sensL
sense light

design | detect | today

The Leaders in Silicon Photomultipliers Since 2004

SensL Technology Update

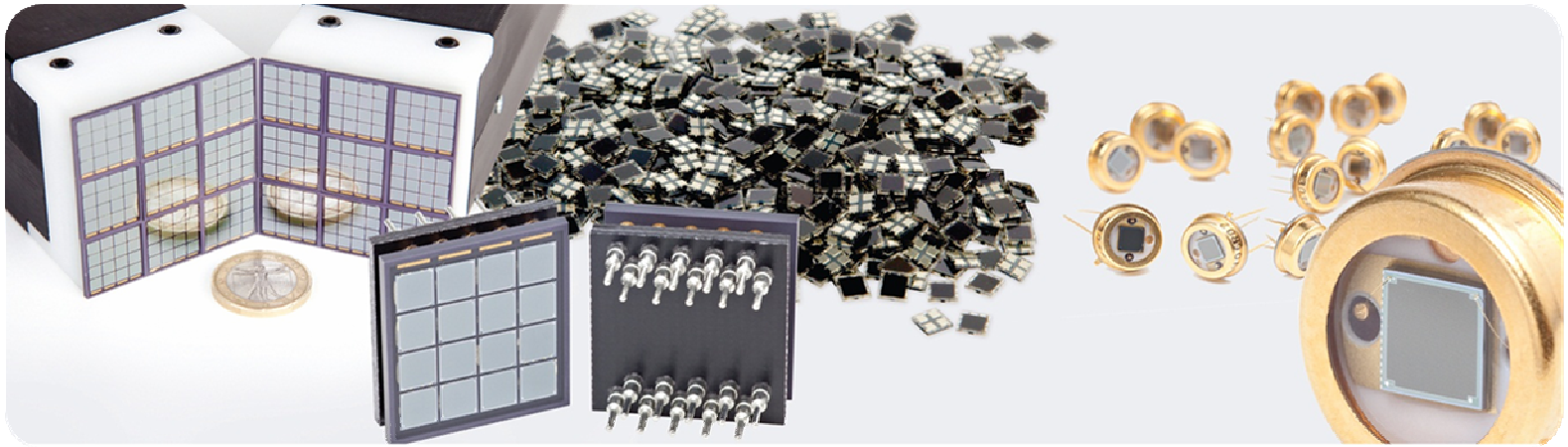
Institute of Nuclear Research,
April 2014

Seminar Overview

- SensL Company Overview
  - History
  - Core value proposition
- SensL Silicon Photomultiplier (SiPM) Technology Overview
  - Low light sensing & technology evolution
  - Current technology status
- Products & Pricing Overview
- Applications Overview
  - Nuclear Medicine, LiDAR, Radiation Detection, Industrial, Automotive
- Supply Chain Overview

SensL Quick Facts

Business	Low Light Silicon Sensors
Markets	Medical Imaging Radiation Detection Automotive & Industrial Biophotonics, HEP, Academic
Model	Fabless Semiconductor



sensL
sense light

SensL Company History

- Pre-2004: Initial research at Tyndall National Institute, Cork

- **2004**: SensL founded, HQ in Cork
- **2005**: Photon counting products & modules
- **2006-2007**: "A-Series" 1st Generation SiPM
- **2008**: Array-2 Introduced
- **2009**: Array-4 Introduced
- **2010**: Transfer to commercial 8" CMOS foundry
  - Second generation of silicon ("L-Series")
  - Matrix9 Introduced
- **2011**: Third generation of silicon ("M-Series")
  - Large area arrays (Array-8)
- **2012**: Surface-mount (SMT) devices introduced
  -High speed output introduced
- **2013**: Fourth generation of silicon ("B-series") introduced
  - SMT Arrays introduced

sensL
sense light

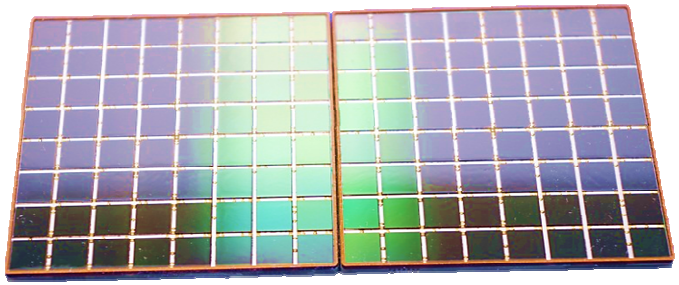
Low Light Sensor Leadership

SensL is the leading developer of Silicon Photomultiplier (SPM) technology manufactured in standard CMOS foundries to replace the aging industry standard Photomultiplier Tube (PMT)

Photomultiplier Vacuum Tube

SensL Uniquely Enables:

High Performance
Uniformity
Large Area
Form Factor Flexibility
Low Cost



SensL Silicon Photomultiplier

sensL
sense light

Low Light Sensing –

Technology Evolution & Update

SensL SiPM

- What is an SiPM?
  - Array of Geiger-mode photon sensors optimized for gain and high speed
- Advantages of SiPM over PIN or APD
  - Gain of SiPM is >1M
  - Output response is picoseconds
  - Temperature stability
  - Uniformity of output response
  - Wide dynamic range
  - Large area array compatible
  - CMOS compatible

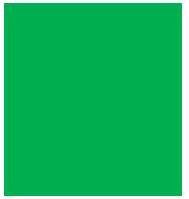
Silicon Photomultipliers

SPM - Principle of Operation

APD

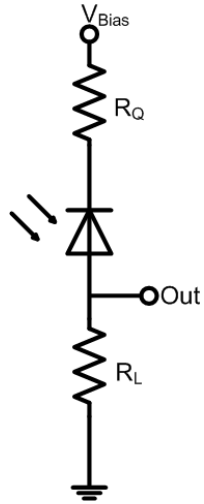
1. Miniaturize
2. Operate in “Geiger Mode”

