Silicon Carbide Solid-State Photomultiplier for UV Light Detection

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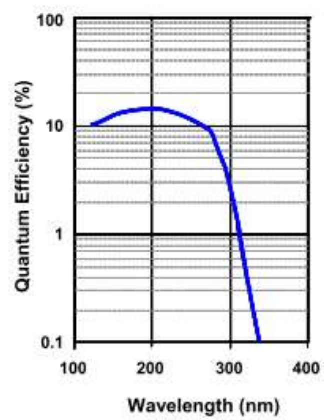
GE Global Research

Why Solid-State?

PMTs are sensitive to magnetic fields, have low quantum efficiency, are bulky and expensive. high voltage power supply and very short lifetime at elevated temperatures

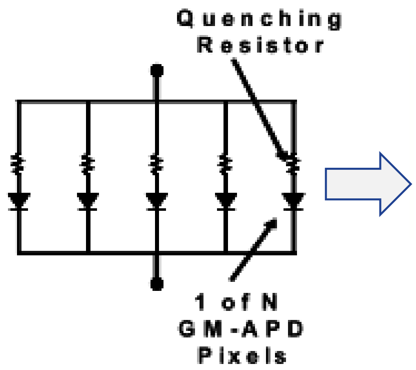
Why UV?

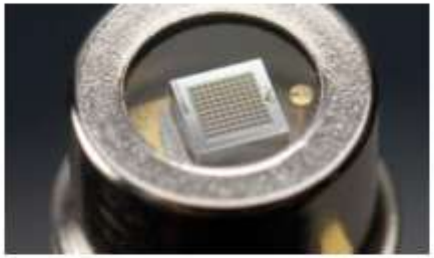
- flame detection,
- biological and chemical detection,
- detection of jet engines and missile plumes
- Bio-aerosol detection
- Micro Flash Ladar for navigation
- Deep-UV Imaging
- Harsh-Environment UV and Gamma Detectors



Perkin Elmer Channel MP- series photomultiplier module

Hamamatsu Multiple Pixel Photon Counting (MPPC) array





parallel connection of individual GM-APD detectors comprising the array

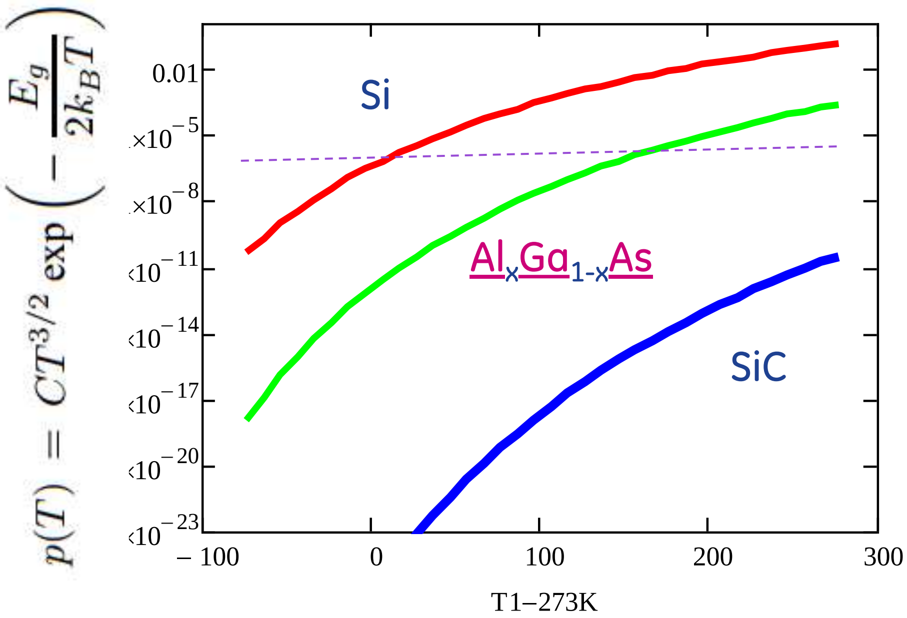
Design of SiC SSPM

Why SiC?

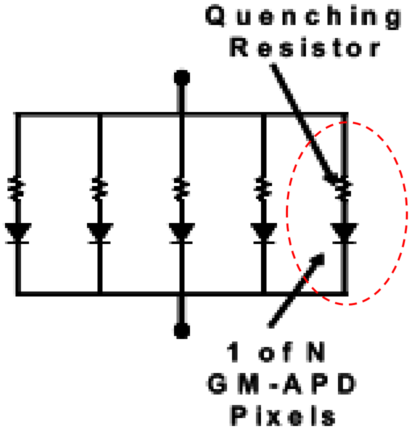
Dark count rate in Si-PM increases rapidly with temperature, resulting in a maximum operating temperature below 50ºC

SiC has larger bandgap (3.26 eV)
- Lower leakage current
- Higher operating Temperature
- Higher sensitivity in UV spectra

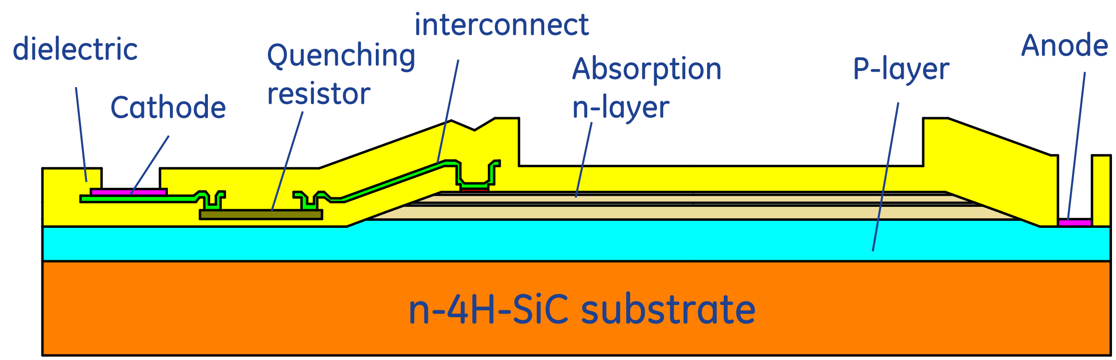
probability of thermally produce electron-hole pairs in perfect crystal.
Theory



