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

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On behalf of “Dubna-APD” collaboration
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Area of expertise: Physics of semiconductor devices.
New APD development.

Experience: more than 20 years.

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Outline

1. From conventional APDs to MRS type APDs and further to AMPDs: a short review.

2. Three main types of AMPDs and their possibilities.

3. Possibilities of mass production.

4. Future plans.
Some forewords

At present time many people consider that the new APDs with inner microstructures are very easy device for understanding of their properties. Various names have been invented for these devices, for example:

• Geiger mode photodiode;
• Micro-cell avalanche photodiode;
• Solid-state photomultiplier;
• Silicon photomultiplier;

(See, proceedings of Beaune Conferences, 1999 and 2002).

I would like to ask these people.
1. Why such device did not develop for many years earlier, for example in 70th years?
2. Whether it was very difficult to connect a few small diodes with individual resistors in parallel?

To my mind there is only one answer.
Main problems of semiconductor avalanche devices

The way to micro-pixel APDs was not easy.


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. Here are these problems.

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

• High spatial heterogeneities that exist in real semiconductor crystals;

• High variation of breakdown voltage $V_b$ over sensitive area of semiconductor diodes.
Main problems of semiconductor avalanche devices

The mentioned above problems clear seen from the expression of multiplication factor (Miller’s formula):

\[ M = \frac{1}{1 - \left( \frac{V_{\text{ap.}}}{V_b} \right)^n}, \quad \text{if } M \gg 1 \text{ than } \]

\[ M \approx \frac{1}{n} \left( \frac{V_b}{V_b - V_{\text{ap.}}} \right) < \frac{V_b}{\max(\Delta V_b)} \quad (\text{Threshold of thermal breakdown}) \]

here \( n \) – an empirical parameter and usually \( n \approx 1 \) for most of silicon APDs; \( \Delta V_b \) – a spatial variation of the breakdown voltage overall sensitive area.
Main problems of semiconductor avalanche devices

Micro-plasma breakdown in p-n junctions with small-area heterogeneities

#1, micro area
$V_{b1} = 41.9 \text{V}$

#2, big area
$V_{b2} = 42 \text{V}$

Guard ring
p-Si wafer

Random micro-plasma pulses (discharge) with amplitude of $\sim 50 \mu\text{A}$.

Conclusion: large spatial variation of breakdown voltage ($V_b$) don’t allow to get a high gain in conventional p-n junctions.
About nature of microplasma breakdown phenomena

This phenomena is investigating by many scientists during more than 50 years. P. Wolf, L.Keldysh, W. Shokly, R. McIntyre, R. Haitz, W.Oldham, P.Antognetti and other scientists gave significant contributions to understanding the charge carrier multiplication and microplasma breakdown phenomena.

In 1964 R.Haitz has proved experimentally, that the uniform p-n– junction may have microplasma performance when the bias on a diode exceed the breakdown voltage. This result opened the way of use of small area diodes for single photon detection measurements.

Publications:
An appearance of Single Photon Avalanche Diodes (SPAD). Sometimes a spurious effect may become very useful!

Really, the microplasma breakdown is a unwished effect for most of semiconductor devices, as well as for the conventional APD’s.

Today the small area diodes with microplasma breakdown mode (SPAD devices) are successfully used for single photon measurements. The microplasma pulses in the SPAD are quenched off by the special external circuits.

Performance of the SPAD devices is very similar to Geiger’s counter that also works in over voltage mode. However nobody named these devices as GMPD (Geiger mode photodiode) or SiPMs (Silicon photomultiplayers).

Publications:
Disadvantages of the SPAD devices.

The SPAD devices have disadvantages listed below.

- sensitive area is very small (d~100m);
- special external quenching circuit is needed;
- they are a binary device. They can’t work in a few photons detection mode.

A large area APD with enough linearity and capable to work in a few photons detection mode was needed for different applications.
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;

• Detail investigation of micro-plasma breakdown phenomena in order to answer the question: “Is it possible to bypass the random micro-plasma breakdown?”

The second approach chosen by our APD-group in 1983.
First steps
The detail investigations of micro-plasma breakdown phenomena in conventional p-n – junctions.

The questions that have been investigated:
1. Spatial distribution of breakdown voltage on conventional low resistive Si wafers.
2. Behaviors of avalanche process in p-n – junctions with artificial heterogeneities.
3. Futures of the photo-response in avalanche structures around the breakdown voltage.

Main results:
1. The maximum spatial variation of the breakdown voltage on conventional low resistive Si wafers is about 0.2V.
2. Amplitudes of micro-plasma pulses are reduced with the diameter of artificial heterogeneities.
3. The curved p-n – junctions have more stable breakdown voltage than planar p-n - junctions.
First steps

A single photoelectron performance of avalanche structures above the breakdown voltage.

An analytic simulation photo response have been carried out. A model structure contains: an abrupt and uniform p-n – junction; ionization factors $\alpha = \beta$; a single photoelectron generation.

Main results:
• The characteristic rise time of photo response may reach $\approx 5$ psec;
• About 50 psec. of signal pulse duration may be received at conditions of $\alpha * W \approx 10$, $M \approx 10^4$.

For more detail information:
A planar Metal-Resistive layer-Semiconductor structure. The first MRS APD

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 APD:
Charge spreading problems in MRS APD.