SPM micro-cell

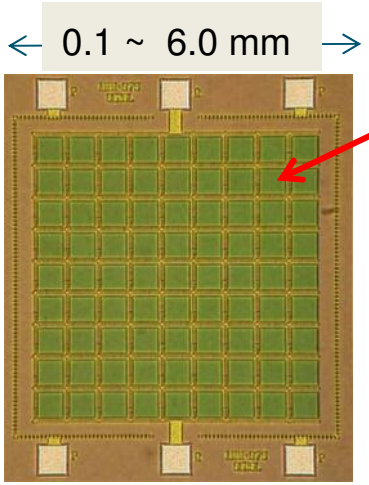


~50µm

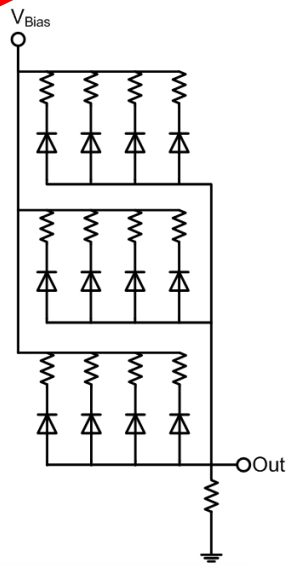
=



- **Single photon sensitivity**
- **Proportional response**
- **High gain**
- **UV through IR sensitivity**
- **Low voltage operation**
- **CMOS process**
- **Low cost**

