High-Density Silicon Photomultipliers with Epitaxial Quenching Resistors at NDL for Potential Applications in High Energy Physics

Kun Liang, Baicheng Li, Hongmin Liu, Yu Pen, Lei Dai, Ru Yang and Dejun Han

NDL (Novel Device Laboratory, Beijing)

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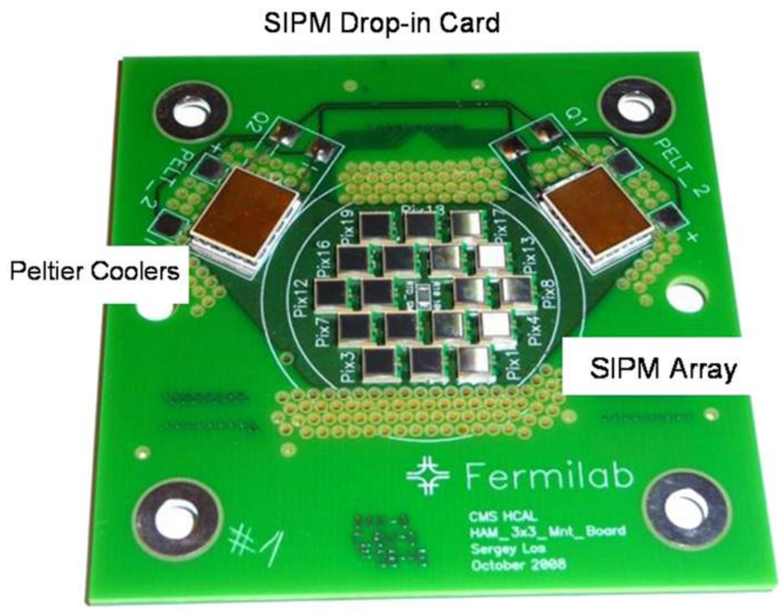
Outline

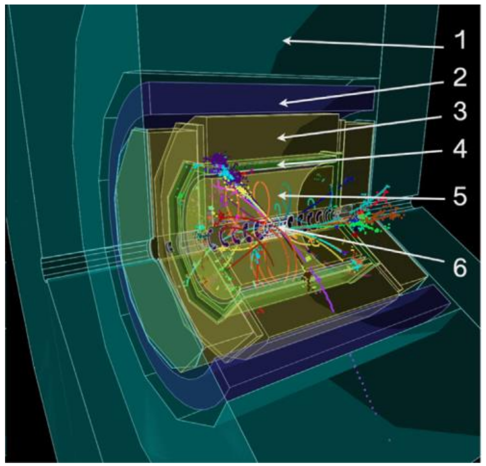
- Motivation
- Features of NDL SiPM Technology
- Results
- Conclusion

Motivation

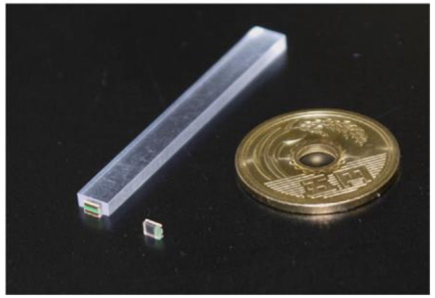
- Scientific Researches, such as hadronic calorimeter (HCAL), electromagnetic calorimeter (ECAL), or SciFi tracker in high energy physics, need huge amount of SiPMs with large dynamic range, or highly resolved imaging with fewer readout channels.



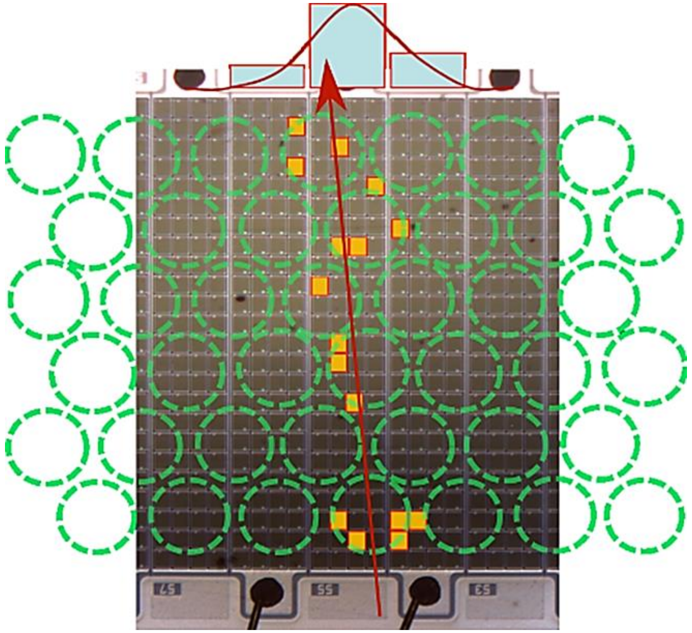
SiPMs for CMS **HCAL**



ECAL

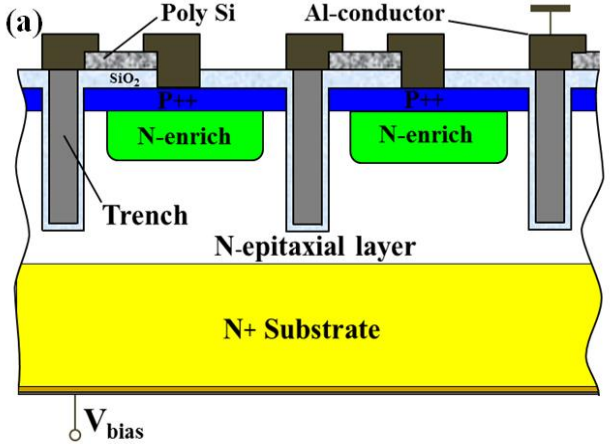


NIM A789(2015)158–164



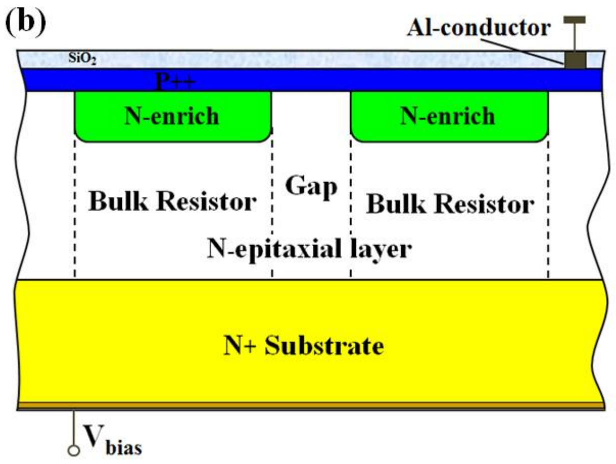
LHCb **SciFi tracker** with 1-D pixel SiPM array [NIM A, 2017]

