Problems in the appearance of silicon photomultipliers: a brief history and perspectives

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Outline

- Main problems of traditional avalanche photodiodes (APDs).
- Two different approaches in development of APDs: improvement of technology and search for new designs (structures).
- A long way from traditional APDs to micropixel avalanche photodiodes (MAPDs or SiPMs) via the avalanche MIS and MRS structures.
- Four advanced designs of micropixel avalanche detectors.
- A few questions about the physics of operation of avalanche photodetectors.
- Comparison of the traditional SPAD and MAPD/SiPMs devices

Main problems of avalanche photodiodes (APDs)

There were two main problems that prevented creation of large-area APDs with high gain. These problems are:

1. Very sharp dependence of the multiplication factor G (gain) on applied voltage $U_{d.}$.

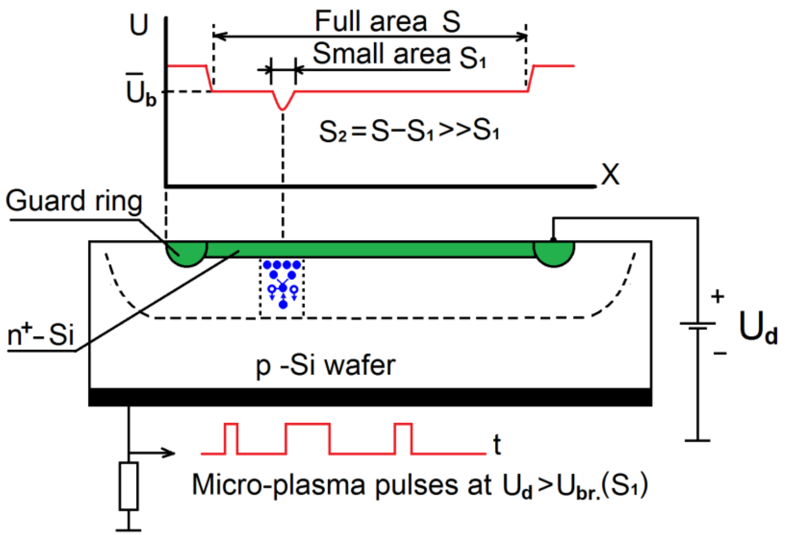
$$G = \frac{1}{1 - \left(\frac{U_d}{U_{br.}}\right)^k} \approx \frac{1}{k} \times \frac{U_b}{U_d - U_{br.}}$$

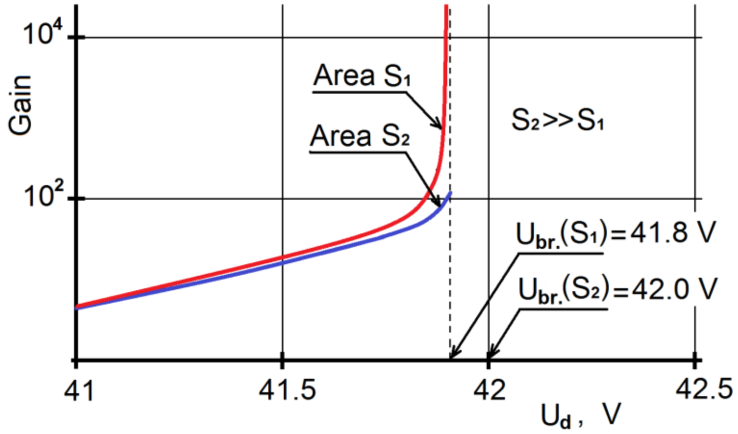
2. Random variation of the breakdown voltage along the surface of semiconductors resulting in a non-controlled local avalanche process known as micro-plasma breakdown phenomenon.

Therefore, the maximum dispersion of the breakdown voltage ($\Delta U_{br.}$) limited the value of applied voltage (U_d) and, consequently, the maximum gain G:

$$G \approx \frac{1}{k} \times \frac{U_b}{U_d - U_{br.}} < \frac{U_b}{\max\left(\Delta U_{br.}\right)}$$

Micro-plasma breakdown phenomena





$$G_{max.} < \frac{U_b}{max.\,(\Delta U_{br.})} \approx 100$$

Micro-plasma phenomena is a non-controlled local avalanche process occurring within nonuniformity of p-n junctions, where the applied voltage (***U**_d*) exceeds the breakdown voltage (***U**_br.*). In this case, some rectangular pulses with the same amplitude but random duration are observed. This phenomena has been investigated in detail by R. McIntyre and R. Haitz [1, 2].

Conclusion. New developments were needed.

Reference:

1. R. McIntyre, Theory of microplasma instability in silicon. J. Appl. Phys. **32** (1961) 983.
2. R. Haitz, Model for the electrical behavior of a microplasma, J. Appl. Phys. **35** (1964) 1370.

Two different approaches to developments

There were two main approaches to development of new APDs:

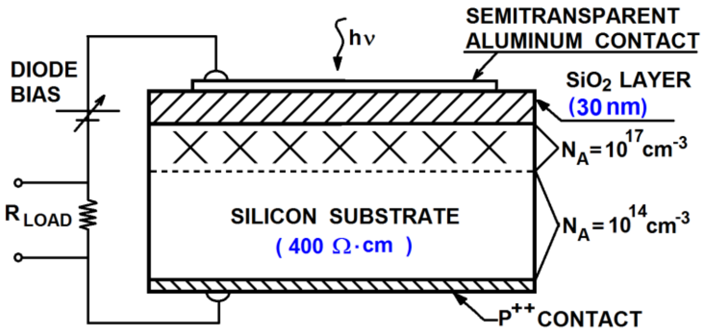
1. Improve the existing APD technology and design. Well-known Companies in the world developed new generations of APDs with high gain (~ 1000) and low excess noise factor (~ 2) for different applications. However, these new APDs could not have a single photoelectron resolution.