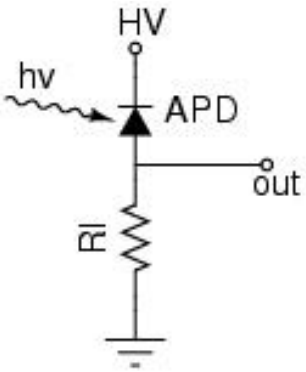


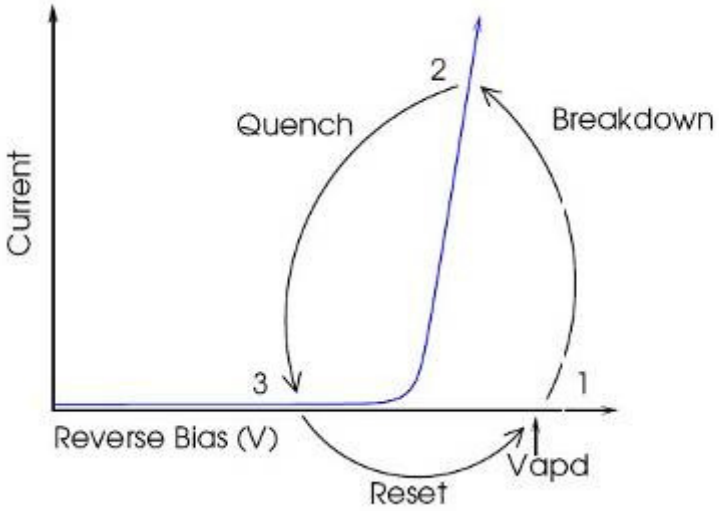
=

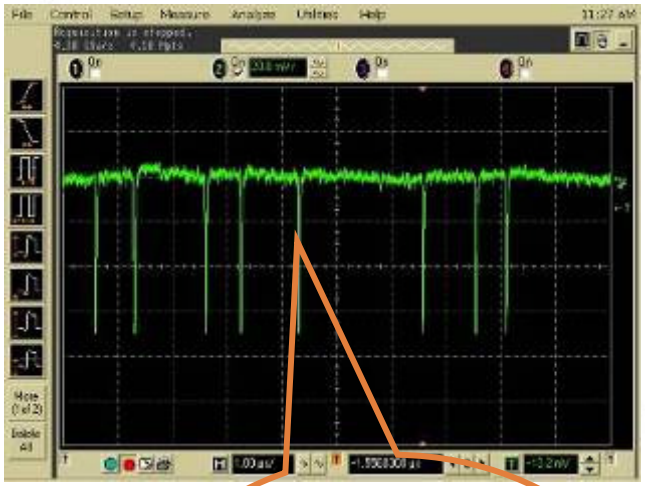


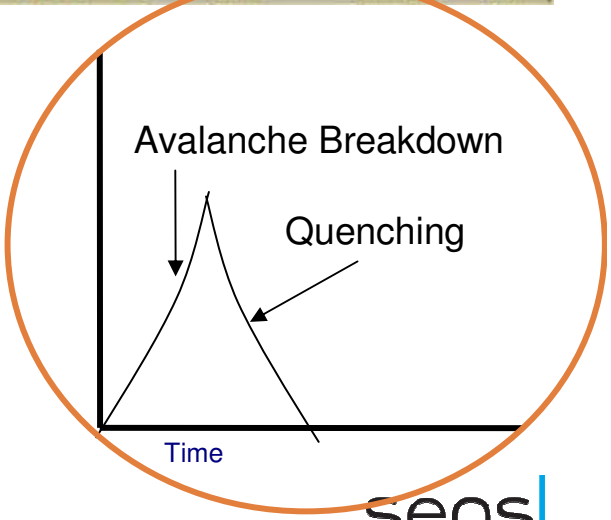
sensL
sense light

Geiger Mode Operation



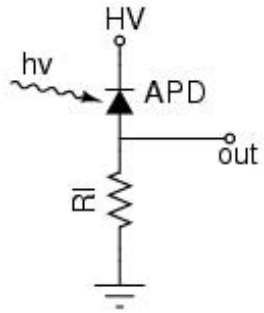


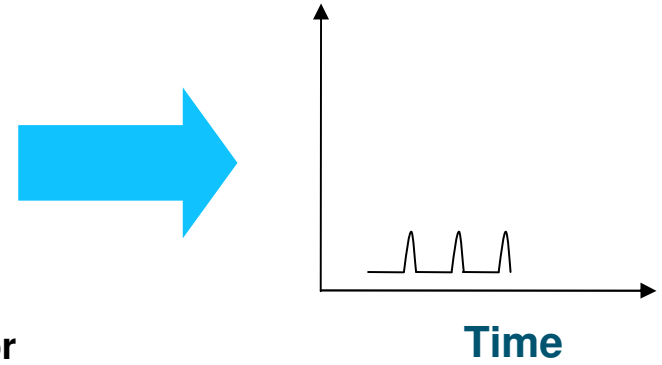




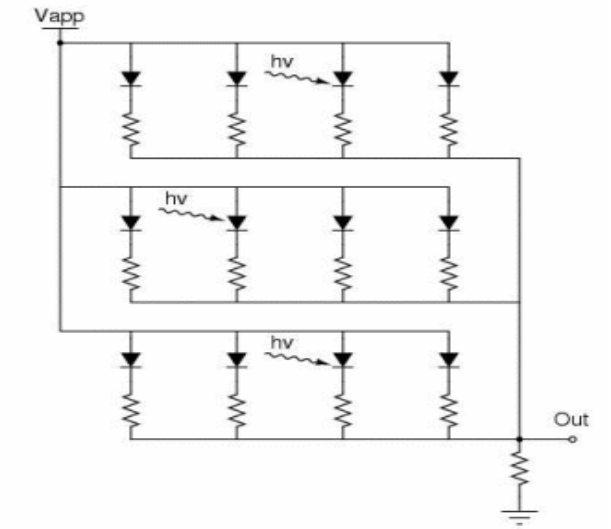
- Breakdown/Quench-Reset cycles per microcell
- Output is a pulse of charge for each photon
- All SensL devices operate <30V

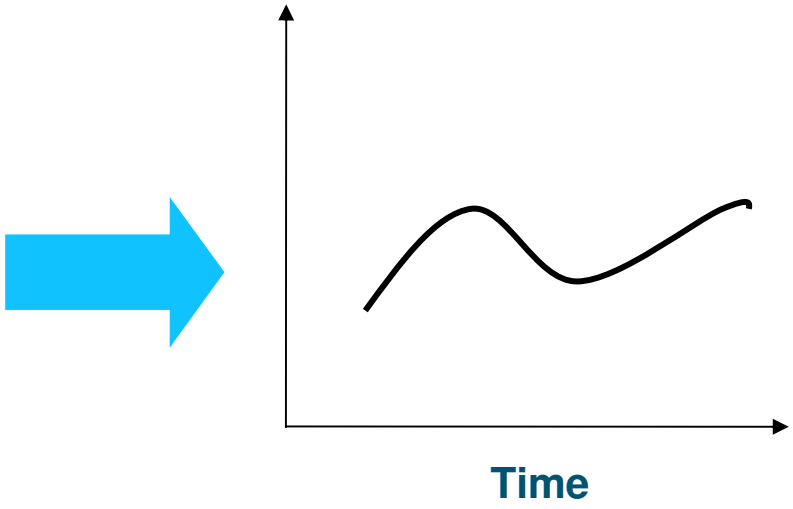
SiPM Concept





Single microcell with integrated quench resistor





Array of Photon Counting Sensors in parallel

Sensor Technology Comparison

	PIN	APD	PMT	SiPM
Gain	1	10^2	10^6	10^6
Operating Voltage	0V to 5V	100V to 1kV	800V to 1kV	30 V
Temperature Sensitivity	Low	High	Low	Low
Mechanical Robustness	High	High	Low	High
Damage by Stray Light	No	Yes	Yes	No
Spectral range	UV-VIS-NIR	UV-VIS-NIR	Blue/UV	UV-VIS-NIR
Readout Electronics Complexity	Complex	Complex	Simple	Simple
Form Factor	Small	Small	Bulky	Small
System Cost	Medium	Medium	High	Lowest
Scalable Technology	Yes	No	No	Yes
Electromagnetic Immunity	No	No	No	Yes
Sensor Noise	Low	Med	Low	Lowest
Response time	Fast	Slow	Fast	Fastest

SiPM provides highest performance and lowest system cost

sensL
sense light

sensL
sense light

Current Technology

M & B Series Overview

Technology Spotlight

L Series

» Base Technology
» 495nm peak sensitivity

Released

M Series

» Improved PDE over L Series
» 495nm peak sensitivity
» High Resolution timing using fast output*

Released

B Series

» Maximum PDE and fast timing
» 420nm peak sensitivity
» High Resolution timing*

Q1 2013 Release

N-on-P

P-on-N

sensL
sense light

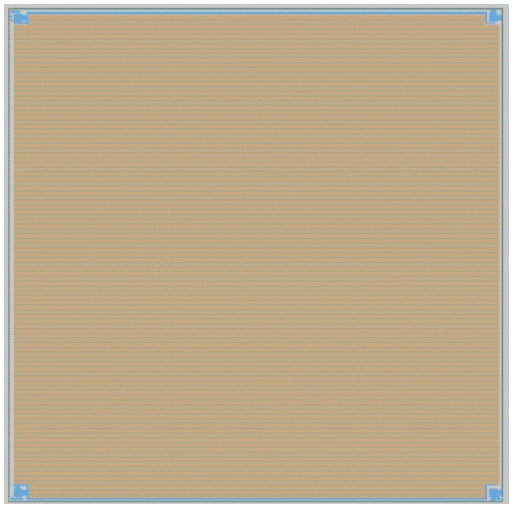
Terminology

- M-Series - A family of SiPM products based upon a N-on-P structure, featuring a third terminal that carries a *fast output*.
- B-Series - A family of SiPM products based upon a P-on-N structure, featuring a third terminal that carries a *fast output*.
- FM - An M-Series SiPM product that has at least 3 pins (or pads) accessible that include *anode*, *cathode* and the *fast output* and can therefore be used in fast mode configuration
- FB - A B-Series SiPM product that has at least 3 pins (or pads) accessible that include *anode*, *cathode* and the *fast output* and can therefore be used in fast mode configuration
- SM - An M-Series SiPM housed in a 2-pin package that only gives access to the *anode* and *cathode*. The third terminal (fast output) is not accessible, and so SM sensors can only work in standard mode.
- SB - A B-Series SiPM housed in a 2-pin package that only gives access to the *anode* and *cathode*. The third terminal (fast output) is not accessible, and so SB sensors can only work in standard mode.
- Fast mode - Using the *fast output* signal from an FM or FB product.
- Standard mode - Using only the *anode* and *cathode* of either an M or B product where the *fast output* terminal is not connected.