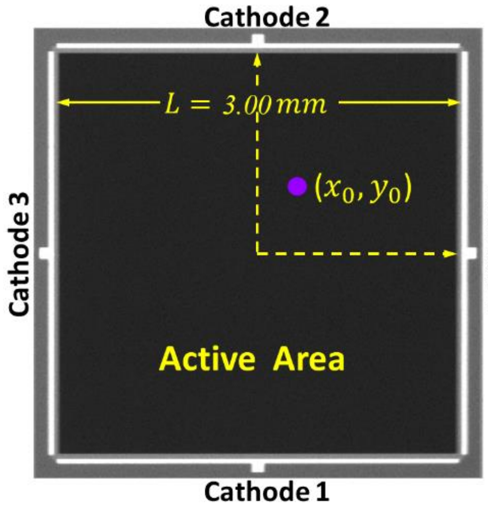
Features of NDL SiPMs



Conventional SiPM

NDL SiPM





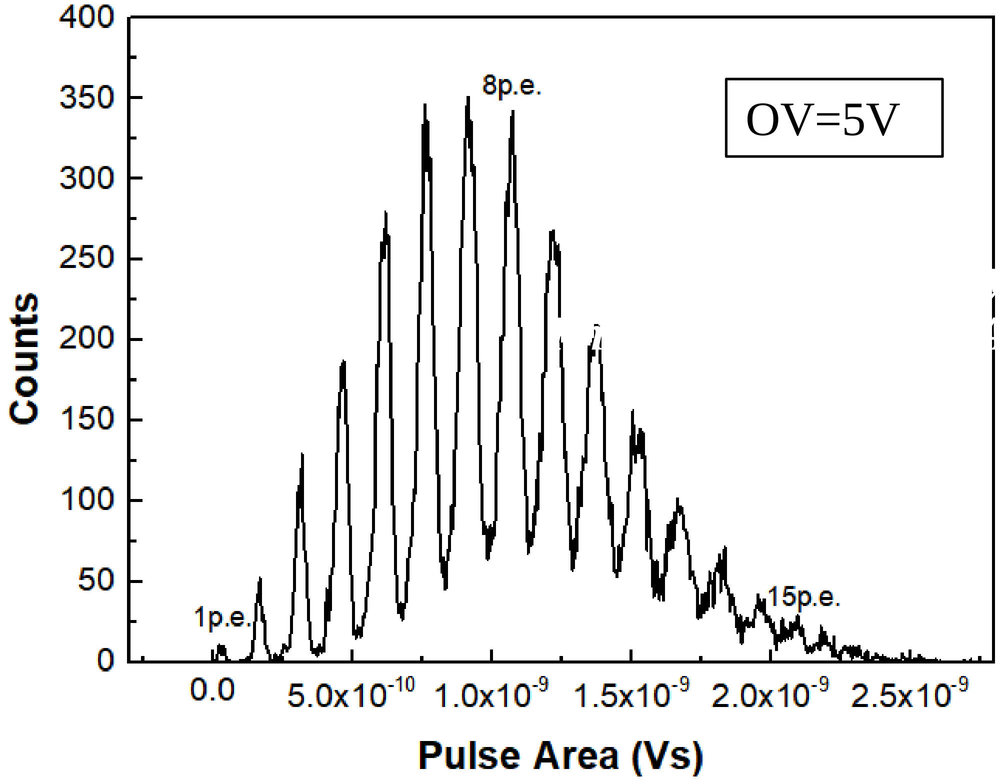
Features

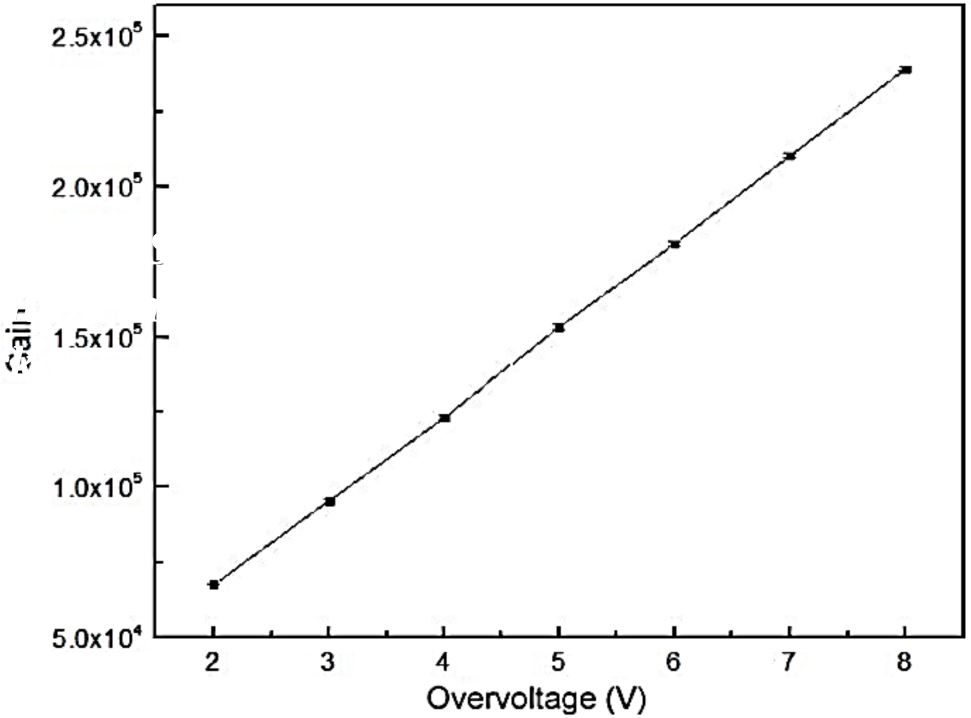
- The bulk resistor under each APD cell in the epitaxial layer is used as the quenching resistors
- A continuous cap resistive layer at the surface to connect all the micro APD cells

Advantages

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

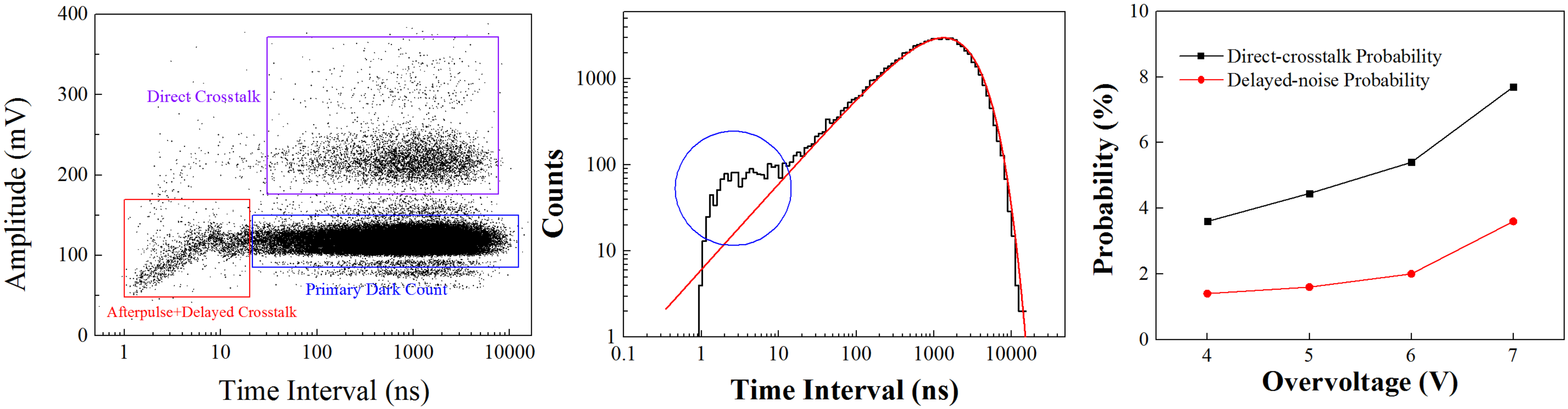
Results--Pulse Area Distribution and Gain