2. Study of avalanche process behavior in various multi-layer semiconductor structures to find new ways to reduce the impact of semiconductor nonuniformities on avalanche process quality.

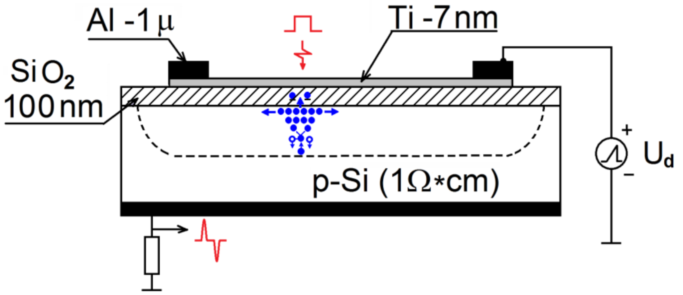
The second approach was chosen by our APD-team (A. Gasanov, V. Golovin,
Z. Sadygov, M. Tarasov and N. Yusipov) in 1983.

At that time, the idea of local suppression of avalanche process in MOS (metal-oxide-silicon) structures was widely discussed at the American Institute of Physics (N. Foss and S.Ward) and at the Lebedev Institute of Physics (V. Shubin and A. Kravchenko). This was very promising idea.

Plane Metal-Oxide-Semiconductor avalanche photodiodes (MOS APDs)



Continuous-mode MOS APD [1].
Gain – up to 20



Pulsed-mode MOS APD [2].
Gain – up to 1000

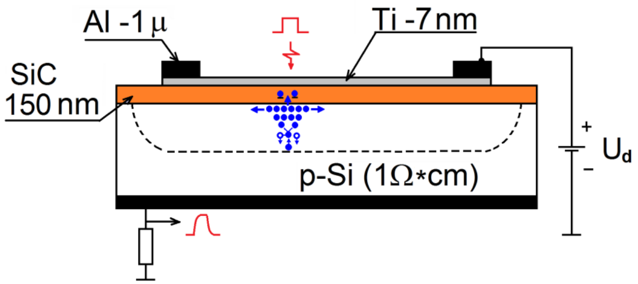
The avalanche multiplication factor in the regions of micro nonuniformities of devices is stabilized due to the accumulation of charge carriers at the silicon-silicon oxide interface. However, both devices had a fundamental drawback: injection and capture of hot charge carriers into the volume of the oxide and as a result, the device could work only a few hours.

Conclusion. It was necessary to replace the dielectric layer with some resistive layer that did not capture hot charge carriers. Our studies showed that silicon carbide is the most suitable material for this purpose.

Reference:

1. N. Foss, S. Ward - J. Appl. Phys., Vol.44, No.2 (1973) 728.
2. A. Plotnikov, V. Shubin, A. Kravchenko, N. Golbraich - Microelectronics, vol.8 (1979) 49.

A plane **M**etal-**R**esistive layer-**S**emiconductor avalanche photodiode (MRS APD)



This design was free of the charge capture phenomenon and demonstrated high signal gain (up to 1000). However, it had new problems [1].

Problems:

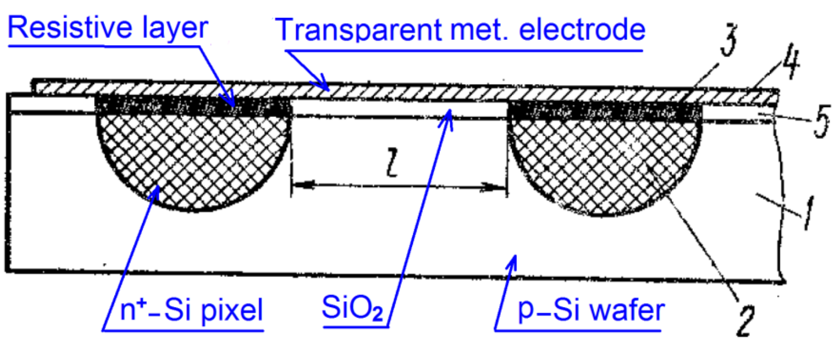
1. Low yield because of short-circuit effect through SiC layer of 0.15 μ.
2. High dark current because of low quality of the Si-SiC heterostructure, due to deposition of amorphous SiC material on crystalline Si wafer.
3. Limited gain (up to 1000) because of charge carriers spreading along the Si-SiC boundary suppressing avalanche process in the neighboring regions.

Conclusion. It was necessary to prevent the spreading of charge carriers along the device surface.

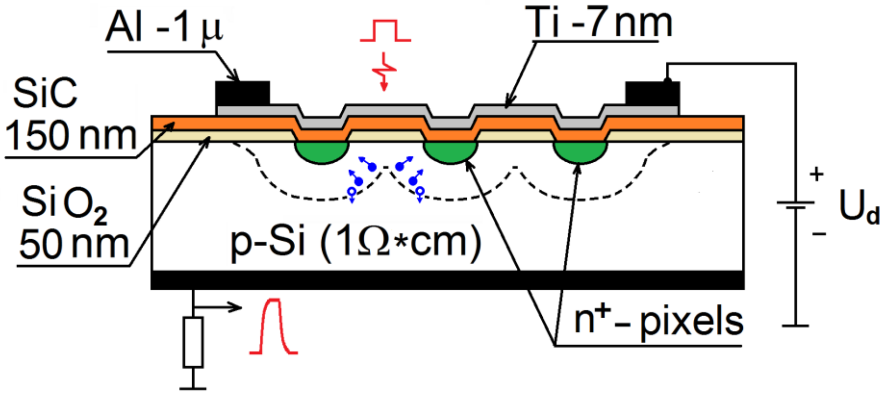
Reference:

1. A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov – Technical Physics Letters (in Russian), v.14, No.8, p.706, (1988).

