Three advanced designs of avalanche micro-pixel photodiodes: their history of development, present status, maximum possibilities and limitations.

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Outline

1. From conventional APDs to MRS type APDs and further to AMPDs.

2. Three main types of AMPDs and their possibilities.

3. Possibilities of mass production.

4. Future plans.
Main problems of semiconductor avalanche devices

At present many people consider that the new APDs with inner microstructures are very easy devices. To my mind, the way to micro-pixel APDs was not easy. This development took about 20 years.


- CCD and MW type APDs. 2002- present
Main problems of semiconductor avalanche devices

There were a few problems that didn’t allow an appearance of large area APDs with high gain (~1000 and more). Here are these problems.

• Very sharp dependence of the multiplication factor $M$ (gain) on applied voltage $V_{ap}$;

• Micro-plasma breakdown phenomena which limits the maximum value of applied voltage, consequently the maximum gain.

   Micro-plasma phenomena is connected with an appearance of local non-controlled avalanche process in p-n junctions, where the breakdown voltage is lowered because of heterogeneities.
Two different approaches

In the beginning of our activity there were two main approaches to development of new APD’s:

• Improving purity of semiconductor wafers and using high-technology for production. However this may results in high APD cost;

• investigation of avalanche process in various multi-layer silicon structure with local suppression effect in order to answer the question: “Is it possible to develop a low- cost APD device on basis of Russian technology?”

The second approach have been chosen by our APD-group about 20 years ago. (A.Gasanov, V.Golovin, Z.Sadygov, M.Tarasov and N.Yusipov).

That time the idea of local suppression of avalanche process in MOS (metal-oxide-silicon)-structures had wide discussions in the Lebedev Institute (V. Shubin, A. Kravchenko).

The MRS (metal-resistive layer-silicon) has been chosen by our team as a main object of investigation.
A planar **Metal-Resistive layer-Semiconductor structure.** The first **MRS APD**

![Diagram of MRS APD structure](Image)

**Advantages:**
1. Simple technology and low cost.

**Problems:**
1. Low yield because of short circuit effect through SiC layer.
2. Limited gain because of charge carriers spreading along Si surface.

The first publications on “MRS” type APDs:
An appearance of Avalanche Micro-channel/pixel Photo Diodes (AMPD).

A list of the basic results that support the AMPD appearance:

1. Amplitudes of micro-plasma pulses is reduced with the diameter of heterogeneities. Possible way for suppressing.
2. The curved p-n – junctions have more stable breakdown voltage than planar p-n – junctions. Possible way for stabilization.
3. The characteristic rise time of photo response at over voltage conditions may reach ~5psec. Excellent promising for timing.
4. Avalanche micro-regions must be localized (separated from each other) in order to obtain a high gain overall sensitive area of avalanche devices. Excellent promising for a few photons detection mode.

For more detail information:
The main result. Localization of the avalanche micro-regions results in the unique device properties: high and uniform gain; abnormal behavior of the excess noise factor that may be reduced up to 1 at high gain!

The first publications:
Problems of the AMPD of basis version.

1. Low yield because of short circuit effect through the thin resistive layer (SiC or Si* of ~0.15m thickness).
2. Low sensitivity in blue and UV ranges of spectrum because of light absorption in the both a resistive layer and a deep n+ array (deepness ~1-2µ).

Conclusion. New designs of AMPDs are needed!
A new AMPD with individual surface resistors.

Version #1. (Some people call this version as GMPD, SiPM)

Advantages:

• relatively simple technology;
• high yield of working sample (~50%).
• high signal gain (~10^6);
• very good single photo electron resolution.

Disadvantages of the AMPD of version # 1.

Problems:
• Low geometrical transparency (max. ~ 50%);
• Limited pixel density (max.~1000 pixel/sq.mm);
• high capacitance (~60 pF/sq.mm).
• technology of micro-resistors with so high values (~1MΩ) are not accepted in standard microelectronics.

Conclusion. An adequate alternative is necessary
An AMPD with individual surface drift channels.  

**Version # 2**

**Advantages:**
- Standard CMOS technology and high yield of working samples.
- High signal gain and very good single photoelectron resolution.