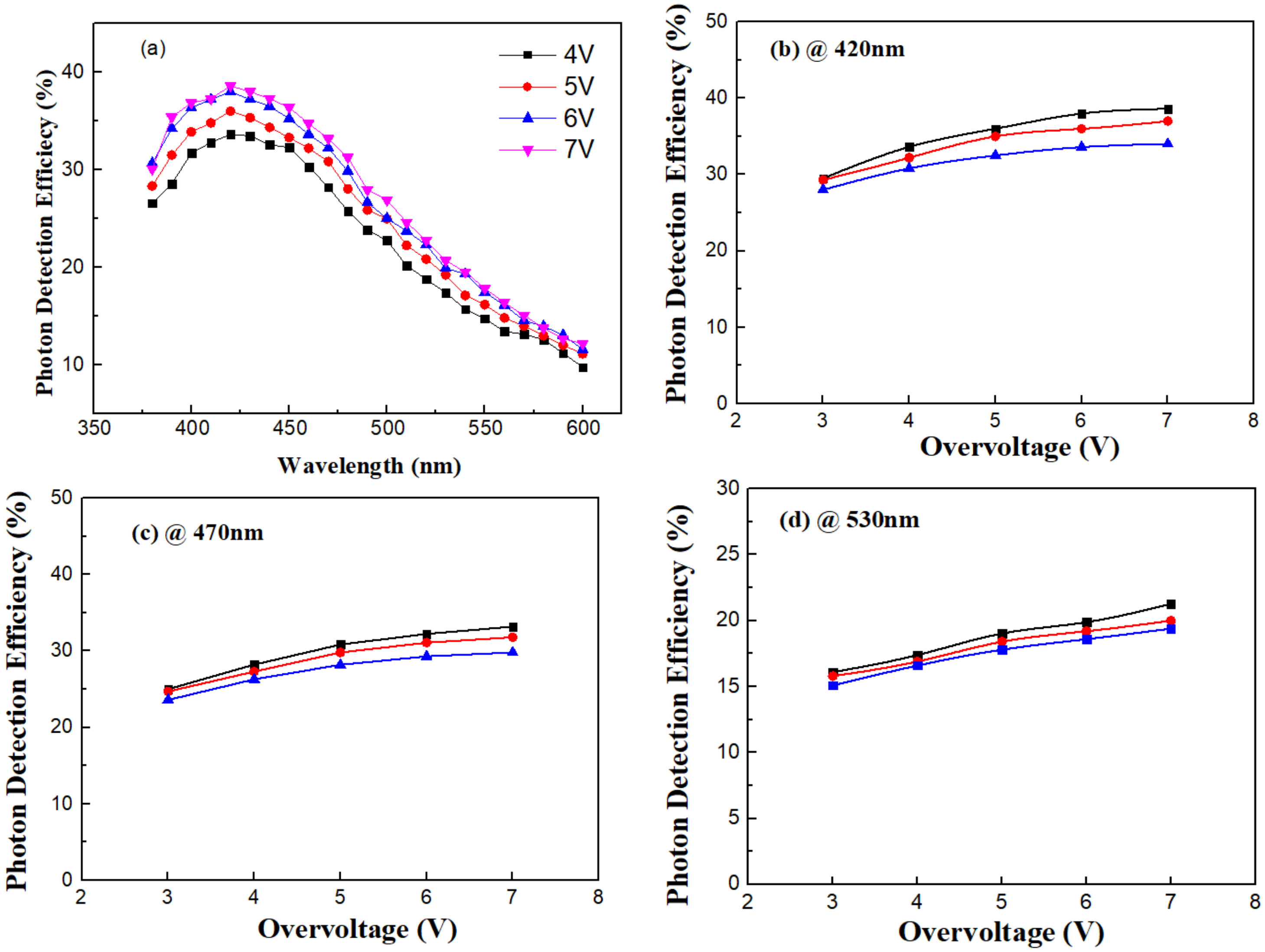
1×1 mm² NDL SiPM with pitch of 10 μm at 20°C

Results--Correlated Noise

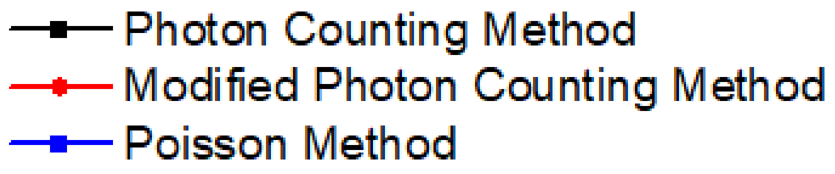


- The scatter plot analysis and the histogram distribution versus the time interval for dark pulses of 1×1 mm^2 NDL EQR SiPM with pitch of 10 μm under **7 V** overvoltage at **20°C**.
- The direct crosstalk probability and the delayed-correlated-noise probability was **7.7%** and **3.6%** respectively.