Design of the first micropixel MRS APD



First design of the micropixel MRS APD [1, 2].



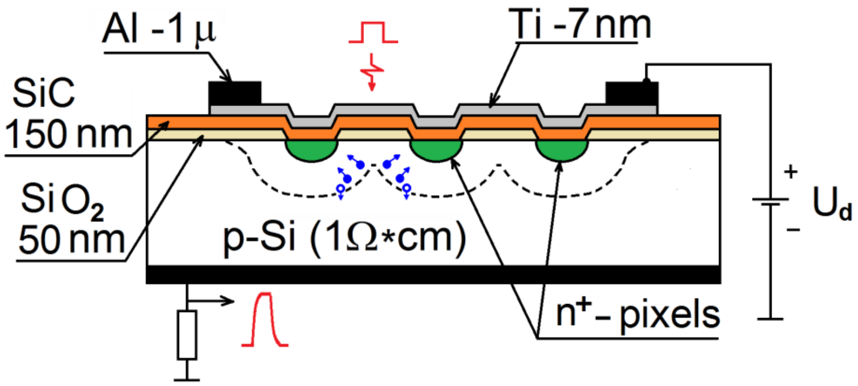
Working samples of the micropixel MRS APD

This device contains a semiconductor substrate on which is formed an array of independent p-n junctions (pixels). Each pixel is connected to the common semitransparent metal layer via a vertical micro-resistor. The p-n junction (pixel) creates around itself a potential barrier of about 0.7 V. This prevents transfer of charge carriers from one pixel to another. Therefore all pixels in this design may operate independently.

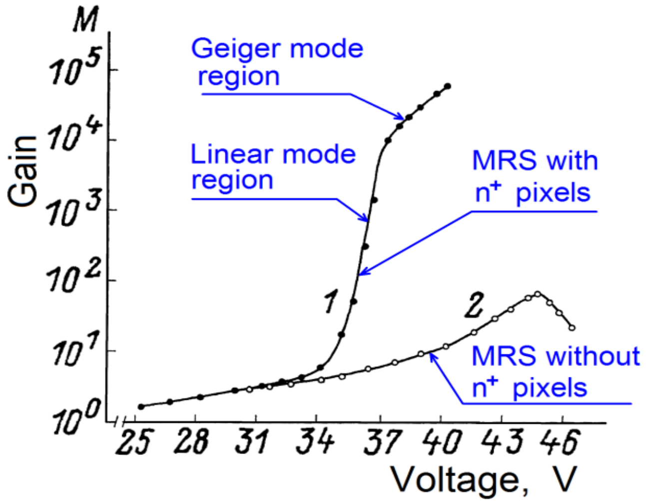
Reference:

1. V. Golovin, Z. Sadygov, M. Tarasov and N. Yusipov. Russian patent #1644708. Priority date: 03.02.1989.
2. A. Gasanov, V. Golovin, Z. Sadygov and N. Yusipov. Russian patent #1702831. Priority date: 11.09.1989.

First sample of the micropixel MRS APD



Working samples of the micropixel MRS APD



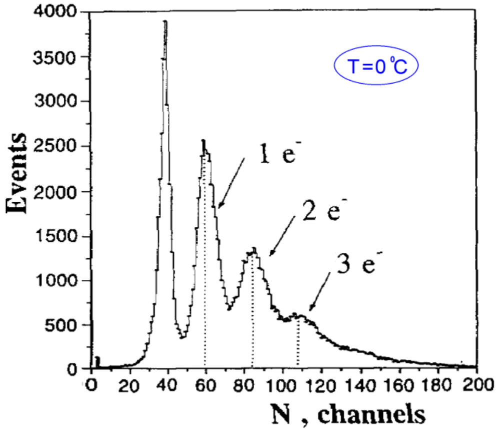
First results with the micropixel MRS APD

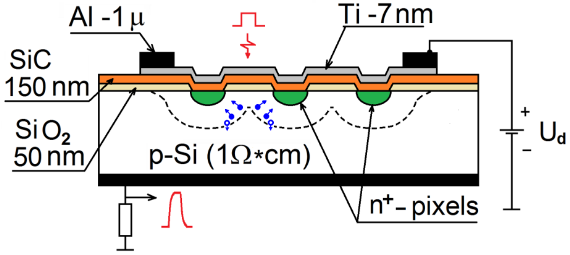
Testing the first sample demonstrated unique parameters: high gain (up to 10^5) and uniform signal amplitude along the device surface. The new device could operate in both linear mode and Geiger mode. An abnormal behavior of the excess noise factor was found, which made it possible to reduce the noise factor down to unity at high gain [1, 2].

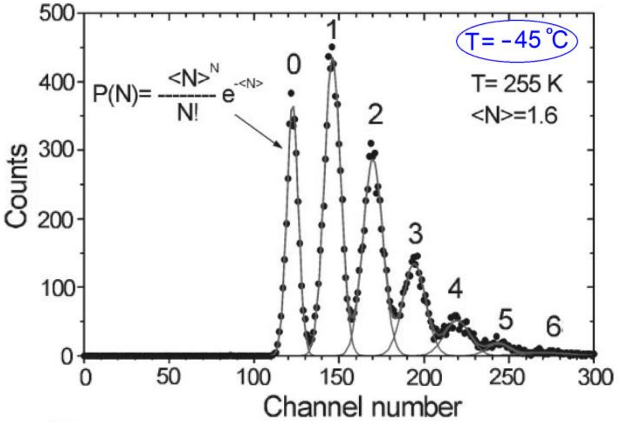
Reference:

1. A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov. Technical Physics Letters (in Russian), v.16, No.1, p.14, (1990).
2. Z. Sadygov. Physical processes in avalanche photodetectors..., Dissertation for the degree Doctor of Sciences, MEPhI, 1997 (in Russian).

