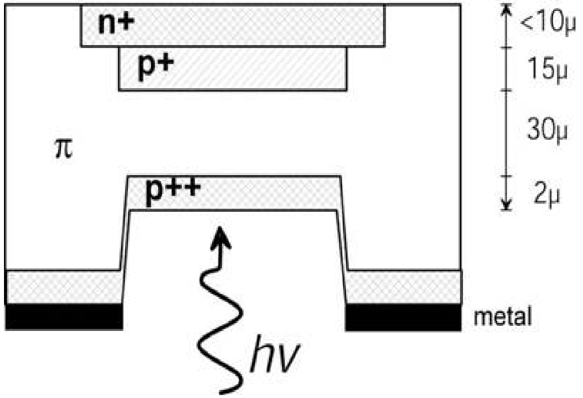
The performance of the first devices was not very good but single photons have been seen and with improving technology the development was leading to the Single Photon Avalanche Diode (SPAD) and to the SLIK™ structure produced by Perkin-Elmer (a device with 1 mm diameter was in seventies a commercial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

History of Solid State Single Photon Detectors

The first 2 silicon single photon detectors 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.



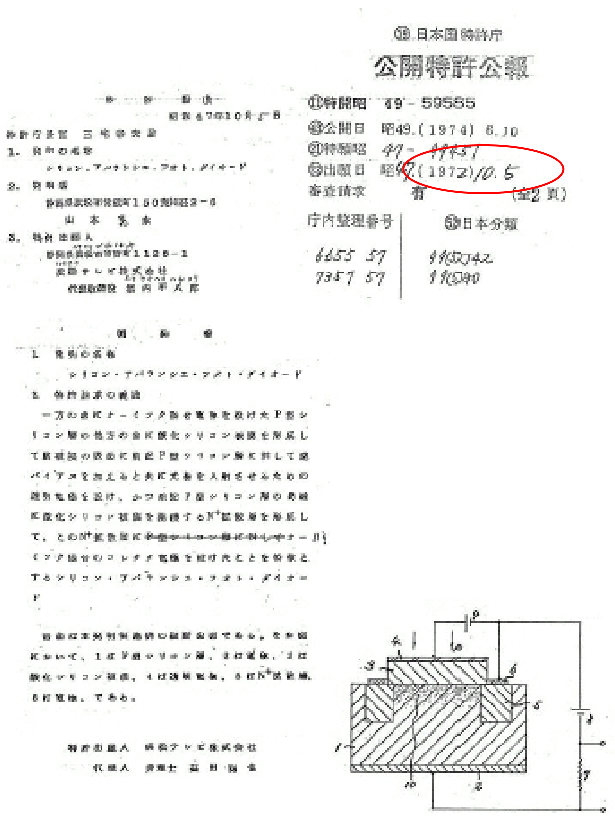
planar diode (Haitz)



reach-through diode (McIntyre)

History of Solid State Single Photon Detectors

A somewhat different design was patented 1972 in Japan (K. Yamamoto, Hamamatsu Photonics).



⑲日本国特許庁

公開特許公報

⑪特開昭 49-59585
㊸公開日 昭49.(1974) 6.10
㉑特願昭 47-[illegible]
㉒出願日 昭47(1972)10.5
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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.

Finocchiaro

History of Solid State Single Photon Detectors

Radiation Monitor Devices Inc. (RMD) developed an array of APD‘s with single photon detection capability for DIRC applications (Detection of Internally Reflected Cherenkov light).

It consists of 6 x 14 individual APD‘s with a size of 150 x 150 μm^2, is operated in Geiger-mode and has an active quenching circuit for each APD.

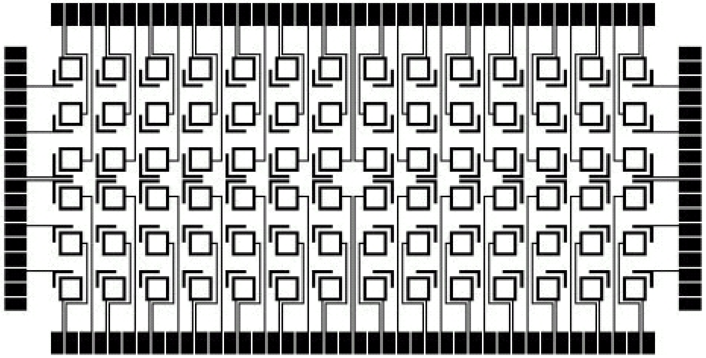


Figure 2: Layout of the interconnection layer for 6 x 14 pixels μAPD array. All pixels in a row will have the anodes connected to the lateral pads (row isolation). The cathodes of each APD are wired to the pads lined on the long sides of the rectangle. The pitch size is 300 μm and the APD active area is 150 μm x 150 μm.

