EQR SiPMs : From Lab to Industry, and Recent Progress of Key Characteristics

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Outline

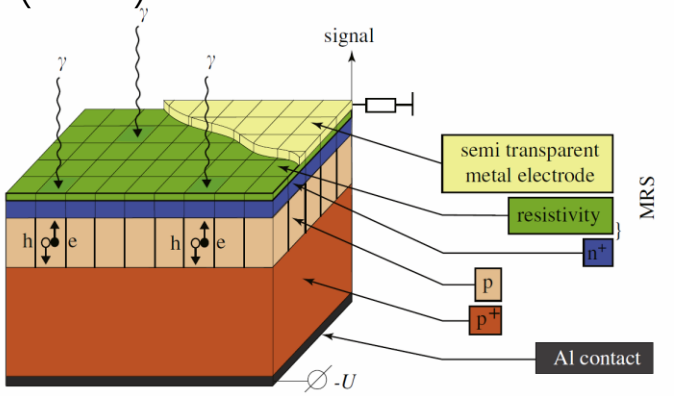
- **Historical Review of Representative SiPM Structures**
- **Features of EQR SiPM**
- **From Lab to Industry**
- **Recent Progress on Key Characteristics of EQR SiPM**
- **Conclusion and Outlook**

What is a silicon photomultiplier (SiPM)?

- SiPM is a solid state PMT with advantages of compact, high PDE, low operating voltage, and low cost (due to mass production with semiconductor technology), etc.
- SiPM is composed of hundreds to thousands avalanche photodiodes (APDs) in parallel connection, and each APD cell is connected with a quenching resistor or circuit in serious
- The SiPM operates with bias above breakdown voltage, the quenching mechanism plays a key role in operation
- SiPM is getting more and more popular as optical sensor in scintillation detector, in various fields such as HEP, medical imaging, radiation monitoring, and so on

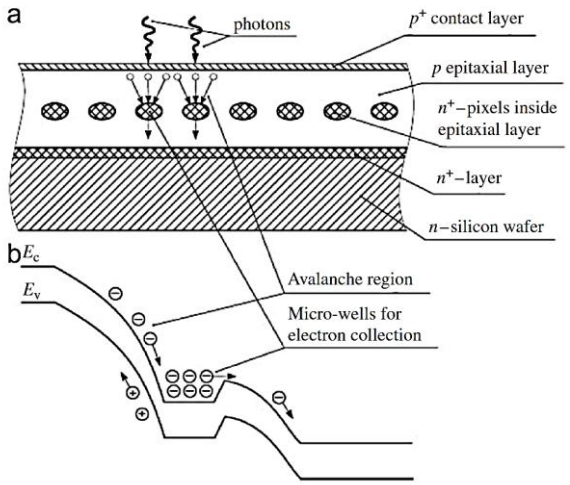
Historical Review of Representative SiPM Structures (1)

CPTA, V. Golovin, Patent No. RU 2142175, 1998. ; Z. Sadygov, Patent No. RU 2102820, 1998; V. Saveliev, V. Golovin, NIM-A, 442 (2000) 223.



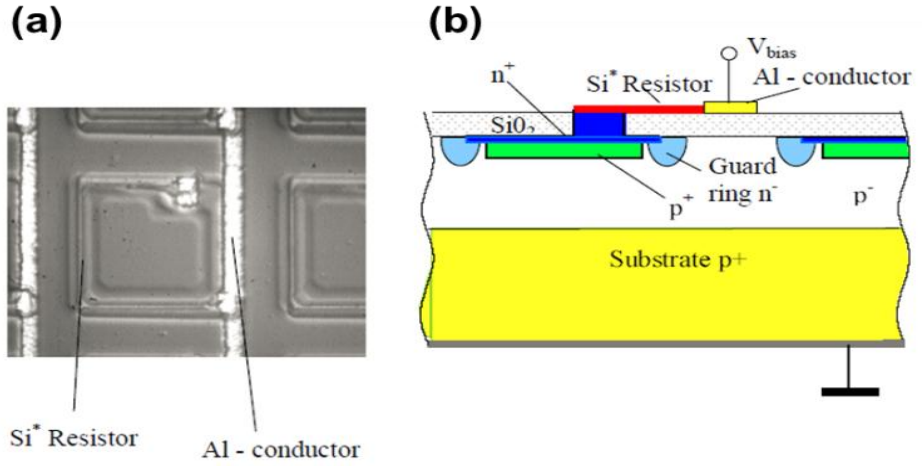
1989-1990 **First SiPM**, **MRS** structure , SiC or SiXOY is used as the quenching resistor, and semi-transparent metal Ti is used as the electrode