Single-photoelectron spectra of the micro-pixel MRS APD







A. Akindinov and G. Bondarenko first observed a single photoelectron spectra with micropixel MRS APD samples at low temperature [1, 2].

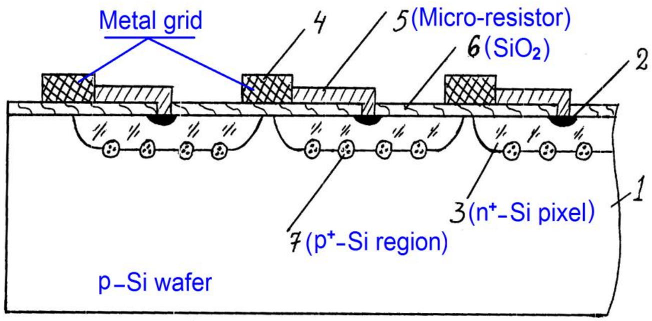
There were two drowbacks:

- Low sensitivity in visible and UV spectrum due to significant loss of light intensity in the semitransparent metal layer and resistive layer fully covering the sensitive area of pixels.
- Low yield because of short-circuit effect through the thin resistive layer (SiC or Si* of ~0.15 μ thickness).

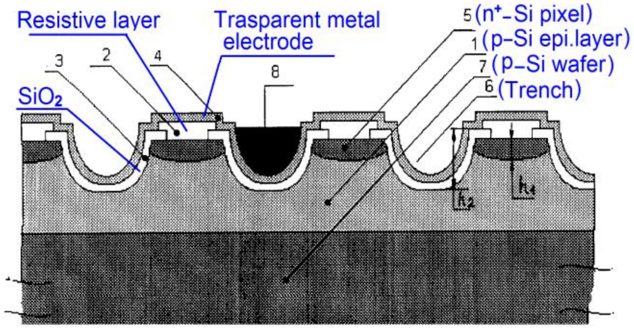
Reference:

1. A. V. Akindinov et al. Nucl. Instr. and Meth. A367 (1997) 231.
2. G. Bondarenko et.al. Nucl. Instr. and Meth. A442 (2000) 192.

Basic designs of future surface pixel MAPDs



MAPD with individual surface microresistors (a copy from [1]).



MRS APD with grooves (a copy from [2]).

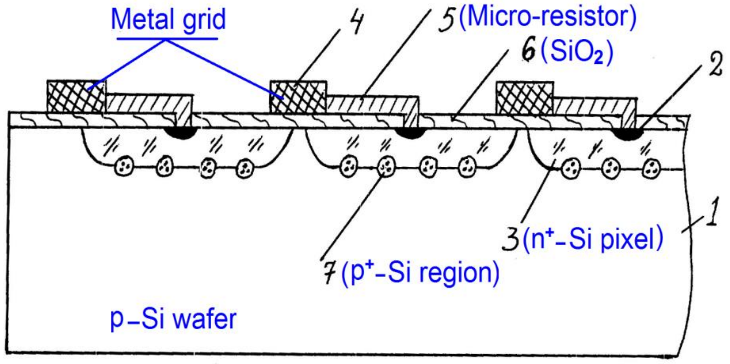
In 1996, Z. Sadygov first proposed the MAPD design with surface micro-resistors for visible and UV light detection. The device contained a semiconductor substrate on which a matrix of p-n-junctions (pixels) was made. Each pixel was connected to a common metal grid through individual micro-resistors.

In 1998, V. Golovin, M. Tarasov, G. Bondarenko first proposed to add grooves between pixels in previous design of the MRS APD to eliminate the optical cross-talk effect . However, the spectral sensitivity of the device remained the same – red and infra red region of the spectrum.

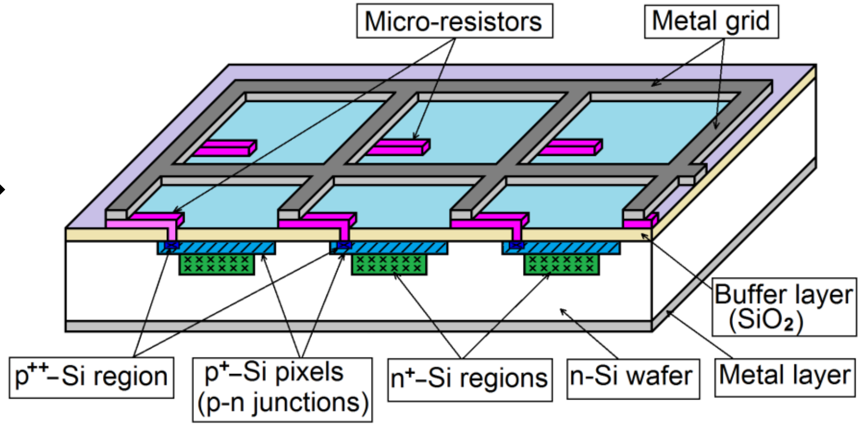
Reference:

1. Z. Sadygov. Russian patent #2102820. Priority date: 10.10.1996, http://www1.fips.ru/fips_servl/fips_servlet?DB=RUPAT&DocNumber=2102820&TypeFile=html
2. V. Golovin, M. Tarasov, G. Bondarenko. Russian patent # 2142175. Priority date: 18.09.1998, http://www1.fips.ru/fips_servl/fips_servlet?DB=RUPAT&DocNumber=2142175&TypeFile=html

Design #1: MAPD with individual surface resistors (or SiPM – Silicon photomultiplier)



Basic design [1]



Realized version.

Today, all commercial SiPMs (or MPPC) products are based on this design.