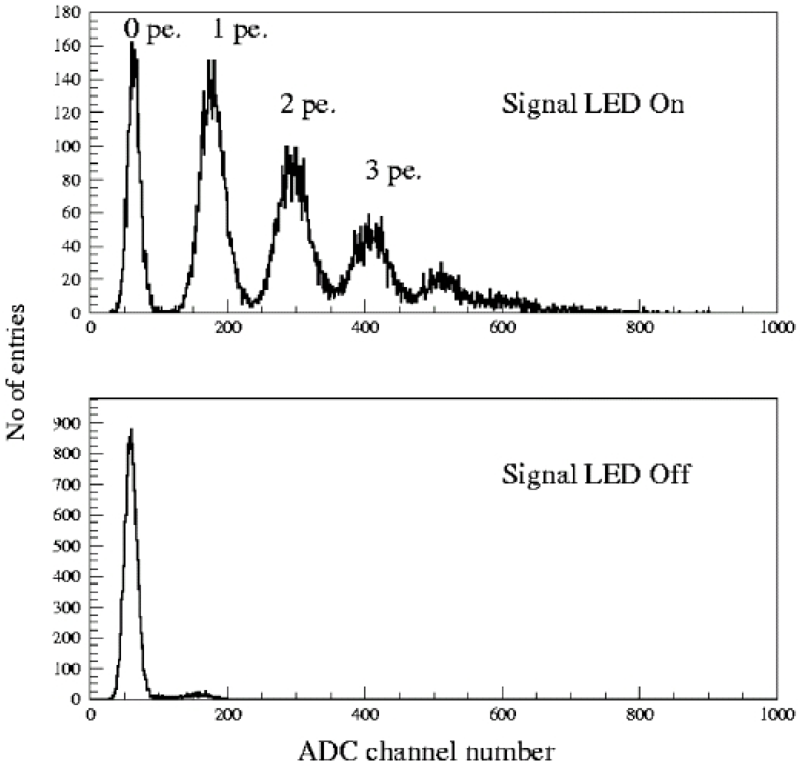
http://www.rmdinc.com/papers/HighGainAvalanchePhotodiodeArraysforDIRCApplications.htm

History of Solid State Single Photon Detectors

In the Rockwell International Science Center Stapelbroek et al. developed 1987 the **Solid State PhotoMultiplier** (**SSPM**). 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.



Atac

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

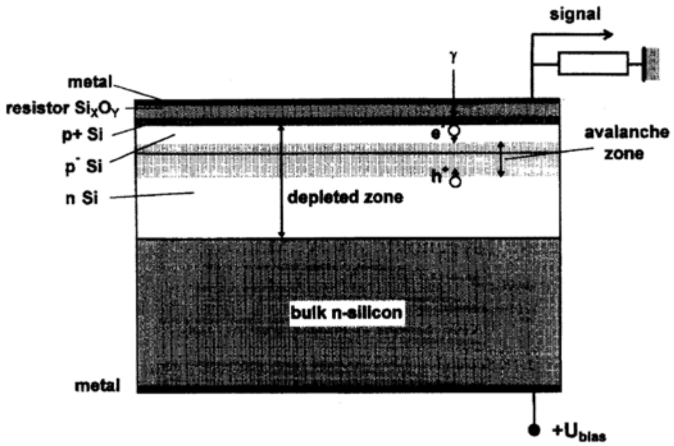
History of Solid State Single Photon Detectors

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

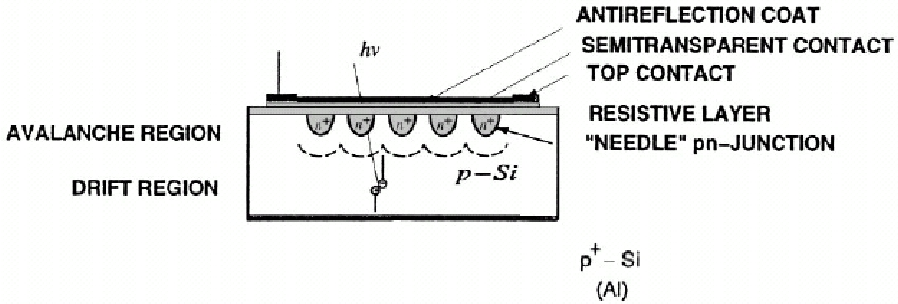
A very thin metal layer (Ti,~ 0.01 µm) and a layer of SiC or Si_XO_Y with a resistivity of 30 to 80 MΩcm limits the Geiger breakdown by a local reduction of the electric field.

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

Two examples out of a great number of different designs are shown. Both have been presented here in Beaune (99, 02)



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



Saveliev and Golovin, Beaune 1999 (NIM A 442 (2000) 223)

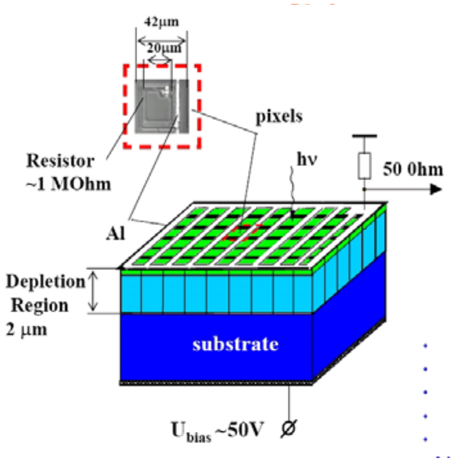
History of Solid State Single Photon Detectors

The next step was logical:

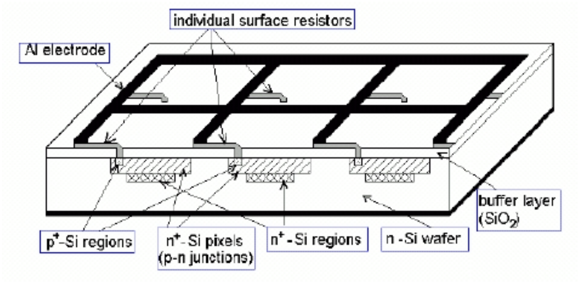
Subdivide the MRS structure into many cells and connect them all in parallel via an individual limiting resistor. The **SiPM** is born.