Z. Sadygov – JINR/Micron (Dubna)- *NIMA 567 (2006)70*



2002 Avalanche Micro-channel/pixel Photo Diodes (**AMPD**)

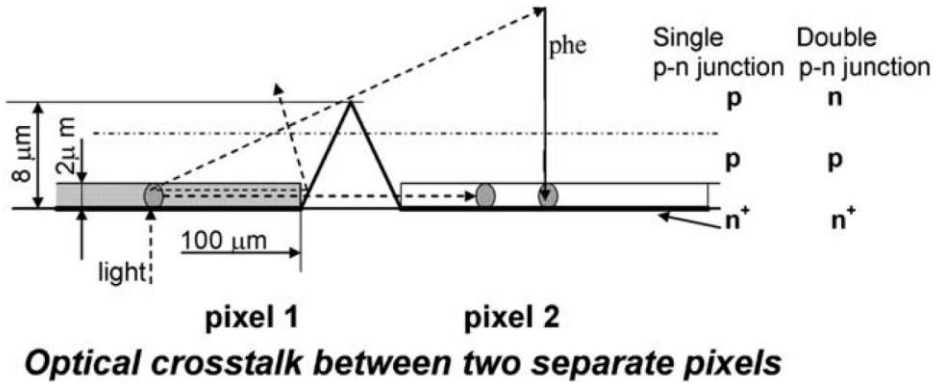
MePhi/Pulsar, Dolgoshein, NIMA 563 (2006)



2002 **Most popular**, **Strip polysilicon** is used as quench resistors at device surface

Historical Review of Representative SiPM Structures (2)

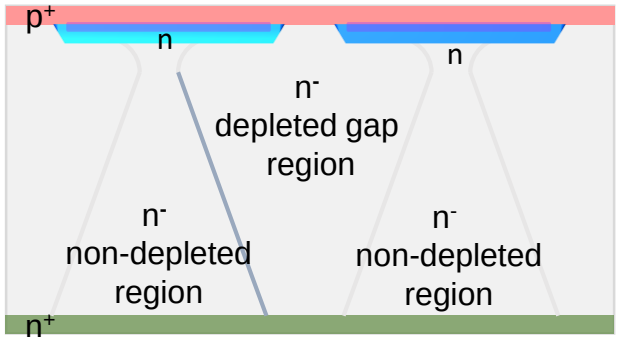
MePhi/Pulsar ,P.Buzhan, B.Dolgoshein, NIM-A610 (2009) 131–134



Optical crosstalk between two separate pixels

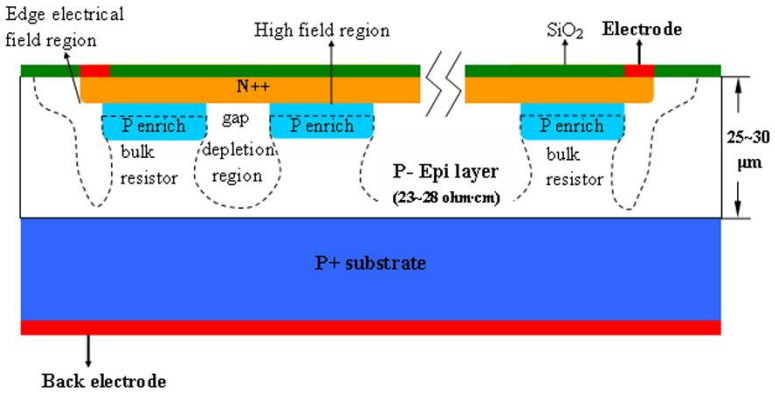
2009 Deep trenches around micro cells for alleviating optical cross talk

MPI, Ninkovic et al NIM A610 (2009) 142



2009 Quenching resistors integrated in bulk silicon aiming at enhancing PDE

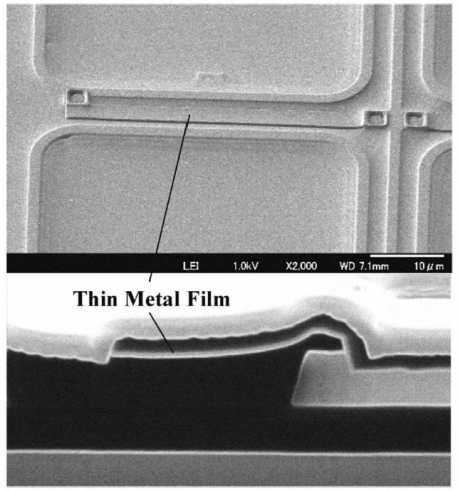
NDL（Novel Device Laboratory), NIM A621 (2010) 116-120



2010 EQR SiPMs, quenching resistors in epitaxial layer on substrate aiming at enhancing dynamic range

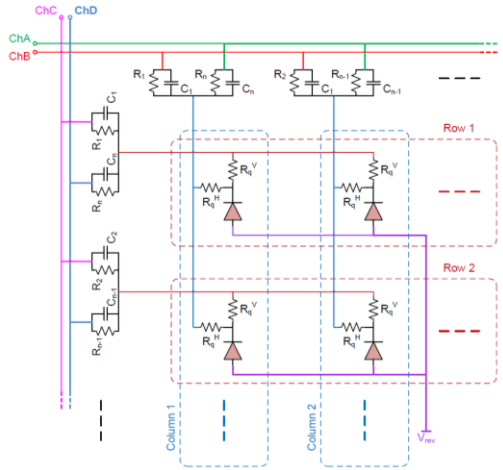
Historical Review of Representative SiPM Structures (3)

