HAMAMATSU
PHOTON IS OUR BUSINESS

MPPC® - A photon counting detector for scientific, medical, and industrial applications

607. WE-Heraeus Seminar, Bad Honnef 02/2016

Hamamatsu Photonics Deutschland GmbH
Group Leader HEP/Academic
Christian Dille

Agenda

1. Company Introduction
2. What is an MPPC?
3. Key Parameters and Technologies
4. Hamamatsu Lineup
5. Summary

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1. **Company Introduction**
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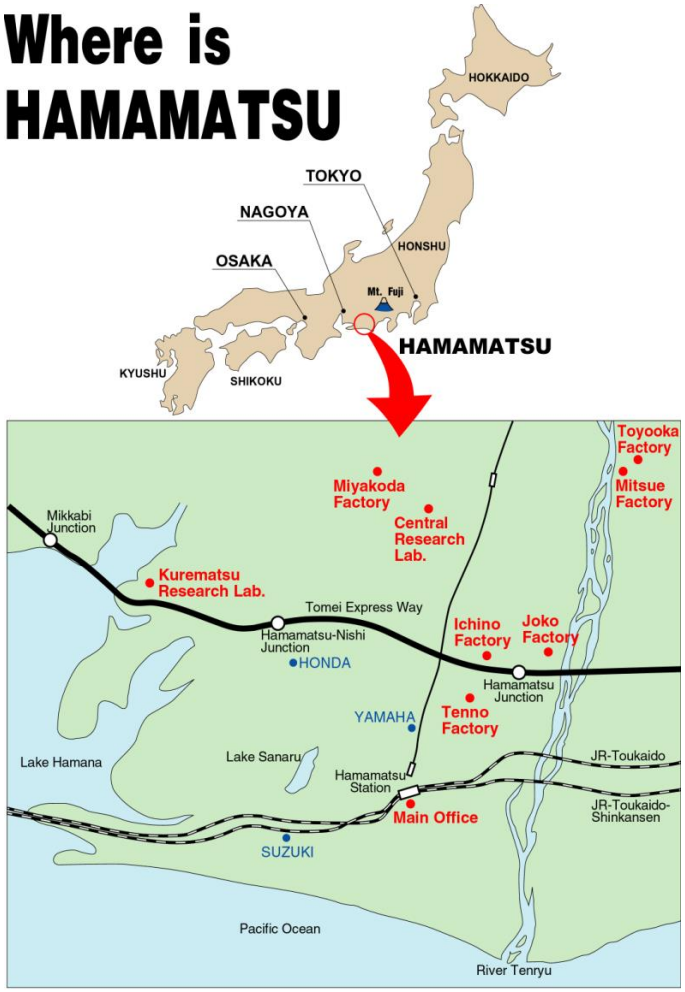
Company Information: Headquarter - Hamamatsu Photonics K.K.

- Established: September 29, 1953
- Stock listing: Tokyo Stock Exchange
  (1st Section, ID number: 6965)
- Capital : 35 Billion YEN
- Turnover FY15: 120 Bio Yen net sales / 1 Bio US$
  (+7% compared to FY14)
- Number of employees : > 4400



Hamamatsu Photonics K.K. - Divisions:

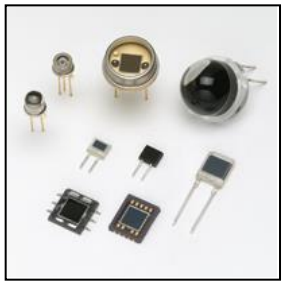
Photomultiplier Tubes, Light Sources, Fiber Optics Plates, Image Sensors, X-ray Products, etc.

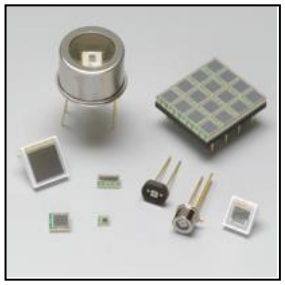
Photodiodes, Photo ICs, Image Sensors, Infrared Sensors, X-ray Sensors, Solid State Emitters, etc.

Imaging & Measurement Instruments in the diverse fields such as biological/ medical/pharmaceutical fields, semi-conductor, spectroscopy and industry

High Power LD, CW LD, etc.

Products of Solid State Division:


Si photodiodes


APD/ MPPC

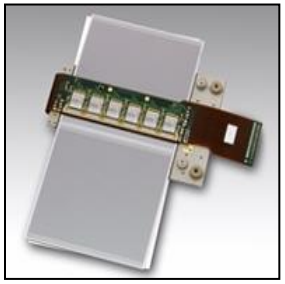
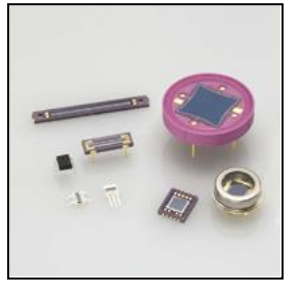
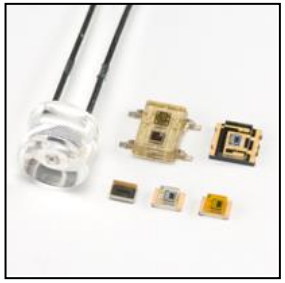

Si-Strip Detectors


Image sensors


PSD

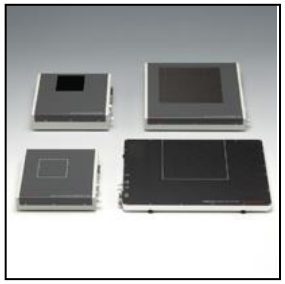

Infrared detectors


Visible sensors


Colour sensors


LED


Optical communication devices


Flat panel sensors


Mini-spectrometers


Opto-semiconductor modules

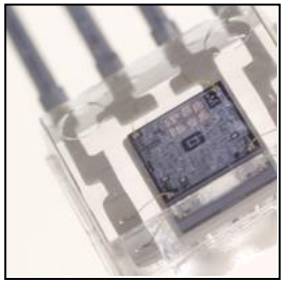
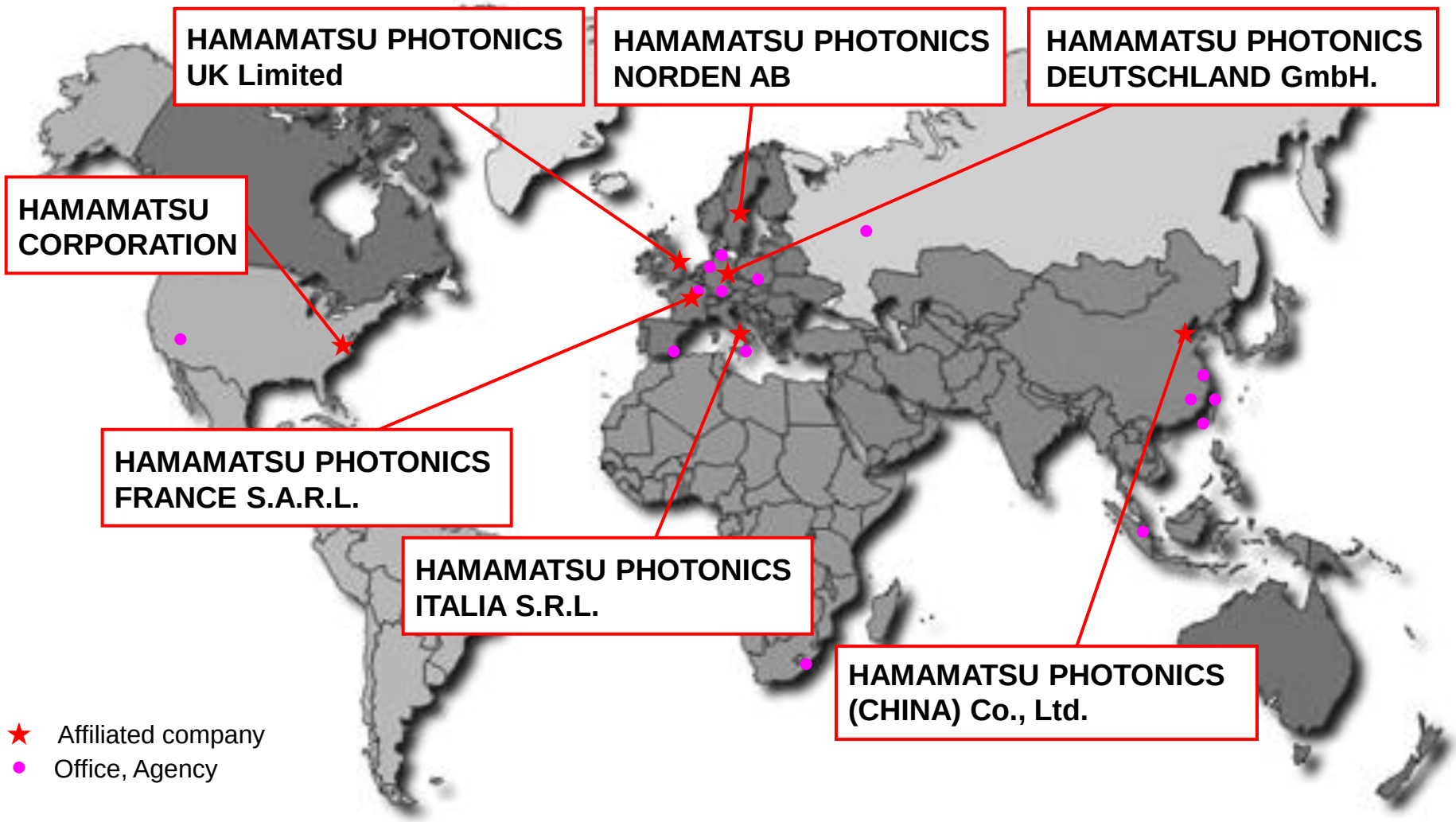


Photo-IC


SLM (spatial light modulator)

Global Network

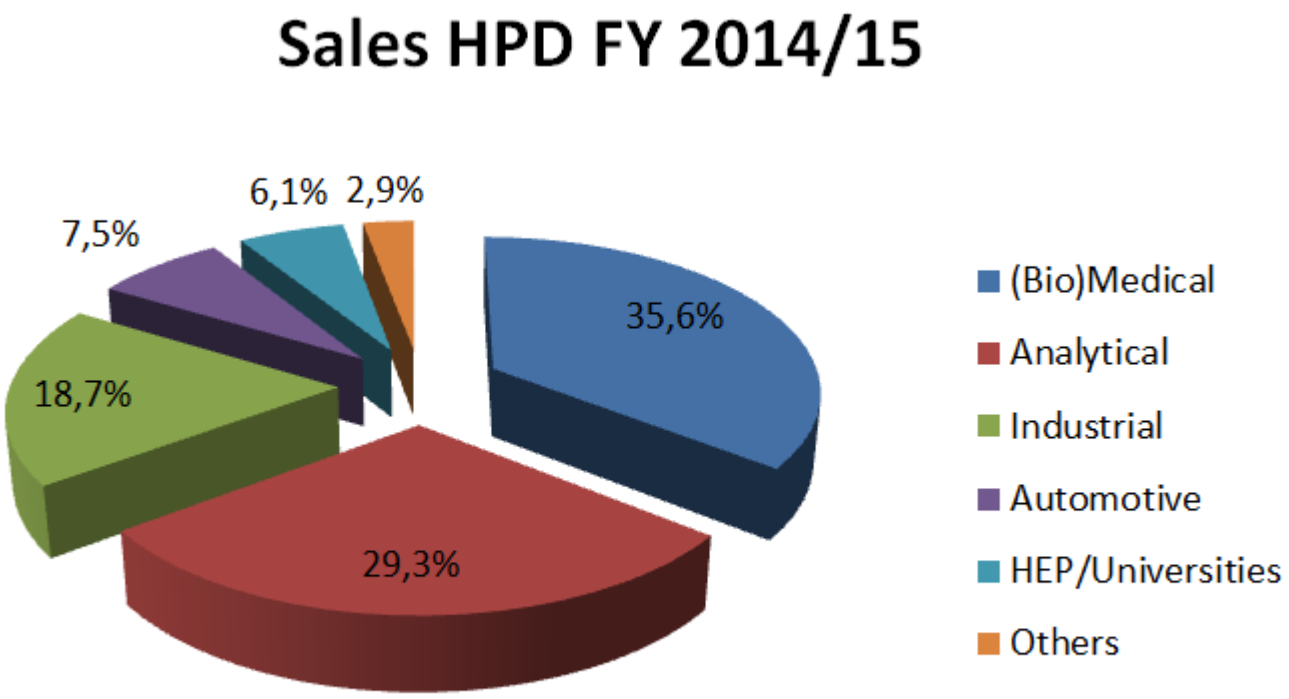


Company Information: Hamamatsu Photonics Deutschland GmbH

- Location: Herrsching
- Founded: 1986
- Turnover: 106 Mio. € (FY 2014/15)
- Employees: 90

- Certified: ISO 9001:2000
  ISO 14001:2005
- Services: Sales, Service, Technical Support, Stock

Turnover by Group – Hamamatsu Photonics Deutschland



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2. **What is an MPPC?**
3. Key Parameters and Technologies
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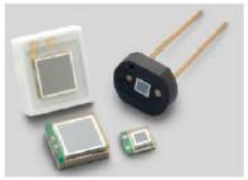
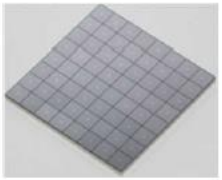
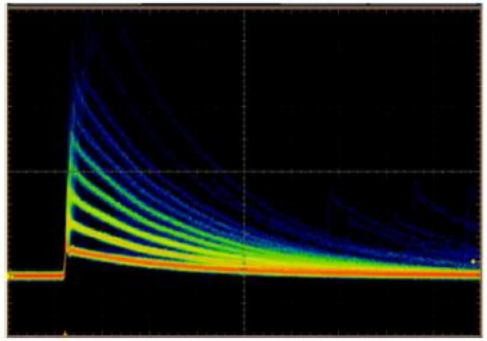
What is an MPPC?