Key personalities in this development are V. Golovin and Z. Sadygov.

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 some 10 € per cm^2.



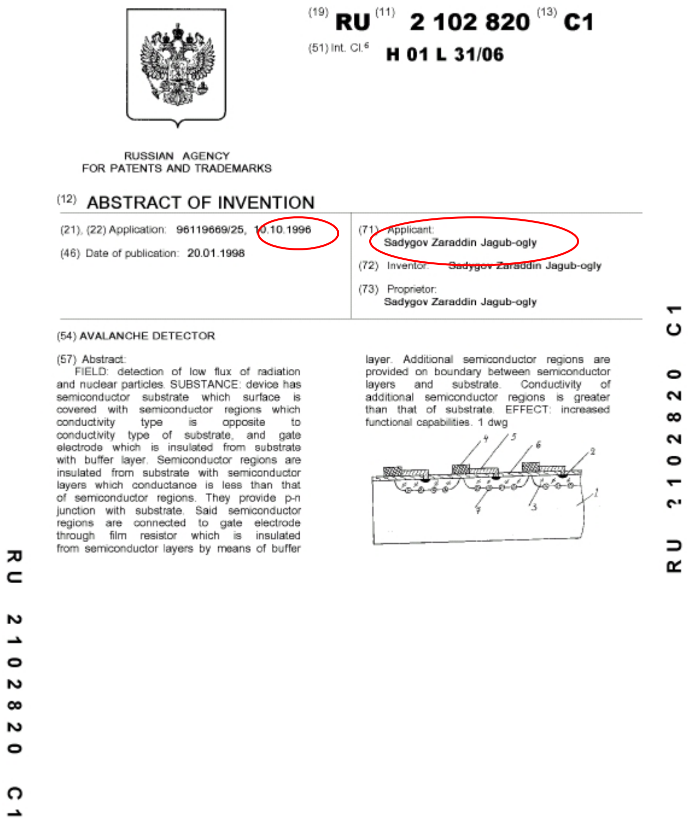
Picture taken from B. Dolgoshein's presentation in Beaune 2002 (NIM A 504 (2003) 48)



Savaliev, Musienko, Popova, Sadygov, Dolgoshein, Swain, Renker

From Sadygov's patent (1998)

History of Solid State Single Photon Detectors



(19) **RU** (11) **2 102 820** (13) **C1**

(51) Int. Cl.⁶ **H 01 L 31/06**

RUSSIAN AGENCY
FOR PATENTS AND TRADEMARKS

(12) ABSTRACT OF INVENTION

(21), (22) Application: 96119669/25, 10.10.1996

(46) Date of publication: 20.01.1998

(71) Applicant:
Sadygov Zaraddin Jagub-ogly

(72) Inventor: **Sadygov Zaraddin Jagub-ogly**

(73) Proprietor:
Sadygov Zaraddin Jagub-ogly

(54) AVALANCHE DETECTOR

(57) Abstract:
FIELD: detection of low flux of radiation and nuclear particles. SUBSTANCE: device has semiconductor substrate which surface is covered with semiconductor regions which conductivity type is opposite to conductivity type of substrate, and gate electrode which is insulated from substrate with buffer layer. Semiconductor regions are insulated from substrate with semiconductor layers which conductance is less than that of semiconductor regions. They provide p-n junction with substrate. Said semiconductor regions are connected to gate electrode through film resistor which is insulated from semiconductor layers by means of buffer layer. Additional semiconductor regions are provided on boundary between semiconductor layers and substrate. Conductivity of additional semiconductor regions is greater than that of substrate. EFFECT: increased functional capabilities. 1 dwg

