Feasibility of PET Detector Readout by High-Density Silicon Photomultipliers with Epitaxial Quenching Resistors

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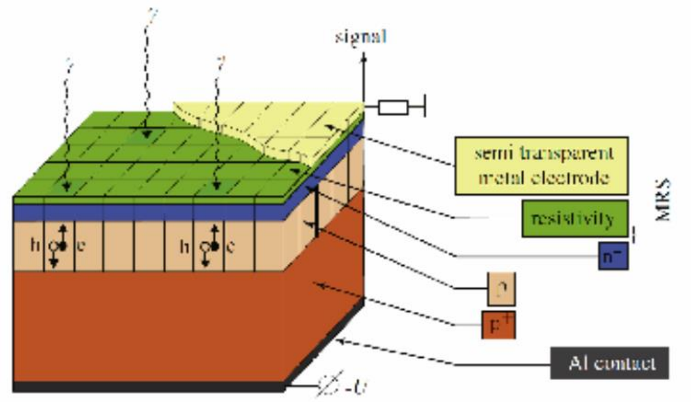
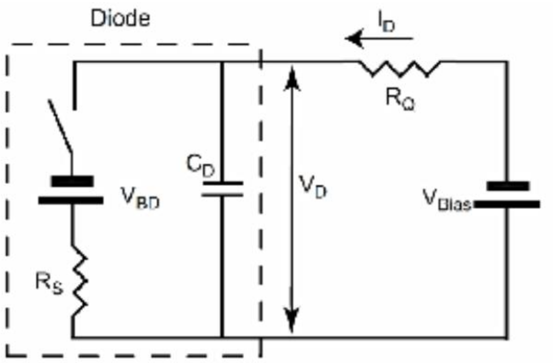
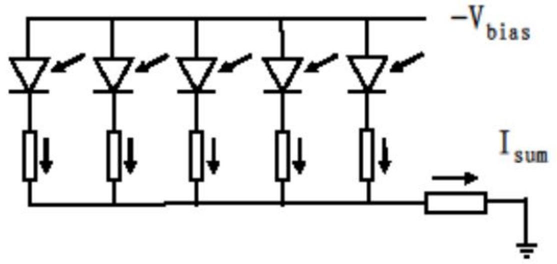
Outline

- Motivation
- NDL SiPM Technology
- Experimental setup
- Results & discussions
- Summary

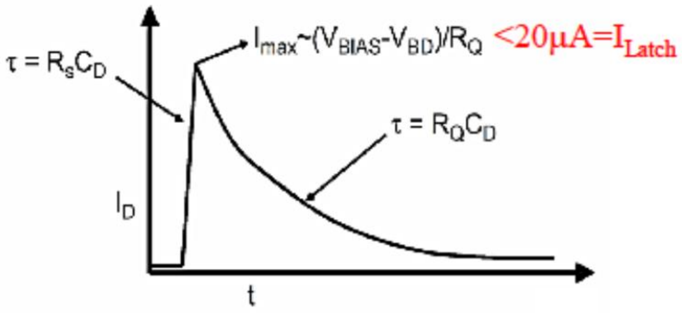
Silicon Photomultipliers, SiPMs







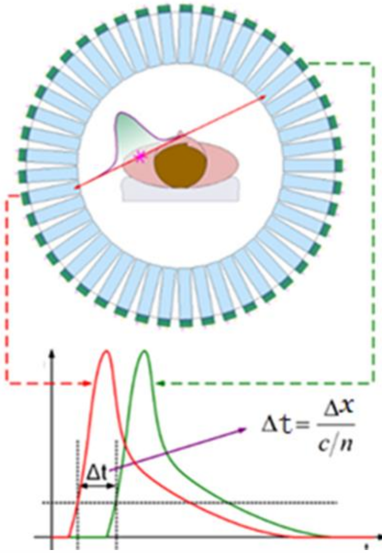
GAPD Array – Sum Individual Pixels



- ➢ High gain
- ➢ Photon number discrimination
- ➢ Insensitive to magnetic field
- ➢ Low bias voltage
- ➢ Excellent timing properties
- ➢ Small volume and robustness

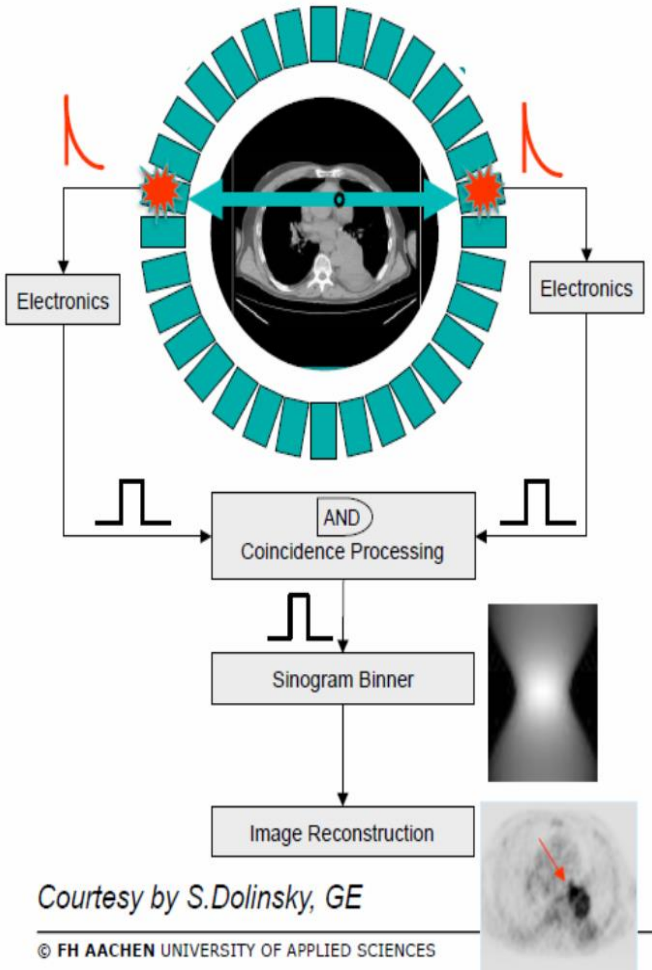
❖ **SiPMs replace PMTs and APDs in many low level light detection and sensing applications: particle physics, nuclear physics, nuclear medical imaging, etc.**