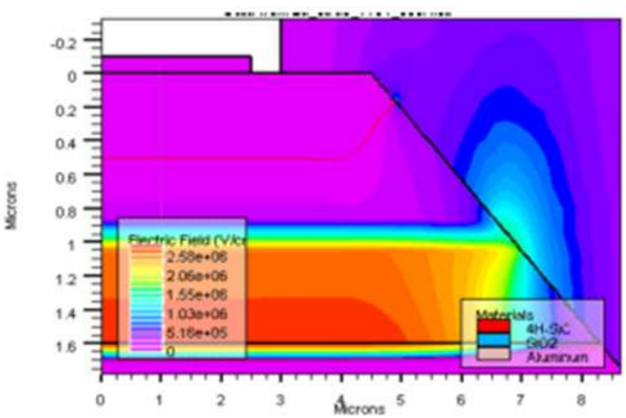
Design of SiC SSPM



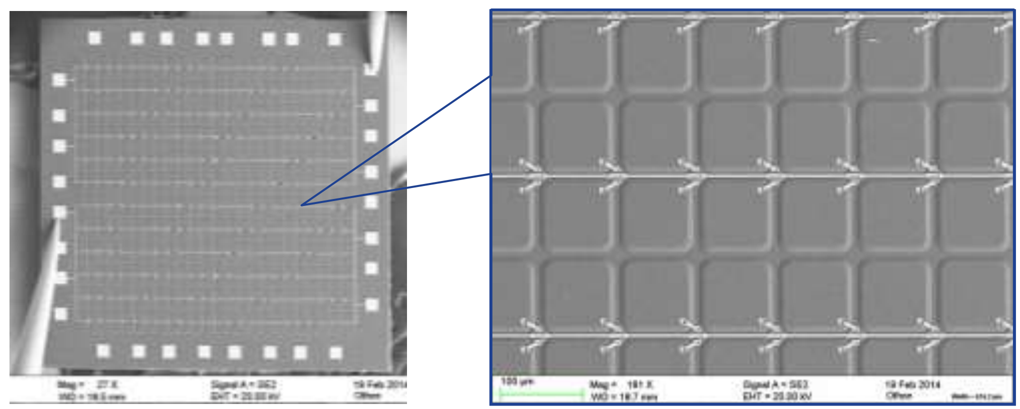
Schematic cross section of individual pixel



2-D distribution of electric filed at avalanche breakdown voltage

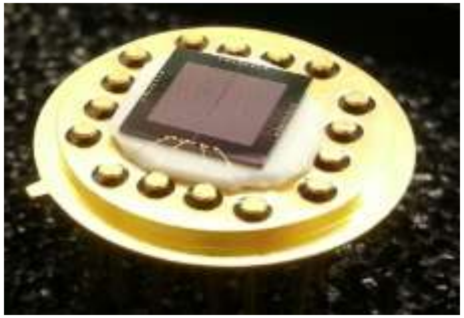


SEM images of fabricated SiC SSPM dies

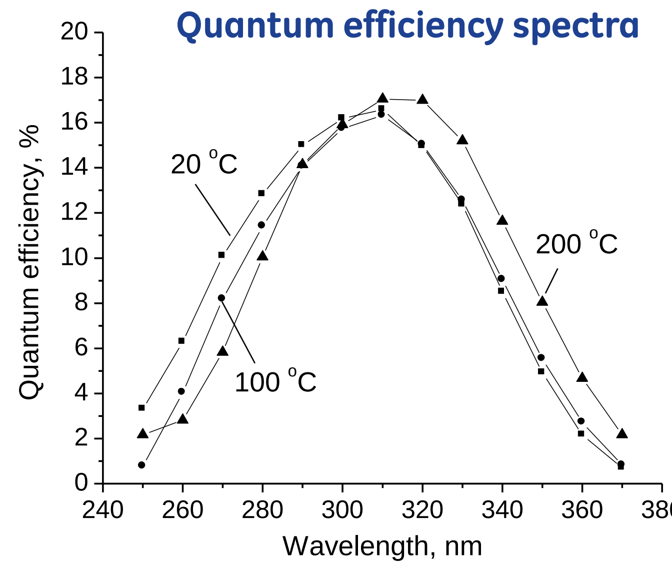


Characterization of SiC SSPM

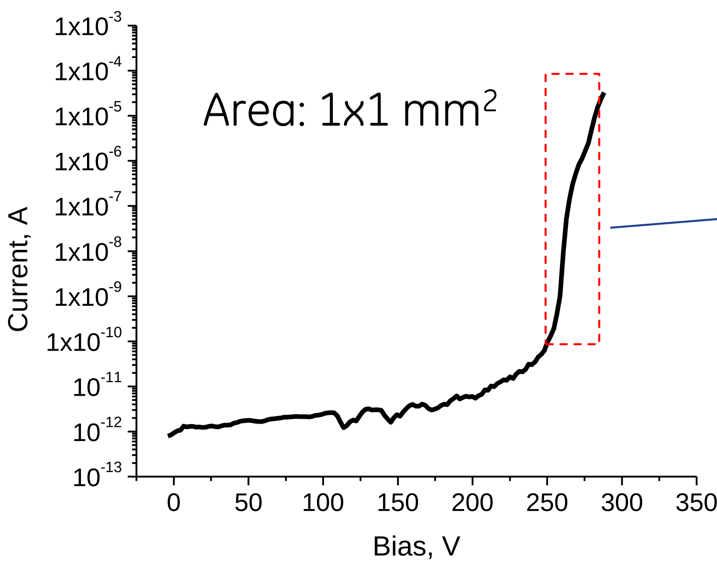
Packaged SiC SSPM



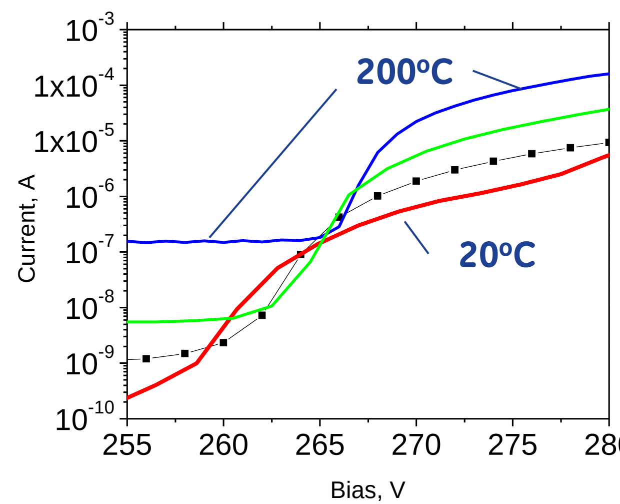
Active area: 4x4 mm^2
Pixel size: 60 um
16 sub arrays
Area of sub-array:
1x1 mm^2