The MPPC (Multi-Pixel Photon Counter) is one of the devices called Si-PM (Silicon Photomultiplier). It is a photon-counting device using multiple APD pixels operating in Geiger mode.





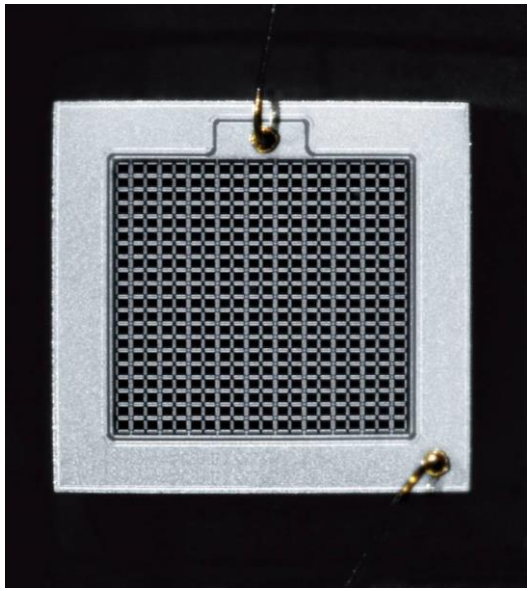


Features

- ✓ Small size
- ✓ Low bias operation
- ✓ High gain: 10^5 to 10^6
- ✓ High Photon detection efficiency
- ✓ Room temperature operation
- ✓ Excellent photon-counting capability
- ✓ Excellent timing resolution
- ✓ Insensitive to magnetic fields
- ✓ Highly resistant to excessive light

Multi-Pixel-Photon-Counter (MPPC)

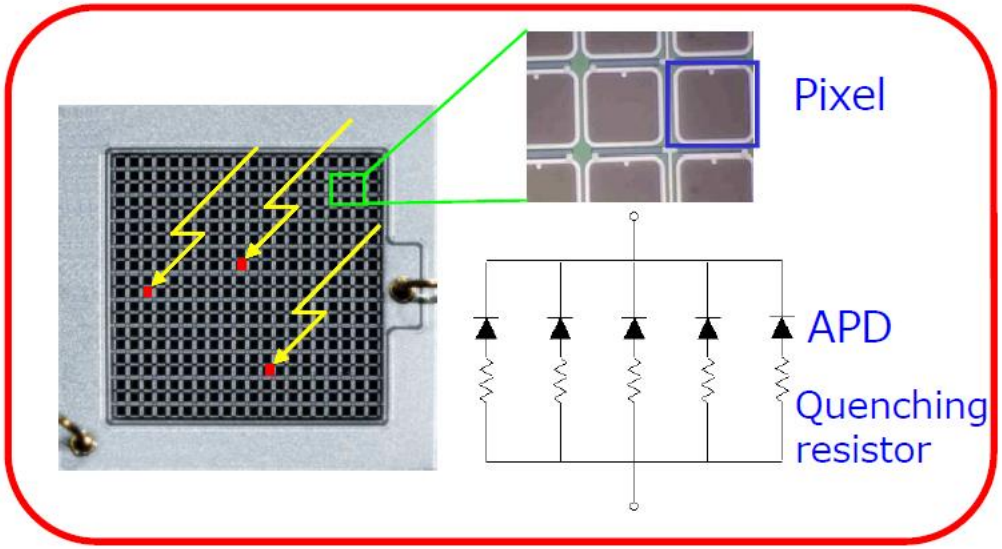
MPPC®

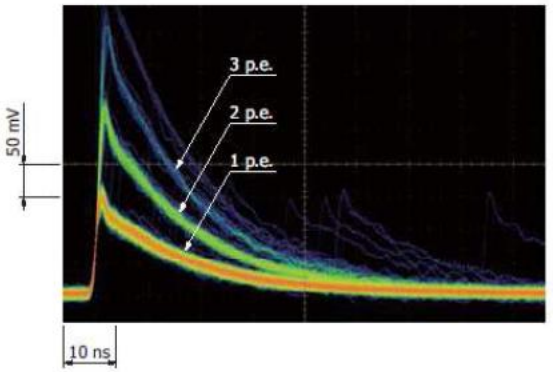


micro µPMT HAMAMATSU

SiPM (Silicon-Photo-Multiplier)
SiPMT (Silicon-Photo-Multiplier-Tube)

Operating Principle





Basic Operation

- ✓ Each pixel operates separately in Geiger-mode
- ✓ Each pixel outputs a same amplitude pulse
- ✓ Pulse generated by multiple pixels are output while superimposed onto each other (detected at the same time)
- ✓ No position information

$$Q_{out} = N_{fired} \times C_{pixel} \times (V_{bias} - V_{breakdown})$$

V_{over}

N_{fired} : Number of fired pixels

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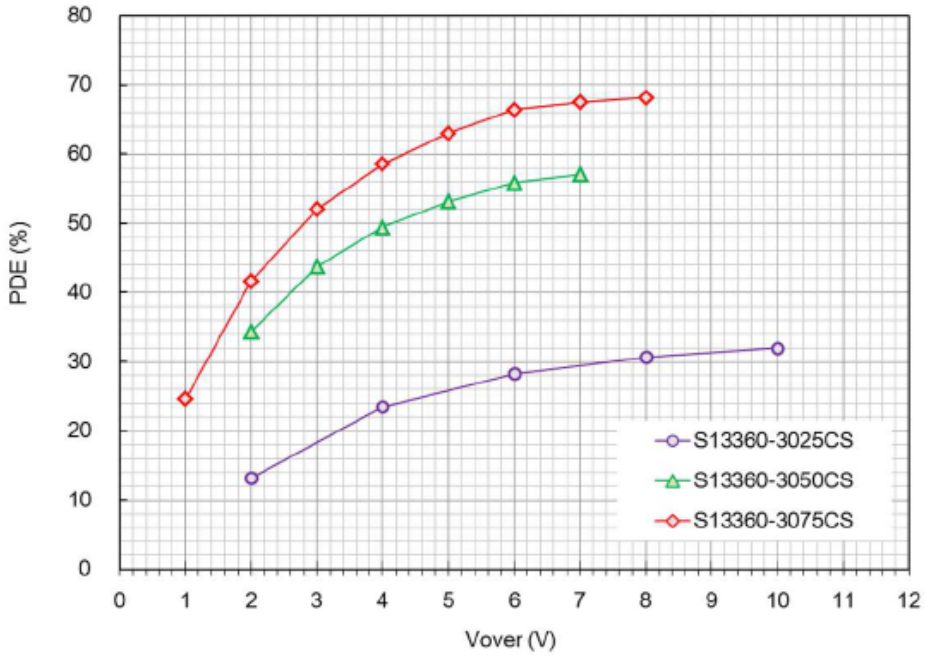
Key Parameters and Technologies

- Photo Detection Efficiency (PDE) and Spectral Response
- Time Response
- Fill factor and Quenching Resistor Material
- Dynamic Range and Linearity
- Gain and its stabilization
- Dark Count Rate (DCR)
- Optical cross talk (CT)
- Afterpulsing (AP)
- Temperature Dependence of Parameters
- Assembly Technology

Photo Detection Efficiency and Spectral Response

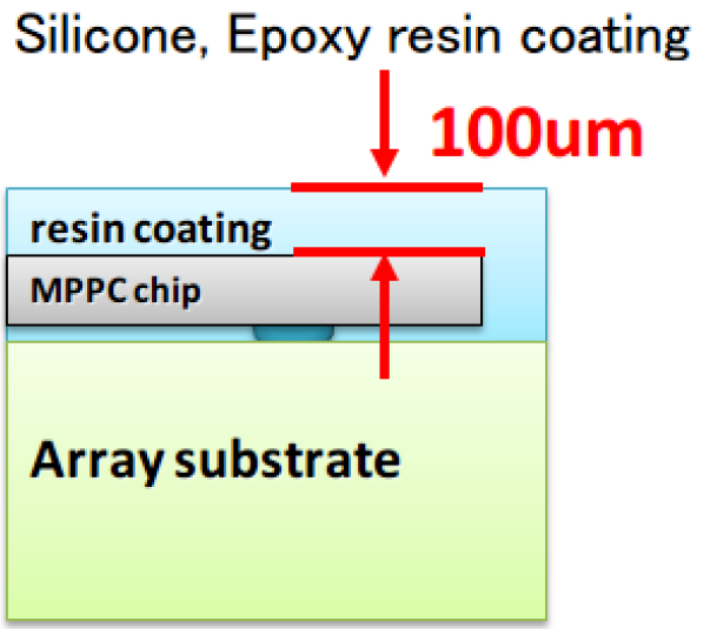
- S1336x Series (25, 50, 75 µm)

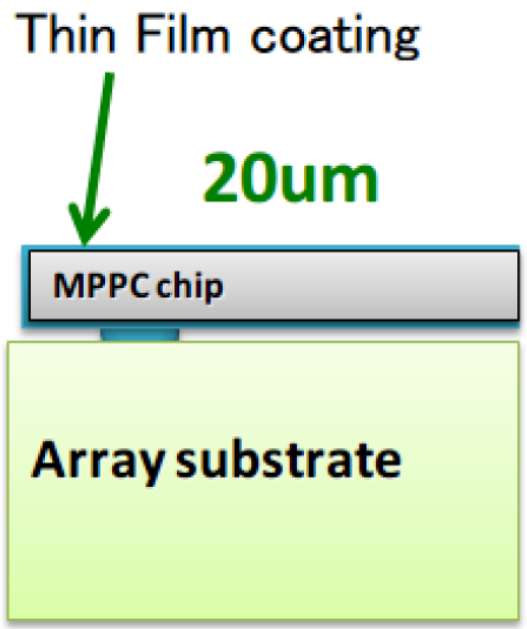


PDE = FF x QE x AP
FF: Geometrical Fill Factor
QE: Quantum Efficiency
AP: Avalanche Probability

- High PDE achieved by the high fill factor and high overvoltage
- **Larger pixel has higher PDE**