Advantages:

- Relatively simple technology;
- High yield of working samples (~90%);
- High signal gain (~10^6) and very good single-photoelectron resolution.

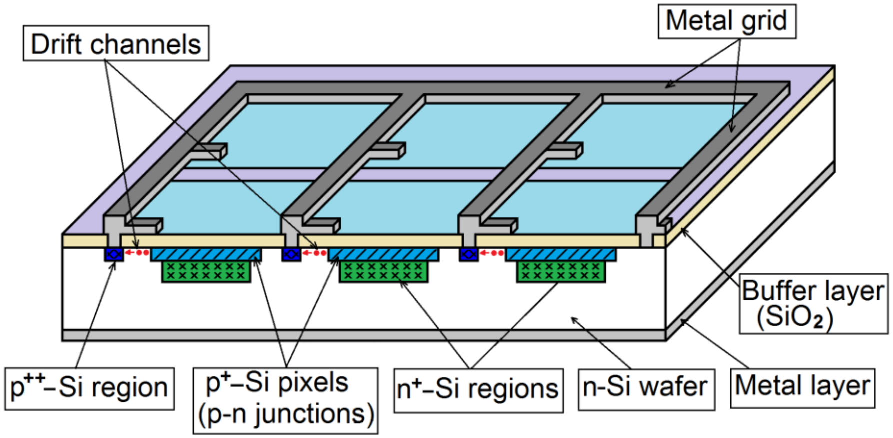
Drawbacks:

- Low geometrical fill factor;
- Limited pixel density;
- High specific capacitance.

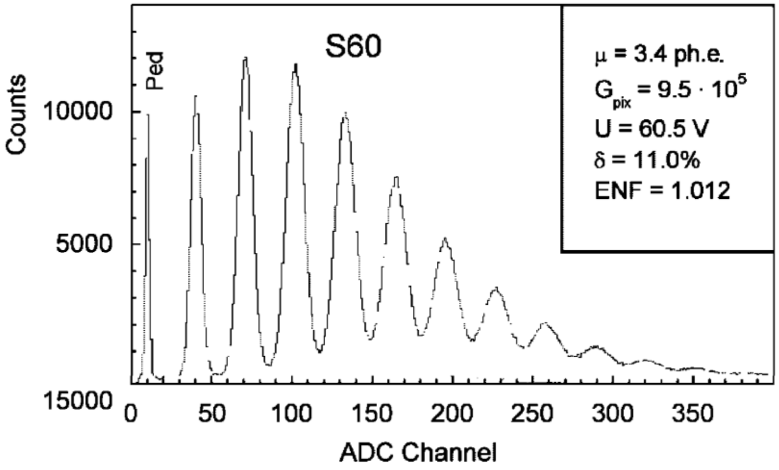
Reference:

1. Z. Sadygov. Russian patent #2102820, priority date: 10.10.1996.

Design #2: MAPD with individual surface drift channels.



Cross-section of MAPD with drift channels [1].



Typical spectrum of the MAPD signal [2].

Here each pixel is connected with the metal grid via an individual field induced cannel. In this sense this MAPD look like a field effect transistor where a drain and a gate are connected together. This design allows manufacturing of a MAPD with an adjustable resistor or manufacturing an avalanche CCD.

Advantages:

- Standard CMOS technology
- Very good single photoelectron resolution.

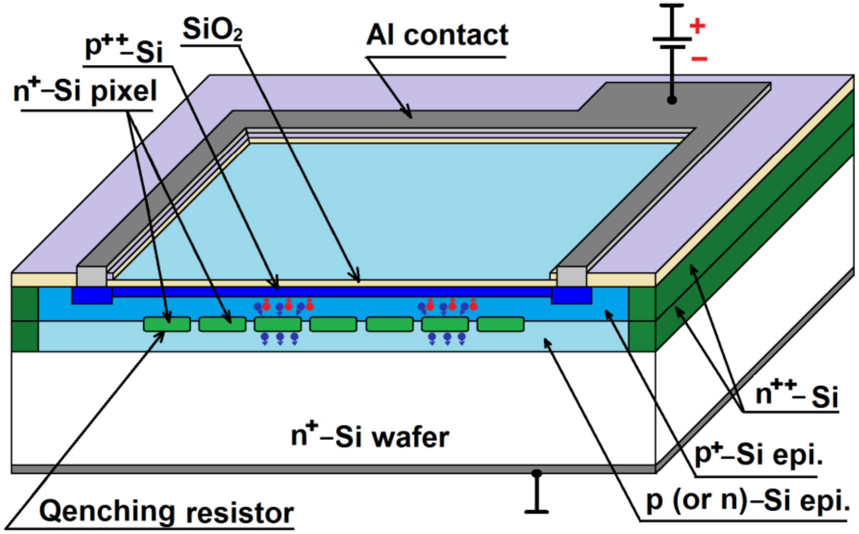
Drawbacks:

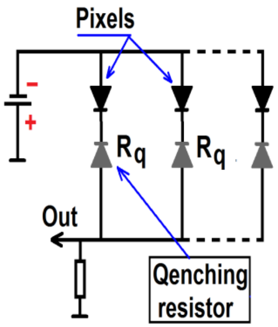
- Limited pixel density.
- High specific capacitance.

Reference:

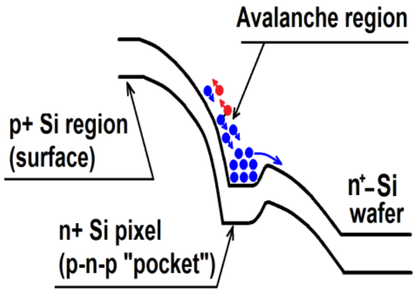
1. Z. Sadygov. Russian patent # 2086047. Priority date: 30.05.1996.
2. N. Anfimov et al., Nucl. Instr. and Meth. A 572 (2007) 413.