Main result: The avalanche micro-regions must be localized (separated from each other) for getting a high gain overall sensitive area.

The first publications:
The **Avalanche Micro-channel/pixel Photo Diodes (AMPD)** of a single photons detecting capabilities.

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 basis version of AMPDs.

An AMPD with individual vertical resistors. Basic version.

**Conclusion:** The AMPD is a solid-state analogue of the PMT with MCP.

**The first publications:**
Some advantages of the basis version AMPD.

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!

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 ~1-2\(\mu\)).

**Conclusion.** New designs of AMPDs are needed!
A new AMPD with individual surface resistors. Version #1. (Some people call this version as SiPM !?)

Advantages:

• relatively simple technology;
• high yield of working sample (~50%).
• high signal gain (~10⁶);
• very good single photo electron resolution.

The first publication: Z. Sadygov. “Avalanche detector”.- Russian patent # 2102820, application from 10.10.1996.
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).
• technologies of micro-resistors with so high values are not accepted in standard microelectronics.

Conclusion. An adequate alternative is necessary
An AMPD with surface drift channel. Version # 2/1.

A prototype of the novel avalanche CCD

Main result: A new prototype of the future avalanche CCD matrix with single photon detection capability has been invented and realized.

Publication: Z. Sadygov. “Avalanche photo detector”.- Russian patent # 2086047, application from 05/30/1996.
An AMPD with individual surface drift channels.

Version # 2/2

Advantages:

• Standard CMOS technology and high yield of working samples.
• High signal gain and very good single photoelectron resolution.

Problems:

• Relatively low geometrical transparency (max. ~55-60%).
• Limited pixel density (max. ~ 1000 - 1500 pixel/sq.mm).

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.

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)
Some AMPD analogs from other producers

AMPD analogs from HAMAMATSU

“DPPD” by HPK
1mmx1mm metal housing

10x10=100 pixels  20x20=400 pixels
An AMPD analog from CPTA (Russia)

Our original design of the AMPD (version 1)

An analog from CPTA (V. Golovin)

AMPD with individual surface resistors
Patent #2102820 from 10.10.1996.

Metal (Al) grid

Individual surface resistors

Independent p-n pixels
An AMPD analog from MEPHI (Russia).

Our original design of the AMPD (version 1)

An analog from MEPHI (B. Dolgoshein)

Information. The real producers of SiPM samples from MEPHI and CPTA are unknown.

We have received an official letter from “PULSAR” enterprise. “PULSAR” never produce the “SiPM” type device (see, the next page).
Уважаемый Зияратдин Ягуб-оглы!

На Ваше заявление от 15 марта 2004 г. о нарушении прав патентообладателя сообщаем следующее:

1) До настоящего момента ФГУП "НИП "Пульсар" не разрабатывал и не производил твёрдотельных фотоэлектронных фотоумножителей.

2) Случаи появления заказов на разработку и производство такого прибора.

3) Сотрудники ФГУП "НИП "Пульсар" Кленин С.И. и Филиатов А.Л. участвовали в работах МИФИ в рамках НТИЦ проекта. Каких либо результатов проекта у нас на предприятии не рассматривается.

С уважением
Зам. директора по научной работе

З. Садыгов
Possibilities of mass production of the AMPD with different versions.

Our APMD samples we are usually producing in “ORION”, “SAPFIR” and “MIKRON” enterprises.

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

PROTOCOL
соглашение о сотрудничестве между
Институтом ядерных исследований РАН (ИЯИ РАН, г. Москва),
Объединенным институтом ядерных исследований (ОИЯИ, г. Дубна) и
ОАО “НИИМЭ и Микрон” (г. Зеленоград).

В 25 февраля 2005 года на территории ОАО “НИИМЭ и завод Микрон” состоялась встреча представителей ИЯИ РАН (зам. директора Л.В.Кривчук и зав. отделом И.М.Железных), ОИЯИ (заместитель директора Лаборатории ядерных проблем ОИЯИ Р.Лейфер и ведущий научный сотрудник З.А.Садыгов) и ОАО “НИИМЭ и завод Микрон” (генеральный директор Н.А.Щербаков, первый заместитель генерального директора М.И.Павлюк, начальник отдела технологических услуг В.Ф.Морозов, заместитель начальника цеха А.Н.Долгов и ведущий технолог А.В.Новиков). Стороны обсуждали возможность изготовления опытной партии образцов лавинных микропиксельных фотодиодов (фотоприемников) на базе двух патентов РФ № 2102820, priority от 10.10.96 года и № 2086047, priority от 30.05.96 года (автор и патентообладатель обоих патентов – З.А. Садыгов).

Стороны отметили заинтересованность всех сторон в разработке и производстве кремниевых лавинных микропиксельных фотодиодов (ЛМФД), способных регистрировать единичные световые кванты в области длины волны 200–960нм. Будучи зеркальным фотозелектронным умножителем с высоким коэффициентом усиления (∼10⁵) сигнала, однозлементные и матричные ЛМФД могут применяться в таких областях, как крупномасштабные детекторы элементарных частиц, медицинские гамма и позитрон эмитирующая томография (ПЭТ), устройства обработки оптической информации и оптические суперкомпьютеры. Учитывая взаимный интерес и необходимость в совместной работе, стороны договорились о ниже следующем.
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.