Photo Detection Efficiency and Spectral Response



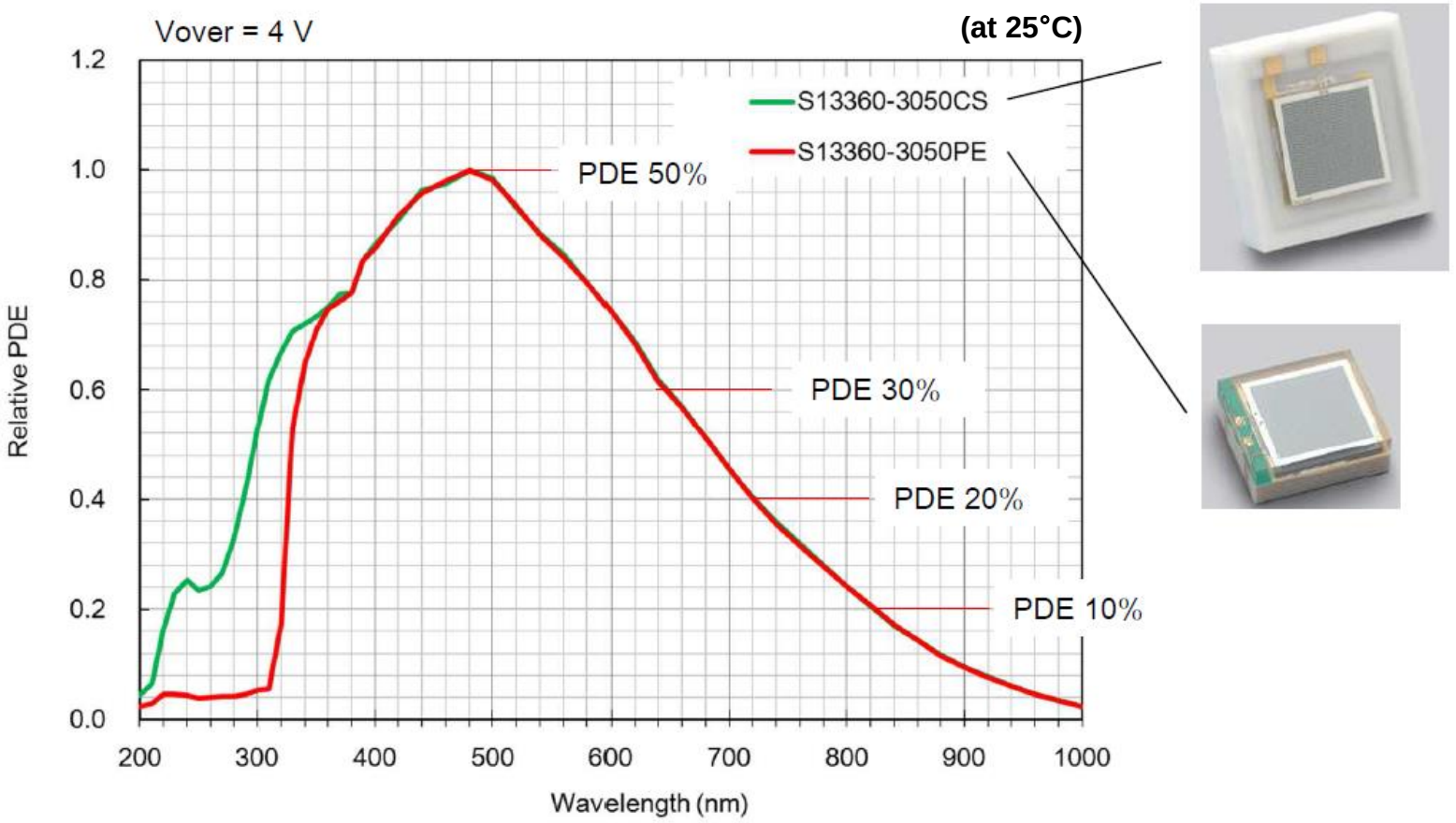


■merit
- robust to the mechanical shock
- easy handling (during assy.)
- superior transparency in UV region

- silicone resin coating type -

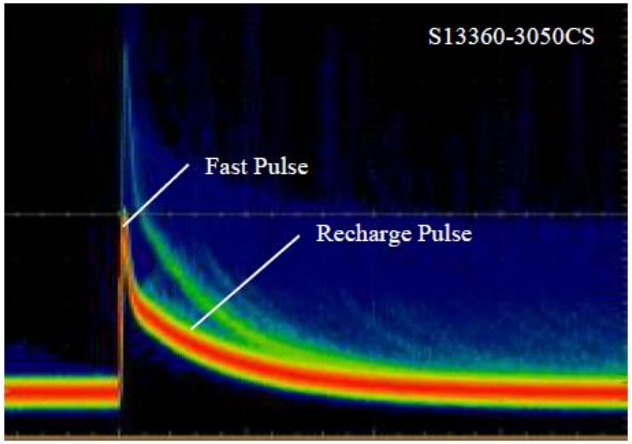
■merit
- tough coating
  (mechanical shock should be avoided)
- superior transparency in UV region
- cross-talk suppression in the coating
- super flatness (minimum bending)

Photo Detection Efficiency and Spectral Response

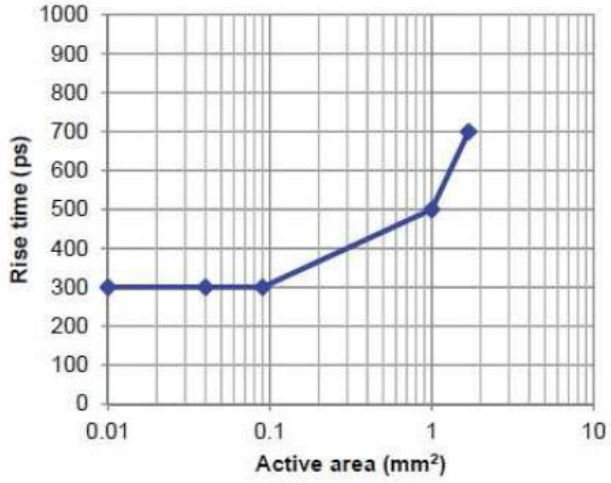


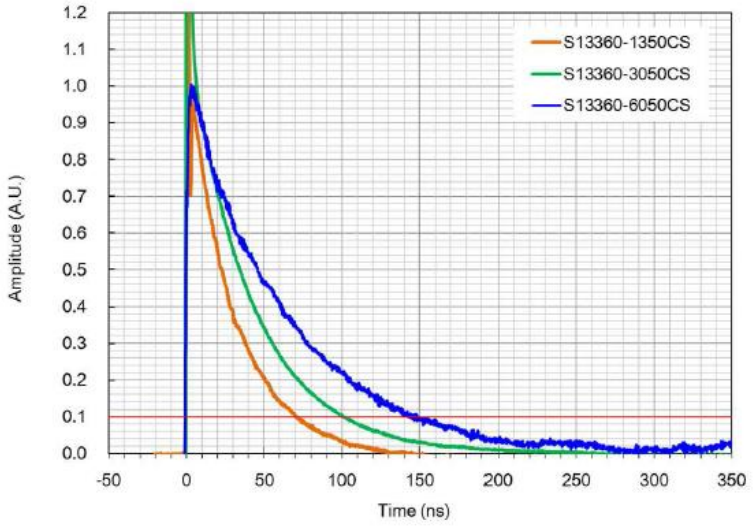
- **Silicone coating : High UV sensitivity**
- **Epoxy coating : Suitable for the coupling with a scintillator**

Time Response

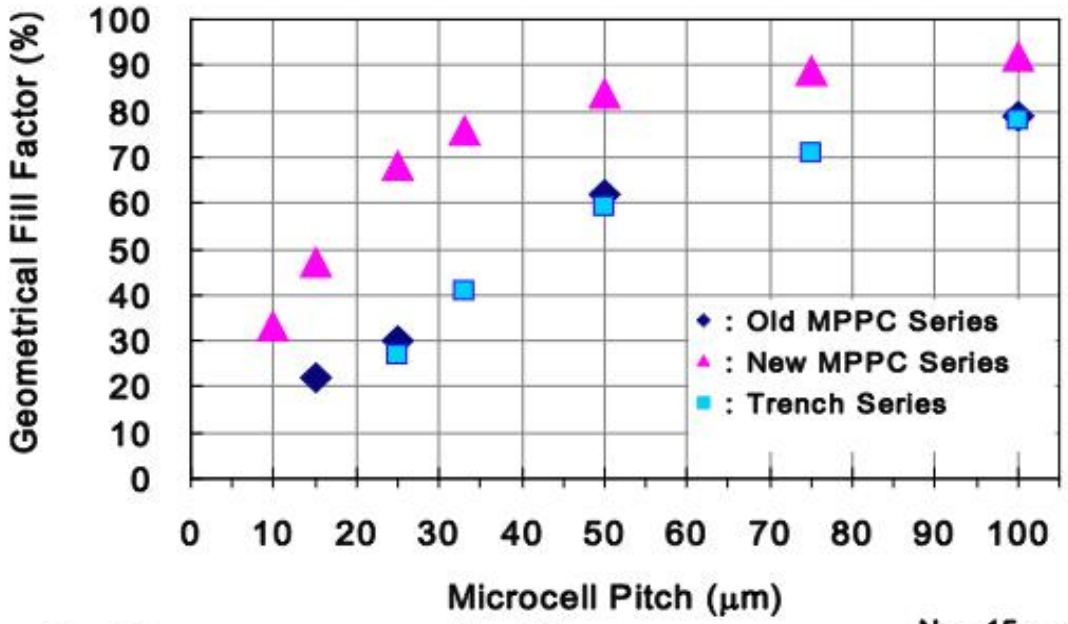


The output pulse of an MPPC consists of 2 components. A fast pulse and a recharge pulse. The fast pulse is the fast component passing through the parasitic capacitance. The recharge pulse is the slow component passing through the quenching resistor. This gives one information of the approximate recovery time of the voltage.

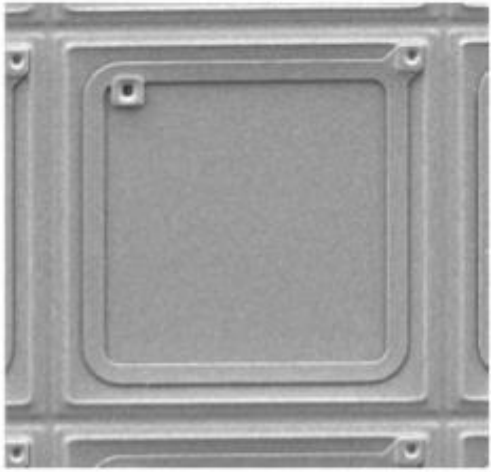




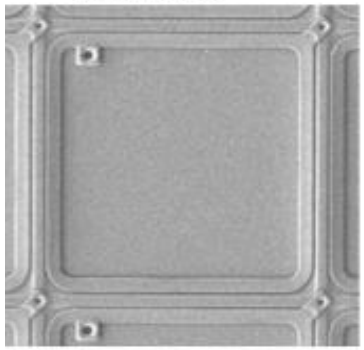
Fill Factor and Metal Film Resistor



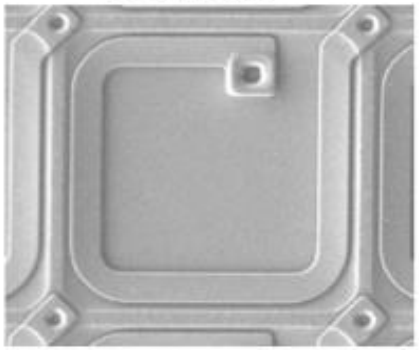
Trench 50 μm



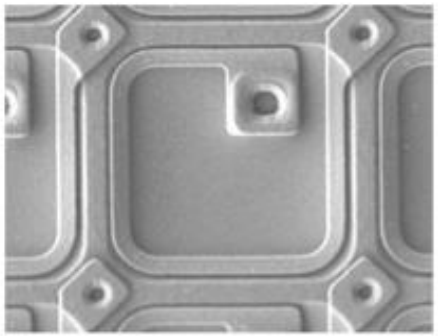
New 50 μm



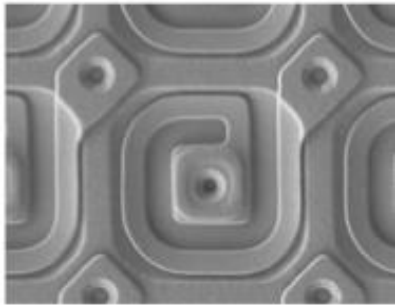
New 25 μm



New 15 μm

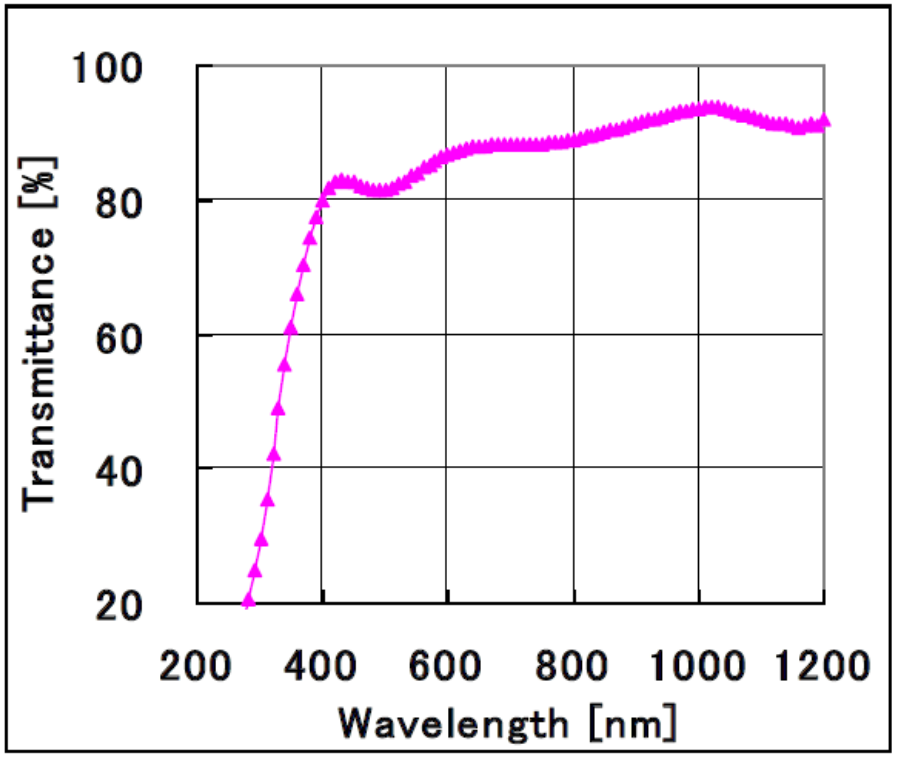


New 10 μm



Fill Factor and Metal Film Resistor

Metal Film Transmittance



Good Uniformity of resistance
(full 6-inch wafer)