Positron Emission Tomography（PET）



PET = Positron Emission Tomography

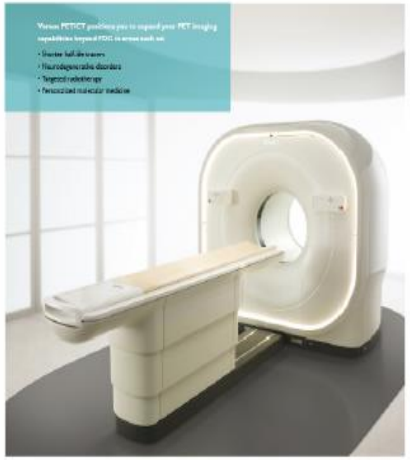
principle of operation



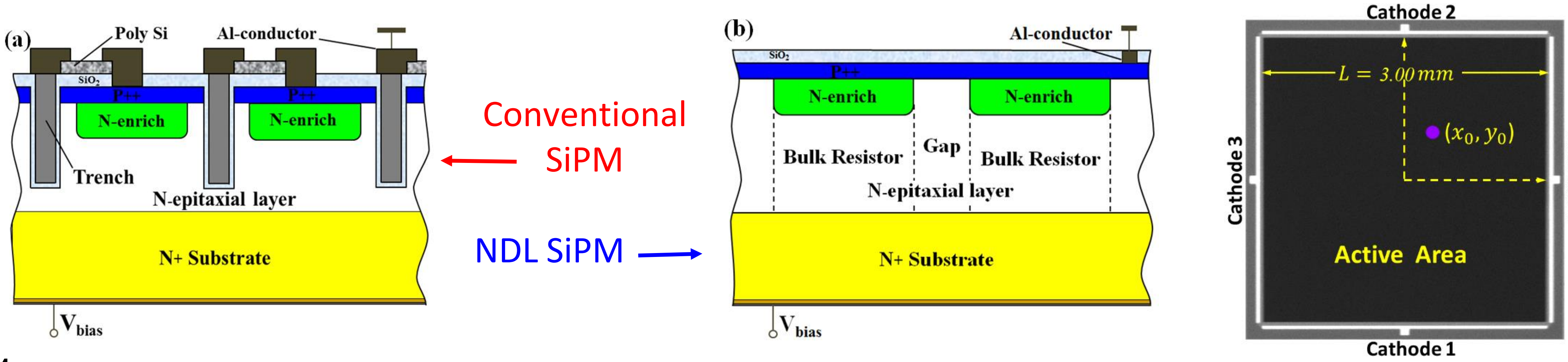
1. **Inject radiotracer**
2. **Detect** (scintillation detectors) two annihilation photons in coincidence
3. **Defines line** along which annihilation lies
4. **Collect** ~10^7-10^8 events
5. Use **reconstruction algorithms** to compute image of radiotracer distribution using multiple views of projection data
6. **Analyze data**
   a) *Lesion detection*
   b) *Quantify radiotracer distribution*
   c) *Tracer kinetics*

Courtesy by S.Dolinsky, GE

State-of-the-art ToF PET Scanners based on Slicon Photo-Multiplier (SiPM)

PHILIPS sense and simplicity	GE	SIEMENS Healthineers
Vereos	Signa PET/MR	Biograph Vision
		
TOF 345ps	TOF 380ps	TOF 249ps

Features of NDL SiPMs



Features

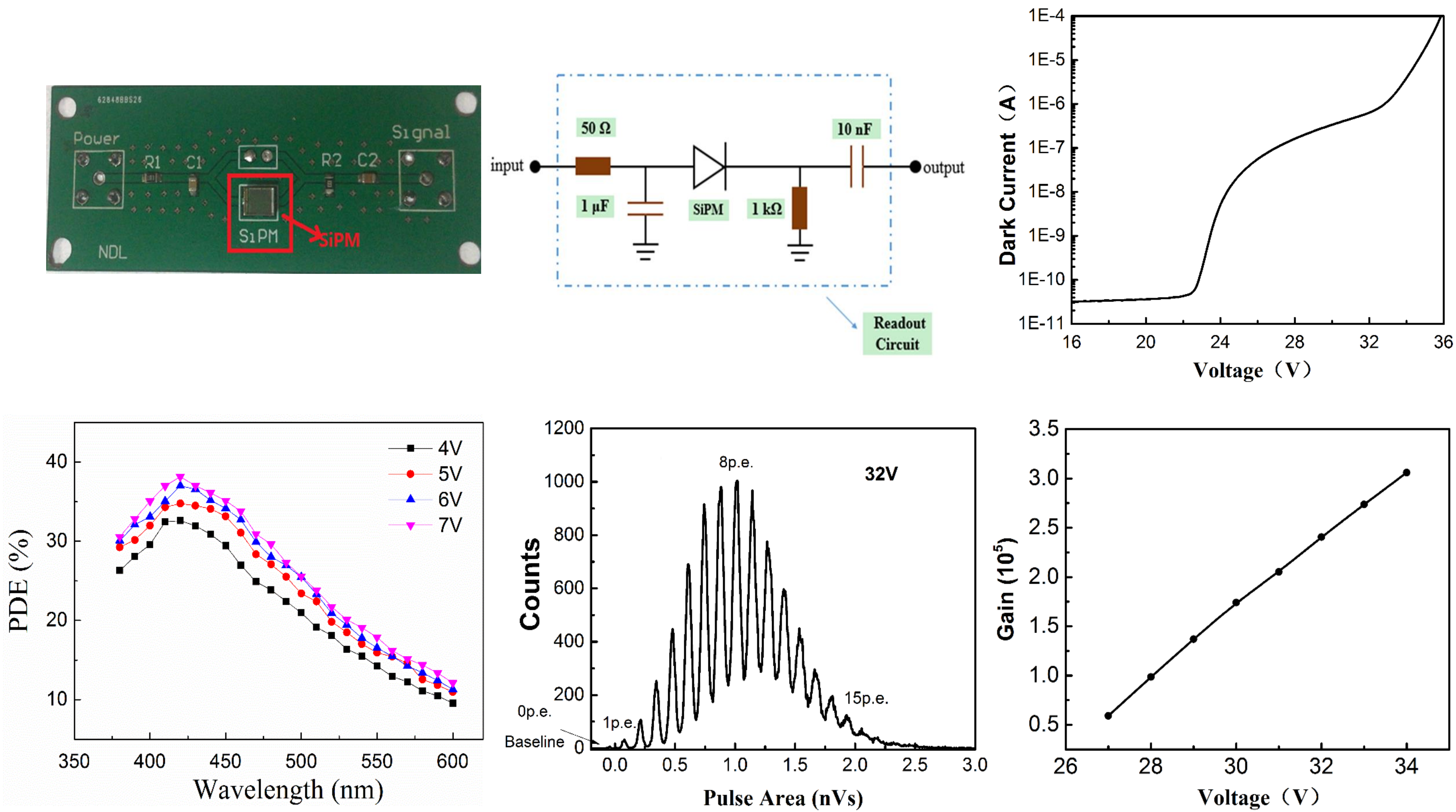
- The bulk resistor under each APD cell in the epitaxial layer is used as the quenching resistors
- A continuous cap resistive layer at the surface to connect all the micro APD cells