SiPM Product Pixel Dimensions

600 series SPM

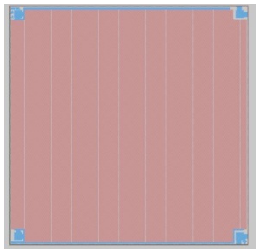
- *Full Body PET*
- *Hazard & Threat Radiation Detection*



6 x 6 mm^2

300 series SPM

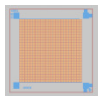
- *Nuclear Medicine*
- *Hazard & Threat Portal Monitoring*



3 x 3mm^2

100 series SPM

- *Biophotonics*
- *LiDAR*



1 x 1mm^2

SensL Part Numbering

*Micro*SM-30035-X05

Product Family (Micro, Array, Mini, Matrix)

Micro*FB*-10020-X18

Silicon Family (B, M) and fast/standard denotation

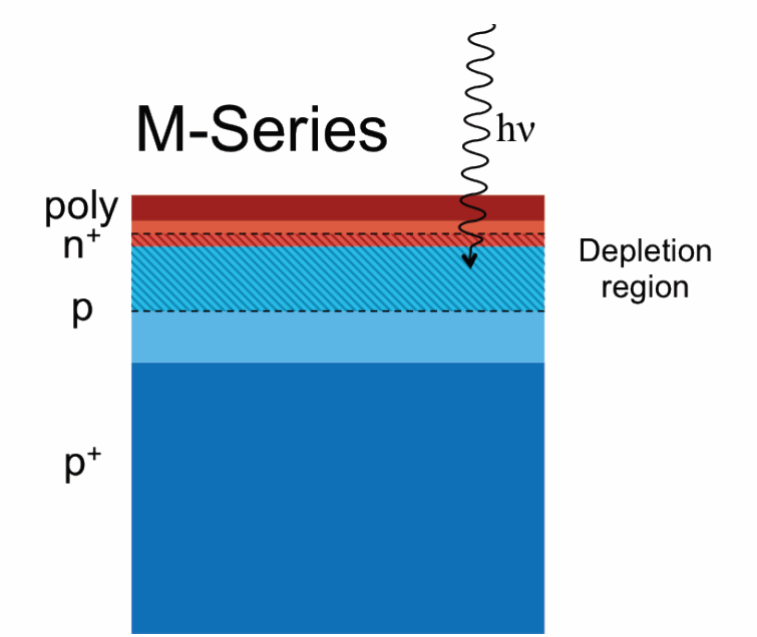
MicroSM-*30050*-X13

Die size and microcell size (3x3mm, 50µm shown)

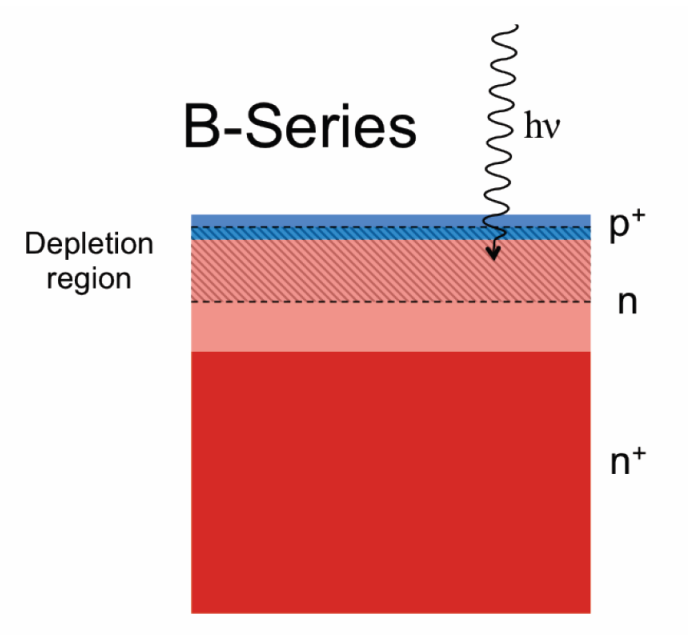
MicroFB-60035-*SMT*

Package type (TO18, TO5, SMT, Ceramic…)

