

# New improvements to a specialized Multi-Pixel Photon Counter (MPPC) for neutrinoless double-beta decay and dark matter search experiments

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## ABSTRACT

Hamamatsu Photonics K.K., a major manufacturer of a wide variety of silicon photodetectors including the Multi-Pixel Photon Counter (MPPC), has developed VUV-MPPCs that are capable of detecting light down to 120 nm, covering scintillation wavelengths of liquid xenon and argon with cryogenically compatible, ultralow-RI packaging options. We developed a 4th generation of VUV-MPPC (VUV4) for cryogenic physics experiments. In addition to diminished afterpulsing and inter-pixel trenches to suppress optical crosstalk, we have achieved improvement of VUV photosensitivity in this new MPPC through new modifications of the device structure. By achieving these results and continuing our MPPC improvements, we hope to make a valuable contribution to the physics community's efforts towards discovery of dark matter and the neutrinoless double-beta decay.

## Introduction

### Physics experiments using LXe or LAr scintillator

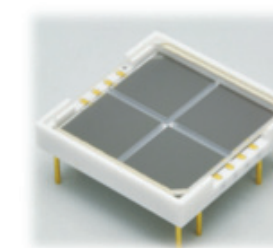
- Liquid xenon (LXe) and liquid argon (LAr) are used as scintillators for dark matter search or neutrinoless double-beta decay experiments.
- Their scintillation peak spectra are in the VUV region, and their temperatures are cryogenic.

Liquid Xenon (LXe)  
- Peak emission wavelength: 178 nm  
- Temperature: 165 K  
- Directly detected by VUV photodetector

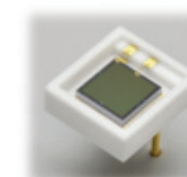
Liquid Argon (LAr)  
- Peak emission wavelength: 128 nm  
- Temperature: 87 K  
- Directly detected by VUV photodetector or indirectly (after WL-shifter) by UV/blue photodetector (typically ~420 nm)

### VUV-MPPC in physics experiments

- MEG-II (searching for the  $\mu^+ \rightarrow e^+ \gamma$  decay)  
VUV-sensitive MPPC (VUV-MPPC) will be installed in a  $\gamma$ -ray calorimeter to detect scintillation light from LXe. The LXe detector will have improved resolution by using approx. 4,000 pieces of VUV-MPPC.
- ANKOK (WIMP dark matter search)  
VUV-MPPC was evaluated for an argon detector, and it is expected to directly detect 128 nm scintillation light from LAr.
- VUV-MPPC is being evaluated in a number of research institutes as a direct detector of scintillation light from LAr and LXe.