Advantages

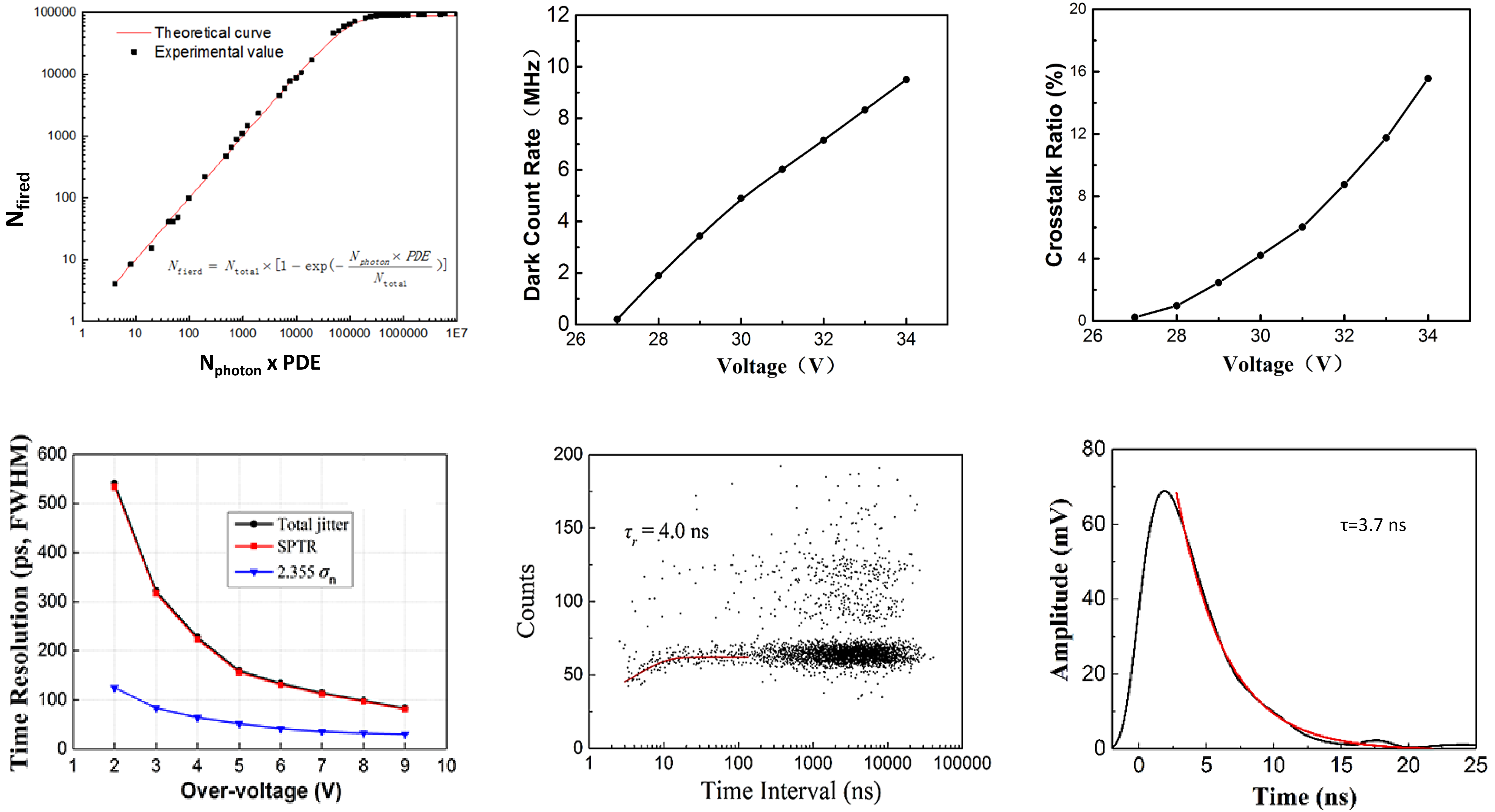
- Small micro cell and high micro cell density (thus large dynamic range) while retaining high fill factor and photon detection efficiency, fast response to even a single photon.
- No extra fabrication processes for quenching resistors are needed, thus simple fabrication technology and cost effective.
- **Easy to implement charge division mechanism to realize a position-sensitive SiPM**.

High-Density SiPMs with Epitaxial Quenching Resistors

Active area (mm^2)	3.0×3.0	**Microcell density**	90000 / mm^2
Gain	$\geq 2 \times 10^5$	**Dark count rate**	700 kHz / mm^2
Peak PDE	34% @ 420 nm	**Optical crosstalk**	～8 %
Breakdown voltage	27.5 ± 0.4 V	**Temperature coefficient for V_b**	25 mV/ ℃
Recovery time	~ 4 ns	**Single photon time resolution**	81 ps