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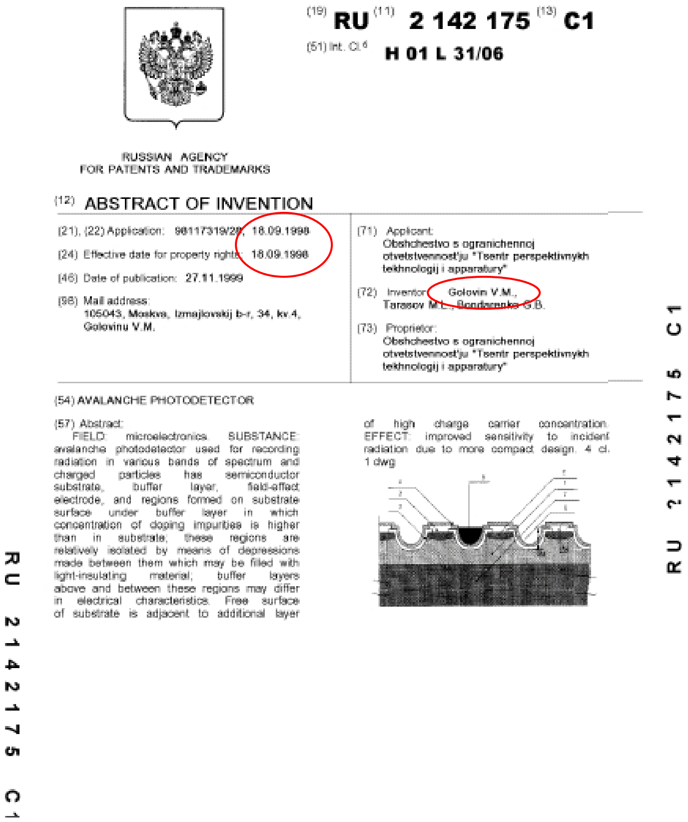

(19) **RU** (11) **2 142 175** (13) **C1**

(51) Int. Cl.⁶ **H 01 L 31/06**

RUSSIAN AGENCY
FOR PATENTS AND TRADEMARKS

(12) ABSTRACT OF INVENTION

(21), (22) Application: 98117319/28, 18.09.1998

(24) Effective date for property rights: 18.09.1998

(46) Date of publication: 27.11.1999

(98) Mail address:
105043, Moskva, Izmajlovskij b-r, 34, kv.4,
Golovinu V.M.

(71) Applicant:
Obshchestvo s ogranichennoj otvetstvennost'ju "Tsentr perspektivnykh tekhnologij i apparatury"

(72) Inventor: Golovin V.M., Tarasov M.L., Bondarenko G.B.

(73) Proprietor:
Obshchestvo s ogranichennoj otvetstvennost'ju "Tsentr perspektivnykh tekhnologij i apparatury"

(54) AVALANCHE PHOTODETECTOR

(57) Abstract:
FIELD: microelectronics. SUBSTANCE: avalanche photodetector used for recording radiation in various bands of spectrum and charged particles has semiconductor substrate, buffer layer, field-effect electrode, and regions formed on substrate surface under buffer layer in which concentration of doping impurities is higher than in substrate; these regions are relatively isolated by means of depressions made between them which may be filled with light-insulating material; buffer layers above and between these regions may differ in electrical characteristics. Free surface of substrate is adjacent to additional layer of high charge carrier concentration. EFFECT: improved sensitivity to incident radiation due to more compact design. 4 cl. 1 dwg

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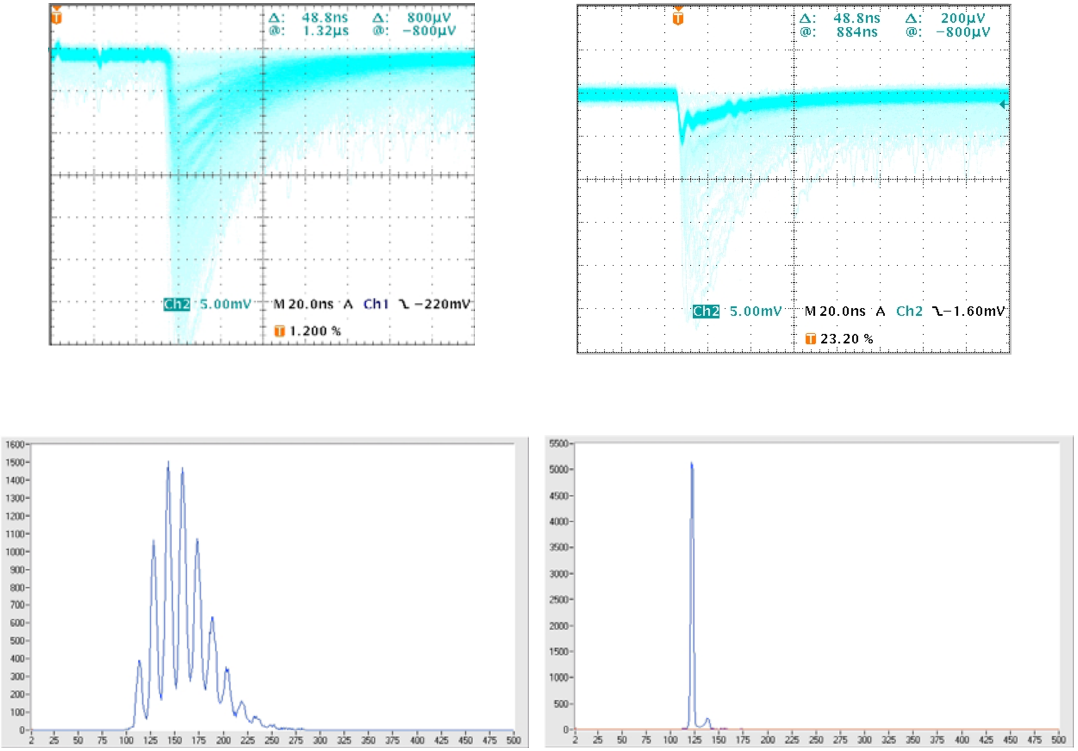
Properties and Problems

SiPM 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

$$A = \sum A_i$$



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

Properties and Problems: High Gain

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 APD‘s) the excess noise factor is very small, could eventually be one.