Design # 3. MAPD with deeply buried micropixels





EQUIVALENT CIRCUIT



ZONE DIAGRAM

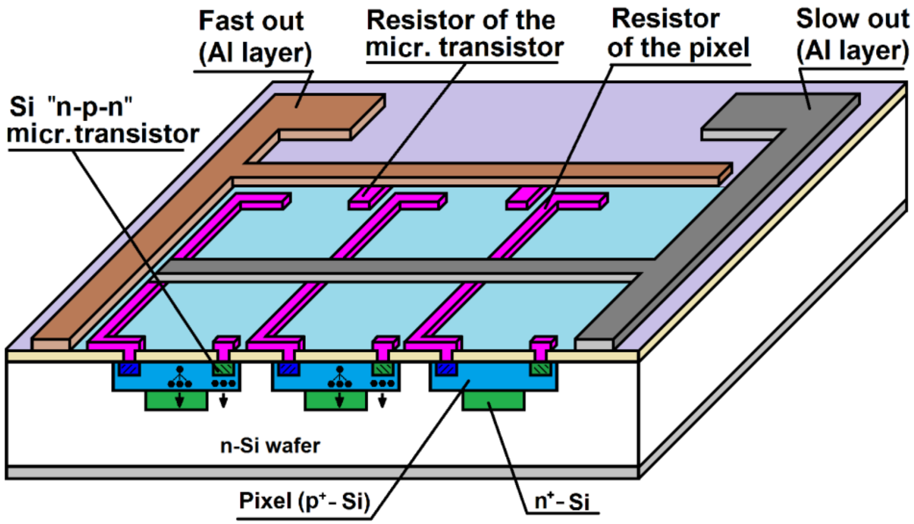
Cross-section of MAPD with deeply buried micropixels [1].

The third type of MAPD has a common p–n junction and a clear sensitive surface as a standard APD. Here both, the matrix of avalanche regions and the individual passive quenching elements are placed inside of the silicon substrate. About 10^4 independent avalanche regions (vertical channels) per mm^2 with individual micro-wells for charge collection are created at a depth of about 4 µm using an epitaxial technology. Charge collection in individual micro-wells provides the local quenching of avalanche processes in the MAPD. This design allows to reach about 40% of PDE at pixel density of 10^4 pix./mm^2.

Reference:

1. Z. Sadygov et al. Nucl. Instr. and Meth. A 567 (2006) 70

Design # 4. Micropixel avalanche phototransistor (MAPT)



Advantages:

- Low specific capacitance.
- Low cross-talk and low after-pulsing effect due to low avalanche gain.

The MAPT is the novel avalanche detector containing a matrix of phototransistors and having two independent signal outputs. The first output provides signal from pixels, as in conventional SiPMs. Second output provides fast signal from individual micro-transistors [1, 2].

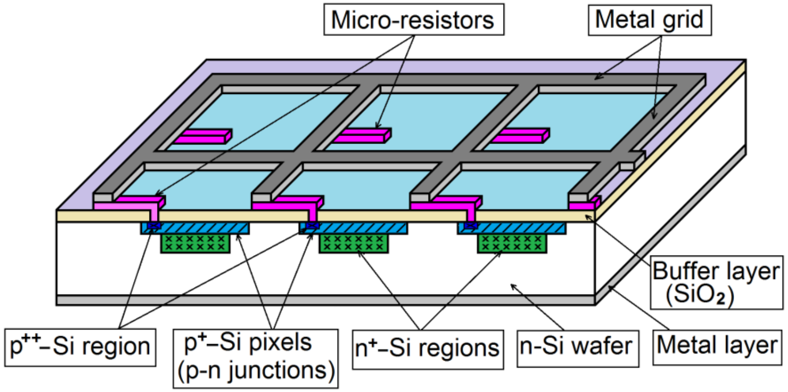
Total signal gain $G_{tot}=G_{pix.}xG_{tr.}\sim10^5x10=10^6$, where G_{pix} – gain of pixel, G_{tr} – gain of the micro-transistor.

More detailed results on this issue will be presented by my colleague from Azerbaijan.

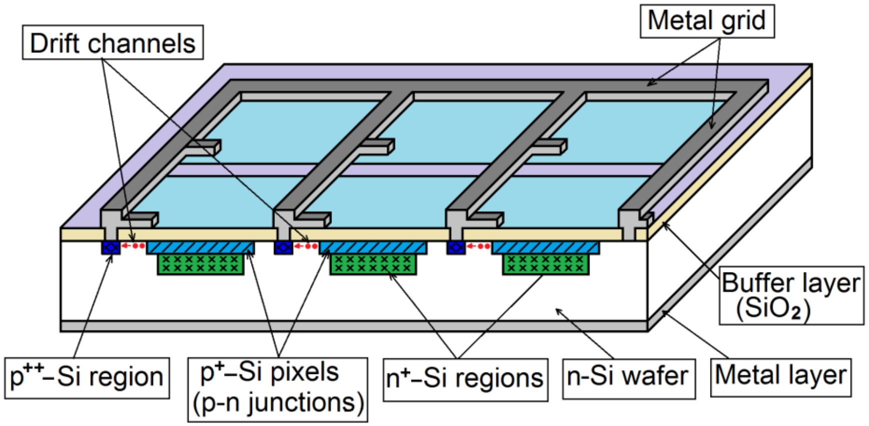
Reference.

1. Z. Sadygov and A. Sadigov. Russian patent # 2650417. Priority date: April 25, 2017. Published: April 13, 2018.
2. A. Sadygov et al., Nucl. Instrum. Meth. A 845 (2017) 621.