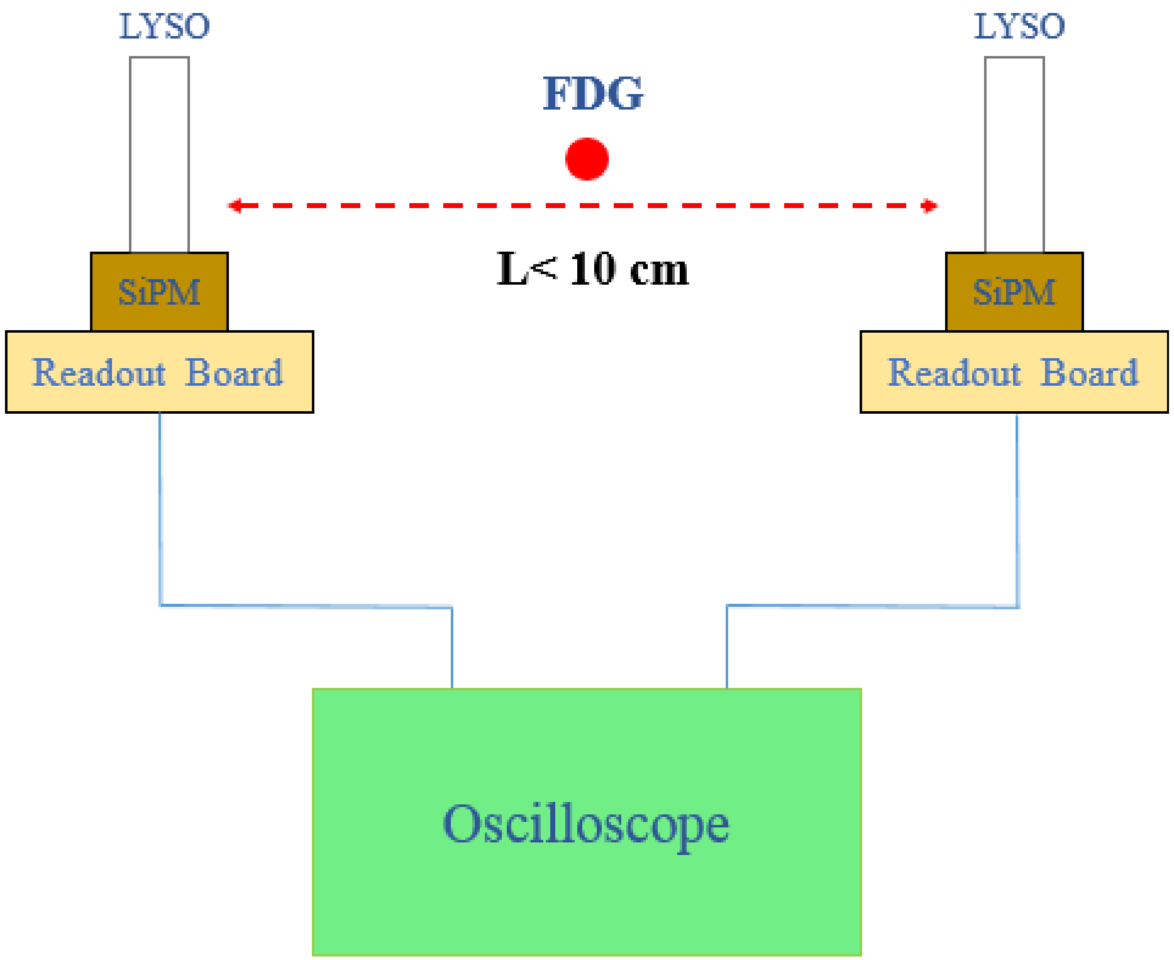


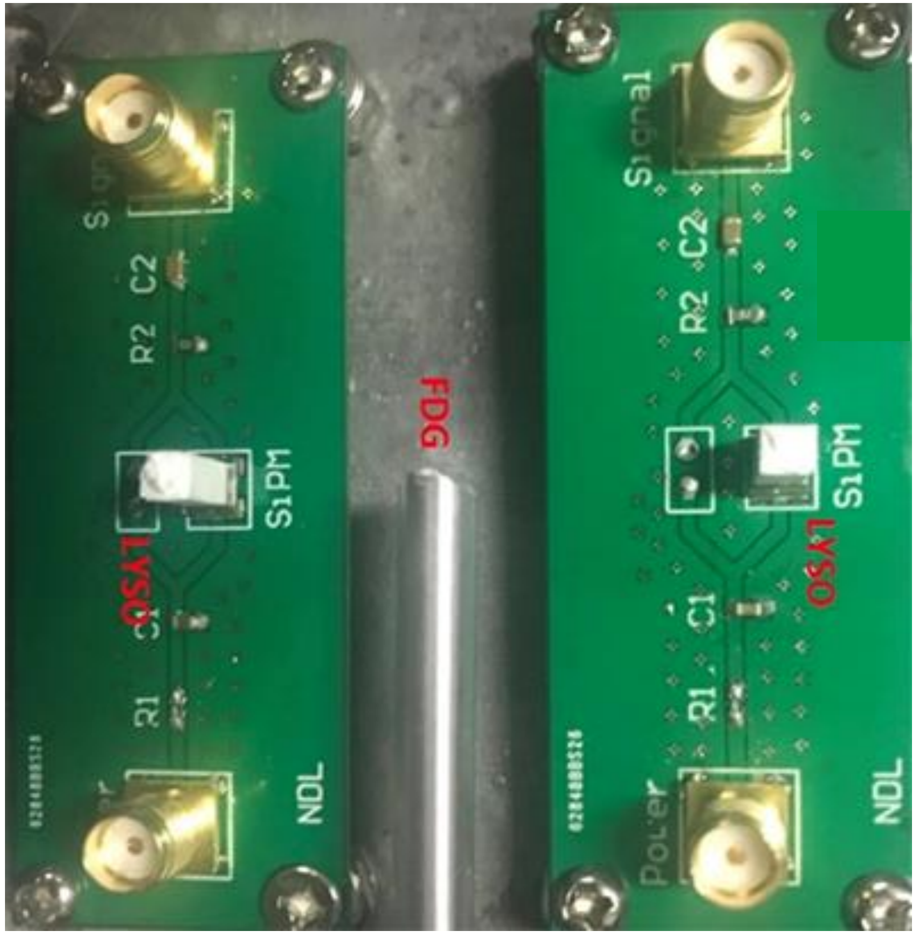
Power
R1
C1
R2
C2
Signal
SiPM
NDL
SiPM
input
output
50 Ω
1 μF
SiPM
1 kΩ
10 nF
Readout Circuit
Dark Current（A）
Voltage（V）
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
16
20
24
28
32
36
PDE (%)
Wavelength (nm)
4V
5V
6V
7V
Counts
Pulse Area (nVs)
32V
8p.e.
15p.e.
0p.e.
1p.e.
Baseline
Gain (10^5)
Voltage（V）