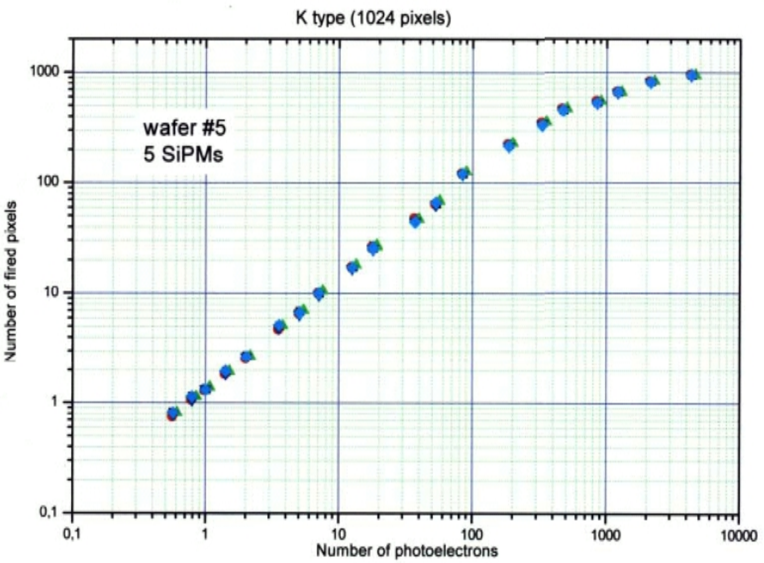
Grooms theorem (the resolution of an assembly of a scintillator and a semiconductor photodetector is independent of the area of the detector) is no more valid.

Properties and Problems: 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 significant 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



from B. Dolgoshein, The SiPM in Particle Physics

Properties and Problems: Dark Counts

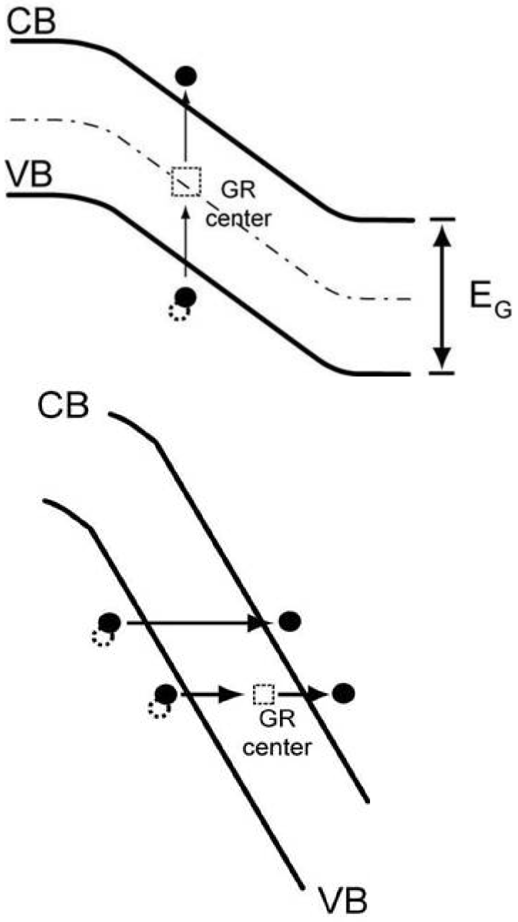
A breakdown can be triggered by an incoming photon or by any generation of free carriers. The latter produces dark counts with a rate of 100 kHz to several MHz per mm^2 at 25°C and with a treshold at half of the one photon amplitude.

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 SiPM production process.