6 mm sq - 2 x 2 ch

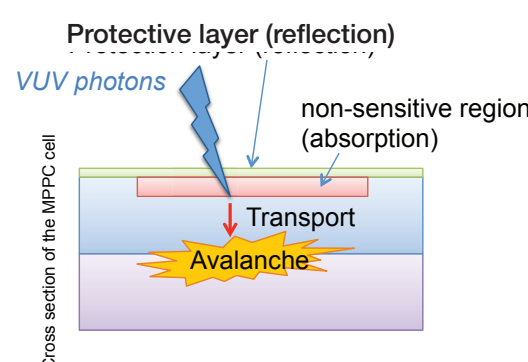


3 mm sq

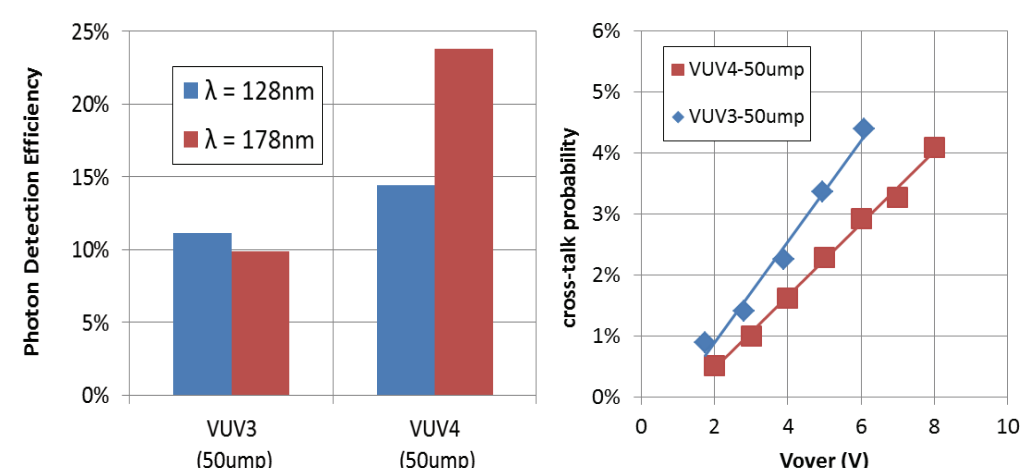
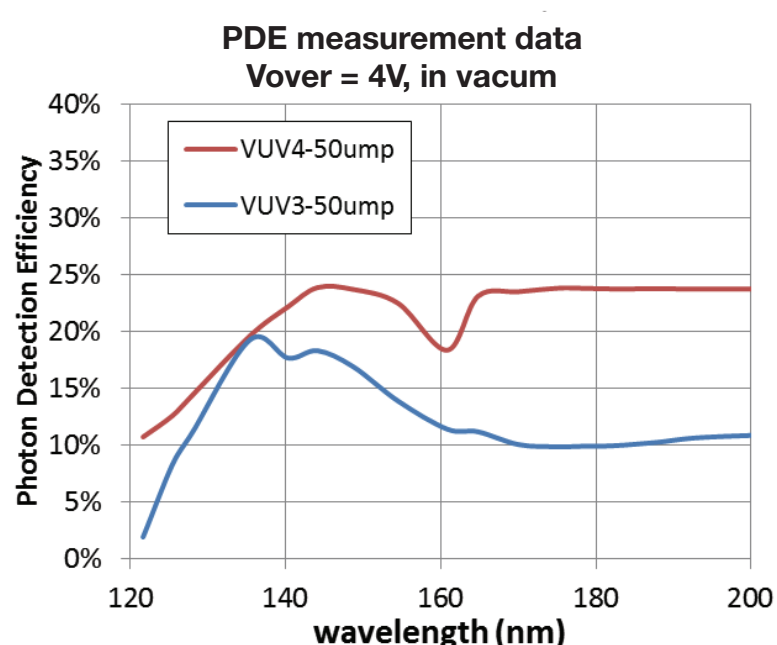
## VUV-sensitivity improvement

### Our solution for direct detection is the "VUV-MPPC" series.

- For VUV light detection, precise control of MPPC's protective layer and non-sensitive region is required.
- Electrons excited by VUV light are transported to the avalanche region by an electric field. To obtain higher carrier collection efficiency, a defect-less device is required because crystal defects cause recombination of electrons and holes.