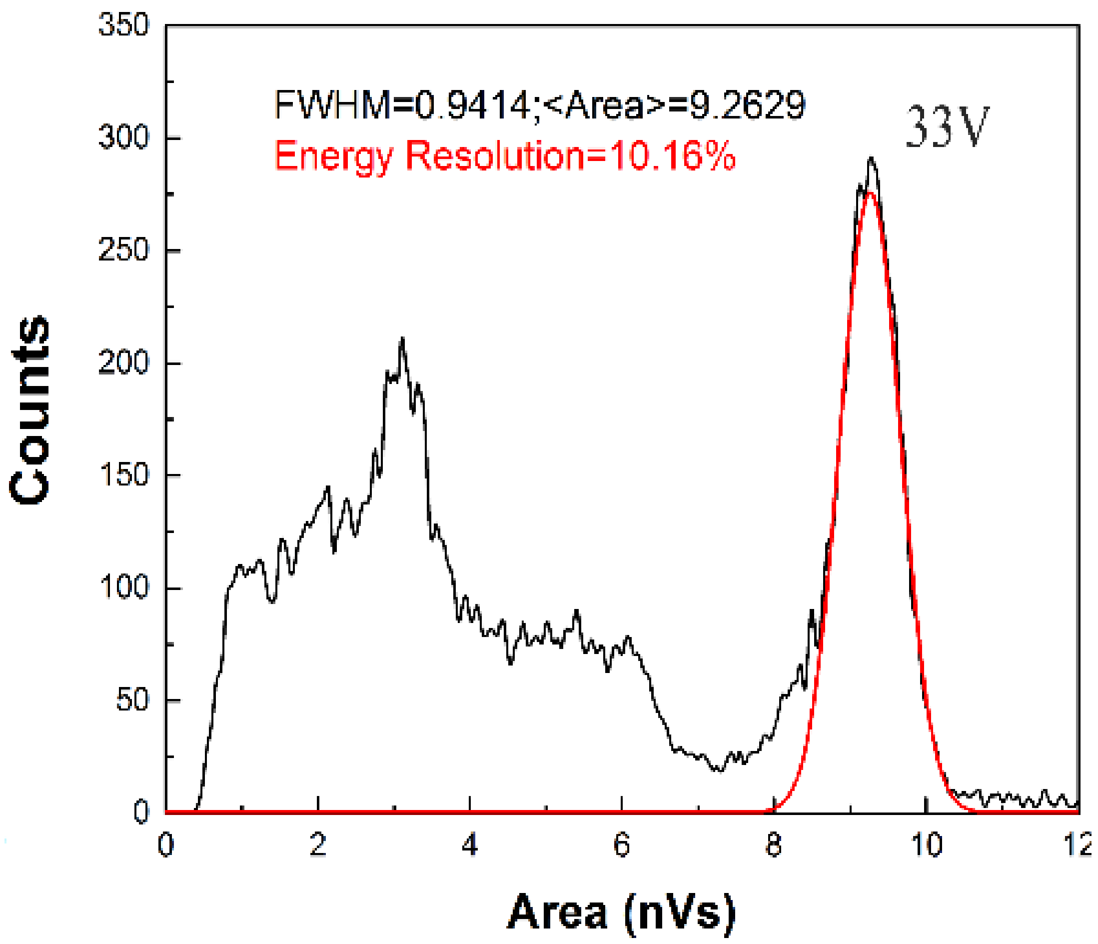
Theoretical curve
Experimental value
$N_{fierd} = N_{total} \times [1 - \exp(-\frac{N_{photon} \times PDE}{N_{total}})]$
N_{fired}
N_{photon} x PDE
Dark Count Rate（MHz）
Voltage（V）
Crosstalk Ratio (%)
Voltage（V）
Total jitter
SPTR
2.355 σ_n
Time Resolution (ps, FWHM)
Over-voltage (V)
$\tau_r = 4.0$ ns
Counts
Time Interval (ns)
τ=3.7 ns
Amplitude (mV)
Time (ns)