Hamamatzu, T. Nagano, et al., 2011 IEEE Nuclear Science Symposium, NP5.S-130



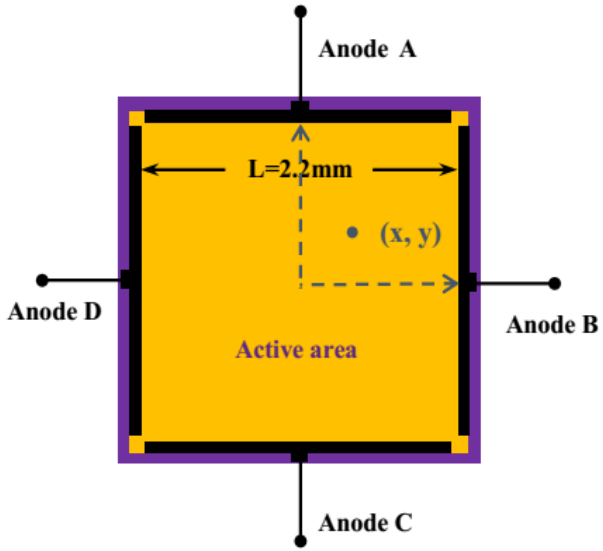
2011 Strip metal is used as quench resistors at device surface

FBK, Gola A, et al., 2013 IEEE Nuclear Science Symposium Conference Record



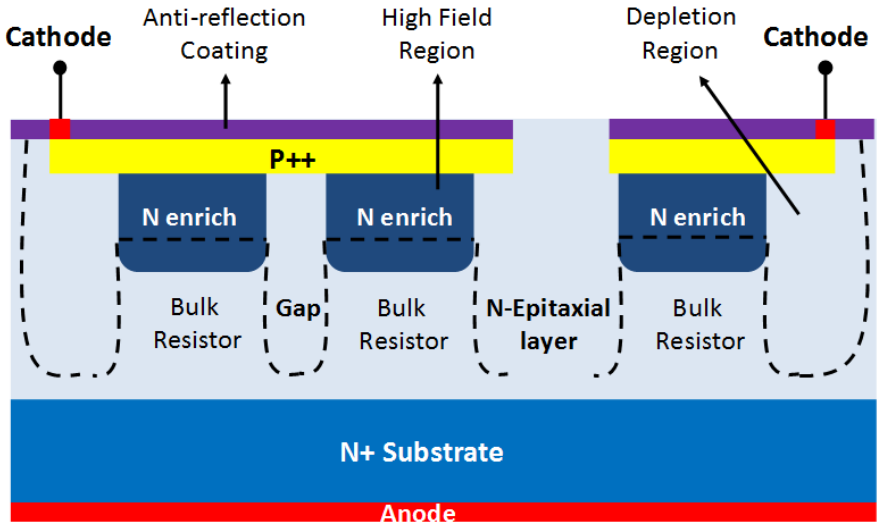
2013 Position sensitive SiPM (LG-SiPM) based on position encoding of microcells

NDL, IEEE TRANS. ON ELECTRON DEVICES, 61(2014) 3229-3232

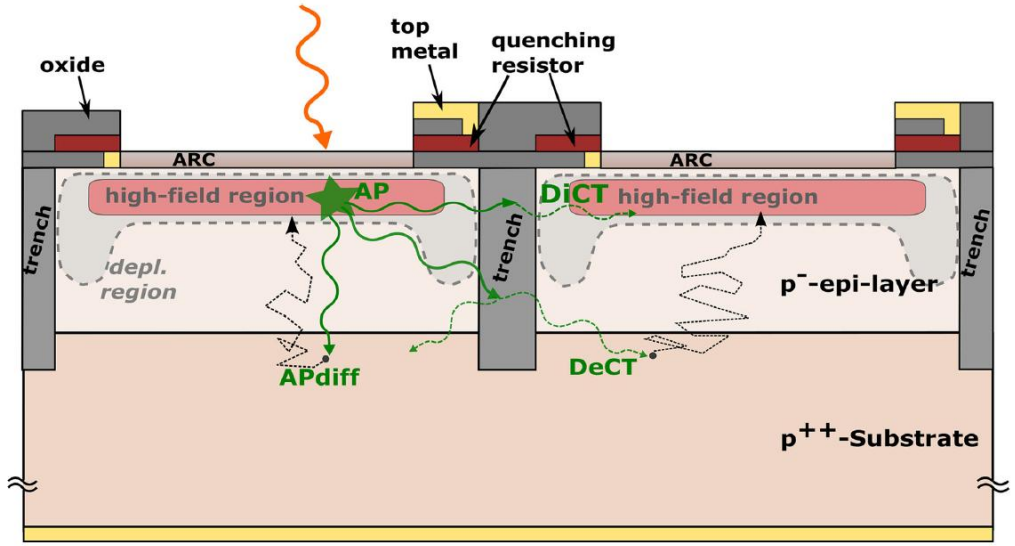


2014 Position sensitive SiPM (CRL SiPM) based on charge division by cap resistive layer.

Features of EQR SiPM



VS



- **Epitaxial quenching resistor + Without deep trench** → Simple fabrications → Low cost, but without fairly controlled optical cross talk
- **High fill factor (high density) + Small micro APD cells** → large dynamic range while high PDE, but relatively small gain
- **Small terminal capacitance** → Narrow and high pulses, low electronic noise, high count rate
- High doping Cap Resistive Lay connecting micro cells → **Position Sensitive SiPM (CRL SiPM)**