Detector Architecture



M-Series Silicon, n-on-p design



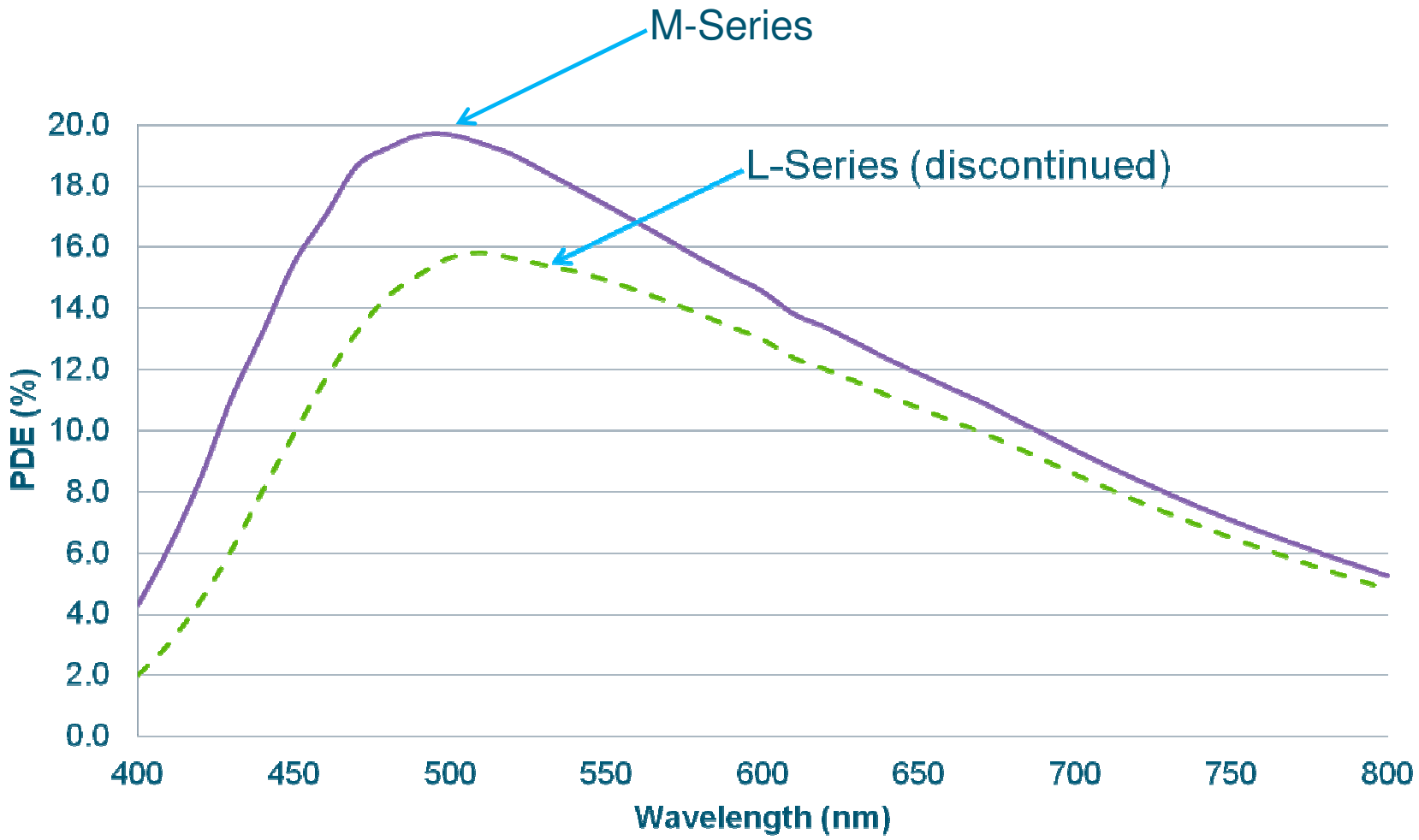
B-Series Silicon, p-on-n design

The M-series (and now discontinued L-Series) use an n-on-p junction design giving peak photon detection efficiency (PDE) centered around 500nm producing a green-sensitive device.

The B-Series is based on a p-on-n junction which makes the device more suited to shorter wavelengths – it's peak response is at 420nm producing a more blue-sensitive device

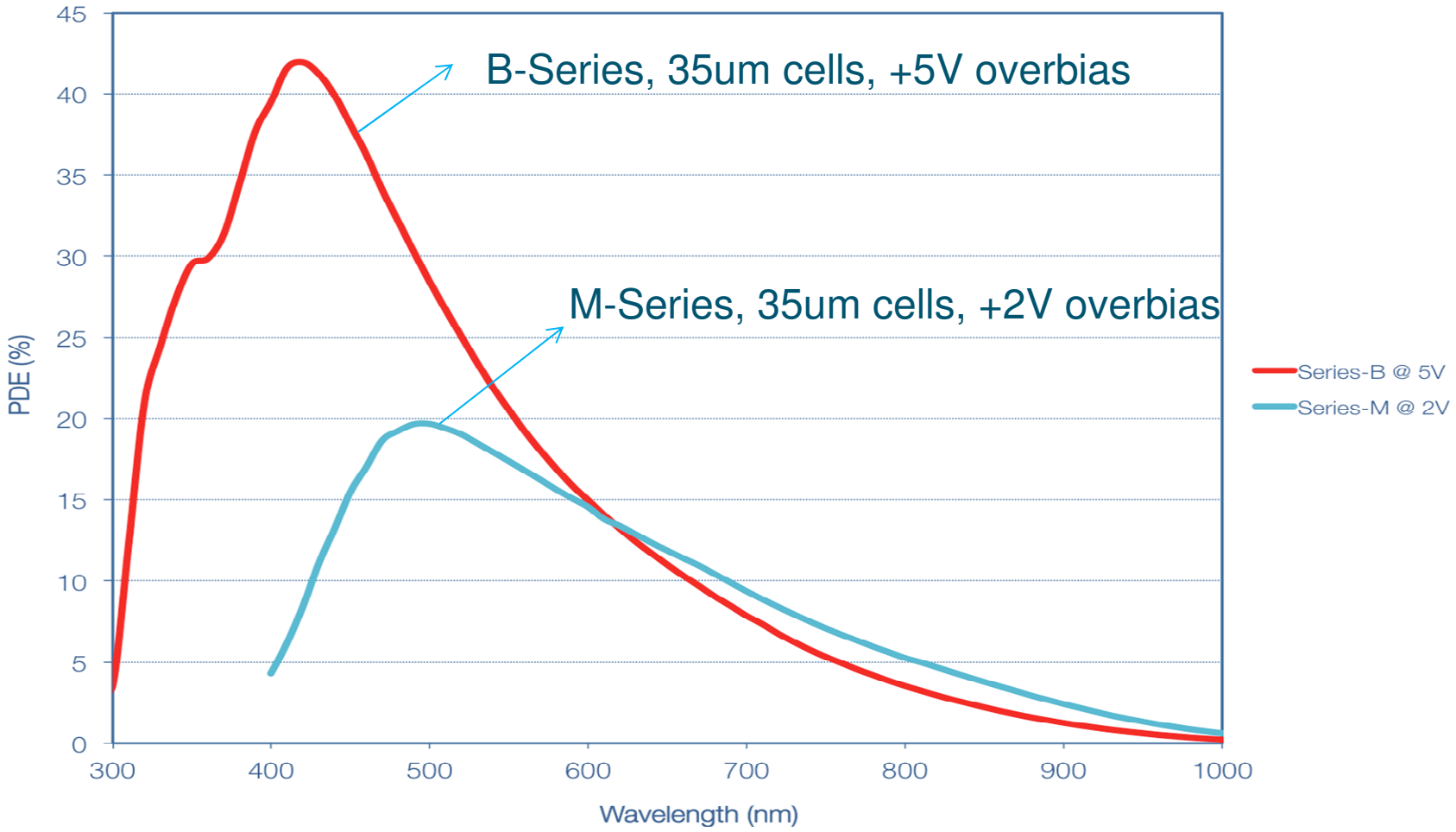
This presentation will concentrate on the B-Series