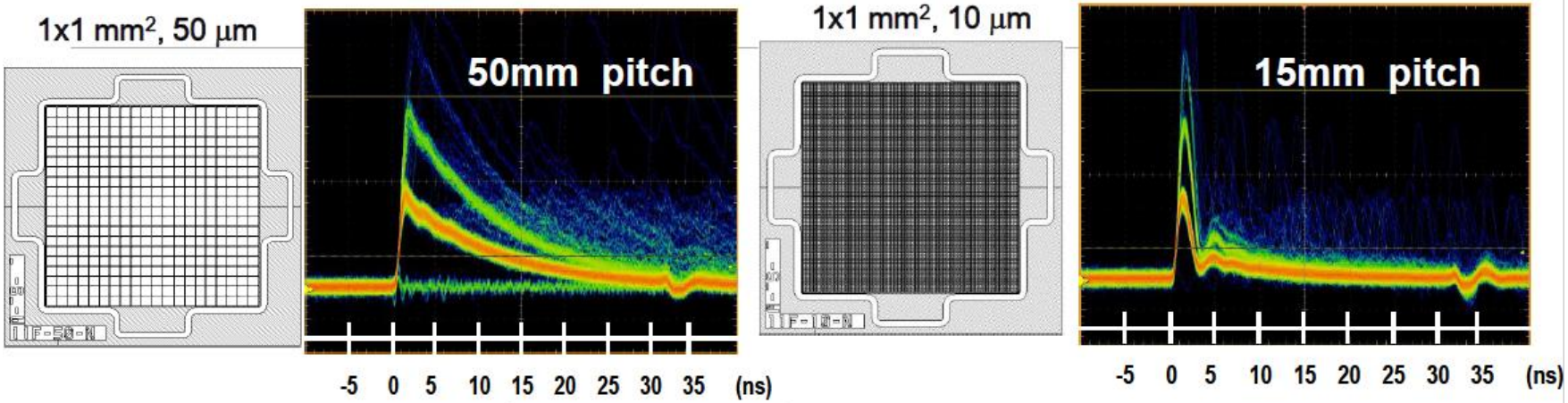
Width	Poly-Si	Metal
2 μm	19%	9%
1 μm	37%	11%

Low Temperature coefficient of resistance

Poly-Si	Metal
-2.37 kΩ	-0.43 kΩ

(/deg C)

Dynamic Range and Linearity



$$N_{fired} = N_{total} \times \left(\frac{P_w}{t_d}\right) \times \left[1 - \exp\left(\frac{-\left(N_{photon} \times PDE\right)}{N_{total} \times \left(\frac{P_w}{t_d}\right)}\right)\right] \qquad P_W > t_d$$

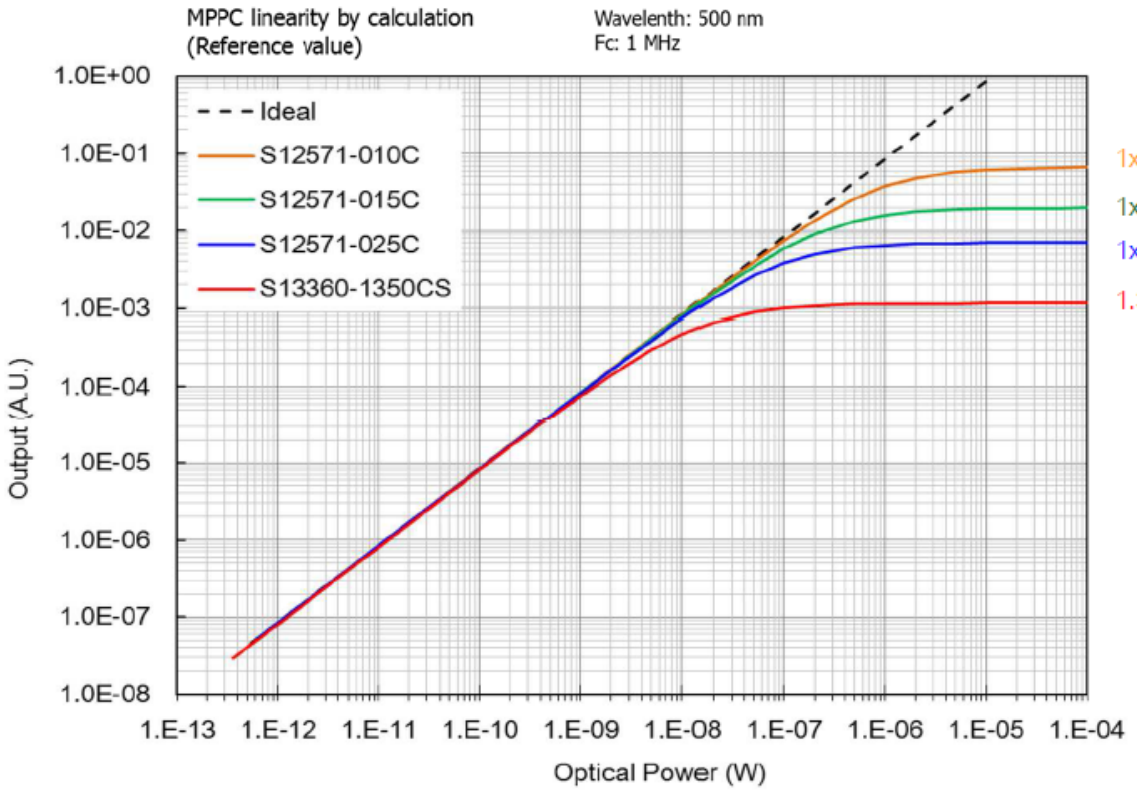
N_{fired} : number of excited micro cells
N_{total} : total number of micro cells
N_{photon} : number of incident photons
P_w : light pulses duration width
t_d : dead time of fired cells

*2) NSS/MIC 2011. 6154111 ISBN:978-1-4673-0118-3, P.553-562

When 50% of the cells fire the deviation from linearity is approx. 20%. (D. Renker, TUM)

Dynamic Range and Linearity

S1257x Series (10, 15, 25 μm)



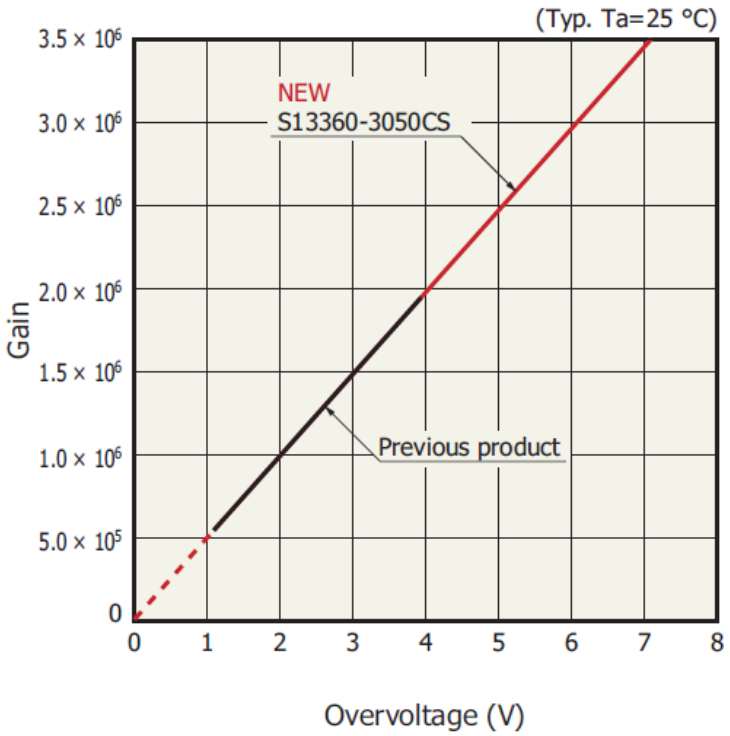
1x1 mm², 10μmP
1x1 mm², 15μmP
1x1 mm², 25μmP
1.3x1.3 mm², 50μmP

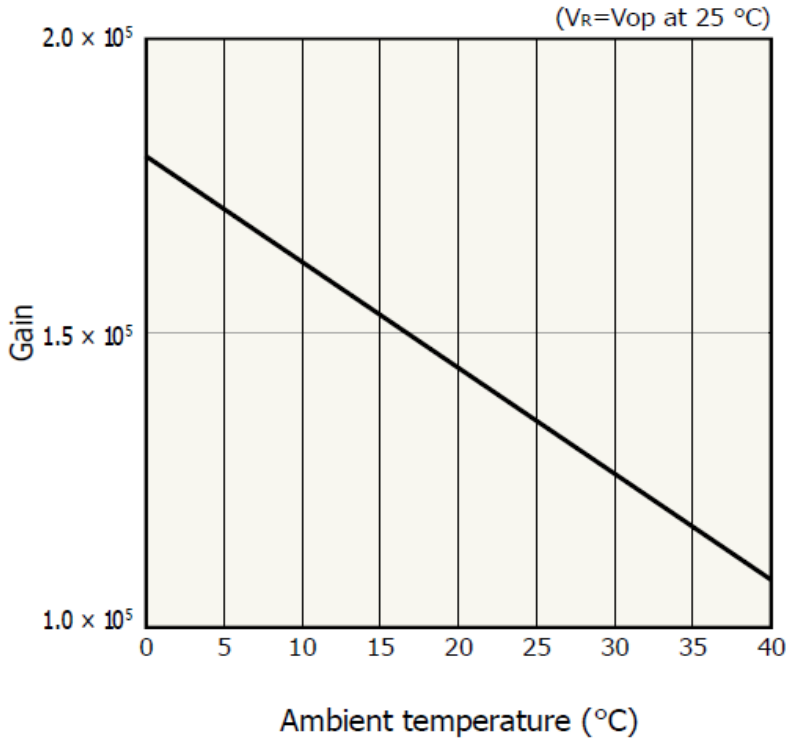
	Number of microcell	Geometrical fill factor
S12571-010P	10,000	33%
S12571-015P	4,489	53%
S12571-025P	1,600	65%
S13360-1350PE	667	74%
S13360-1375PE	285	82%

- Dynamic range depends on the number of micro cells in the active area
- Larger microcell has higher geometrical fill factor

Gain and its Stabilization

$$\frac{dV}{dT} = -\frac{dG}{dT}\frac{1}{\frac{dG}{dV}}$$





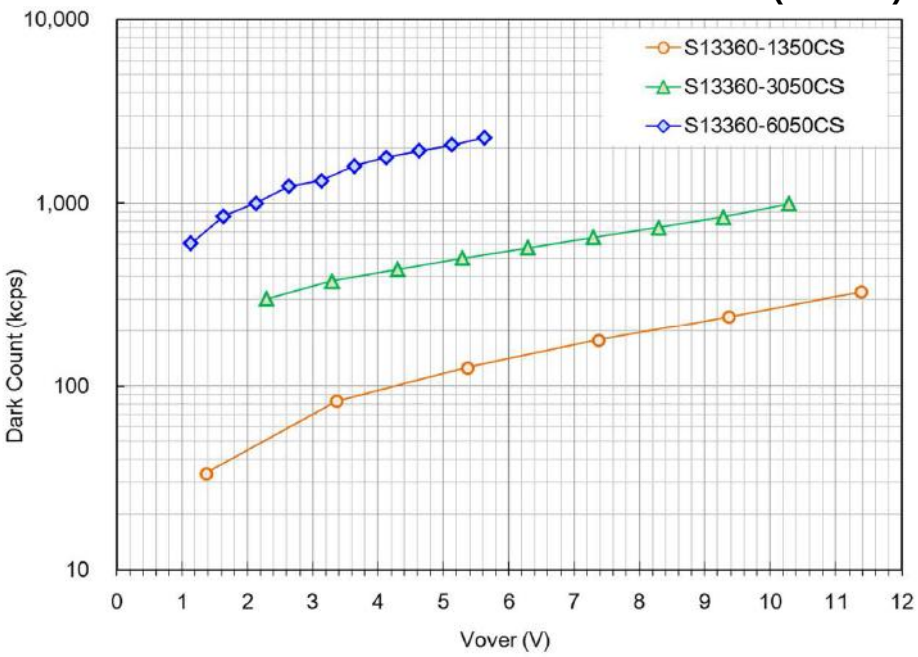
Dark Count Rate

The **Dark Count Rate** is the rate at which a Geiger avalanche is randomly initiated by thermal emission.
For Hamamatsu MPPCs the DCR is defined as the number of pulses, which are generated in dark state and exceed the threshold of 0.5 p.e.