From Lab to Industry

- **CGN Capital Photonics Technology (Tianjin) Co., Ltd. (referred as CPT) was established on June 28,2023, jointly founded by CGN Nuclear Technology Development Co., Ltd., Beijing Normal University and the research team of Novel Device Laboratory (NDL), with a registered capital of 79.37 million RMB.**
- **CPT focus on the R & D, production, sales, and technical services of semiconductor sensors, related to silicon photomultiplier (SiPM) technology.**
- **NDL focus research and new applications on SiPM and related photon detectors now.**

Package Production Line

- The high-standard cleanroom covers an area of over 500 square meters.
- Equipped with advanced automated systems that cover the entire package process.
- The facility is designed to produce 3 million SiPMs annually.

Probe Station

Dicing Machine

Test Handler

Tape Feeder

Recent Progress on Key Characteristics of EQR SiPM

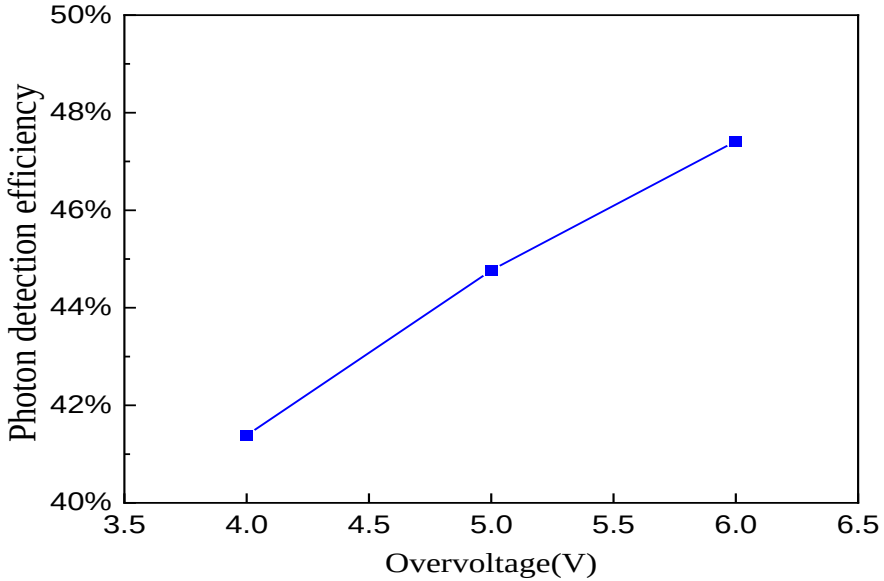
Key Performance Parameters of Different Manufacturers(1)

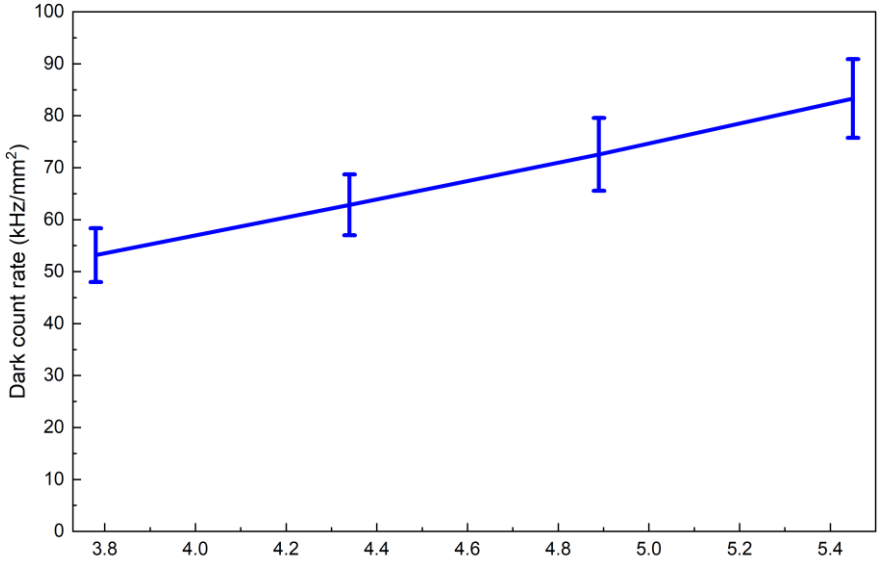
Company	Capital Photonics Technology (CPT)	Novel device Lab (NDL)	Onsemi	Broadcom	Hamamatsu (HPK)
Series	EQR20-4040D-SN	EQR15 3030D-S	J-series 40035	AFBR-S4N44P014M	S14160-4050HS
Microcell Pitch (μm)	20	15	~40	40	50
Microcell Number	35344	40000	9260	8334	6331
Fill factor (%)	64	54	75	--	74
Breakdown voltage (V)	26.4	27.5	24.5	32.5	38
Recommended Over-voltage (V)	6	8	6	12	2.7
Photon detector efficiency	47% @420 nm	45% @420 nm	50%@420 nm	63%@420 nm	50%@450 nm
Dark count rate (kHz/mm^2)	100	250	150	125	--
Dark current (μA)	1.0	0.14	3.0	3.3	1.1
Gain	8.0×10^5	4.0×10^5	6.3×10^6	7.3×10^6	2.5×10^6
Optical Crosstalk (%)	32	30	25	23	7
Terminal Capacitance (pF)	80	51	1800	580	900
Recovery time (ns)	16	12	48	55	--
Temperature Coefficient (mv/°C)	24.8	28	21.5	30	34
Active area (mm^2)	3.76×3.76	3.00×3.00	3.93×3.93	3.72×3.62	4.0×4.0
Package dimensions (mm^2)	4.12×4.12	3.55×3.75	4.00×4.0	4.31×4.18	4.4×4.4
Package type	Conductive glue bonding (CGB)	Chip on board (COB)	Through silicon Via(TSV)	Chip on board (COB)	Through silicon Via (TSV)
Package efficiency	83.28%	67.60%	96.53%	74.74%	82.64%