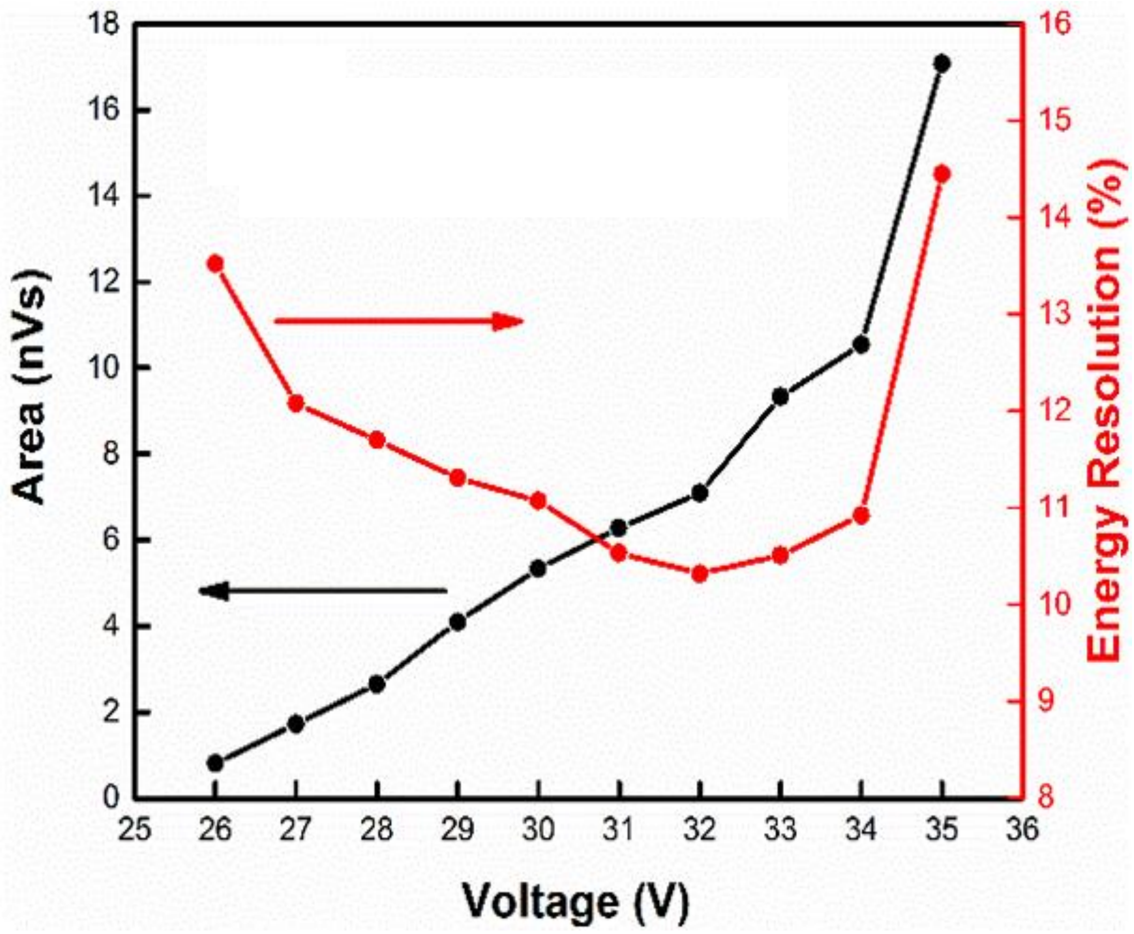
Experimental setup



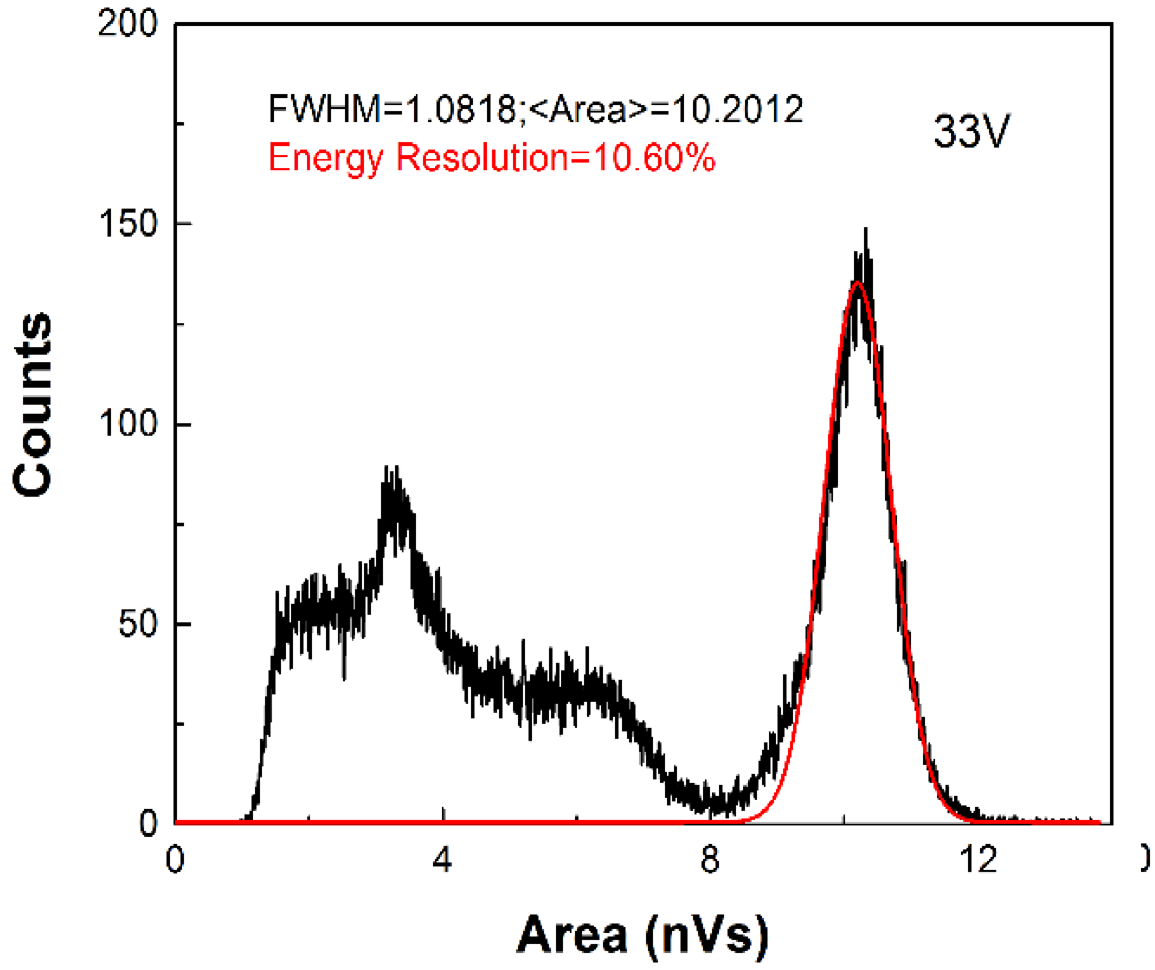