Results—Photon Detection Efficiency

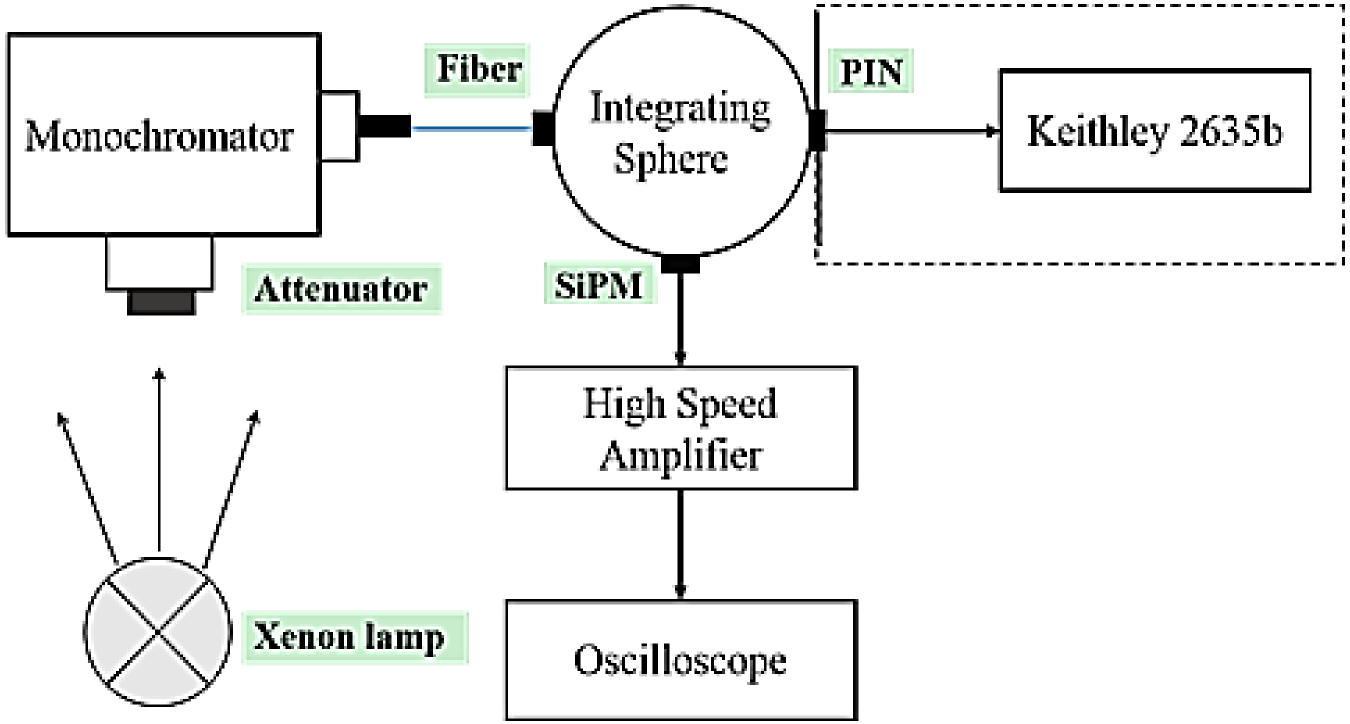


- 1×1 mm^2 NDL SiPM with pitch of 10 μm at 20^{o}C.
  - (a) PDE measured by photon counting method at different overvoltage.
  - (b), (c) and (d) are measured by different methods at 420nm, 470nm and 530nm. The over-voltage are 7V.



Characterization of PDE

Photon Counting Method: based on counting photon response pulses of random low level light



$$PDE(\lambda)=\frac{CR_{total}(\lambda)-DCR}{N_{in}}\times 100\%=\frac{(CR_{total}(\lambda)-DCR)\cdot R(\lambda)\cdot h\cdot c\cdot S_{PIN}}{I(\lambda)\cdot\lambda\cdot S_{SiPM}}\times 100\%$$

Characterization Method

Poisson Method: According to the Poisson statistical principle, the average number of photoelectrons before and after illumination is obtained, so that the number of net photoelectrons is obtained, and PDE is obtained according to the following formula.

Average number of photons detected per pulse

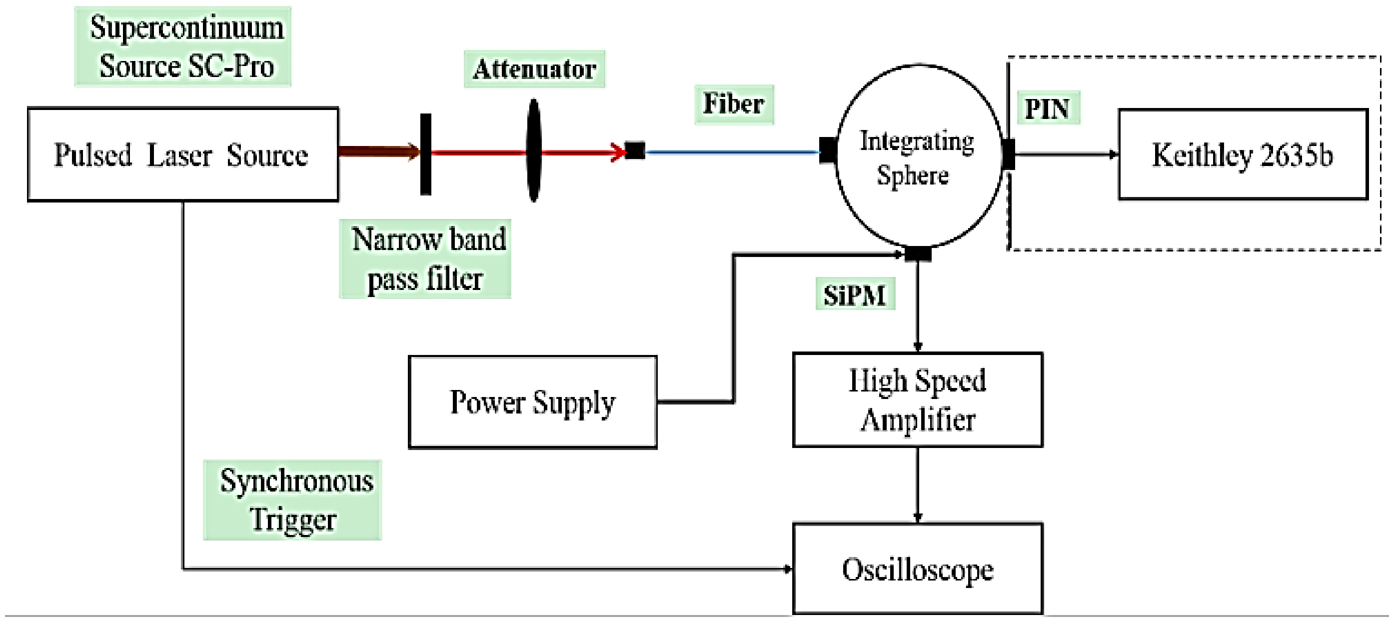
$$\mu = -ln\frac{N_0}{N_{total}}$$

Average net photoelectron number

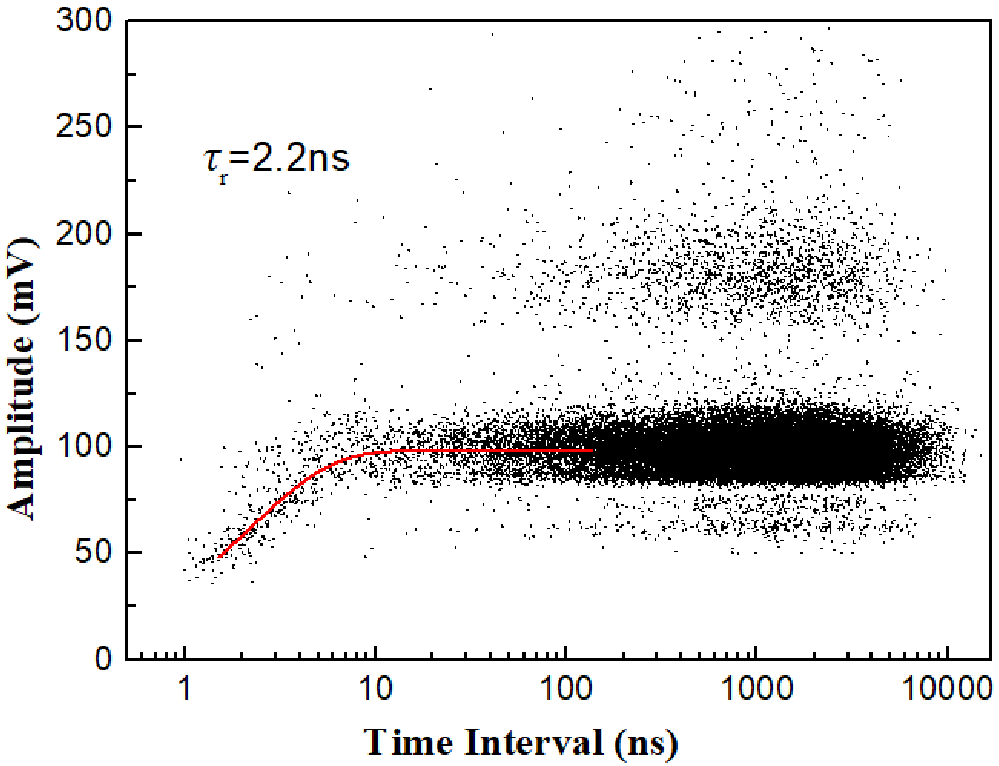
$$\mu = \mu_{light} - \mu_{dark} = -ln\frac{N_0}{N_{total}} + ln\frac{N_0^{dark}}{N_{total}^{dark}}$$