L-Series & M-Series PDE Comparison



Both curves are for 35um cells at +2V overbias

B-Series & M Series PDE Comparison

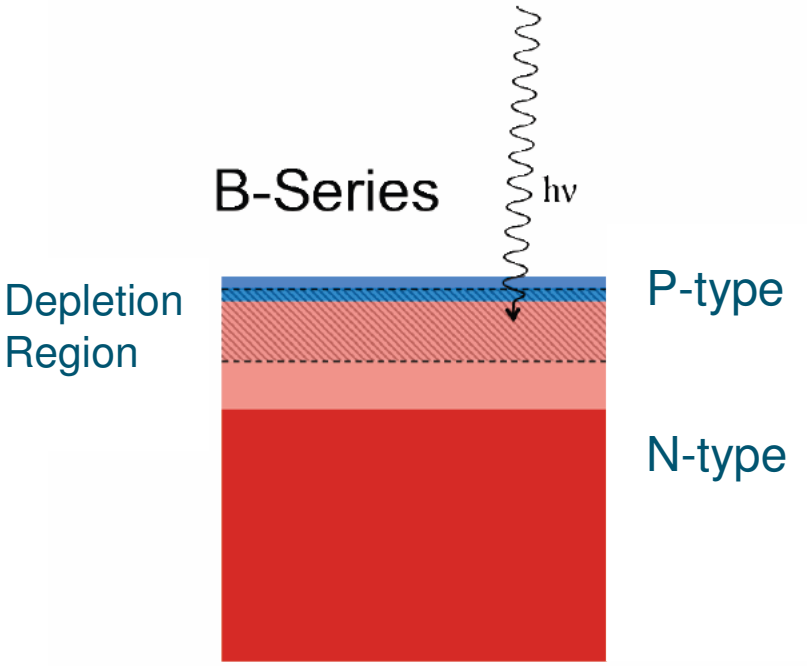


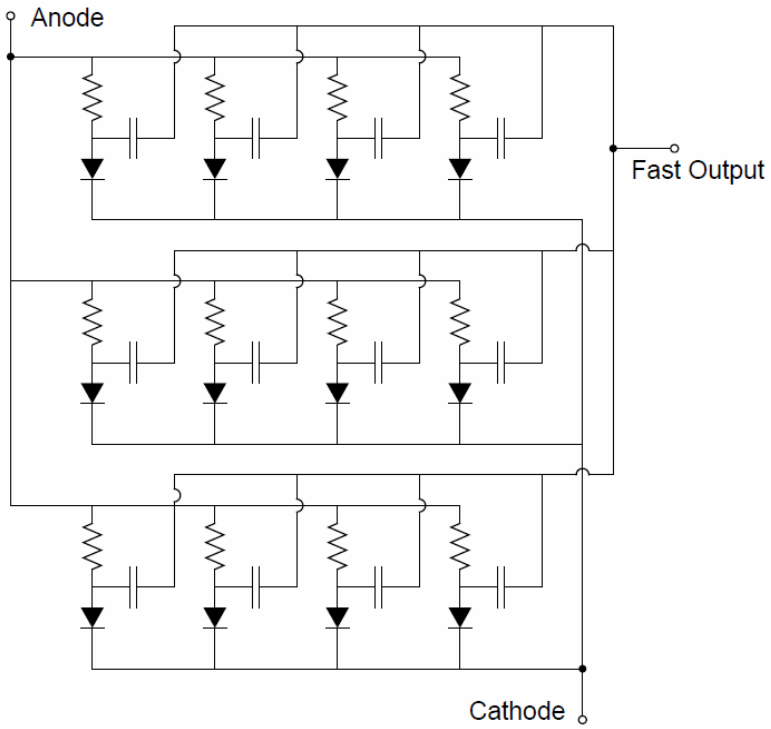
B Series Characteristics

Datasheet Plots

Production Silicon Revision

B Series Technology:





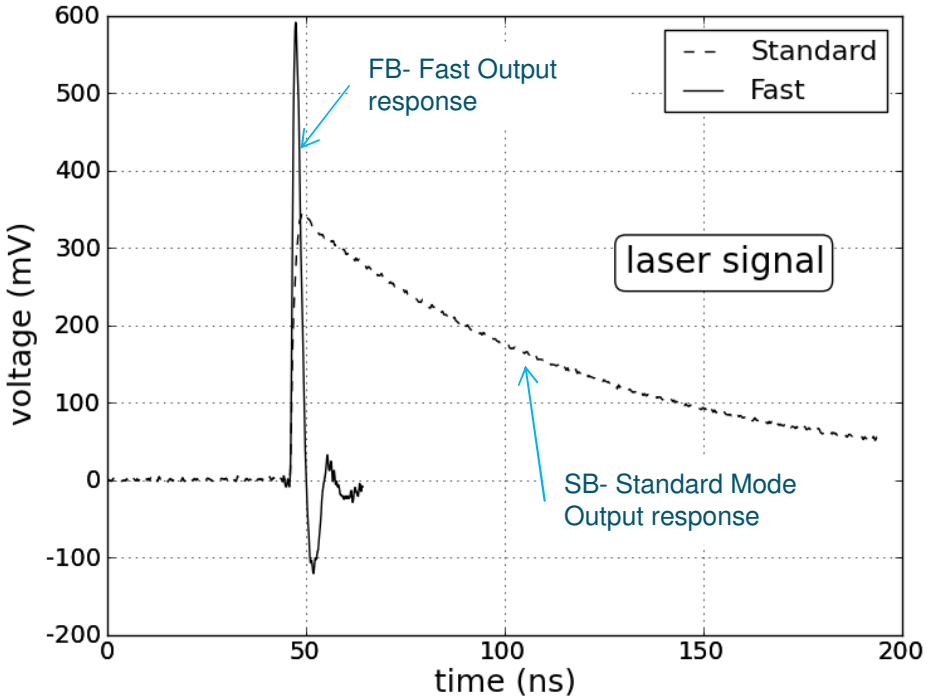
P on N technology provides the highest levels of Blue and UV photon sensitivity