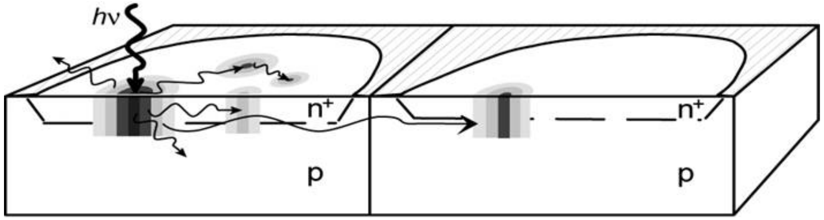
Open question: Radiation hardness



Properties and Problems: 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)*

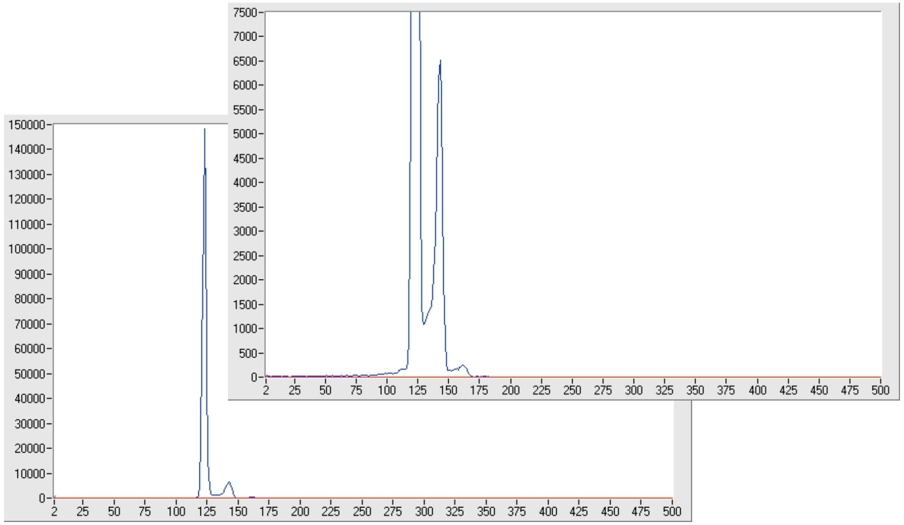


When these photons travel to a neighbouring cell they can trigger a breakdown there.

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

➞ Optical isolation between pixels

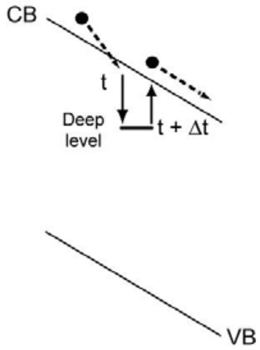
Operate at relative low gain

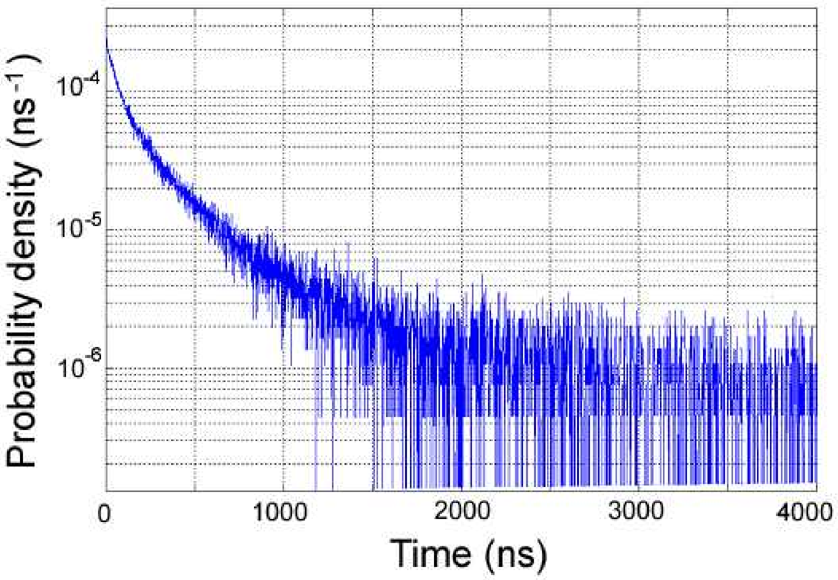


Type: Hamamatsu 1-53-1A-1, cell size 70 x 70 μm

Properties and Problems: Afterpulsing

Carrier trapping and delayed release causes afterpulses during a period of several microseconds.





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

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

Low temperatures elongate the release (factor of 3 for 25°C).

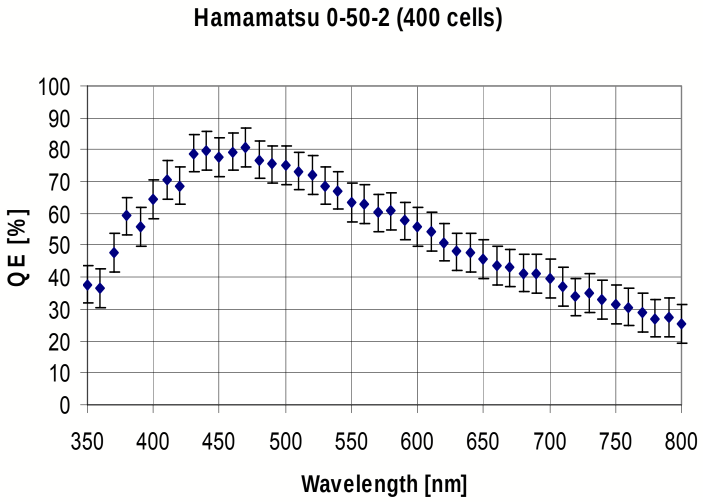
Properties and Problems: Photon Detection Efficiency