$$N_{0.5\,p.e.}(T) \approx AT^{\frac{3}{2}} \exp\left[\frac{Eg}{2kT}\right]$$

A: arbitrary constant
Eg: band gap energy [eV]
T: absolute temperature [K]
k: boltzmann's constant [eV/K]

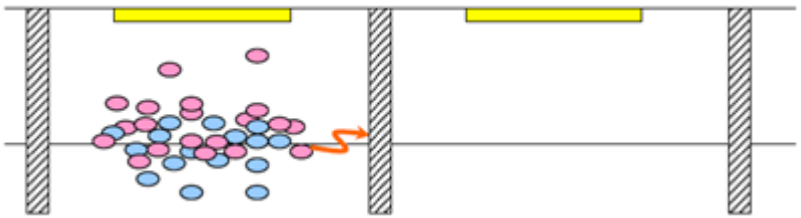
(at 25°C)

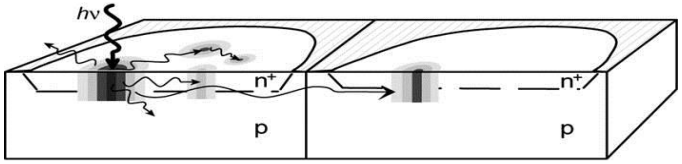


	Dark Count Vover = 3 V	Capacitance Ct
1.3x1.3 mm	90 kcps	60 pF
3x3 mm	500 kcps	320 pF
6x6 mm	2 M cps	1280 pF

Optical Cross Talk

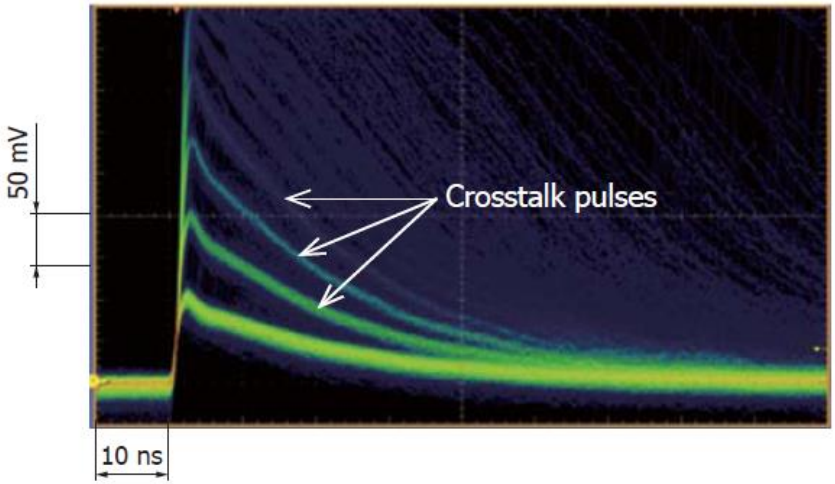
Hot Carrier Luminescence:
10^5 carriers in an avalanche breakdown emit in average 3 photons with an energy higher than 1.14 eV. (A. Lacaita et al, IEEE TED (1993))

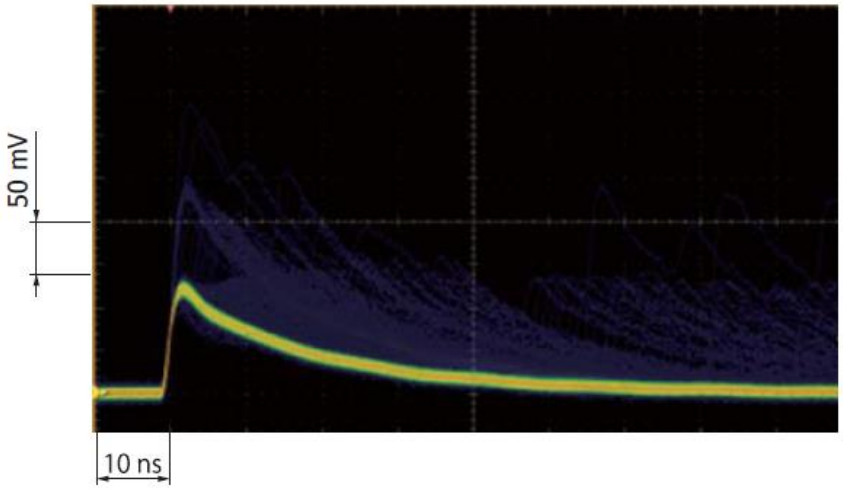




A. Lacaita et al, IEEE TED (1993)

Optical Trenches between the cells

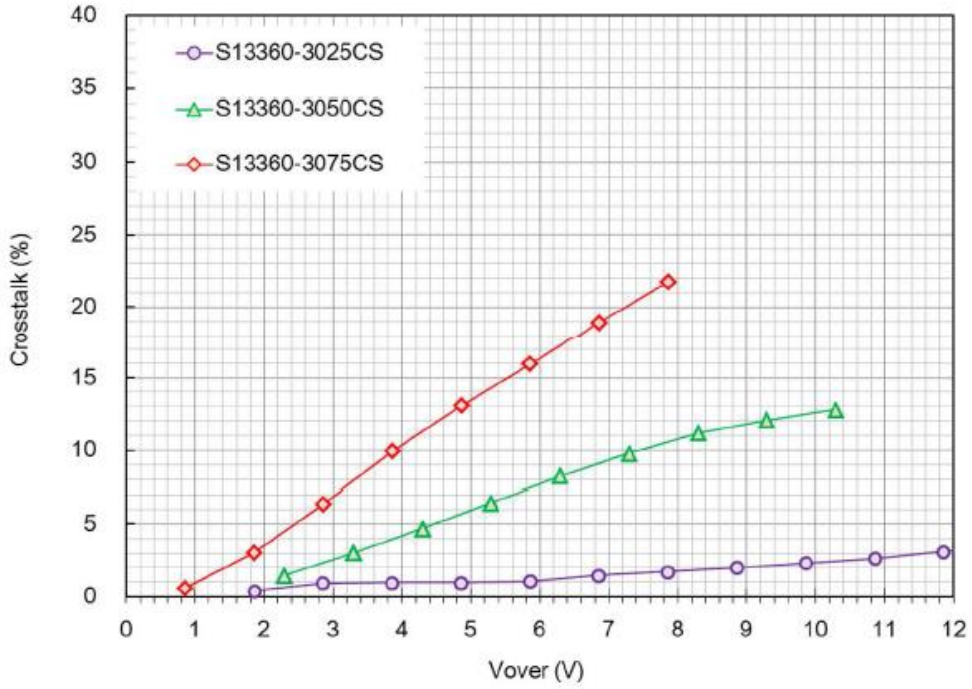




Optical Cross Talk

- S1336x Series (25, 50, 75 µm)

(at 25°C)

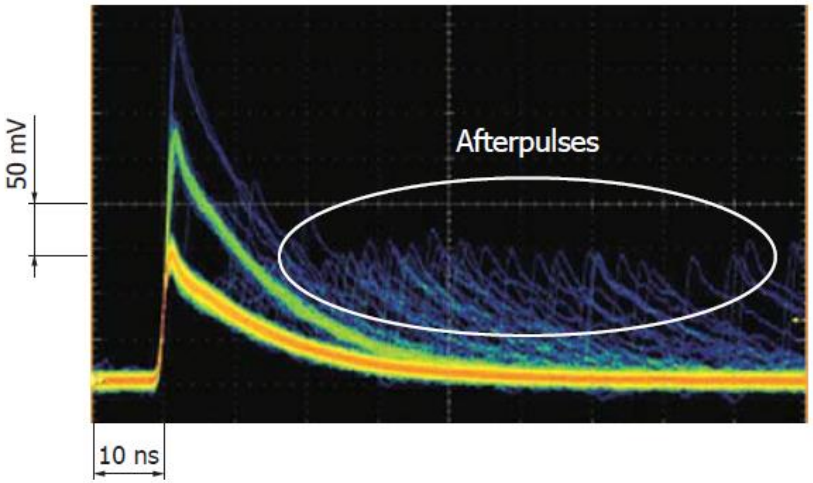


	Crosstalk Vover = 3 V	Gain
25 µm	1 %	7.0×10^5
50 µm	3 %	1.7×10^6
75 µm	7 %	4.0×10^6

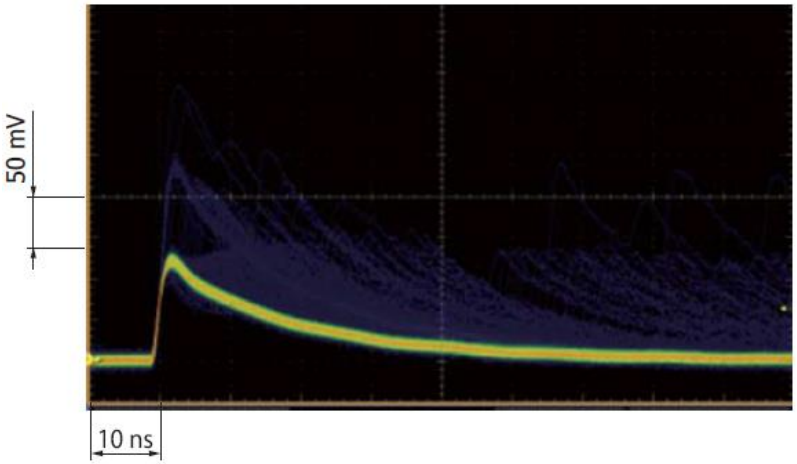
- **S1336x series employs a structure that suppresses the occurrence of crosstalk**
- **Crosstalk depends on gain**

Afterpulses

A high temperature plasma (several 1000°C) in the breakdown region is formed and some of the generated charge carriers are trapped within impurities in the silicon. These charge carriers will be released delayed and cause afterpulses with a delay up to several 100ns after the breakdown.