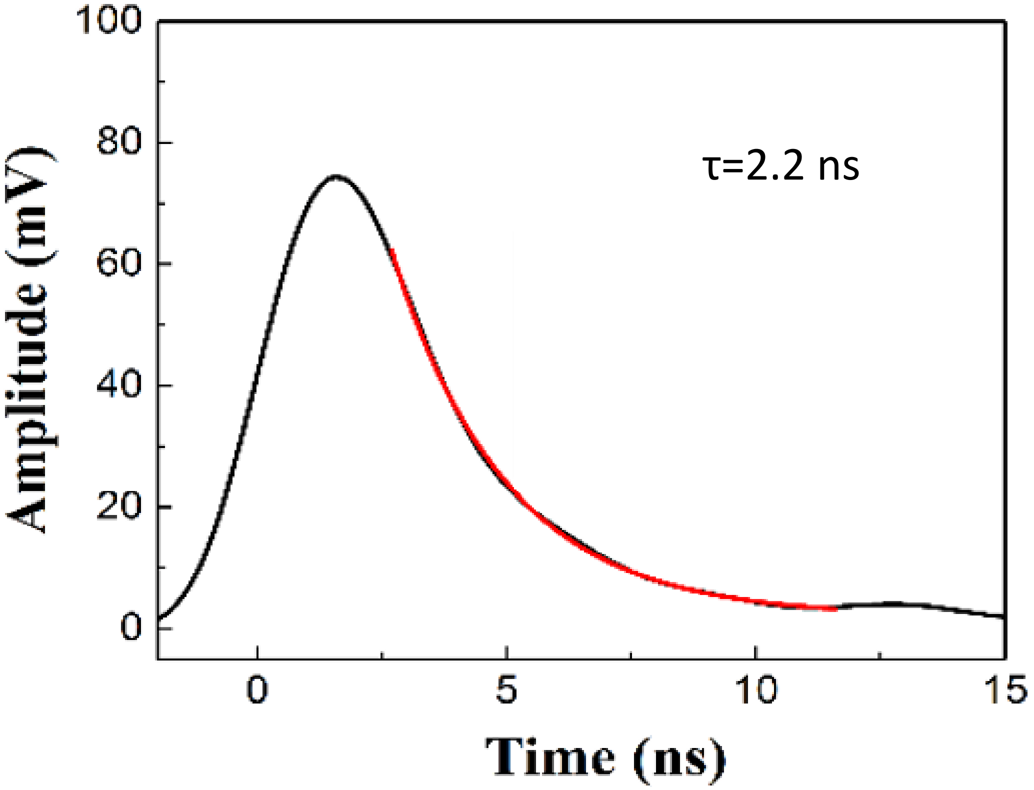
Average number of incident electrons

$$N_{in} = \frac{I_{PIN}\cdot\lambda}{R(\lambda)\cdot f\cdot h\cdot c}\cdot\frac{A_{SiPM}}{A_{PIN}}$$