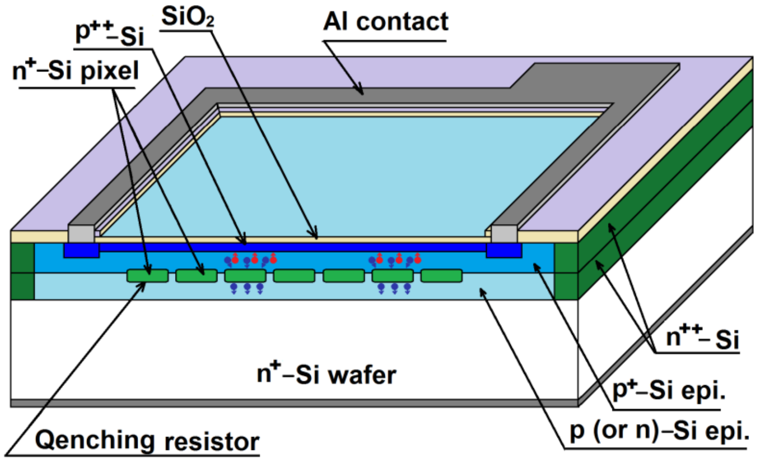
Four advanced designs of micro-pixel avalanche detectors



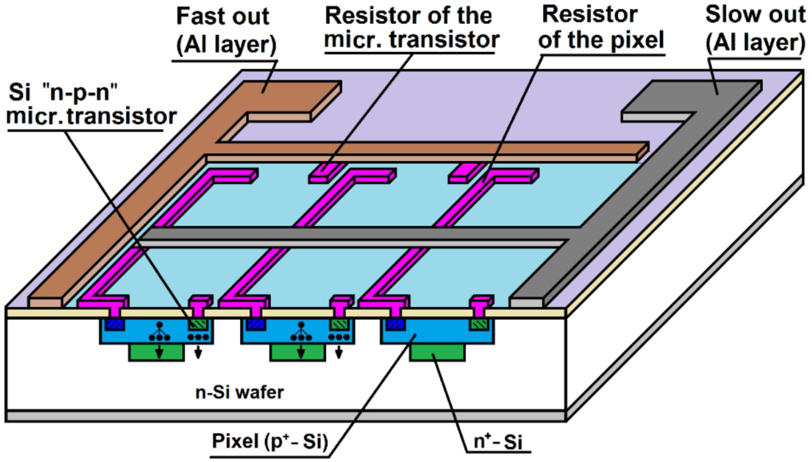
MAPD with individual surface microresistors (SiPMs)



MAPD with individual surface drift channels



MAPD with deep micropixels



MAPT – Micropixel avalanche phototransistor

A few questions about the physics of operation the avalanche photodetectors

A number of our colleagues believe that the MAPD is a very simple device. It consists of a matrix of known SPAD detectors. In this regard, the following questions arise.

1. What is the main reason for the stabilization of signal amplitudes in avalanche channels of the MCP and VLPC?

2. Why is the avalanche process in traditional SPAD detectors quenched when the device is discharged to breakdown voltage?

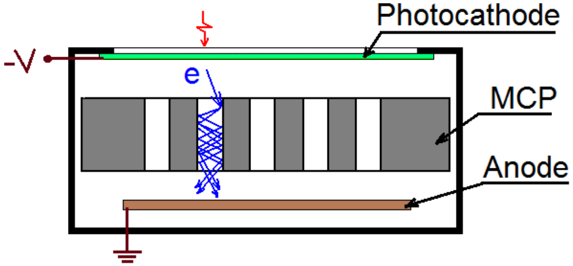
3. Why is an external active quenching element (electronic unit) required for fast quenching the avalanche process in traditional SPAD detectors?

4. Why is the SiPM (or MAPD) pixels fast quenched without any active quenching element?

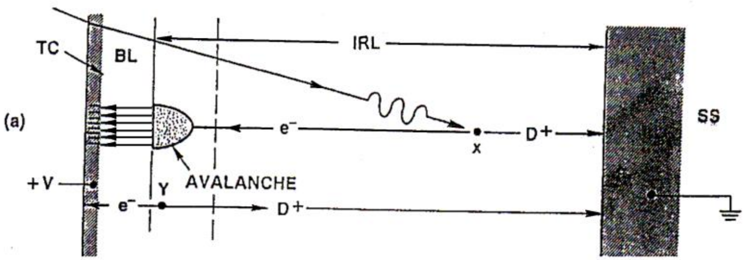
In order to answer these questions, it is necessary to consider the physical mechanism of avalanche process in these devices.

Two nearest analogues of MAPD devices

Now I would like to talk about the physics of operation of MAPD devices. It is known that the MAPD working in Geiger mode demonstrates a single photoelectron resolution, but this is not the main reason. Actually, the MAPD is a matrix of the parallel connected signal amplifiers operating in saturation mode. In this sense, the MAPD is a solid-state analogue of a Micro Channel Plate Photomultiplier (MCP PMT) and a known Visible Light Photon Counter (VLPC). These devices do not have pixels and do not work in Geiger mode. These two devices do not have a breakdown voltage because of a single-particle avalanche process taking place in them. Each channel in these detectors operates in saturation mode which results in stabilization of the signal amplitude. Therefore these devices have an excellent 1, 2, 3 photoelectron resolution with excess noise factor F = 1.



Cross-section of an MCP PMT with highly resistive channels.



Cross-section of a VLPC with volume quenching resistors [1].

Conclusion. Single photoelectron resolution in MAPDs is possible due to saturation of the signal gain in avalanche channels. In principle, MAPD operating below breakdown voltage may demonstrate a single-photoelectron resolution at very high quenching microresistors.