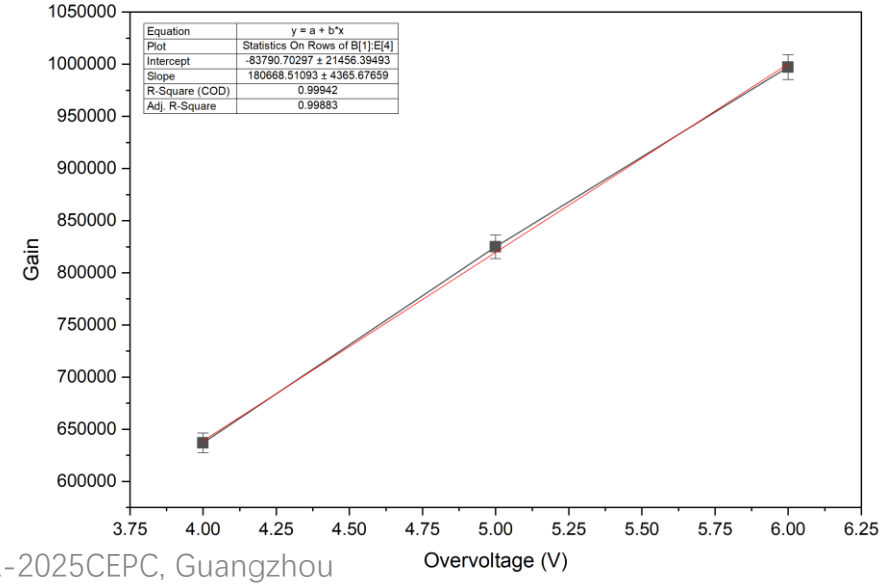
Red: better; Green: poor

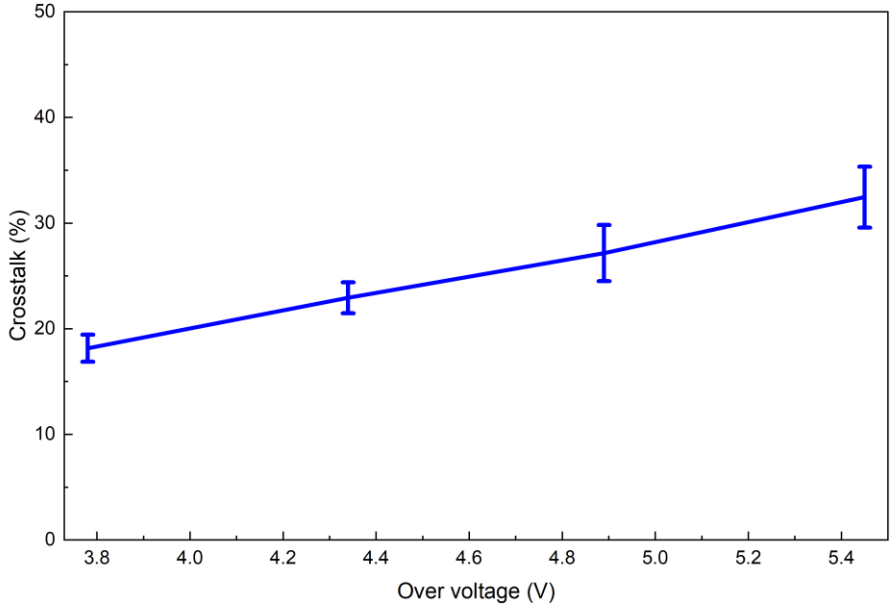
Data from the manufacturer's online datasheet