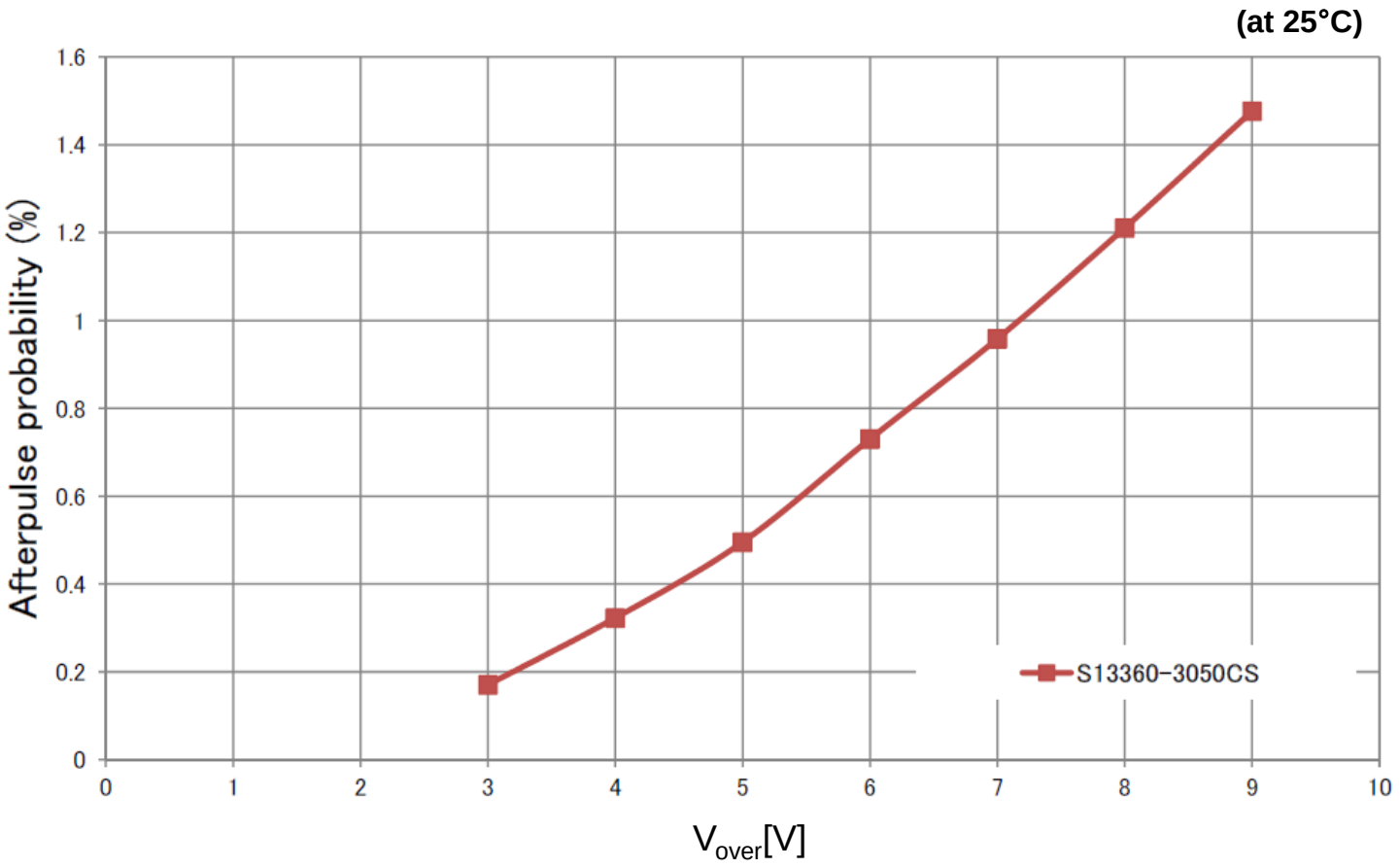


The afterpulse probability has been suppressed by optimization of structure and material.
All new MPPC series have very low after pulse probability compared to the conventional types.



Afterpulses

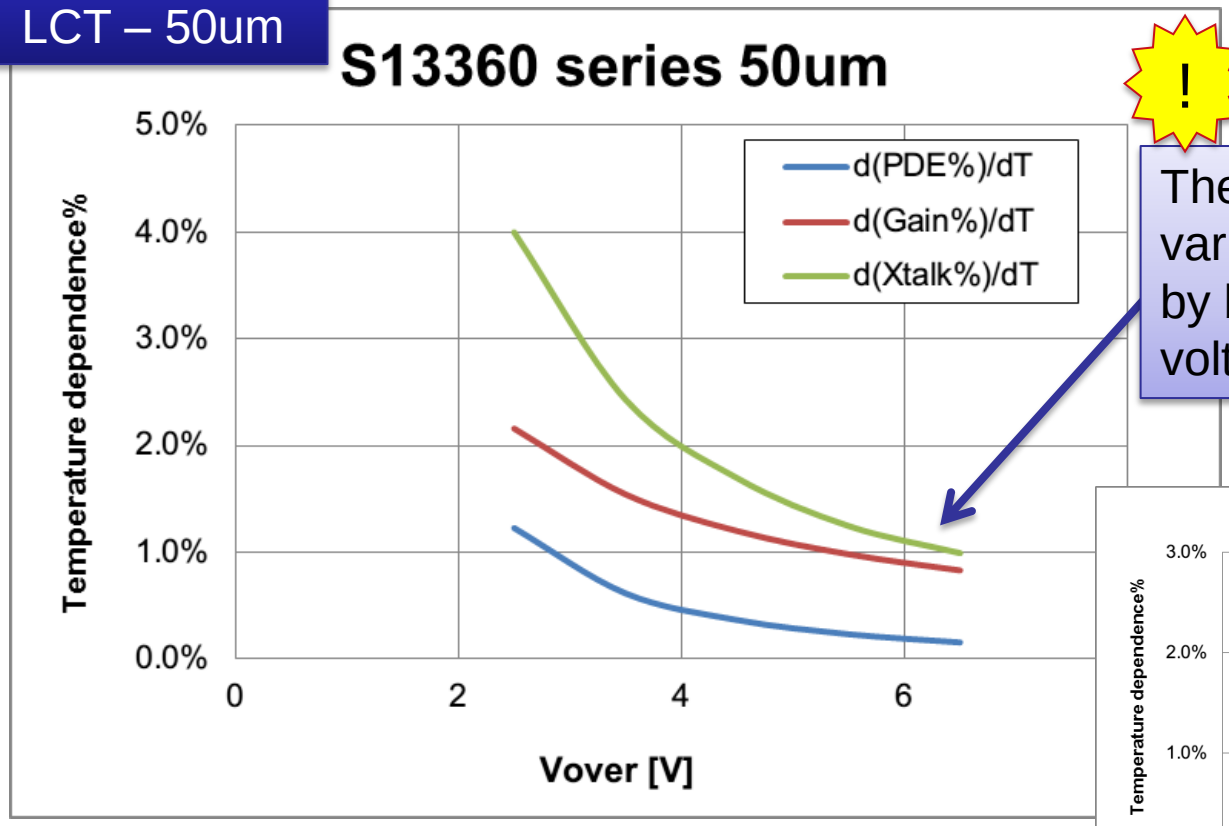
- S1336x Series (25, 50, 75 µm)



Temperature Dependence of Parameters

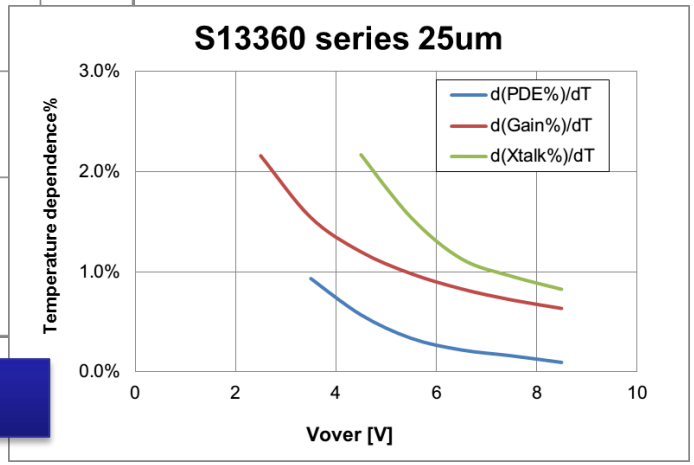
- Stability to temperature variation at higher Vover

LCT – 50um



!

The stability to temperature variation is much improved by biasing higher over voltage.

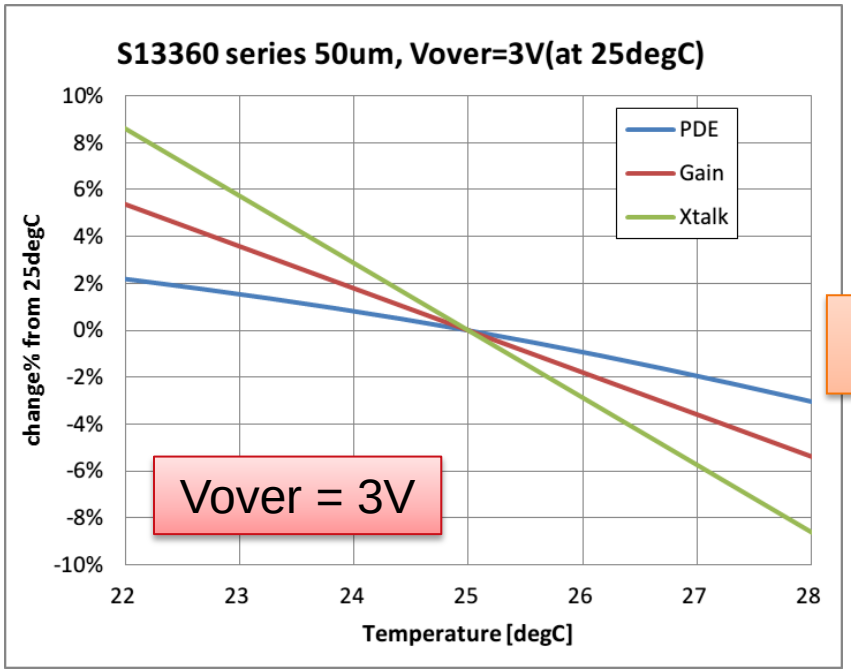


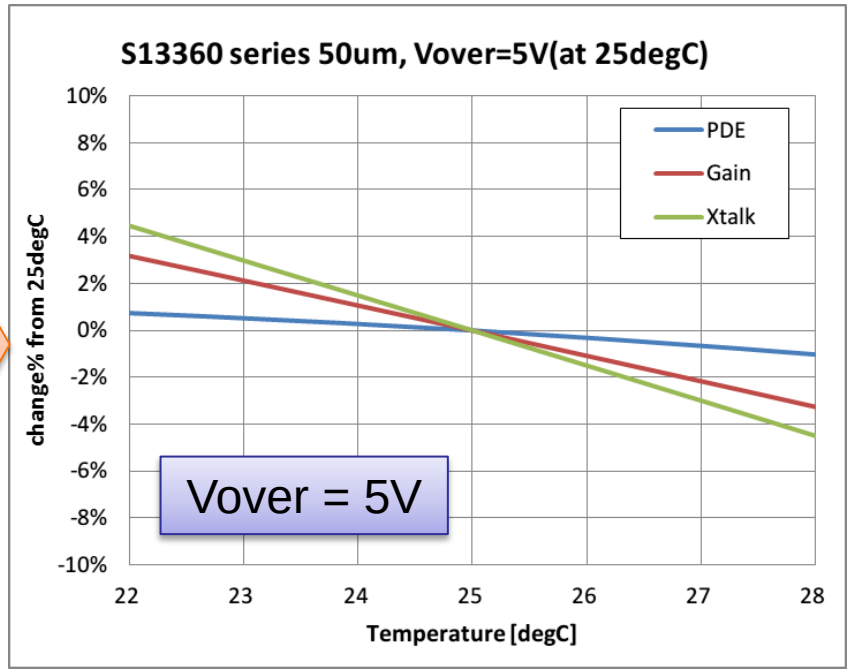
around the room temperature

LCT – 25um

Temperature Dependence of Parameters

- Stability improvement at higher Vover
- Characteristic variation with temperature change around RT