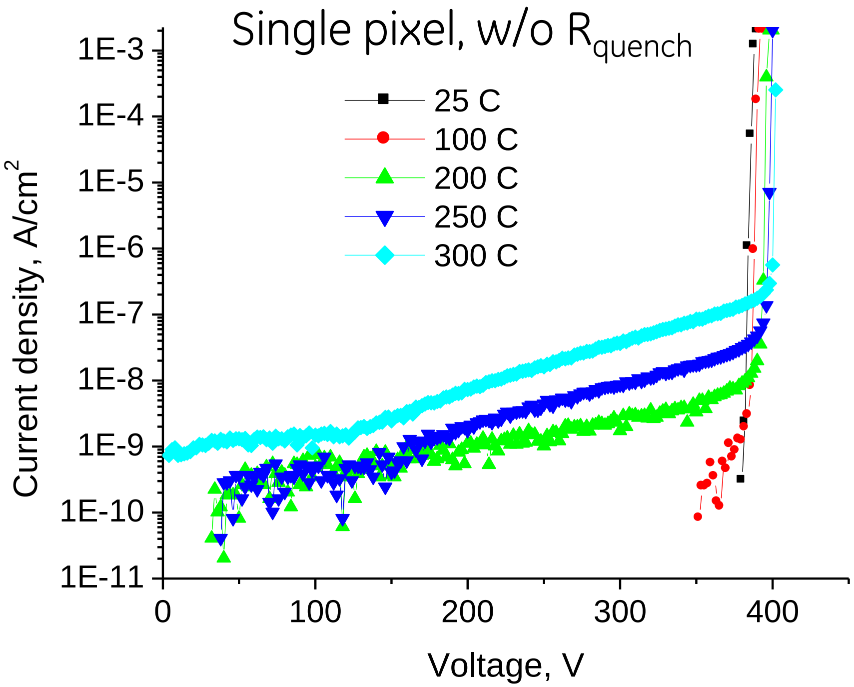
Dark I-V curve at room temperature

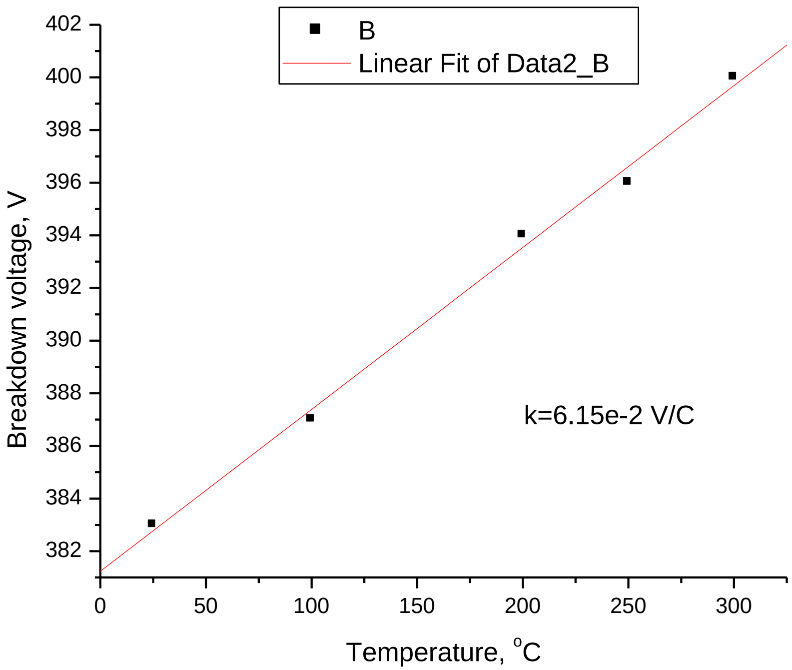


Dark I-V curves vs. temperature at avalanche breakdown



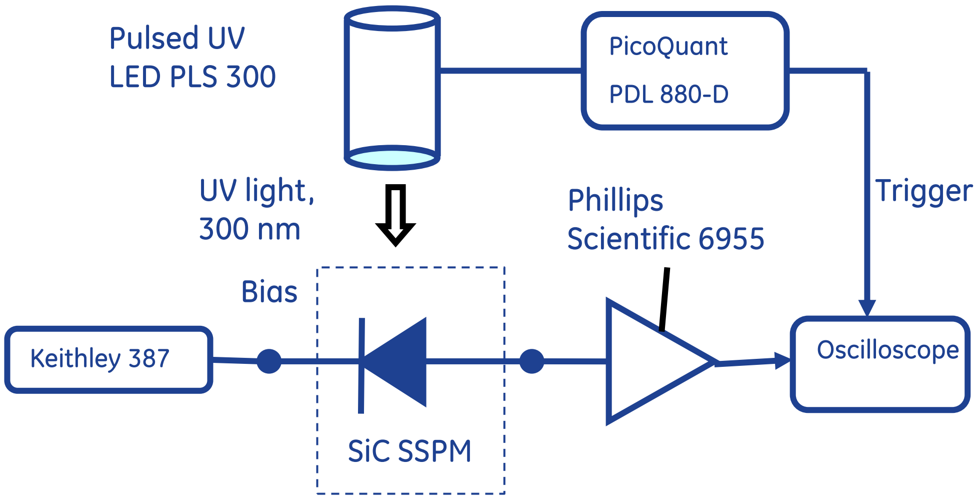
Breakdown voltage vs. Temperature





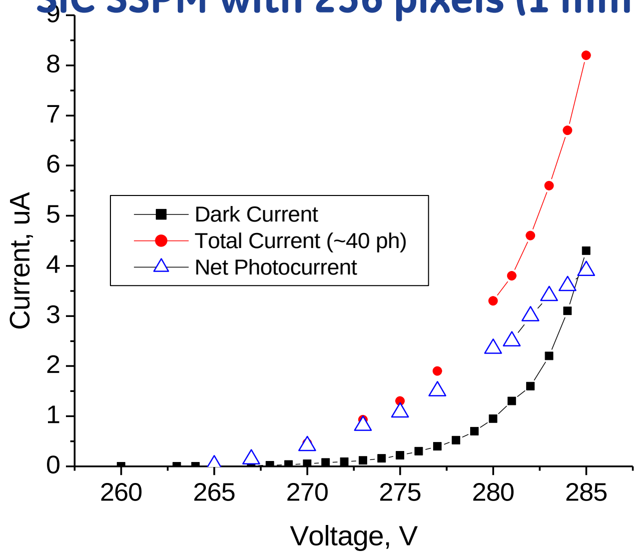
Breakdown voltage changes with temperature 62 mV/^{o}C