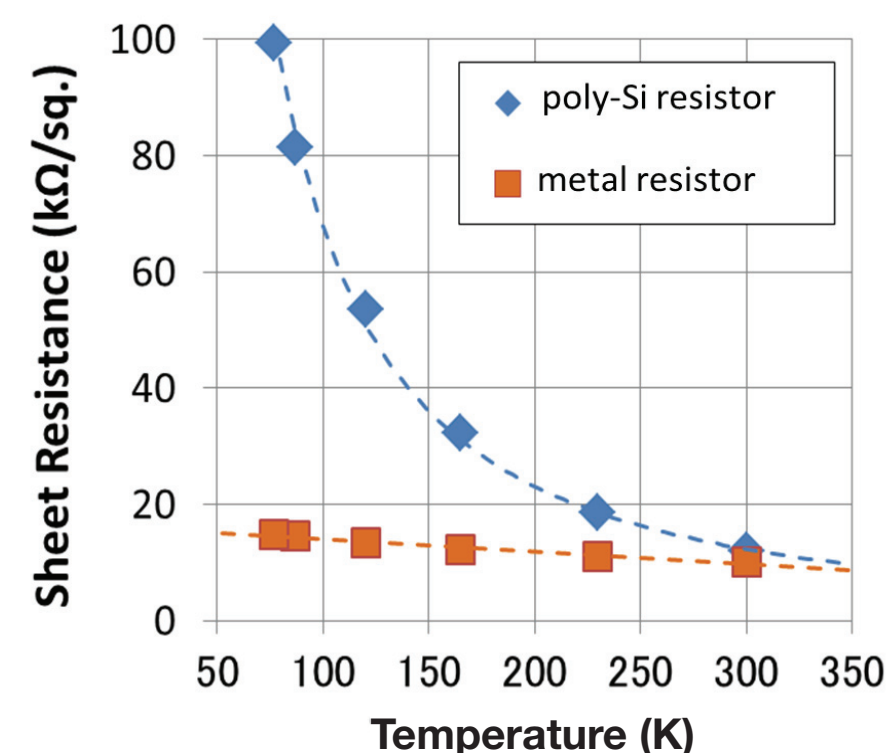


### VUV-sensitivity improvement

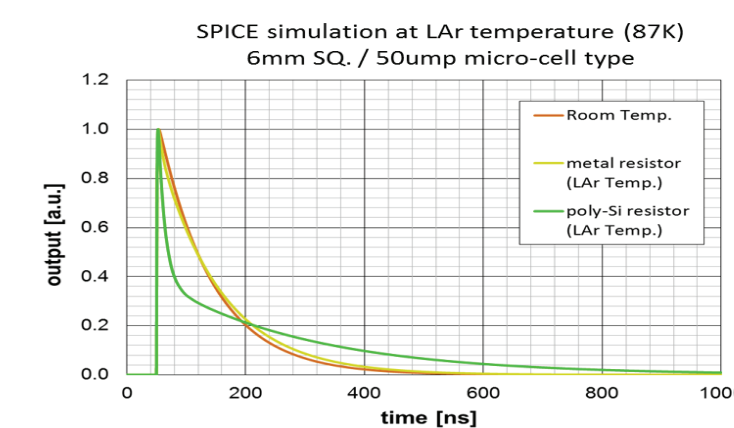
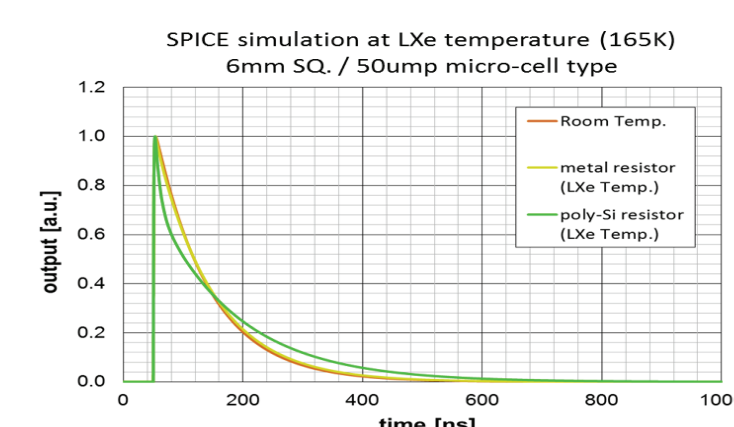


- VUV-MPPC has VUV-sensitivity down to 120 nm.
- The new 4th generation VUV-MPPC (VUV4) has improved photon detection efficiency, which is much higher than the 3rd generation VUV-MPPC (VUV3).
- Since optical crosstalk is still suppressed by the inter-pixel trench structure, VUV4-MPPC has improved signal-to-noise ratio.

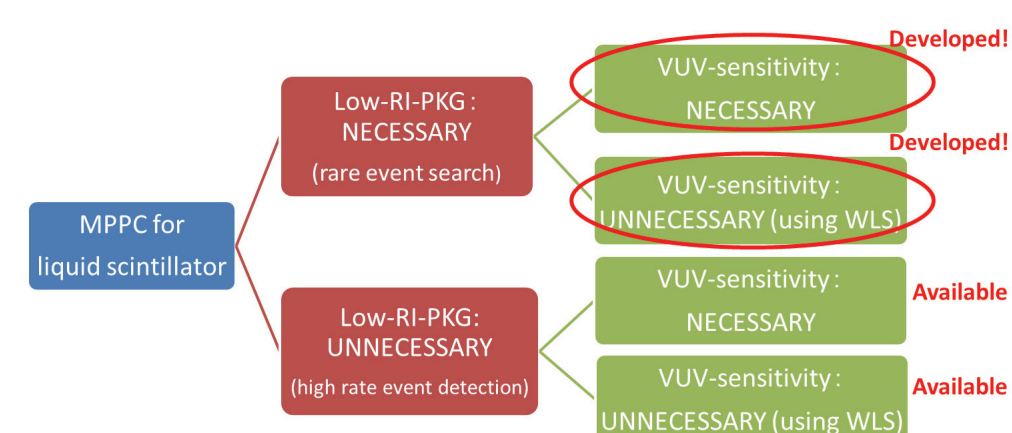
### Cryogenic temp. stability



- VUV-MPPC contains a metal quenching resistor to maintain its pulse shape at low temperatures. The metal resistor has 1/5 the temperature coefficient of the poly-Si resistor, so its resistance has excellent stability against temperature changes.
- SPICE simulation confirmed that there is a clear difference in pulse shapes between the metal and poly-Si resistors at lower temperatures.
- VUV-MPPC with metal quenching resistor maintains its pulse shape at both room and low temperatures, but MPPC with poly-Si resistor has longer pulse tails and recharge time at low temperatures.