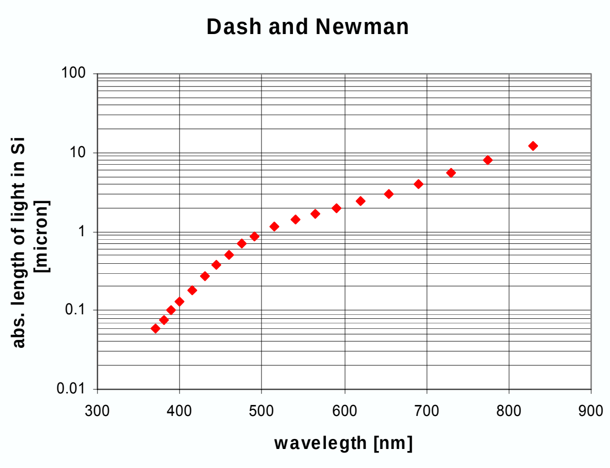
The photon detection efficiency (PDE) is the product of quantum efficiency of the active area (QE), a geometric factor (ε, ratio of sensitiv to total area) and the probability that an incoming photon triggers a breakdown ($P_{trigger}$)

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

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)





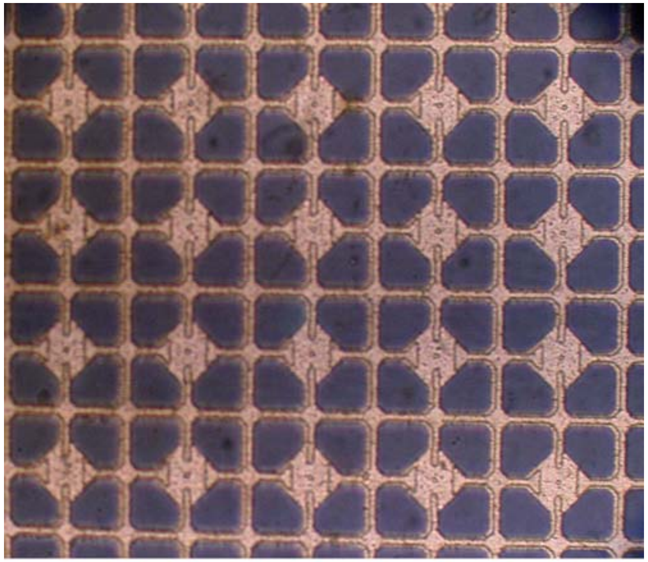
Properties and Problems: Photon Detection Efficiency

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 50% and more is possible.

LSO crystals for PET produce many photons and 1000 or more can be collected at the endface of the crystals. In order to avoid a saturation effect the number of cells needs to be big and the cells small. The geometric factor will be in the range of 20 to 30%.



Microscopic view of a SiPM produced by Z. Sadygov

Properties and Problems: 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.

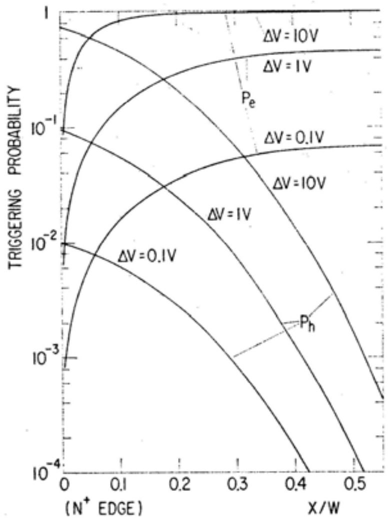


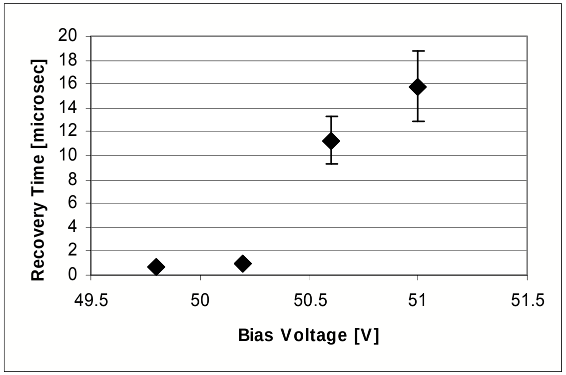
Fig. 4. The triggering probabilities P_e and P_h of an n+-p diode at several voltages above breakdown. $P_e(x, \Delta V)$ is the probability that an electron starting at position x will trigger an avalanche in a diode that is biased ΔV V above breakdown. $P_h(x, \Delta V)$ is the similar probability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

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

Properties and Problems: 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 SiPM need hundreds of microseconds after a breakdown until the amplitude of a second signal reaches 95% of the first signal. Smallest values for SiPM‘s with small cells and small resistors.

Since 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.