Key Performance Parameters of CPT EQR20 serious SiPM







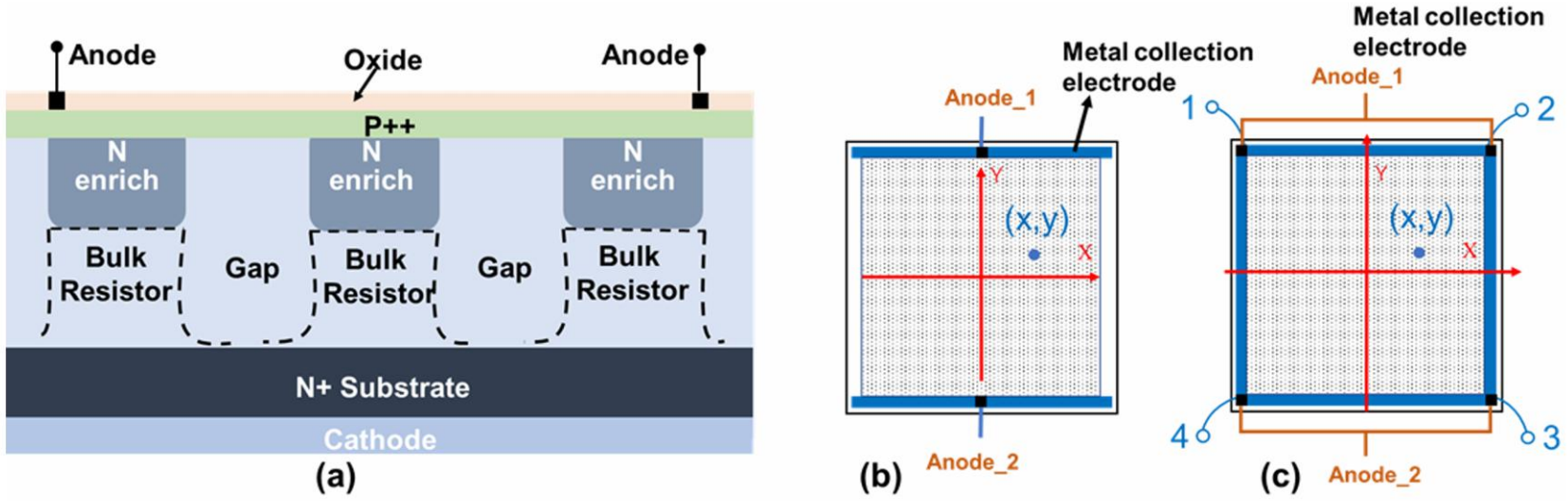


There is no "best" SiPM — only the one that best fits your needs.

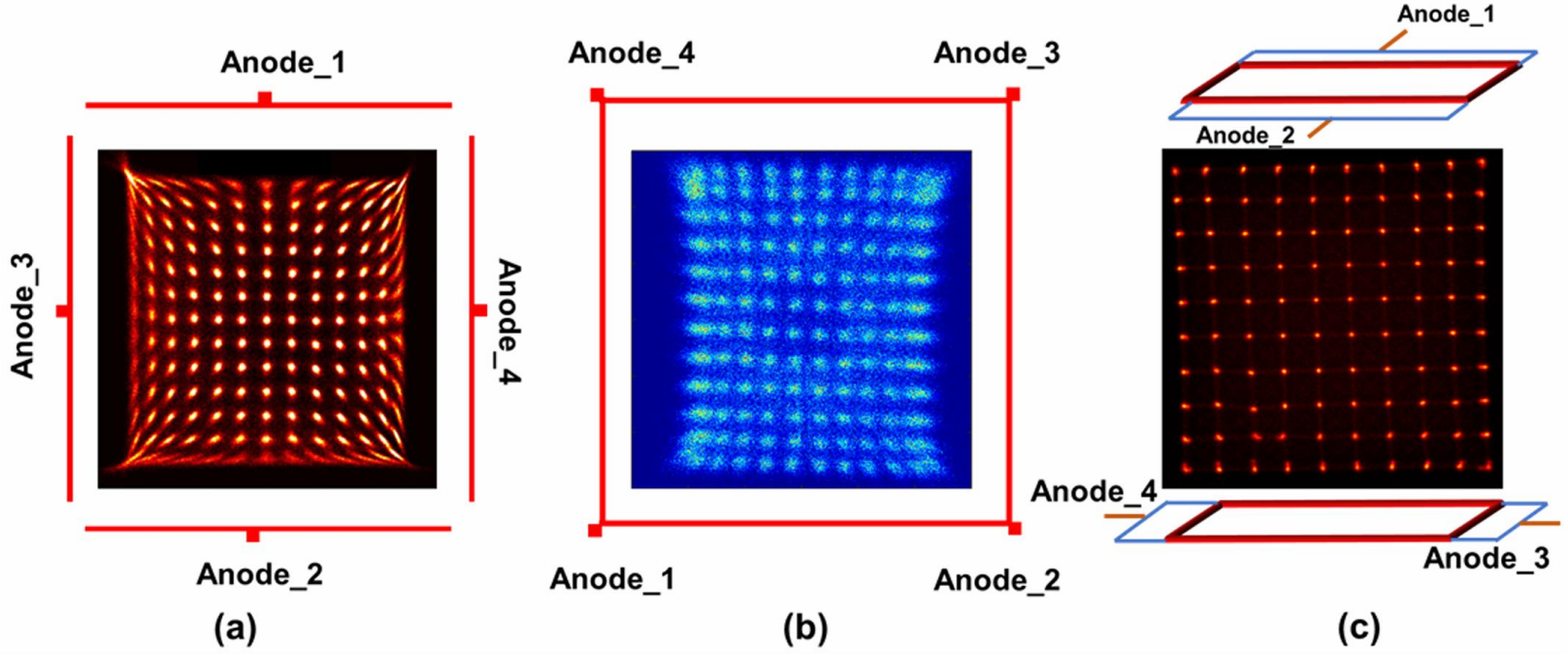
What are the application advantages that the unique features of EQR SiPM may bring?