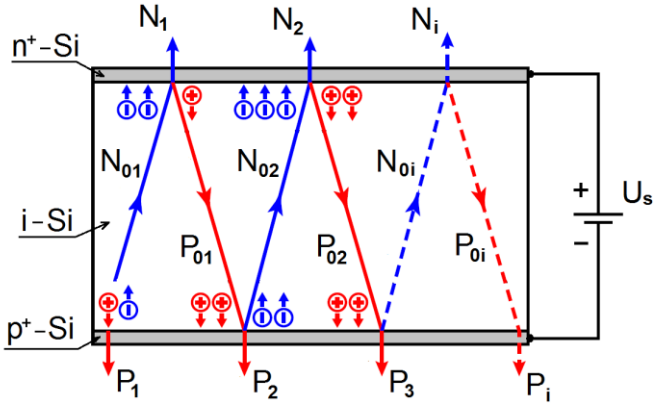
Reference.

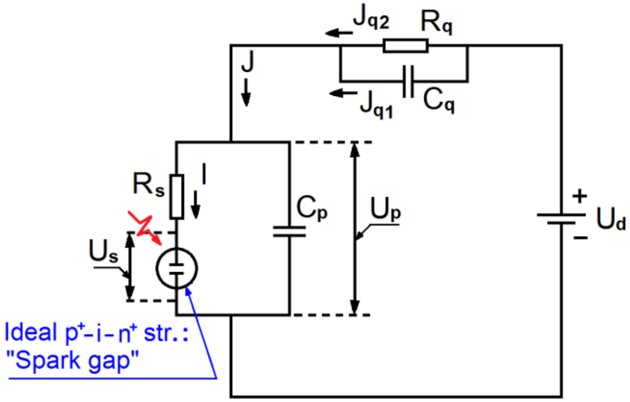
1. M. Petroff et.al. IEEE Trans. on Nucl. Sci. V.36, No.1, 1980, P. 158.

Physical model of the MAPD operation

Recently, we proposed a new physical model of operation the MAPD and the SPAD devices [1]. This model assumes that the MAPD pixel has a p^+-i-n^+ structure that is represented here as an ideal “spark gap” without any capacitance C_p and space charge resistance R_s. The pixel capacitance C_p, space charge resistance R_s and the individual quenching micro-resistor R_q are placed as shown in the proposed equivalent circuit of the MAPD pixel. It is further assumed that the ionization factors for electrons (α) and holes (β) are constant during one avalanche cycle. After each avalanche cycle, the model takes into account the change in pixel potential, as well as the change in the ionization factors, caused by both the discharge (I) and recharge (J) currents.

It should be noted that our equivalent circuit does not introduce a breakdown voltage ($U_{br.}$), as in the Haitz model. Here we study the behavior of the pixel potential U_p during the avalanche process as a function of the space charge resistance R_s and the quenching resistance R_q.





Reference.

1. A. Sadigov et.al. https://www.arcjournals.org/pdfs/ijarps/v3-i2/3.pdf

Physical model of the MAPD operation

Results of simulation based on the proposed physical model showed that the space charge resistance R_s defines the pixel discharge potential ($\Delta \boldsymbol{U_{dis.}}$) just after quenching of avalanche process. The R_s depends of the thickness of the space charge region (W) and the diameter of the avalanche channel (D) [1]:

$\boldsymbol{R_s} = \frac{2}{\varepsilon_{si}\pi v_s} \times (\frac{W}{D})^2 \approx \boldsymbol{60\ k\Omega} \times \left(\frac{W}{D}\right)^2$. Results of simulation showed that $\Delta \boldsymbol{U_{dis.}} = \boldsymbol{m} \times \Delta \boldsymbol{U_{o.v}}$; $\boldsymbol{Q_e} = \boldsymbol{m} \times \boldsymbol{C_p} \Delta \boldsymbol{U_{o.v.}}$; $\boldsymbol{C_{eff}} = \boldsymbol{m} \times \boldsymbol{C_p}$, where $\Delta \boldsymbol{U_{dis.}} = \boldsymbol{U_d} - \boldsymbol{U_{p.min.}}$ – discharge potential just after quenching of avalanche process, $\boldsymbol{Q_e}$– charge of a single photoelectron peak of the amplitude spectrum, $\boldsymbol{C_{eff.}} = \boldsymbol{\partial Q_e / \partial U}$ – effective capacitance of the pixel, **m** – a coefficient that varies from 1 to 2 depending on the device design (or $\boldsymbol{R_s}$).

It was found experimentally, after quenching of avalanche process the potential on the MAPD pixel drops below the breakdown voltage $\boldsymbol{U_{br.}}$ by the overvoltage value $\Delta \boldsymbol{U_{o.v.}}$, that is $\Delta \boldsymbol{U_{dis.}} \approx \boldsymbol{2} \times \Delta \boldsymbol{U_{o.v}}$ and $\boldsymbol{C_{eff}} \approx \boldsymbol{2C_p}$ (i.e. m ≈ 2). Therefore, MAPD pixels are quenched very fast without any electronic units.

However, in case of traditional SPAD devices the potential on the pixel drops to value around the breakdown voltage $\boldsymbol{U_{br.}}$, that is $\Delta \boldsymbol{U_{dis.}} \approx \Delta \boldsymbol{U_{o.v}}$ and $\boldsymbol{C_{eff}} \approx \boldsymbol{C_{p.}}$ (i.e. m ≈ 1). and therefore a special quenching circuit is needed for fast quenching of avalanche process.

My colleague from Azerbaijan will present more results on this issue.

Reference:

1. F. Ahmadov, et all. Presentation in this Conference.
2. Z. Sadygov. Physical processes in avalanche photodetectors..., Dissertation for the degree of Doctor of Sciences, . MEPhI, 1997 (in Russian).

Thank you for your attention!