**Problems:**
- Relatively low geometrical transparency (\(\text{max} \sim 55-60\%\)).
- Limited pixel density (\(\text{max.} \sim 1000 - 1500\) pixel/sq.mm).

**Conclusion.** The next (inverse) type AMPD design is needed.

**Publication:** Z. Sadygov. “Avalanche photo detector”.- Russian patent # 2086047, application from 05/30/1996.
An AMPD with deep micro-wells. Version # 3.

This version of AMPDs demonstrates the unique parameters:
- Geometrical transparency/active area ---------- 100%;
- Quantum efficiency --------------------------- 80%;
- Max. gain (today)----------------------------- 20 000
- Equivalent density of pixels ------------------ 10 000 per mm sq.
- Excess noise factor -------------------------- 1

Publication: A patent application # 2005108324 dated 24.03.2005
The three advanced versions of AMPDs

AMPD with individual surface resistors
Patent #2102820 from 10.10.1996.

AMPD with surface drift channel.
Patent #2086047 from 30.05.1996.

AMPD with deep micro-wells
Patent application #2005108324 from 24.03.2005.
Today available AMPD samples

64-element AMPD matrix for imaging.
4-element prototype for PET
Single element AMPD for muon beam monitor (for PSI)

The AMPD parameters you may find in our site:
http://sunhe.jinr.ru/struct/neeo/apd/
Some results with an AMPD produced by “Sapfir” enterprise

Photon counting efficiency (PDE) versus on the photon wavelength (measured by Y. Musienko)

The Dubna AMPD of version #3 have been tested in PSI and CERN (D. Renker, R. Scheuermann, Y. Musienko, A. Stoykov)
Some results with AMPD samples (v.2) produced by “Mikron” factory

Parameters of AMPD samples: wafer – n and p-Si; S=1mm*1mm.

The AMPD samples are tested in LNP JINR and PSI.
(I.Chirikov, N.Anfimov from LNP JINR and D.Renker, R. Scheuermann, A.Stoykov from PSI)
Other samples for comparison.

Our design of the AMPD (version 1)

The SiPM sample

SiPM

Silicon PhotoMultiplier (SiPM) 
MEPhI&PULSAR

Metal (Al) grid

Individual surface resistors

Pixels of the SiPM

AMPD with individual surface resistors
Patent #2102820 from 10.10.1996.
Other samples for comparison.

Our design of the AMPD (version 1)

The MRS APD sample (CPTA, Russia)
Other samples for comparison.

Our design of the AMPD (version 1)

The DPPD samples (HAMAMATSU)

“DPPD” by HPK
1mm x 1mm metal housing
Possibilities of mass production of the AMPD with different versions.

In February month of this year we agreed with “Mikron” enterprise on joint development and production of the AMPD product with various versions.

Now two versions of AMPDs are produced in “Mikron” enterprise. The both type samples are under testing in JINR and PSI.
Collaboration Protocol between JINR, INR RAN and “Mikron” factory

Institute of Nuclear Research of the Russian Academy of Sciences

PROTOCOL

signed for cooperation

Institute of Nuclear Research of the Russian Academy of Sciences

On 25 February 2005, a meeting was held between representatives of the Institute of Nuclear Research of the Russian Academy of Sciences (IЯИ РАН, Moscow), the Joint Institute for Nuclear Research (IЯИ, Dubna) and OАО “НИИМЭ и Микрон” (IЯИ, Dubna).

The parties discussed the possibility of producing a pilot batch of long-wave micropixelated photodiodes (MPD) capable of registering single photon events with a high quantum efficiency (~10^5) and both elemental and matrix LMFs that could be used in various fields, such as medical gamma and positron emission tomography (PET), and medical imaging.

The parties agreed to discuss the further development and production of long-wave micropixelated photodiodes (MPD), capable of registering single photon events, with high quantum efficiency (~10^5) and both elemental and matrix LMFs.
Future plans of the “Dubna APD” collaboration:

- improve working parameters of single element AMPDs for use in visible and UV spectrum;
- develop a mosaic type AMPD matrix with number of element up to 128;
- investigate possibilities of creation a supersensitive CCD type matrix on basis of AMPD with charge drift channels.

We are very interested in collaboration with other Institutions for joint development and application mentioned above devices.

For more detail information:
http://sunhe.jinr.ru/struct/neeo/apd/