Block diagram of setup for optical measurements

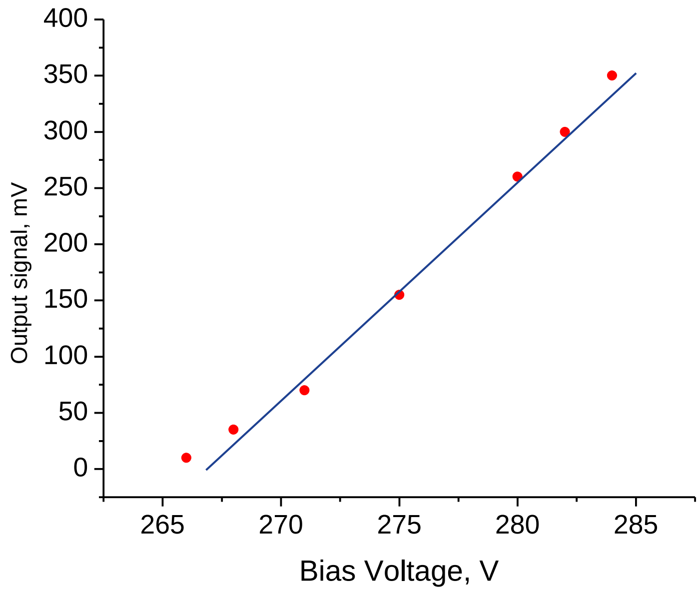


- PicoQuant LED – 300 nm (10 nm FWHM), <0.5 ns, 0.25 pJ per pulse
- Oscilloscope LeCroy – 1 GHz, 40 Gs/sec

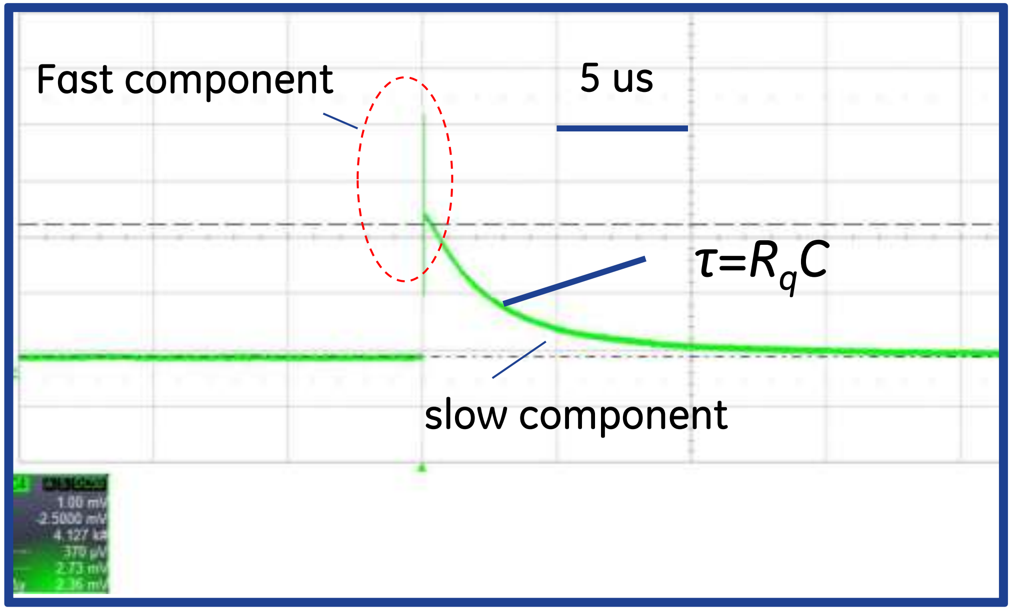
I-V curves of dark and photocurrents SiC SSPM with 256 pixels (1 mm²)

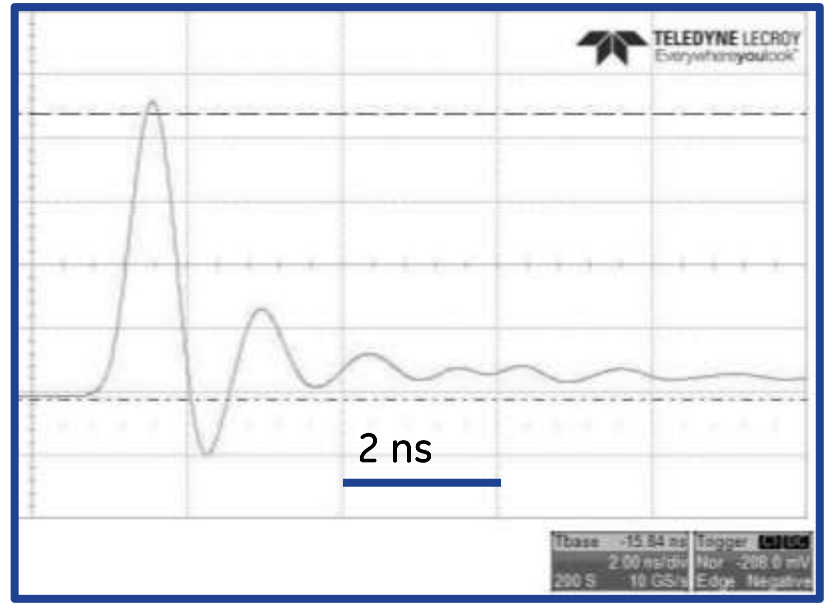


Output signal vs. bias voltage



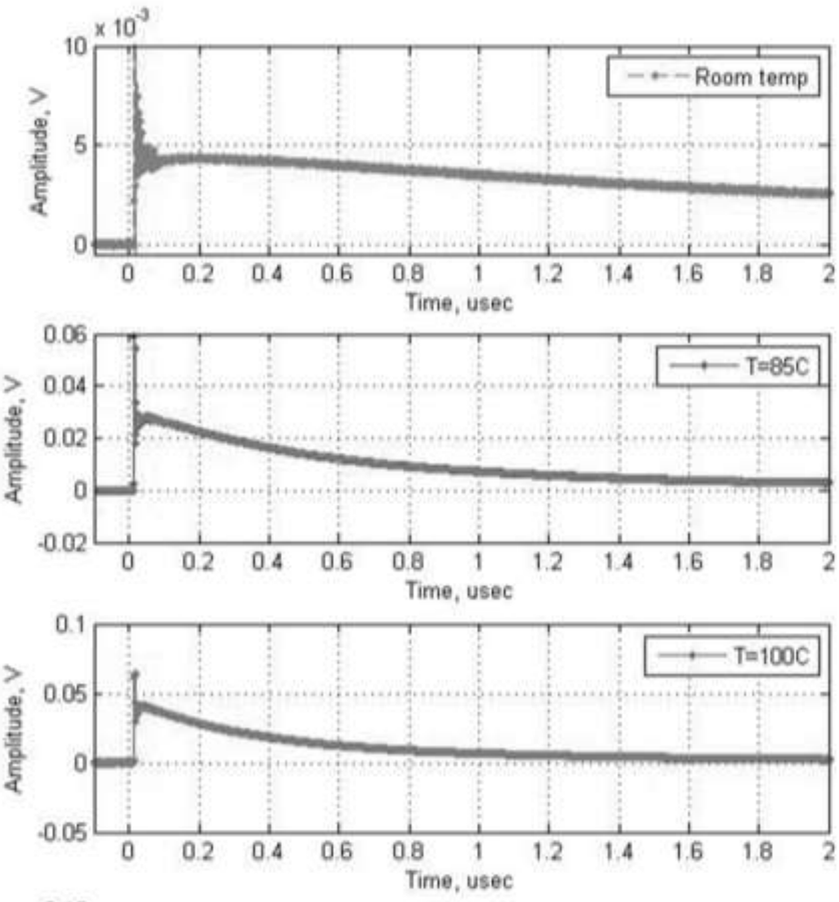
Waveforms of output signal at room temperature