Features	Application Advantages
Small cell	Large dynamic range while high PDE → high count rate while high energy resolution
High cell density	
Low Terminal Capacitance	Low electronic noise, Relative high and narrow pulse → pulse shape discrimination (PSD), high time resolution, high count rate
Fast recovery time	
1D/ 2D Position Sensitivity	High 3D space and time resolution with less readout channels → scintillating Fiber Tracker , high resolution PET/SPECT imaging, high resolution γ camera

CRL SiPM



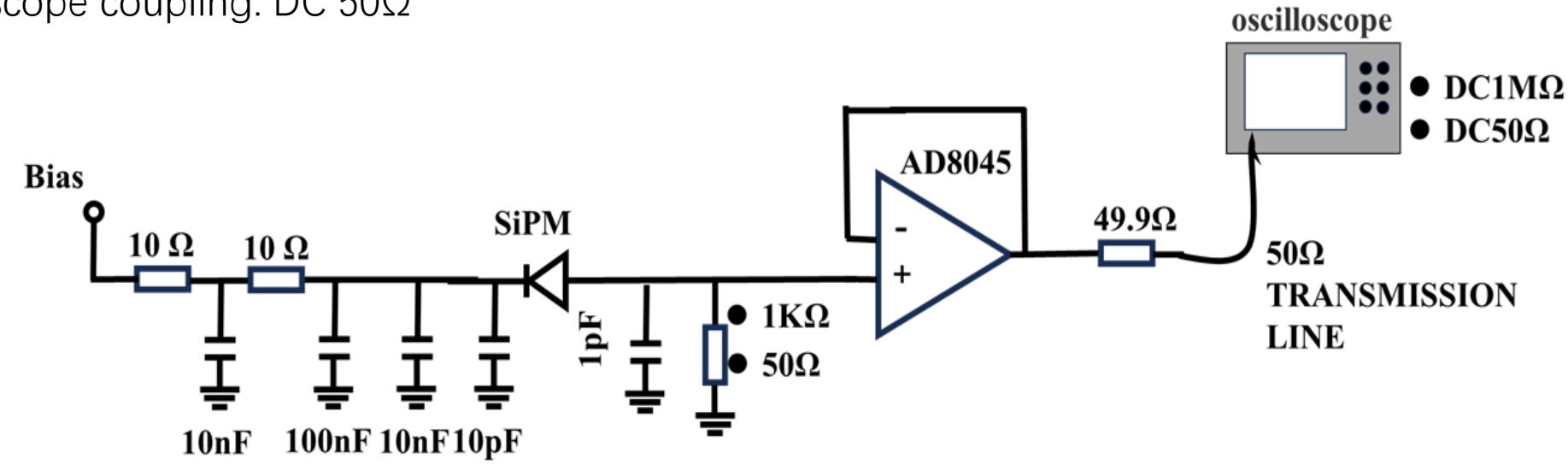
(a) Cross-sectional view of CRL SiPM with P-on-N structured.
(b) dual parallel side strip electrodes structure
(c) square shaped electrode structure.



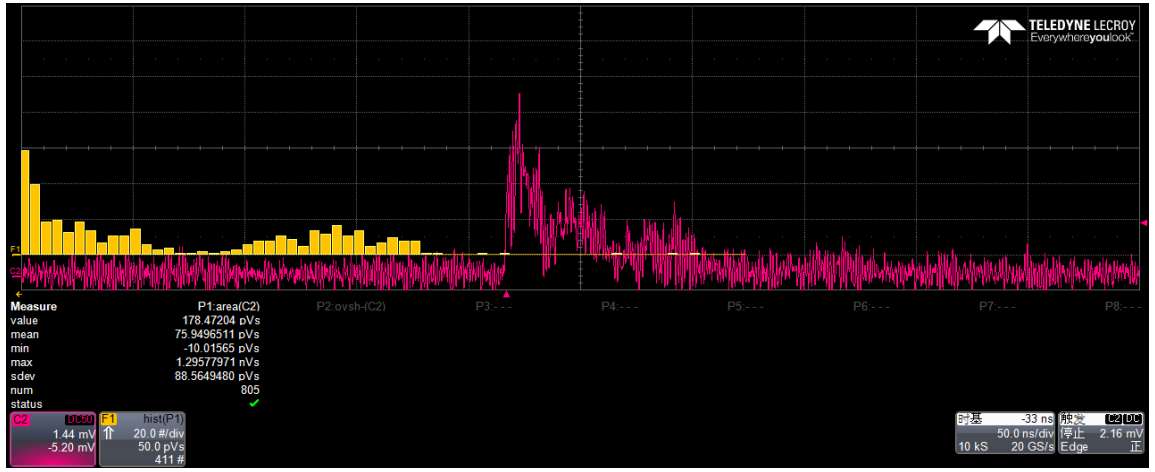
(a) 2D CRL SiPM with tetra-lateral electrodes→laser scanning image;
(b) 2D CRL SiPM with square electrode→intrinsic radioactive light image of a 12×12 LYSO array with each element 0.4×0.4×6 mm^3;
(c) two 1D CRL SiPMs with two perpendicular orientation on the two ends of a scintillator→ intrinsic radioactive-light image of a 10×10 LYSO array with each element 0.52×0.52×20 mm^3.