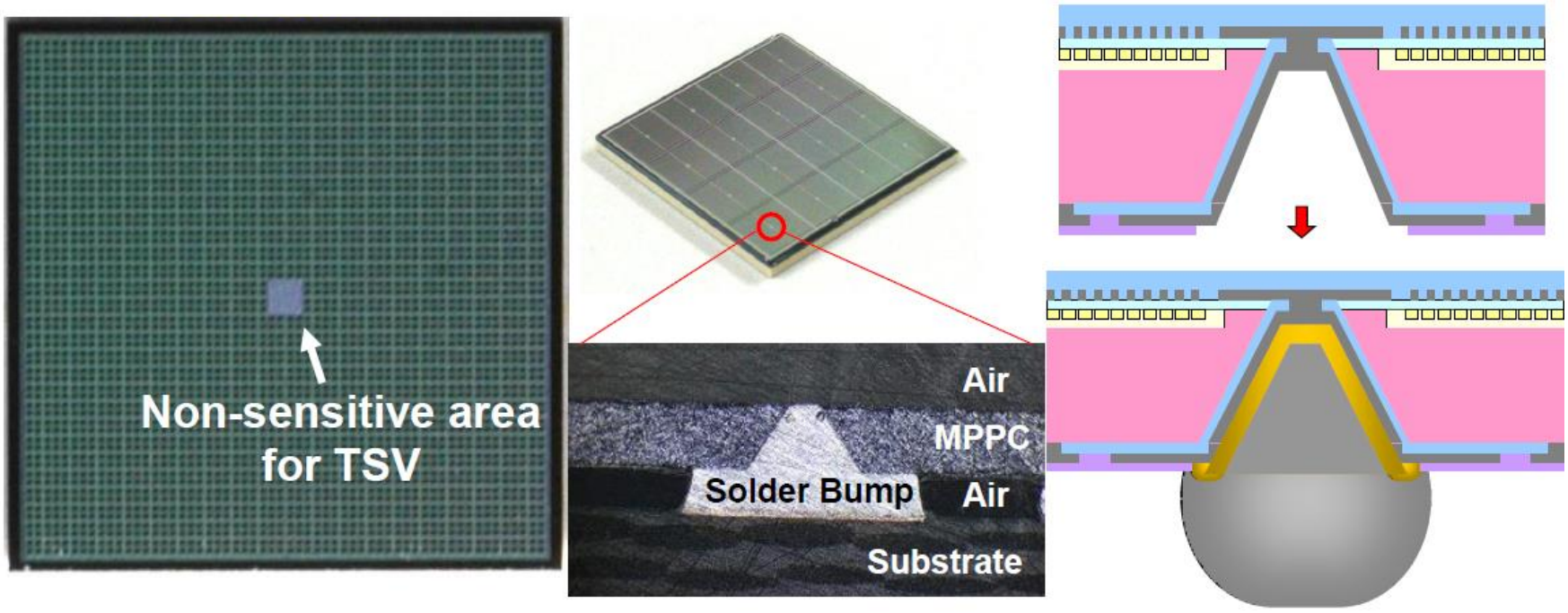




LCT – 50um

calculation data

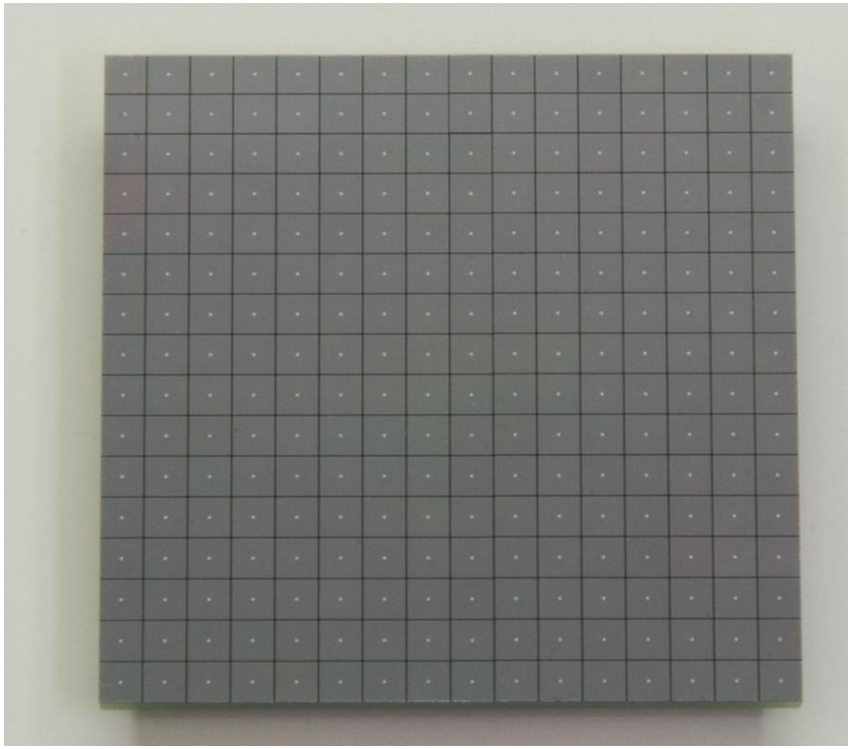
Assembly Technology (Through Silicon Via)

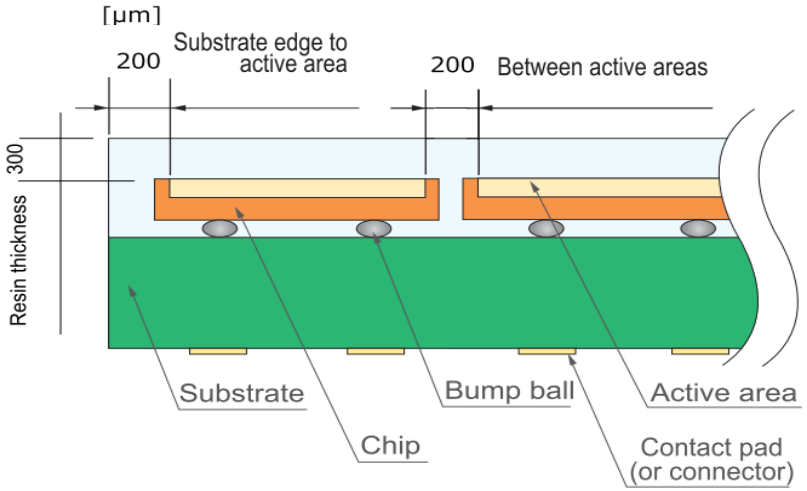


- The TSV process requires a small non-sensitiv area (200um²)
- This area corresponds to 0.44% of the total active area and hardly affects the PDE

Assembly Technology (Through Silicon Via)

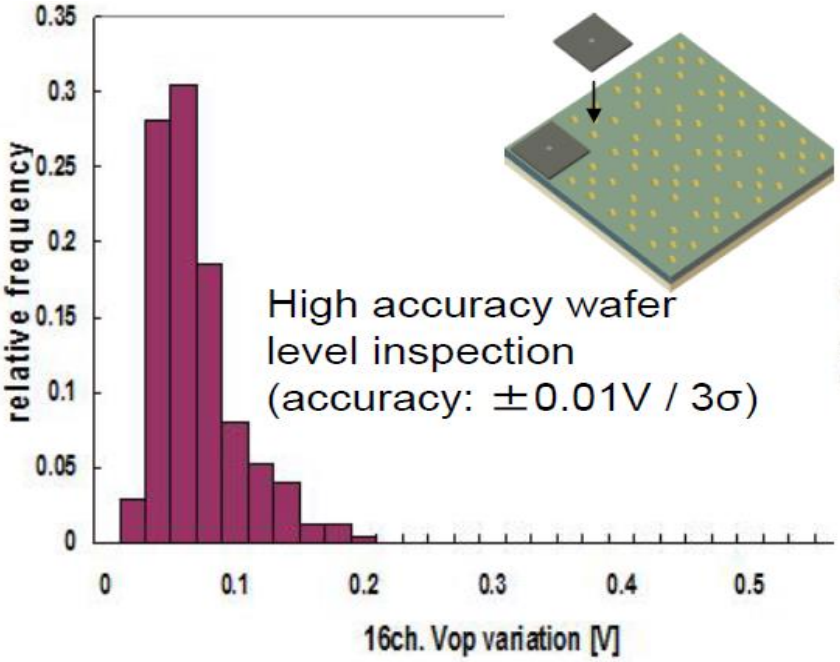
50µm pitch, 3x3mm chip, 16x16 channels with Connector type



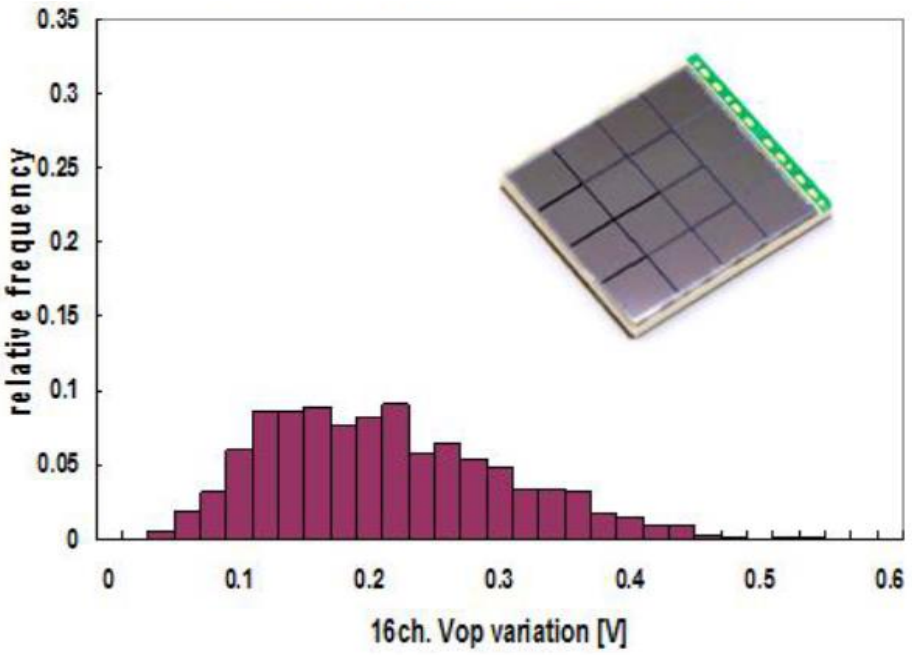


Assembly Technology (Through Silicon Via)

3x3mm² - 4x4ch discrete array



3x3mm² - 4x4ch monolithic array



- Discrete arrays allow for an operation voltage selection of MPPC tiles with an accuracy of 0.1V
- The smallest variation of monolithic arrays is 0.4V

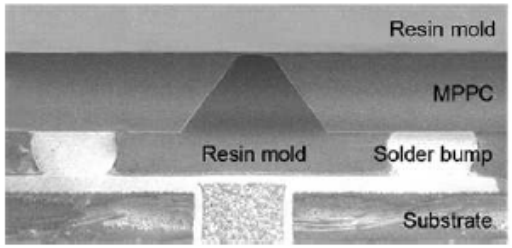
Agenda

1. Company Introduction
2. What is an MPPC?
3. Key Parameters and Technologies
4. **Hamamatsu Lineup**
5. Summary

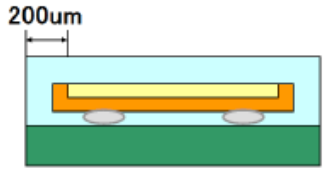
TSV (Through Silicon Via) Technology

S13360 –xxxxVE / S13361 Series

- **Channel size :** 2mm□,3mm□,4mm□ & 6mm□
- **Active area from edge :** 200µm
- **Resin thickness on MPPC chip :** 100µm
- **Channel number :** Single,4x4, 8x8 & 16x16
- **Gap between active area :** 200µm
- **Molding resign :** Epoxy (320nm~), Silicone (270nm~)
- **Surface mount type / Connector type**
- **Application**
  - **PET**
  - **Nuclear Medicine**
  - **High energy physics experiment etc.**



<Single>



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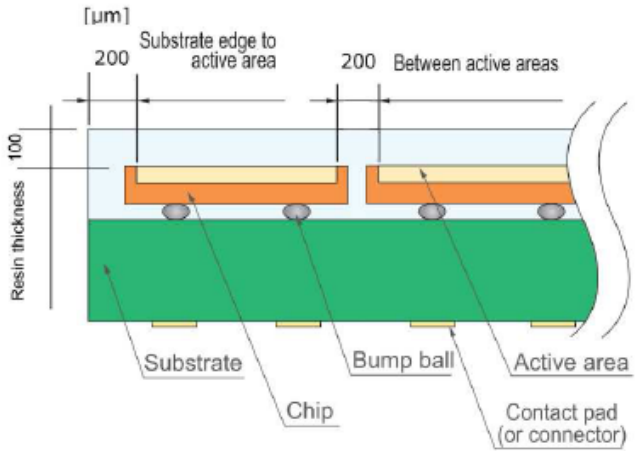
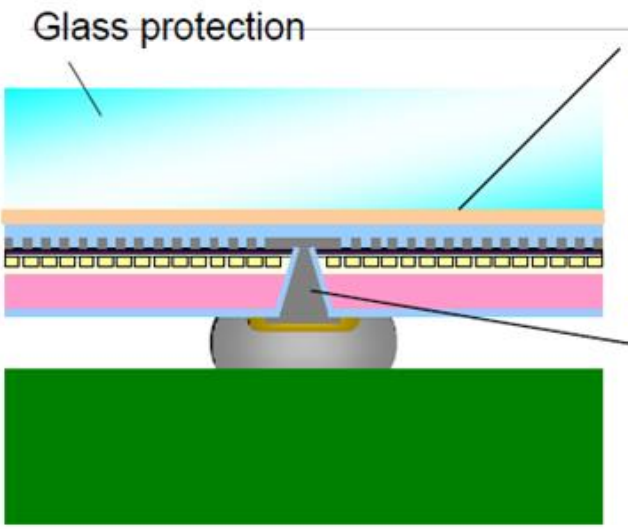
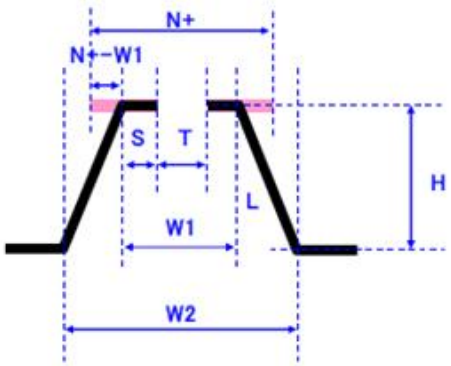