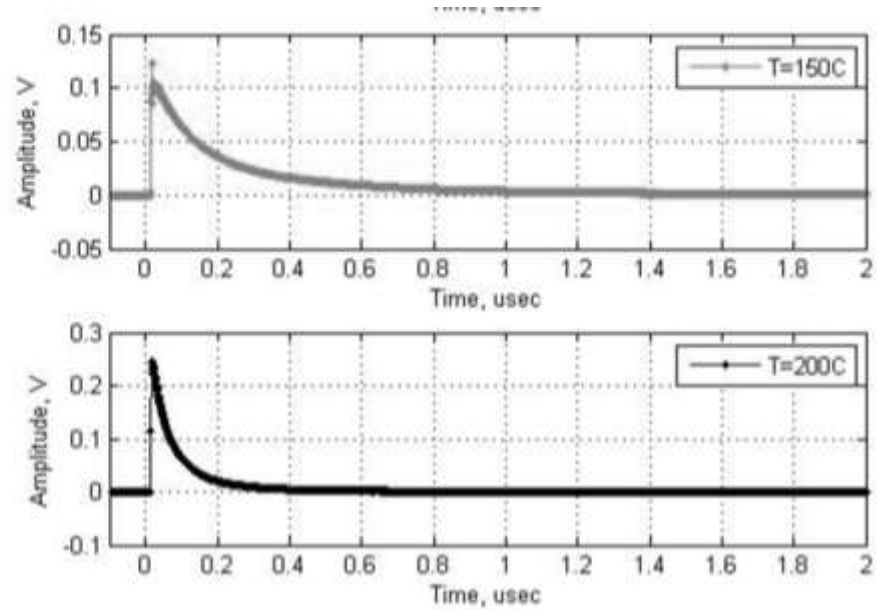


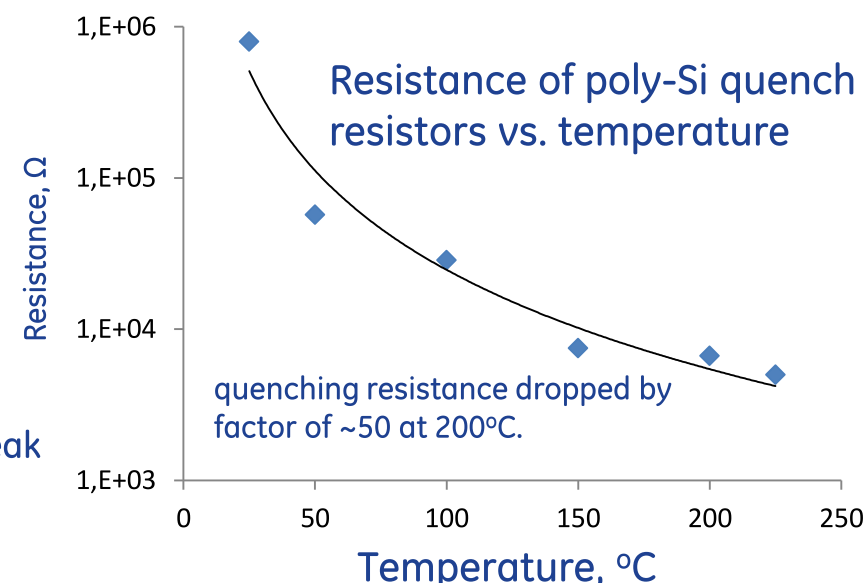


Slow component (~3 us) in the waveform depends on a value of quenching resistor

Impact of temperature on signal waveform



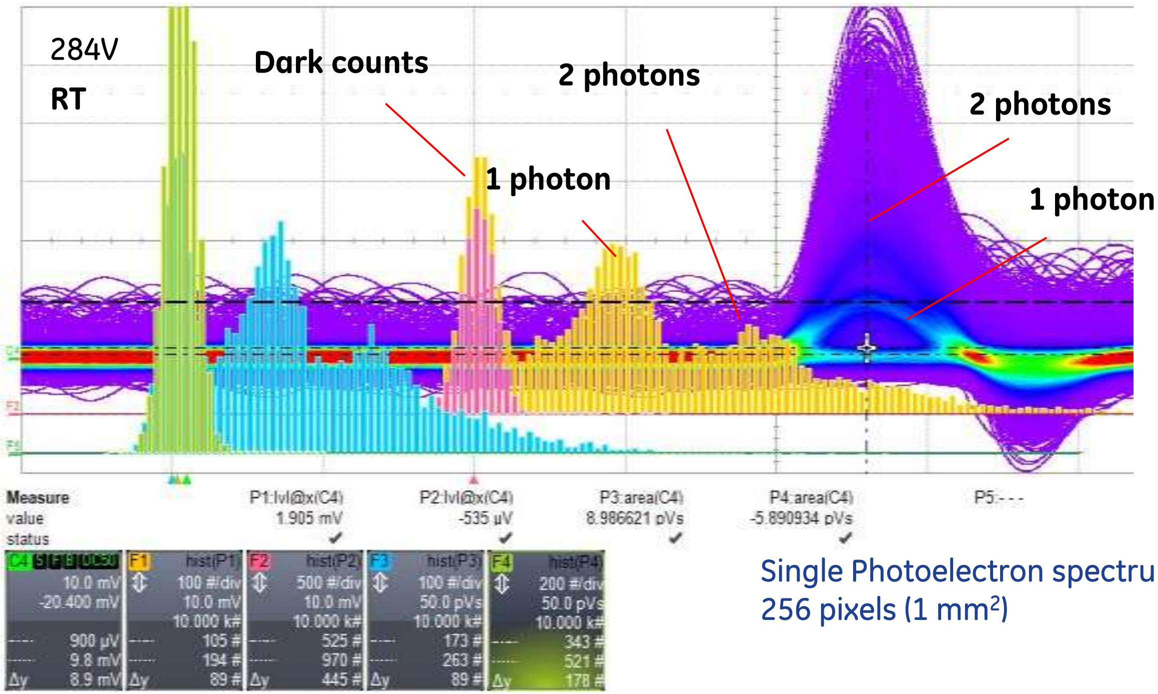




fast component in the waveform of the output signal becomes negligible with temperature increase.
The time constant at 200°C decreases to 60 ns, while peak amplitude increases up to 0.25V