Compatible with Fast Output (3-terminal) & Standard Output (2-terminal)

Fast Output Advantages

Fast Mode Improvements

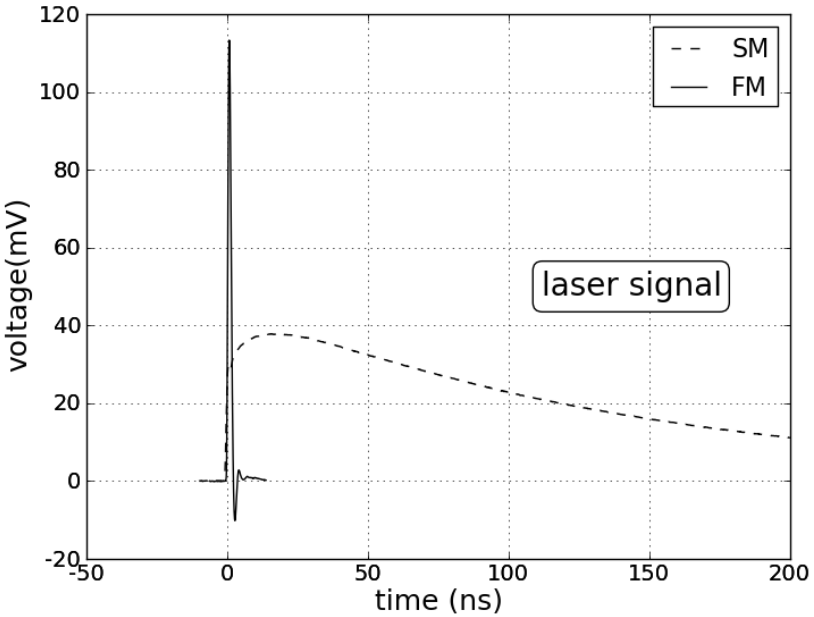
- Rise times <100ps; 2ns recovery
- Short impulse response from 1-2ns FWHM
- Reduced signal output capacitance
- Higher count rate resolution ability
- Ability to clearly distinguish the first photon arrival time

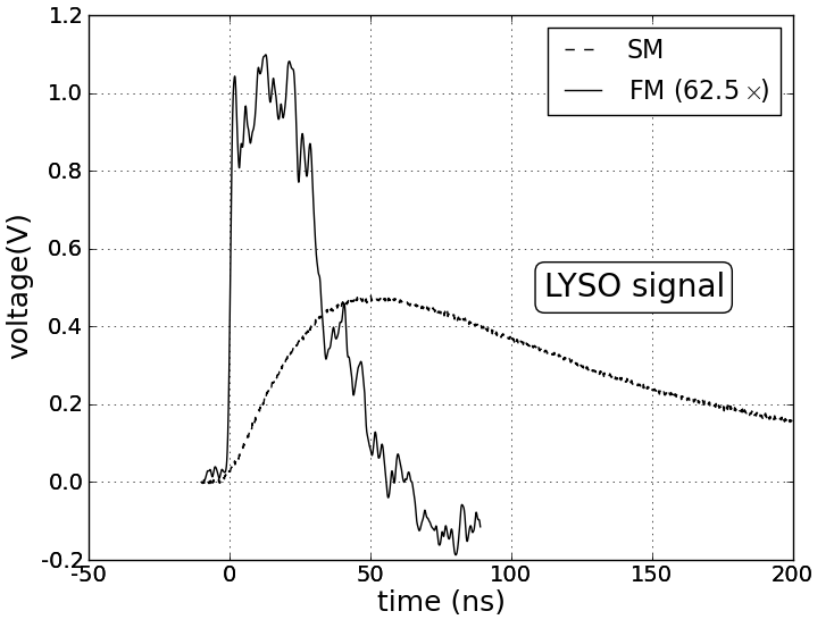


SiPM Type	Fast Output Rise Time	Fast Output Signal Pulse Width (FWHM)
10035	300ps	600ps
30020	501ps	1310ps
30035	609ps	1510ps
30050	638ps	1480ps
60035	884ps	3180ps

SensL's international patent application no. WO2011117309

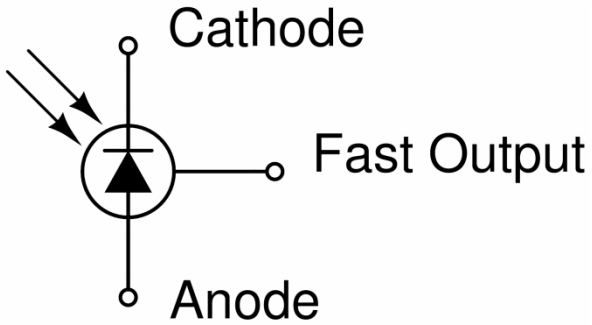
F-Detectors – Fast SPM for Improved Timing