## Packaging technology for physics experiment with liquid scintillator



- For rare event search experiments that require a low-noise background, MPPC must have reduced radioisotope (RI) content in its constituent materials.
- We have measured the RI level of each package material candidate and developed the ultralow-RI MPPC.

### Ultralow-RI MPPC for indirect VUV detection

		RI level of package component				
		Unit: [mBq/unit]	MPPC chip	die bonding resin	molding resin	lead frame
U-chain	Pa-234m	<1.8	<1.7	<41	<96	
	Pb-214	<0.019	<0.019	<0.425	<1.34	
	Bi-214	<0.031	<0.018	<0.51	<1.36	
Th-chain	Ac-228	<0.055	<0.041	<0.92	<2.02	
	Pb-212	<0.013	0.014±0.004	<0.27	<0.5	
	Bi-212	<0.14	<0.12	<2.5	<4.68	
Other	Tl-208	<0.031	<0.03	<0.75	<1.36	
	U-235	<0.011	<0.011	<0.19	<0.3	
	K-40	<0.084	<0.072	<2.99	<3.64	
	Cs-137	<0.006	<0.005	<0.13	<0.3	
	Co-60	<0.005	<0.006	<0.12	<0.19	

\*measured by GeLAtuca (Radiopurity Service of Laboratorio Subterráneo de Cabranc), IFIC INST. FISICA CORPUSCULAR UNIV. VALENCIA CSIC, NEXT group.

Package type : Plastic mold (active area: 1 mm sq)  
Application : Indirect detection of scintillation photons by using a wavelength shifter (WLS)  
Spectral response range : 320 to 900 nm  
RI level : Only <sup>212</sup>Pb has been quantified from die bonding resin, but other radioisotopes in the Th-chain are below the detection limit.

### Ultralow-RI MPPC for indirect VUV detection

		RI level of package component			
		Unit: [mBq/unit]	MPPC chip	die bonding resin	Pure Ceramic
U-chain	Pa-234m	<99	<211	<6.8	<65
	Pb-214	<1.1	<6.8	<105	<105
	Bi-214	<1.7	<13	<6.4	<55
Th-chain	Ac-228	<3.1	<6.4	<2.1	<35
	Pb-212	<0.74	<2.1	<89	<60
	Bi-212	<7.6	<5.6	<22	<220
Other	Tl-208	<1.7	<2.3	<1.8	<15
	K-40	<4.7	<2.3	<1.8	<15
	Cs-137	<0.33	<2.3	<1.8	<15
	Co-60	<0.27	<1.8	<1.8	<15

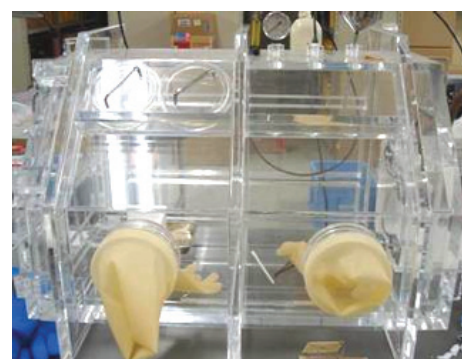
\*measured by Hamamatsu Photonics (on ground equipment).

Package type : Ceramic (active area: 6 mm sq)  
Window : Bare, quartz (for LXe), MgF<sub>2</sub> (for LAr)  
Application : Direct detection of scintillation photons  
Spectral response range : 120 to 900 nm  
RI level : No radioisotopes could be quantified by the measurement setup.

### Low temperature resistivity test

- Package reliability is one of the concerns for liquid scintillator applications.
- A thermal shock test was implemented for each Low-RI MPPC.

Thermal shock test  
● Temperature : 77 K  
● Test cycle : 15 cycles (9 samples each)  
● N<sub>2</sub> purged : To prevent condensation  
● Testing flow :  
1. Put device in liquid nitrogen for 5 min.  
2. Leave device at room temperature for 5 min.  
3. Check conductivity and damage



Results  
● No damage in packages and chips  
● Electrical characteristics did not change.

Cryogenic compatibility is confirmed.

## Conclusion

### Overview of Hamamatsu's product development for physics experiments using liquid scintillator

- VUV-MPPC**  
The 4th generation of VUV-MPPC (VUV4) has achieved a high signal-to-noise ratio, and its pulse shape is not affected by temperature.
- Ultralow-RI packaging**  
Cryogenically compatible, ultralow RI-level packages have been developed for direct and indirect detection of VUV scintillation light.

### Communication & Collaboration

- We'd love to hear your thoughts regarding current product features along with your ideas for improvements.
- We'd also be interested in collaborating with well-equipped researchers on development of ultralow-RI packaging.
- Please feel free to contact us through your local Hamamatsu sales representative.