Single Photon Detection

Oscilloscope snapshot take at room temperature



Single Photoelectron spectrum recorded for SiC-PM with 256 pixels (1 mm^2)

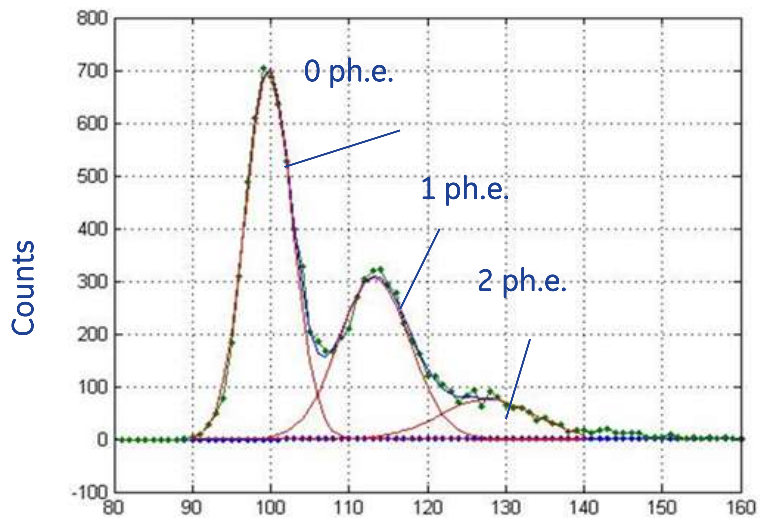
The histograms suggest discrete nature of SiC SSPM output signal when illuminated by very low level light flux

Single Photon Detection Efficiency Measurements

$$PDE = \frac{\langle N_{fired} \rangle}{N_{ph}} = \frac{\langle N_{fired} \rangle h\nu \cdot f}{P_{opt}\, A_{SiC\ PM}}$$

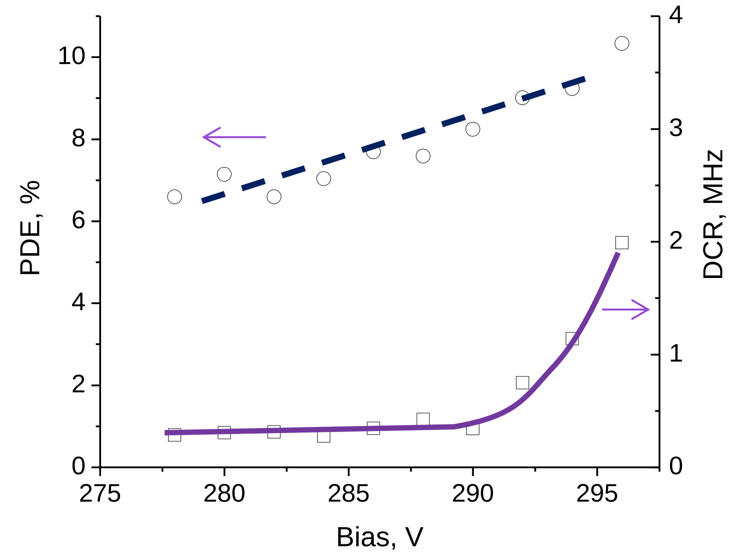
N_{fired} is the average number of triggered pixels,
$h\nu$ is the photon energy,
f is the pulse repetition rate,
P_{opt} is the optical power density,
$A_{SiC\text{-}PM}$ is the area od SiC-PM

Single Photoelectron spectrum recorded for SiC-PM with 256 pixels (1 mm^2)



Each peak corresponds to a certain number of photoelectrons (ph.e).

Photodetection efficiency and dark count rate as functions of voltage bias



PDE increases linearly from 7 to 9% within the measured voltage range, while DCR slightly increases up to 290V and significantly grows up from ~0.4MHz/mm^2 at 290V to 2MHz/mm^2 at 296V

UV scintillators for SIC SSPM

Saint-Gobain Crystals

Physical Properties of Common Inorganic Scintillators

Scintillator	Light yield (photons/keV)	Light ouput (%) of NaI(Tl) bialkali pmt	Temperature coefficient of light output (%/C) 25°C to 50°C	1/e Decay time (ns)	Wavelength of maximum emission lm (nm)	Refractive index at lm	Thickness to stop 50% of 662 keV photons (cm)	Thermal expansion (/C) x 10^{-6}	Cleavage plane	Hardness (Mho)	Density g/cm^3	Hygroscopic	Comments
BrilLanCe™380 $LaBr_3(Ce)$	63	165	0	16	380	~1.9	1.8	8	<100>		5.08	yes	General purpose, best energy resolution, rate of change of light output w/temperature is small
NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	<100>	2	3.67	yes	General purpose, good energy resolution
Polyscin®NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	none	2	3.67	yes	Polycrystalline NaI(Tl), for extra strength
BrilLanCe™350 $LaCl_3(Ce)$	49	70-90	0.7*	28	350	~1.9	2.3	11	<100>		3.85	yes	General purpose, excellent energy resolution
CsI(Na)	41	85	-0.05	630	420	1.84	2	54	none	2	4.51	yes	High Z, rugged
PreLude ™ 420 $Lu_{1.8}Y_{.2}SiO_5(Ce)$	32	75	-0.28	41	420	1.81	1.1	--	none		7.1	no	Bright, high Z, fast, dense, background from ^{176}Lu activity
$CdWO_4$	12 - 15	30-50	-0.1	14000	475	~2.3	1	10.2	<010>	4 - 4.5	7.9	no	High Z, low afterglow, for use with photodioides
$CaF_2(Eu)$	19	50	-0.33	940	435	1.47	2.9	19.5	<111>	4	3.18	no	Low Z, a & b detection
CsI(Tl)	54	45	0.01	1000	550	1.79	2	54	none	2	4.51	slightly	High Z, rugged, good match to photodiodes
BGO	8 - 10	20	-1.2	300	480	2.15	1	7	none	5	7.13	no	High Z, compact detector, low afterglow
YAG(Ce), $Y_3Al_5O_{12}(Ce)$	8	15	--	70	550	1.82	2	~80	none	8.5	4.55	no	b-ray, X-ray counting, electron microscopy
CsI(pure)	2	4-6	-0.3	16	315	1.95	2	54	none	2	4.51	slightly	High Z, fast emission
BaF_2	1.8	3	0	0.6 - 0.8	220(195)	1.54	1.9	18.4	<111>	3	4.88	slightly	Fast component (subnanosecond)
	10	16	-1.1	630	310	1.50	1.9	18.4	<111>	3	4.88	slightly	Slow component
ZnS(Ag)	~50	130	-0.6	110	450	2.36	--	--	--	--	4.09	no	Multicrystal, 15m stops 5.5 MeV a (n detection with ^{6}Li)