About the problem in CEPC ECAL proposal based on BGO and large dynamic range EQR SiPM—too narrow pulse and spikes along failing edge

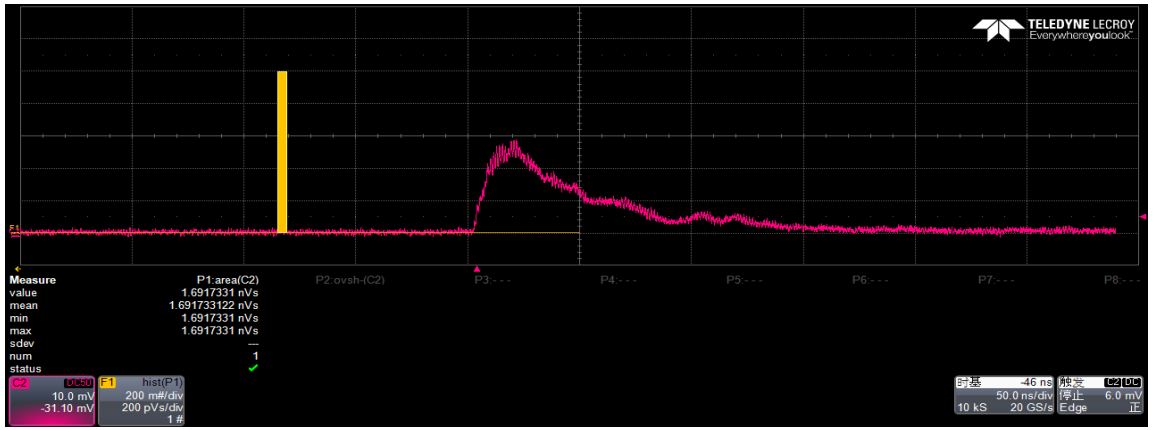
Device under test: EQR10 0.5mmx0.5mm
LYSO 0.42mm * 0.42mm * 1.5mm, Am241, 59.5keV特征射线
Oscilloscope coupling: DC 50Ω



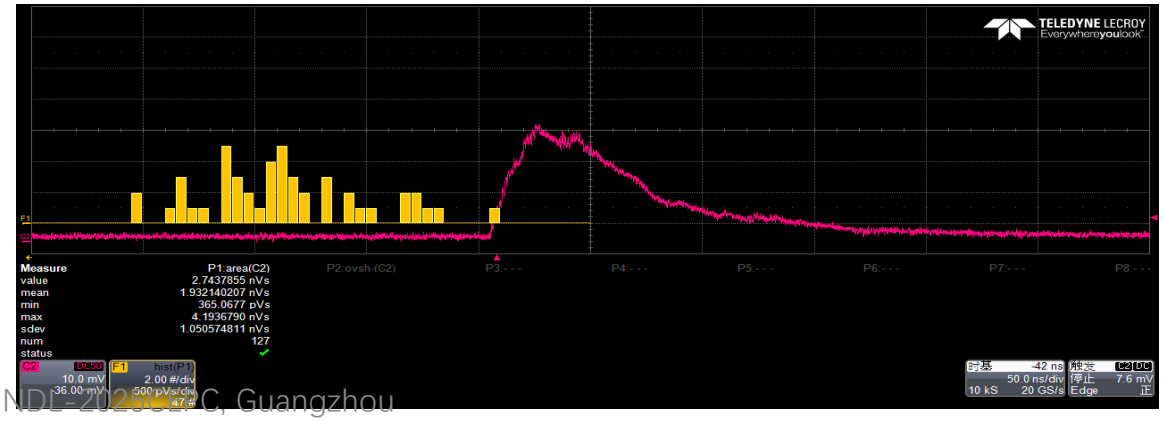
With the load resistor's resistance increase, the pulse intensity is getting increase, the width is getting wider and the failing edge is getting smooth



Load resistor=50 Ω



Load resistor=510 Ω



Load resistor=1000 Ω

Conclusion and Outlook

- With the setup of Capital Photonics Inc., the consistency and reliability of the EQR20 series SiPMs are improved steadily, the dark count rate and other key parameters are compatible to main vendors in the world
- Unique feature of EQR SiPM, such as small cell, high cell density, low terminal capacitance, fast recovery time, and 1D/2D position sensitivity may provide advantageous in various applications
- Next, in addition to continuing to improve the consistency and reliability of the EQR20 series, the PDE will be enhanced from 47 % to 55 %–60 % @ 420 nm.
- Mass production of EQR20 6060/4040/3030/2020/1010 and their array is available in Capital Photonics Inc.
- Customized EQR10/15 SiPMs will be supplied by NDL through MPW (multi-project wafer) shuttle runs every 3–4 months

Thank You for Your Attentions!

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