TSV (Through Silicon Via) with Glass



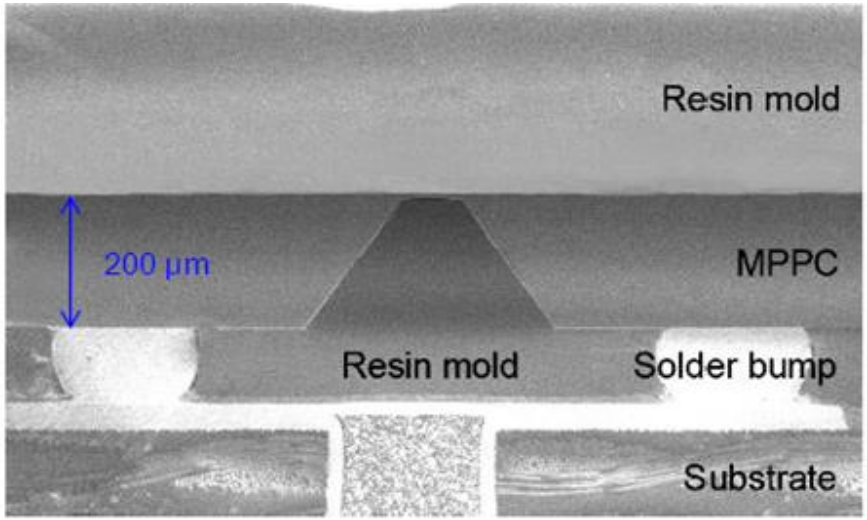
MPPC terminal capacitance
- 3x3 mm : 320 pF
- 1x1 mm : 35 pF



Parasitic capacitance of Through Via

Wafer thickness (H)	Parasitic capacitance
320 μm	20 pF (meas.)
100 μm	7.2 pF
50 μm	5.7 pF
30 μm	5.2 pF

TSV (Through Silicon Via) With Glass



Parasitic capacitance on TSV: ~ 5 pF

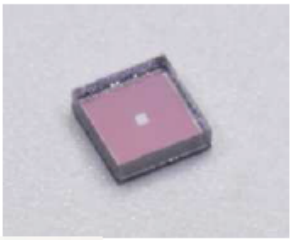
Parasitic capacitance on TSV: < 1 pF

- Use of support glass

TSV (Through Silicon Via) With Glass

S13190 Series / S13615 Series

- **1x1mm² TSV-MPPC with support glass**
- **Active area from edge :** 65µm
- **Glass thickness on MPPC chip :** 300µm
- **Channel number :** Single,4x4, 8x8 & 16x16
- **Gap between active area :** 200µm
- **Small size and low cost**
- **High positional resolution**
- **Application**
  - **·Brain/ Animal / preclinical PET**
  - **·Range finder etc.**



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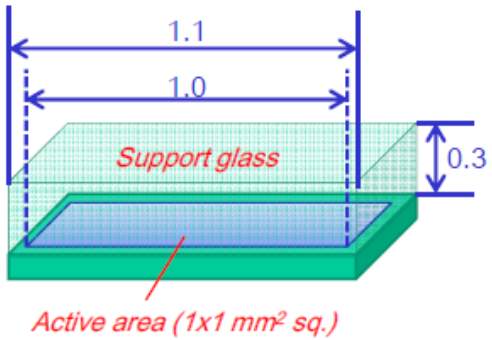
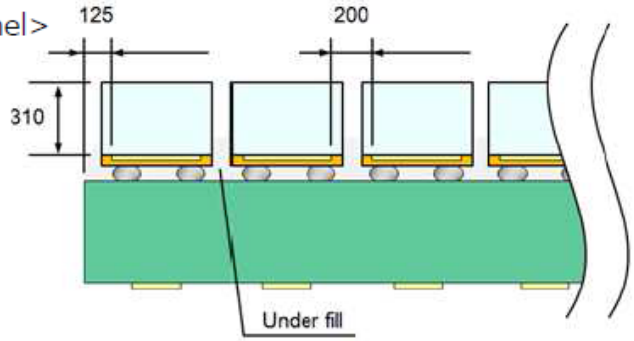


<Multi channel>



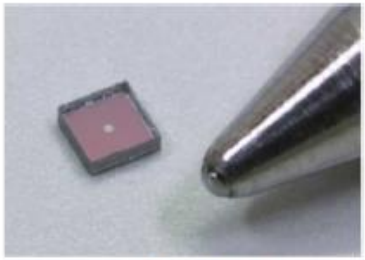
TSV (Through Silicon Via) With Glass

◆ Package Selection / TSV with Glass

■ High dynamic range type

S13190-1015-04

- Number of channels: No/ single, 04/ 4x4ch, 08/ 8x8ch, 16/ 16x16ch
- Micro cell size (μm): 10/ 10μm, 15/ 15μm, 25/ 25μm
- Active area size: 10/ 1x1 mm^2,

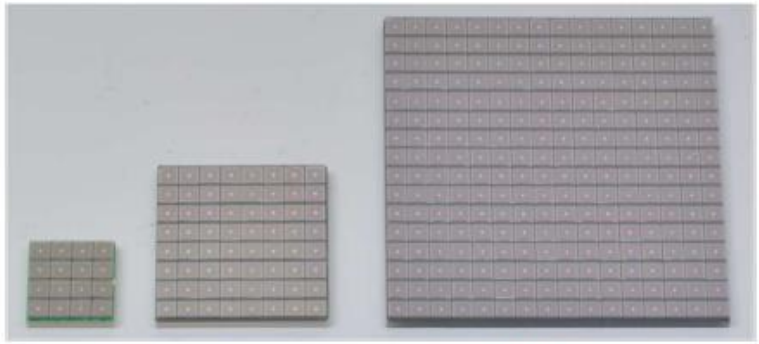


S13190-1015
(1x1 mm^2 Single)

■ Low noise type (Trench technology)

S13615-1025-04

- Number of channels: No/ single, 04/ 4x4ch, 08/ 8x8ch, 16/ 16x16ch
- Micro cell size (μm): 25/ 25μm, 50/ 50μm
- Active area size: 10/ 1x1 mm^2,

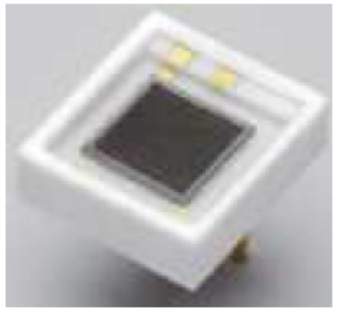


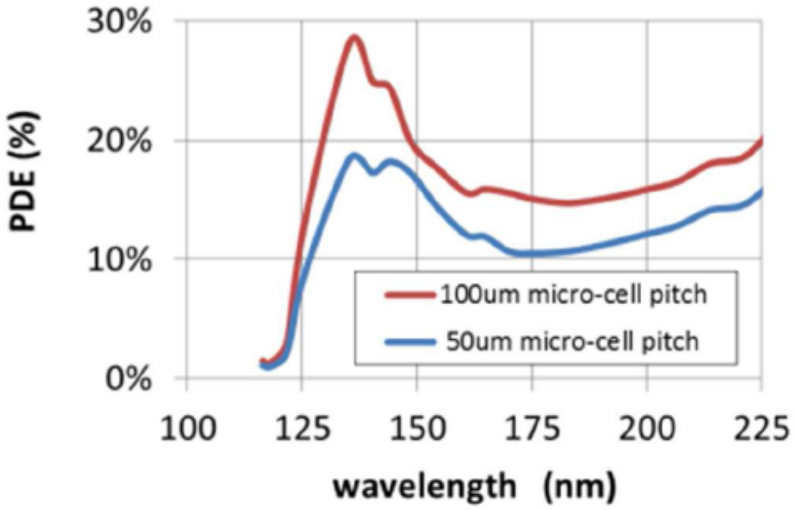
1x1 mm^2 4x4ch | 1x1 mm^2 8x8ch | 1x1 mm^2 16x16ch

VUV sensitive MPPCs

- S13370 Series (50, 100μm)

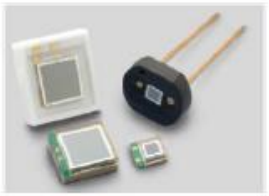
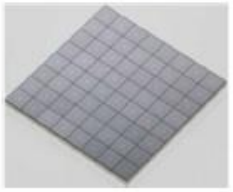
- **VUV sensitivity (> 125nm) & Low Cross-Talk**
- **Low-Radioisotope PKG is under development for physical experiment**
- **Application**
  - **Physical experiment using Liquid-Xe, Ar scintillator (Dark matter search, Neutrino-less double-beta decay)**
  - **Fast signal component detection from BaF2 scintillator**
  - **Wafer inspection device using UV-Laser**



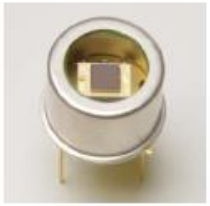


Hamamatsu MPPC Lineup

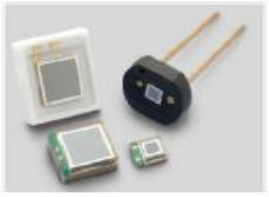
- **S13360, S13361 Series**
  - ✓ Low noise (low after pulse, crosstalk, dark)
  - ✓ High photon detection efficiency

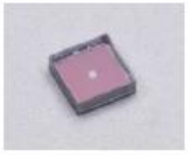
- **S13362 Series**
  - ✓ Integrate thermoelectric cooler
  - ✓ Very low noise
  - ✓ High photon detection efficiency



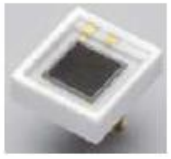
- **S12571, S12572 Series**
  - ✓ High dynamic range
    (Small pixel pitch: 10, 15 μm)



- **S13190, S13615 Series**
  - ✓ TSV with support glass



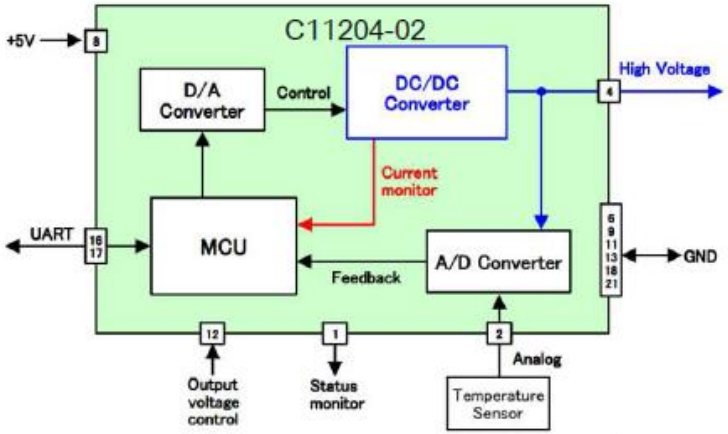
- **S13370 Series**
  - ✓ UV sensitive MPPC



MPPC Power Supply

Features

- ✓ MR Compatible: C11204-03/-04
- ✓ Low cost: C11204-05
- ✓ Include temperature compensating function
- ✓ High temperature stability
- ✓ High setting resolution: 1.8mV
- ✓ Low ripple noise: 0.1mVp-p typ.
- ✓ Small size: 19.4mm x 17mm x 6.3mm



Item		Mount	Stability (ppm/ °C)	Voltage Boost	MR Compatibility	Features
	C11204-01	Pin	10	Inductor	-	- High precision - Low ripple noise
	C11204-02	Surface	10	Inductor	-	- High precision - Low ripple noise - Compact 11.5x11.5mm
	*New* C11204-03	Pin	30	External	Yes	- MR compatible - Low cost
	*New* C11204-04	Surface	30	External	Yes	- MR-compatible - Low cost - Compact 11.5x11.5mm
	*New* C11204-05	Pin	30	Inductor	-	- Low cost

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Summary

● Advantages

①Compact / thin — miniaturization and integrated optics design possible
②High gain — minimal amplifier circuit design
③Low bias voltage — around 60V
④High PDE — SNR is better than a PMT in shot noise limited cases
⑤No ageing degradation effects
⑥Insensitive to magnetic fields

● Design Considerations

⑦High dark count — Suitable for pulsed light as well as scintillator readout
Not suitable for unsegmented large area and single photon event detection

⑧Temperature coefficient 54mV/℃≒1.8%/℃
Digital/Comparator output: Gain shifts do not significantly affect counting
Analog output: Temperature compensation feedback required
Uniform thermal distribution on photosensitive area is crucial
→ Optimize by using thermal simulation software

⑨High terminal capacitance
Area and speed have an inversely proportional relationship
→ For large area coverage, segment area and use multichannel ASICs

Thank you very much!