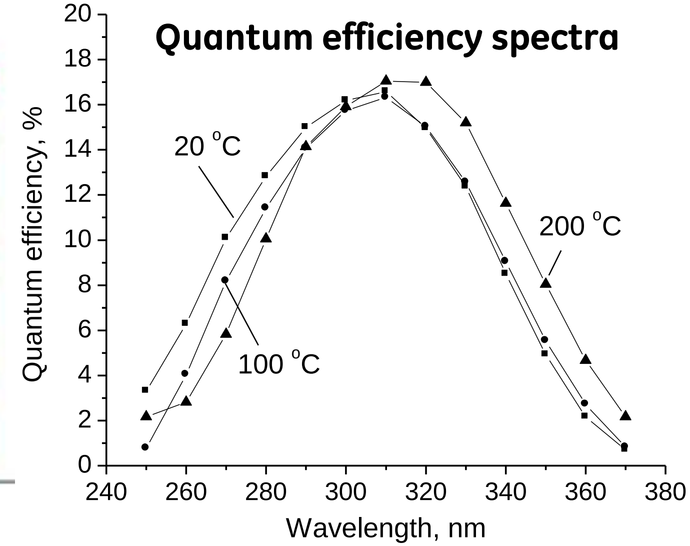
imagination at work

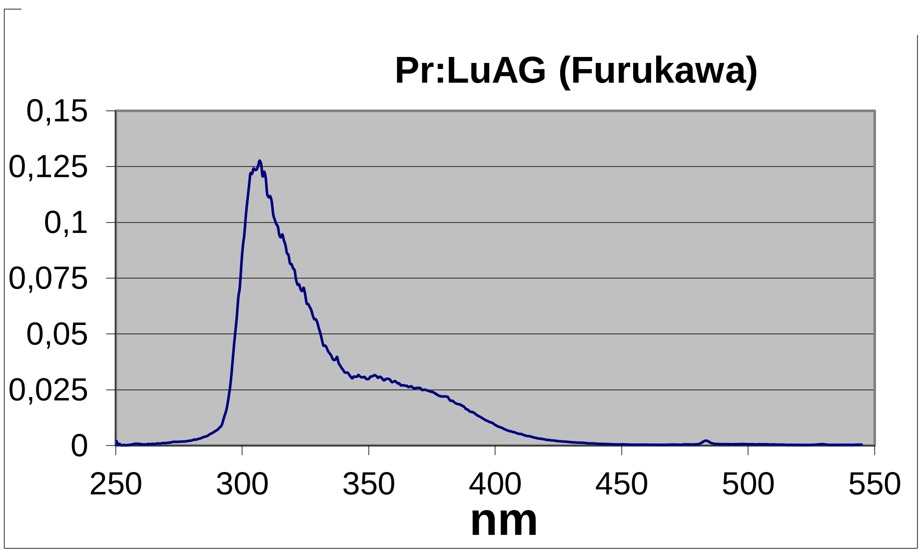
UV scintillators for SIC SSPM

Physical and Scintillation Properties

Scintillators	Pr:LuAG	Ce:LYSO	BGO	Ce:LaBr$_3$
Density (g/cm^3)	**6.73**	7.1	7.13	5.08
Light yield (photon/MeV)	**22,000**	34,000	8,000	75,000
Decay time (ns)	**20**	40	300	30
Peak emission (nm)	**310**	420	480	360
Energy resolution (%@662keV)	**4.2**	10	12	2.6
Hygroscopicity	**No**	No	No	Yes
Cleavage	**No**	No	No	No
Melting point (℃)	**2,043**	2,150	1,050	783

Contact:t-iwata@furukawakk.co.jp





http://www.crystals.saint-gobain.com/BrilLanCe_350_scintillator.aspx

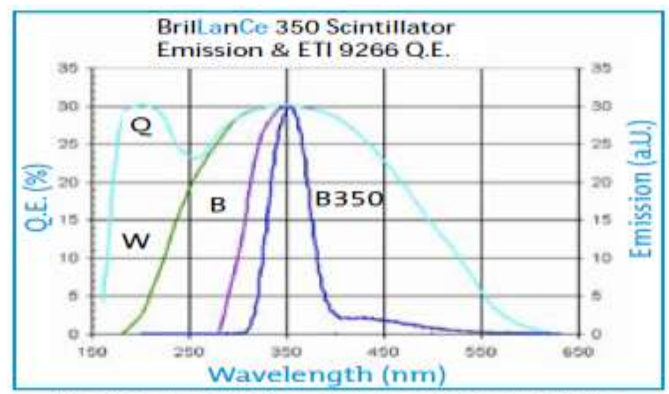
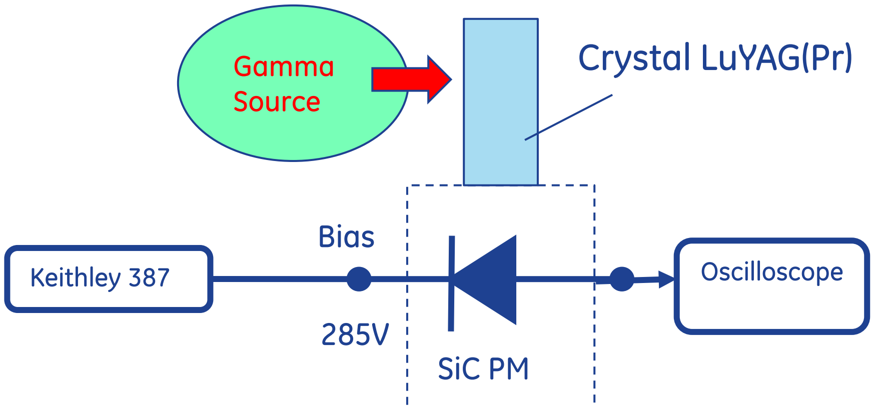