Britvitch

Properties and Problems: Timing

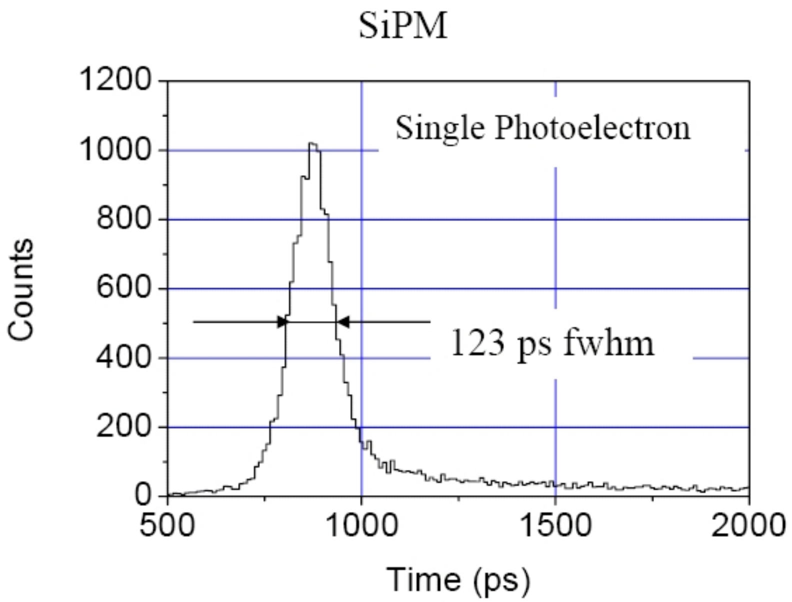
The active layers of silicon are very thin (2 to 4 μm), the avalanche breakdown process is fast and the signal amplitude is big. We can therefore expect very good timing properties even for single photons.

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.

Merck



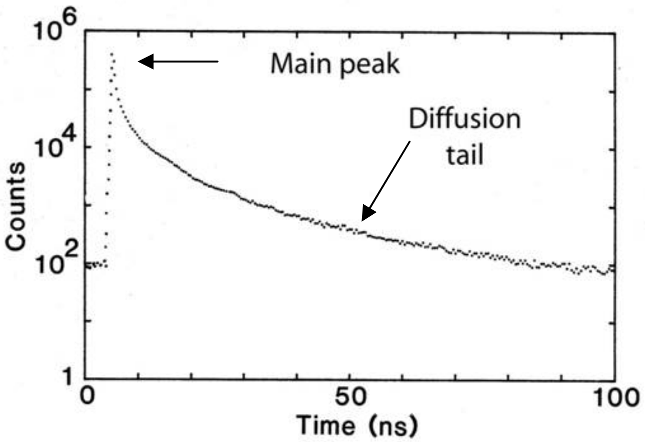
Contribution from the laser and the electronics is 40 ps each. → time resolution 100 ps FWHM

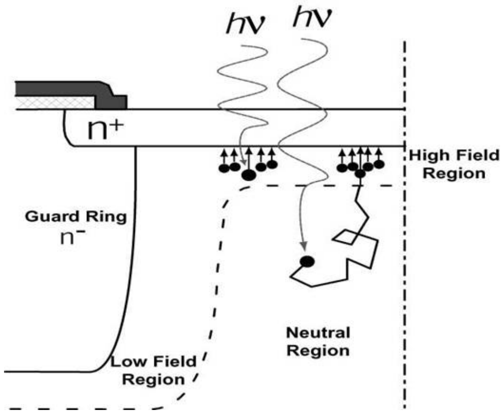
taken from B. Dolgoshein‘s presentation
in Beaune 2002 (NIM A 504 (2003) 48)

Properties and Problems: 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 uncomplete 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)

Properties and Problems

There are more features which are not mentioned yet:

- SiPM‘s 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 and rugged,
- have a very small nuclear counter effect (sensitivity to charged particles),
- have relative small temperature dependence,
- and tolerate accidental illumination

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

Choice of Paramaters

In my opinion the future development should go in few seperate directions:

Many applications need the highest possible photon detection efficiency but don‘t need high dynamic range (RICH, DIRC, IACT, EUSO, photon correlation studies, fluorescence spectroscopy, single electron LIDAR, neutrino detectors).

⟶ best is a SiPM with p- on n-silicon structure, large cells (50 to 100 μm^2), small value of the resistor and optical isolation between the cells

Other applications need large dynamic range (HEP calorimeters, PET, SPECT, scintillator readout, Smart PMT, radiation monitors).

⟶ here the best is p- on n-silicon structure again, small cells (5 to 30 μm^2), thicker p- layer, no optical isolation needed

Some applications like a tile calorimeter are better off with a n- on p-silicon structure.

Akindinov, Borrel

Conclusions

Multi-cell APD‘s operated in Geiger-mode are now an alternative to PM‘s.

They are the better choice for the detection of light with very low intensity when there is a magnetic field and when space and power consumption are limited.

Most of the devices are still small (1x1 mm^2) but areas of 3x3 mm^2 are available and a SiPM with 10x10 mm^2 is planed. Also planed is a monolithic array of 4 diodes with 1.8x1.8 mm^2 each.

The development started some 10 years ago but still there is a broad room for improvements. Many parameters can be adjusted to optimise the devices.

We need a good name and I would like to have a democratic vote. This conference is a good place for it.

Name: SiPM?

- SiPM (Silicon PhotoMultiplier) inherently wrong, it is a photoelectron multiplier
- MPGM APD (Multipixel Geiger-mode Avalanche PhotoDiode)
- AMPD (Avalanche Micro-pixel PhotoDiode)
- SSPM (Solid State PhotoMultiplier) – already in use
- G-APD (Geiger-mode Avalanche PhotoDiode)
- GMPD (Geiger-Mode PhotoDiode)
- DPPD (Digital Pixel PhotoDiode)
- MCPC (MicroCell Photon Counter)
- MAD (Multicell Avalanche Diode)