Results-- Recovery Time

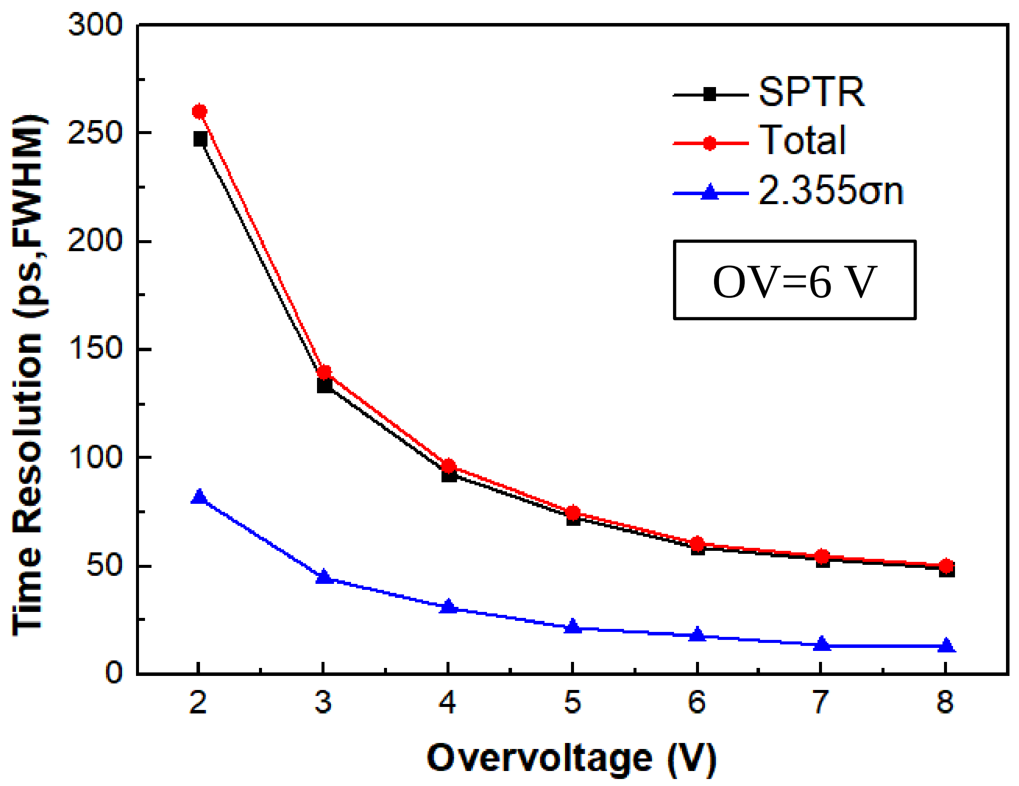


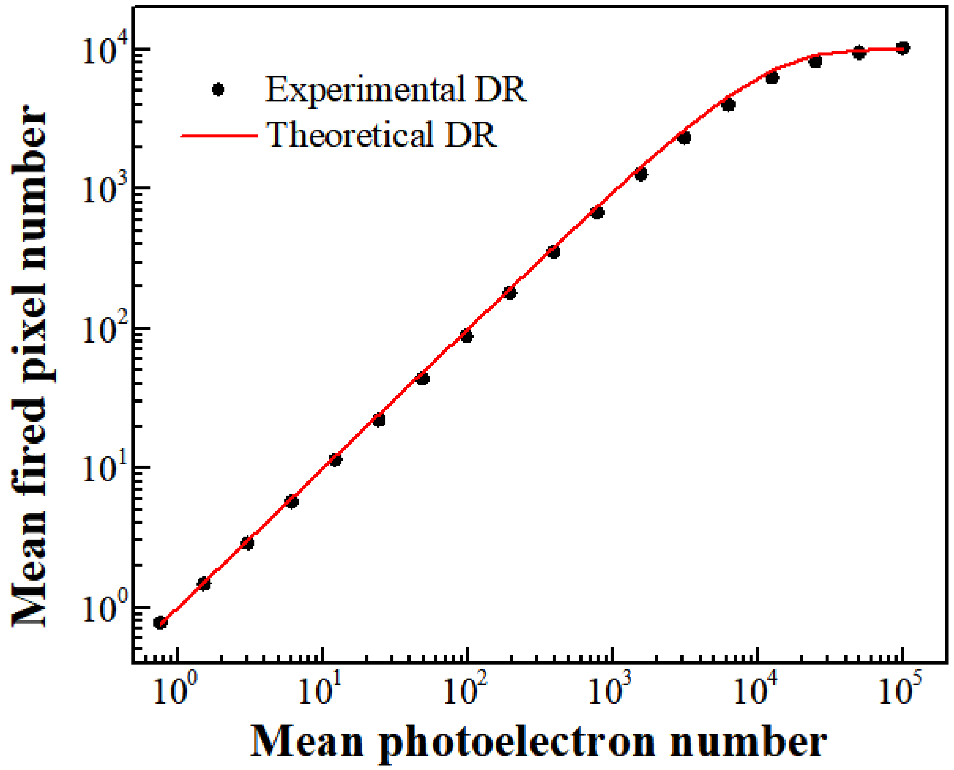


The recovery time of 1×1 mm^2 NDL EQR SiPM with pitch of 10 μm obtained by performing the noise scatter plot analysis (left) and the fitting for pulse falling edge (right) is **2.2 ns**.

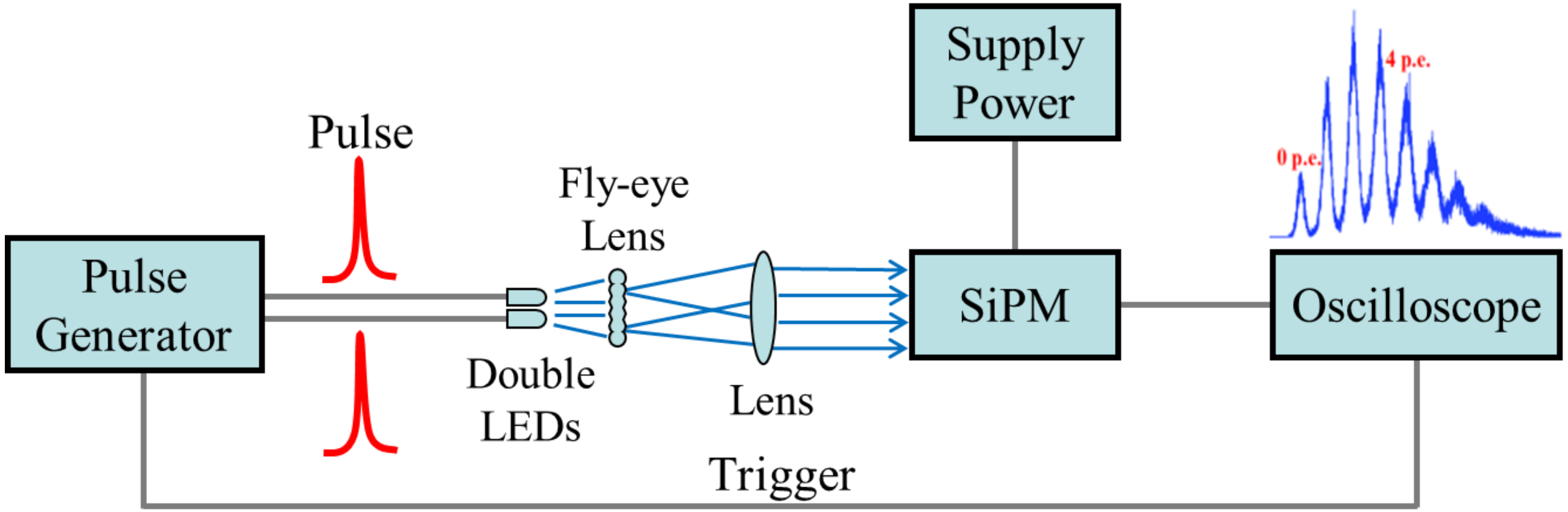
Results— SPTR and Dynamic Range

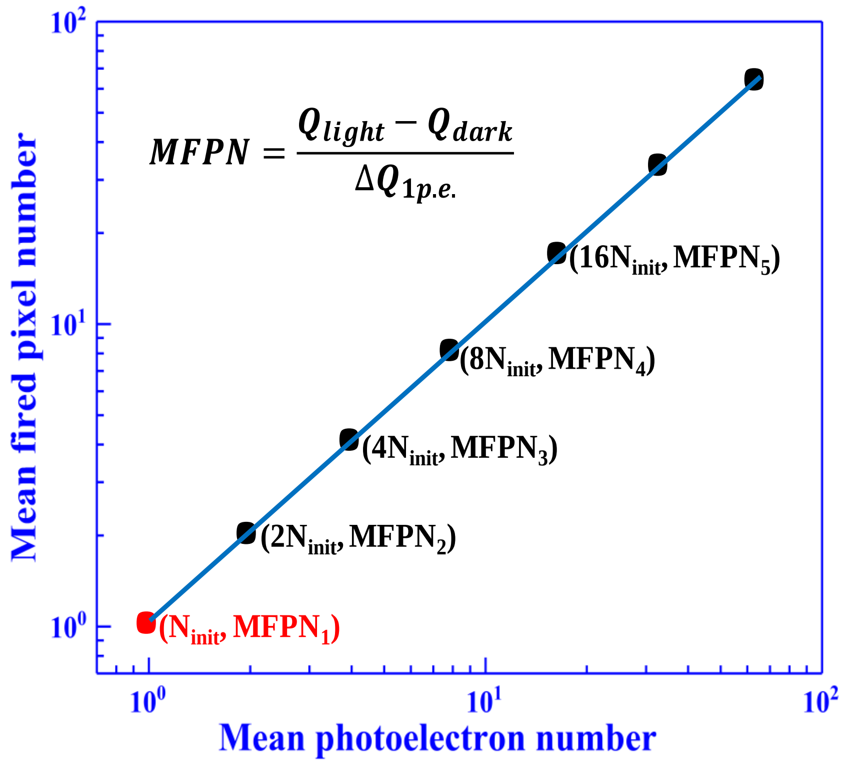
- SPTR of NDL 1×1 mm² SiPM with pitch of 10 μm is ~60 ps.