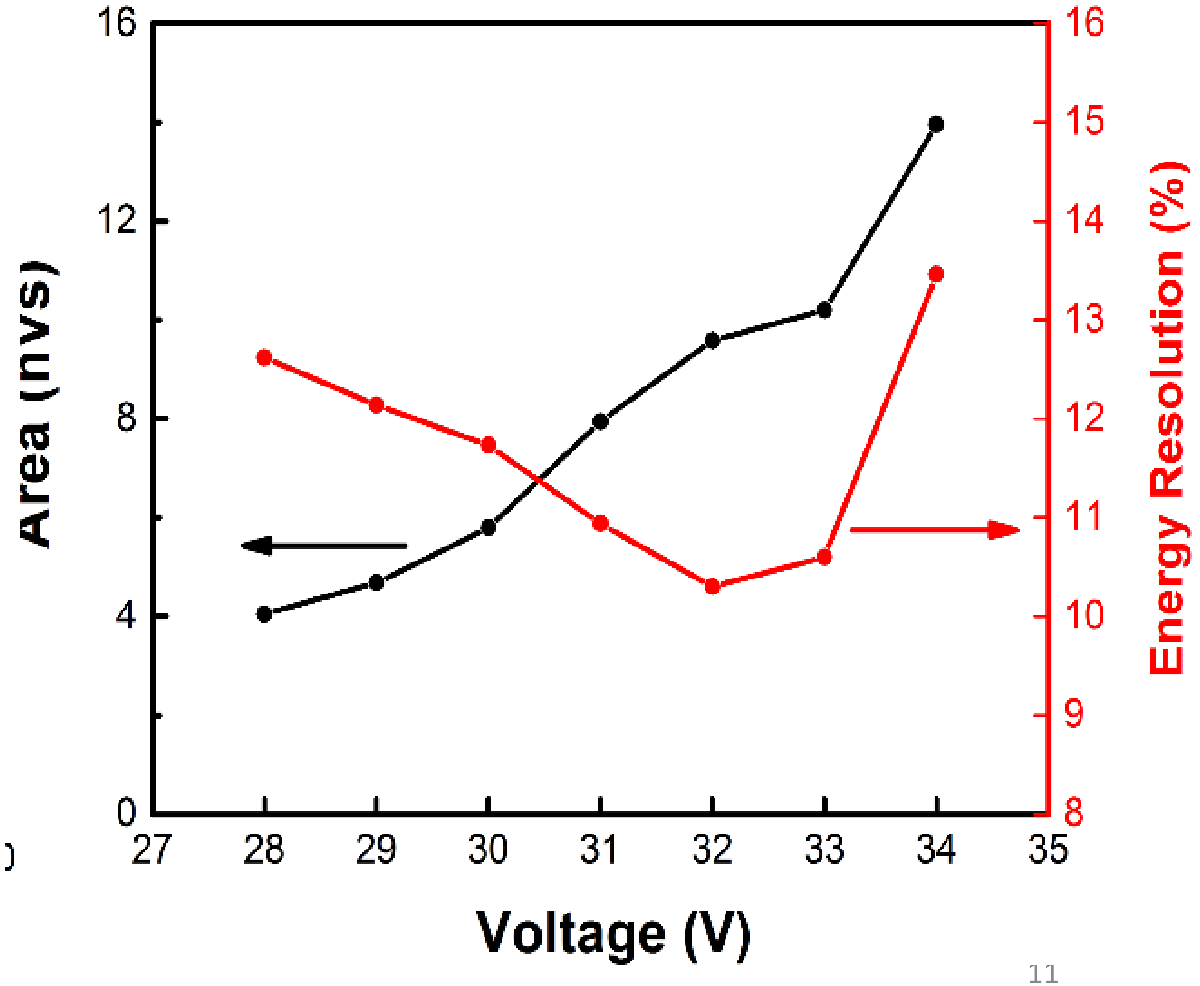
- Energy resolution (ER) of ~10.1 % , with the 2.84×2.84×6 mm^3 LYSO