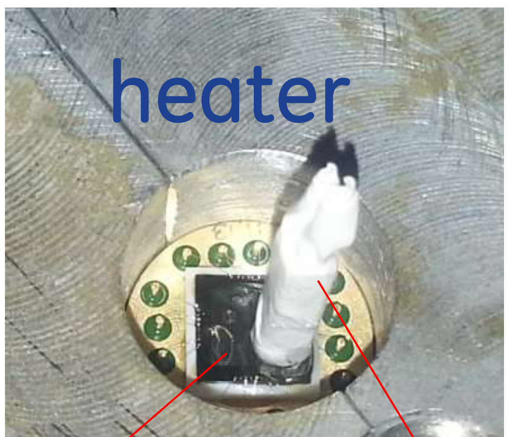
Figure 2. Scintillation emission spectrum of the BrilLanCe 350 crystal and Quantum Efficiency of a bialkali ETI9266 PMT with (B)Borosilicate, (W)UV glass, and (Q)Quartz face plates

(Q.E. data courtesy of Electron Tubes, Inc.)

Testing SiC SSPM with scintillator crystal (LuYAG)

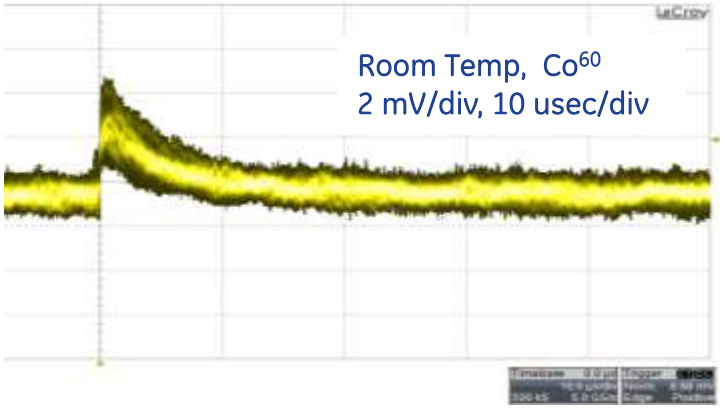


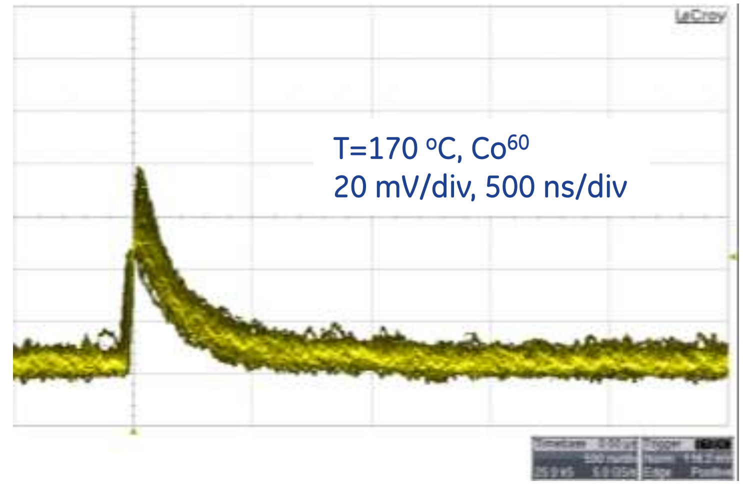
Active area of SiC SSPM 2x2 mm^2

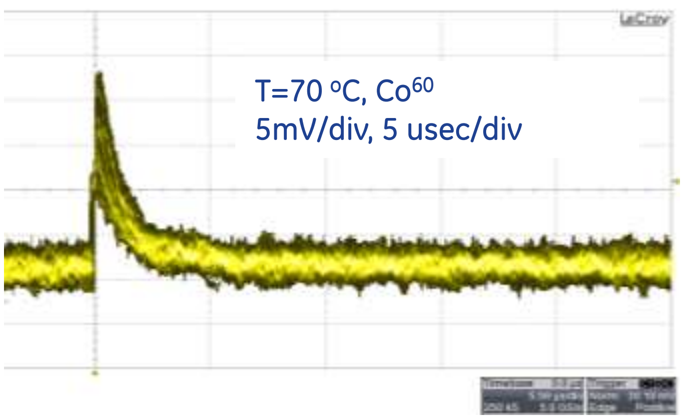


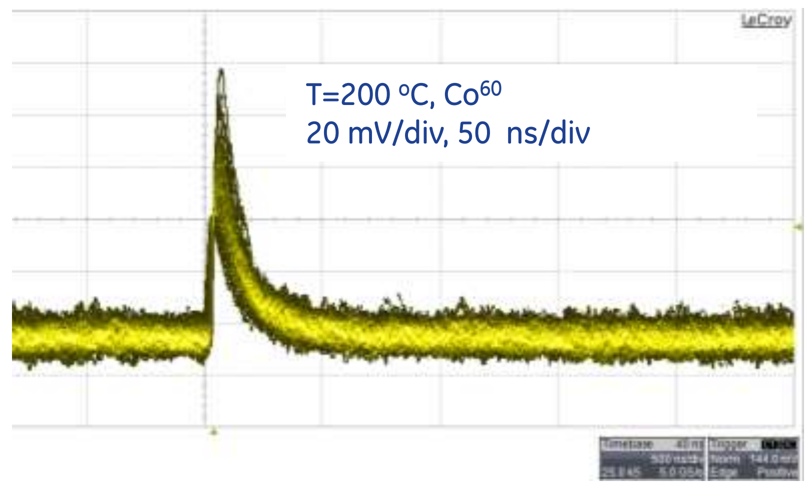
Gamma Source

Output signal waveform at different temperatures









SiC SSPM with LuYAG crystal demonstrated a strong response from Gamma source at 200ºC

Summary

- Silicon Carbide Solid-State Photomultiplier was demonstrated for the first time.
- Photon detection efficiency of the SiC-PM measured at 300 nm was about 8%, while a dark count rate was about 0.3MHz/mm^2 at room temperature.
- Time constant and peak amplitude of output signal significantly dependent on temperature, the time constant decreases from 3 us to 60 ns, while the peak amplitude increases in ~ 25 times with a temperature increase from 20 ^oC to 200 ^oC.
- SiC SSPM works with UV scintillators up to 200 ^oC