Double Light Superposition Method for Dynamic Range Calibration





Features

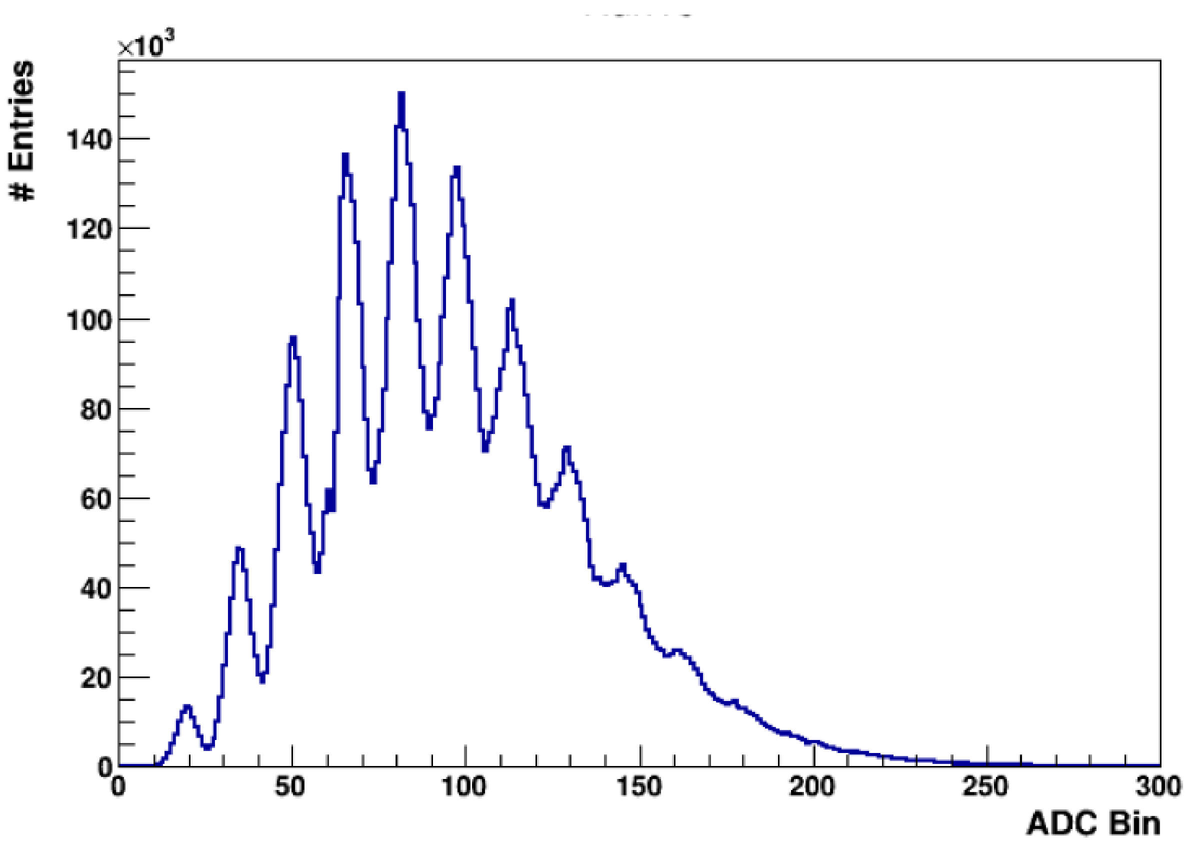
- **To measure the intrinsic non-linearity of SiPM in a self-calibration way using the same test device without external calibration**
- **Compatible to characterize the recovery time**

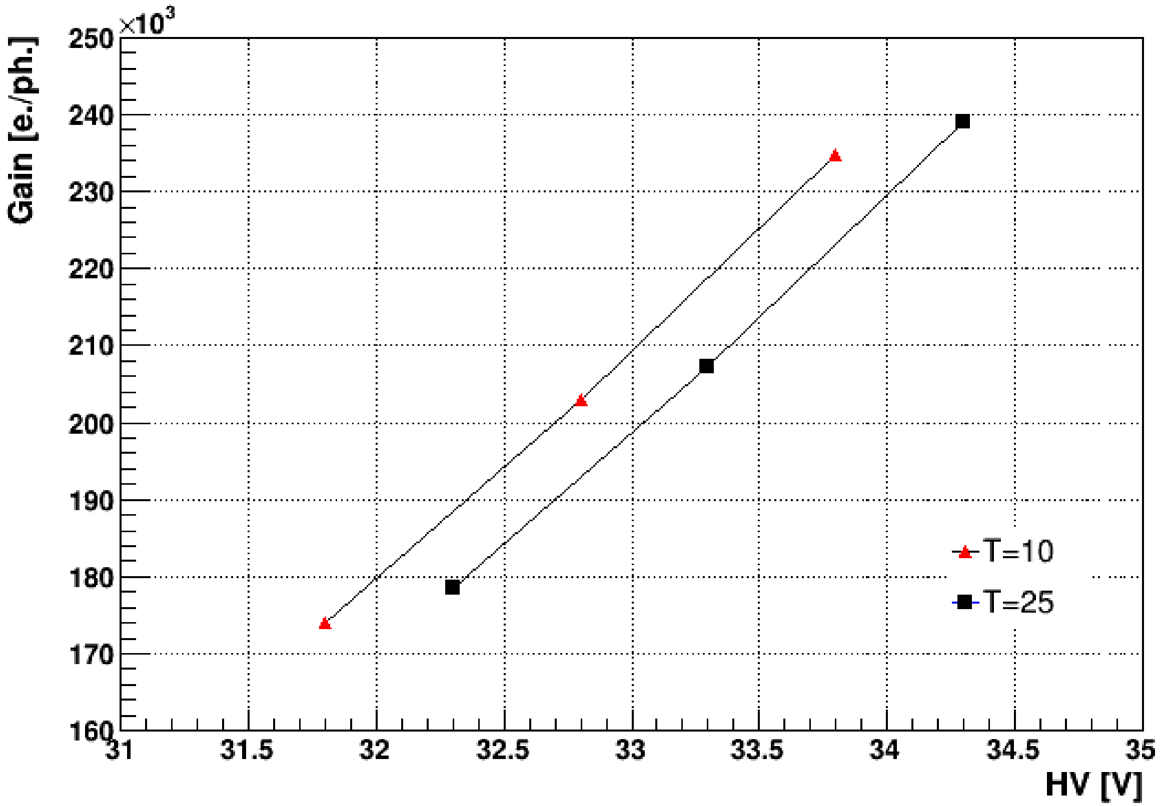
J. Liu, et al., "Dynamic Range Characterization of SiPM with a Double Light Superposition Method", ICASiPM, Schwetzingen on June 11-15, 2018, in Germany