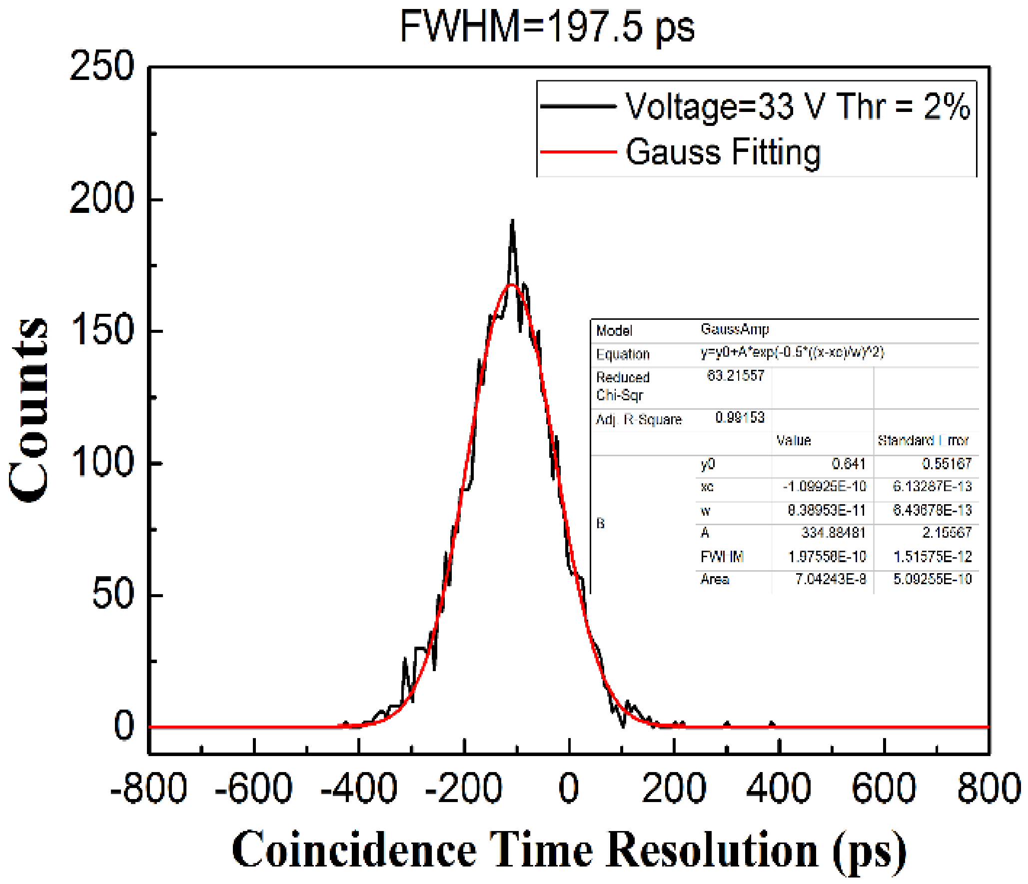


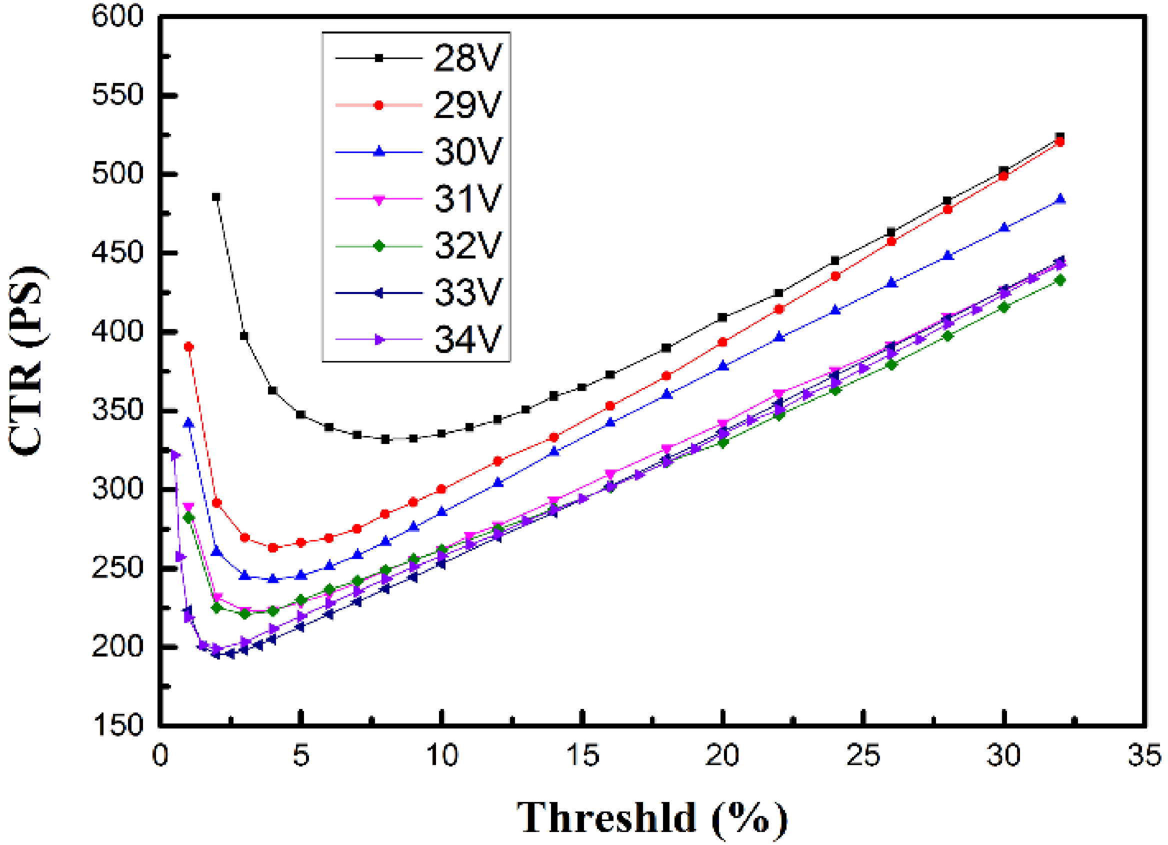
- Energy resolution (ER) of ~10.6 % , with the 2.84×2.84×10 mm^3 LYSO





Coincidence timing resolution (CTR) of ~195 ps (FWHM), with the 2.84×2.84×6 mm^3 LYSO





Summary

- NDL has been developing an unusual SiPM technology. It employs bulk resistor under each APD cell in the epitaxial layer as the quenching resistors, and a continuous cap resistive layer at the surface to connect all the micro APD cells.
- Its main advatages include:

➢Small micro cell, high micro cell density (thus large dynamic range) while retaining high fill factor and photon detection efficiency.

➢No extra quenching resistors and trenches fabrication steps, thus simple fabrication technology and cost effective.

➢Saturation effects involved in most commercial SiPM with limited micro cells is negligible. These results verify that EQR-SiPM is promising in applications of PET imaging.

➢Easy to implement charge division mechanism to realize a PS-SiPM.

- It is very suitable for applications such as preclinical PET and small animal PET , safety & security, and scientific researches, etc.

About Us

NDL (Novel Device Laboratory, Beijing)

Affiliated to Beijing Normal University and
Cooperated with Photoelectric Instrument Factory of Beijing Normal University, Beijing, China

Is committed to R&D of Silicon Photomultipliers for Low-Level-Light Detection Innovation

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High Density SiPM: SensL, Hamamatsu VS NDL

	NDL SiPM		SensL SiPM		Hamamatsu MPPC	
Effective Active Area	11-3030 C-S/T	11-1010 C-S/T	C-30020-SMT	C-10010-SMT	S12572-010-C/P	S12571-010-C/P
	3.0×3.0 mm^2	1.0×1.0 mm^2	3.0×3.0 mm^2	1.0×1.0 mm^2	3.0×3.0 mm^2	1.0×1.0 mm^2
Effective Pitch	10 μm	10 μm	28 μm	18 μm	10 μm	10 μm
Micro-cell Number	90000	10000	10998	2880	90000	10000
Fill Factor	40%	40%	48%	28%	33%	33%
Breakdown Voltage (V_b)	27.5±0.4V	27.5±0.4V	24.2-24.7	24.2-24.7	65±10V	65±10V
Measurement Overvoltage (V)	5	5	2.5	2.5	4.5	4.5
Peak PDE	31%@420nm	31%@420nm	24%@420nm	14%@420nm	10%@470nm	10%@470nm
Max. Dark Count (kcps)	~6000	~500	860	96	2000	200
Gain	2×10^5	2×10^5	1×10^6	2×10^5	1.35×10^5	1.35×10^5
Temp. Coef. For V_b	25mV/℃	25mV/℃	21.5mV/℃	21.5mV/℃	60mV/℃	60mV/℃

Potential Applications

High Energy Physics: Scientific Researches, such as scintillating fiber tracker (SciFi Tracker), hadronic calorimeter (HCAL) and electromagnetic calorimeter (ECAL) in high energy physics, need huge amount of SiPMs with large dynamic range and high resolution.

Preclinical PET: High density (10000/mm^2) SiPMs as PET detector readout, energy resolution (ER) of ~10.1 % and coincidence timing resolution (CTR) of ~195 ps (FWHM) were obtained with LYSO crystals.

Small Animal PET: 511keV gamma ray is detected by coupling a 5×5 array of 0.45×0.45×6 mm^3 LYSO crystals to the NDL PS-SiPM with an active area of 2.77×2.77 mm^2.

Safety & Security: NDL SiPM is attractive in safety and security area due to its large dynamic range (10^4/mm^2 micro cells) and linearity of high energy detections.


Thank You for
Your Attentions!