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/℃

NDL 11-1010C SiPM Readout by KlauS ASIC

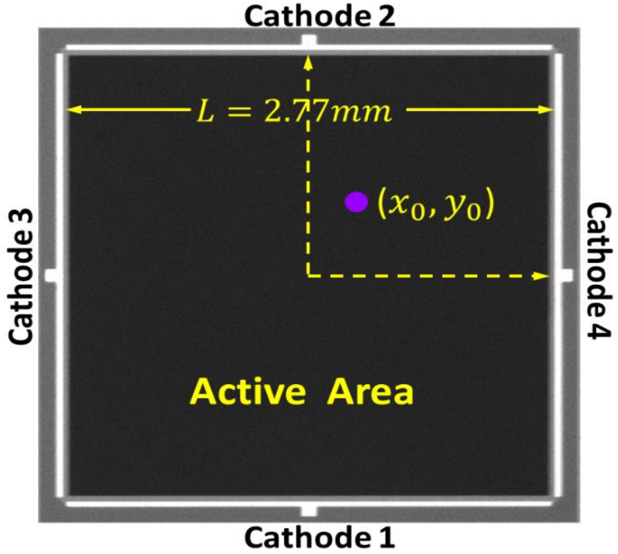


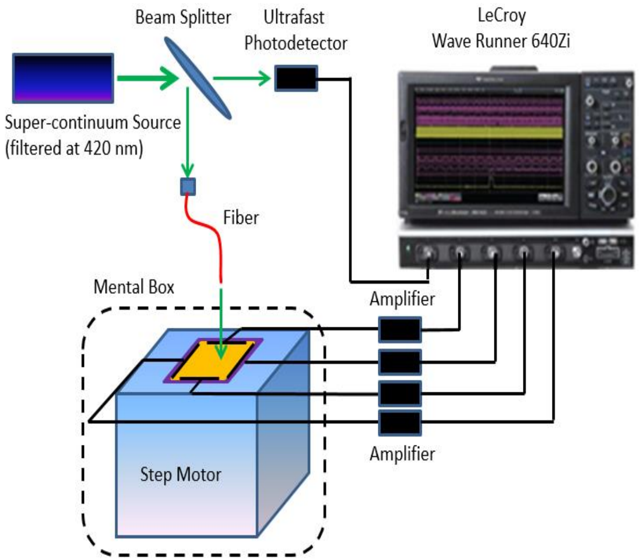


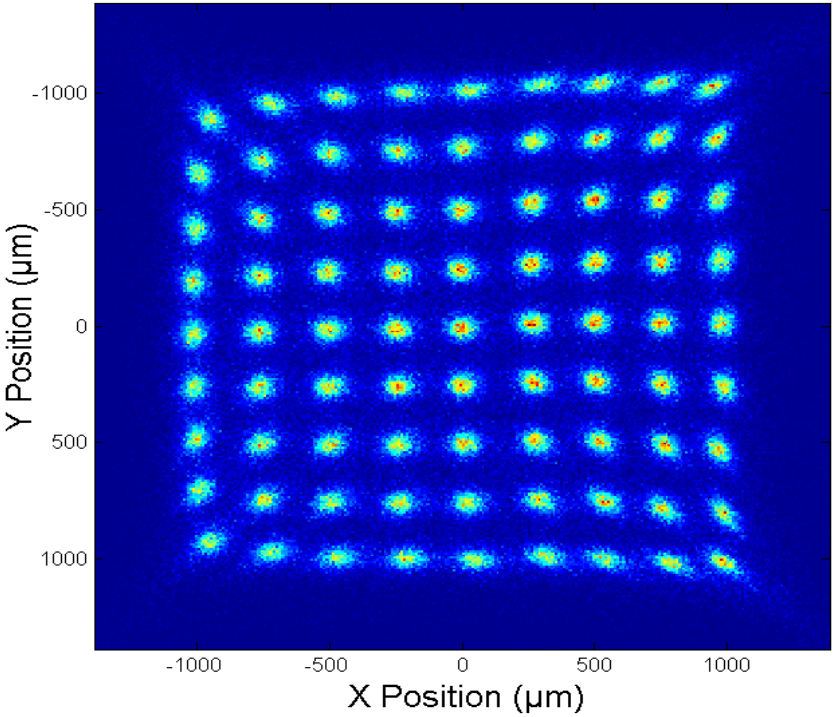
Provided by the KIP, Heidelberg University

KlauS5: A 36-channel low power silicon photomultiplier charge readout ASIC

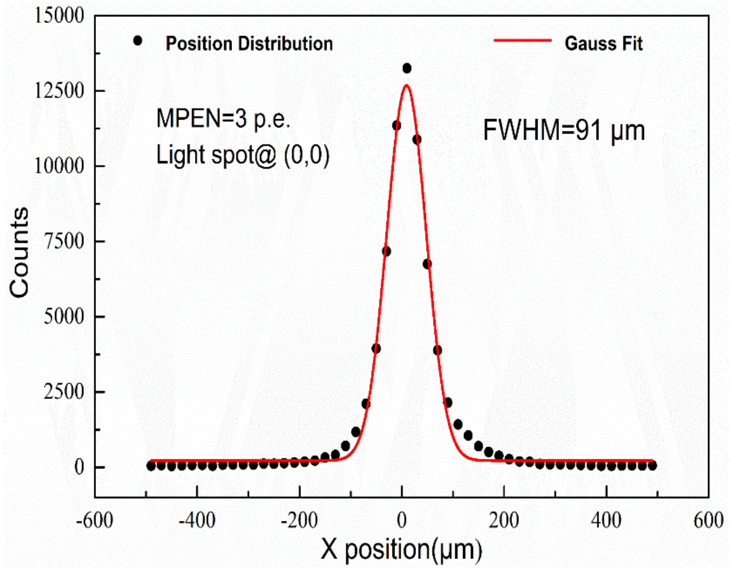
Results--NDL PS-SiPM for high resolved imaging

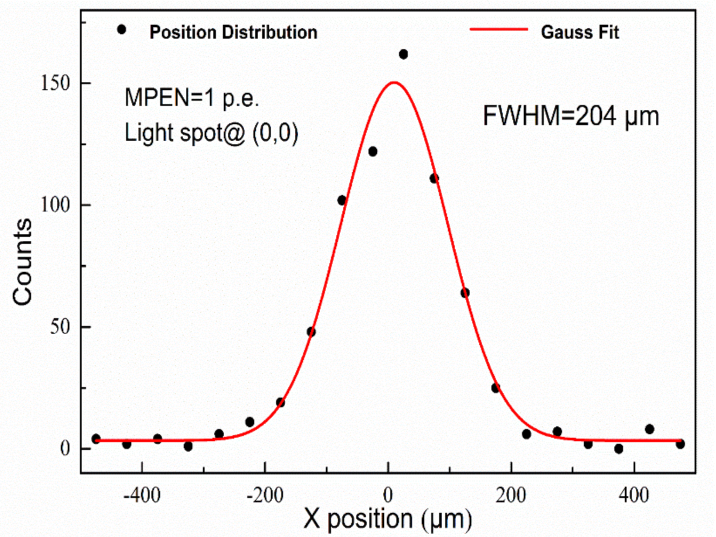






Reconstruction of 9 × 9 incident light spot positions on the 2.77×2.77 mm² of the device, with 5000 events at each position when MPEN is ~ 3.





Conclusion

- 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 advantages include:

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

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

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

- It is very suitable for applications where high PDE while large dynamic range, or highly resolved imaging while fewer readout channels are simultaneously needed .

Thank You for Your Attentions!

(Novel Device Laboratory, Beijing)
Email： info@ndl-sipm.net
http://www.ndl-sipm.net/device.html