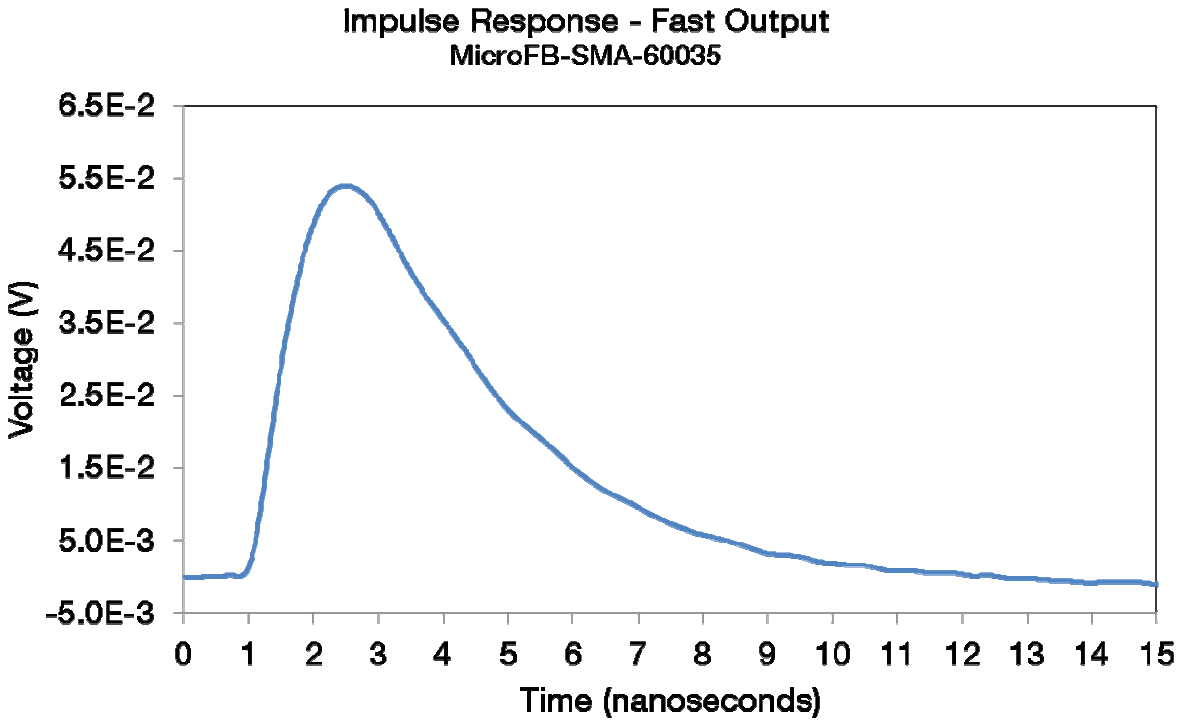




- Significantly faster output signals:
  - rise times 100ps – 2ns (size dependant)
  - fast decay times
  - optimal for timing applications
  - provides higher count rates
  - ability to distinguish the first photon
- Data published at Photodet2012 (June 2012)

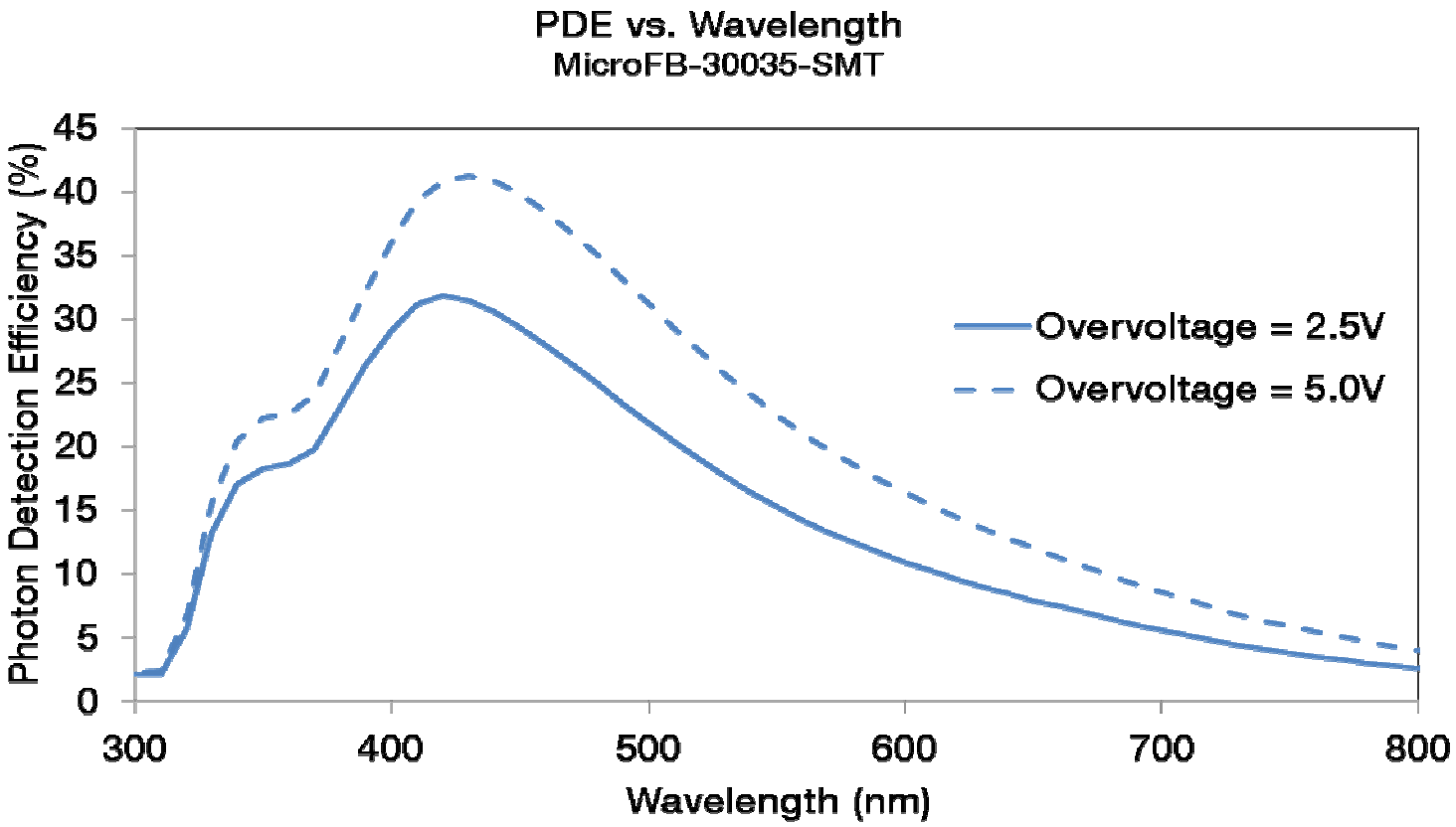
Pulse Shape 6mm Sensor – Fast Output





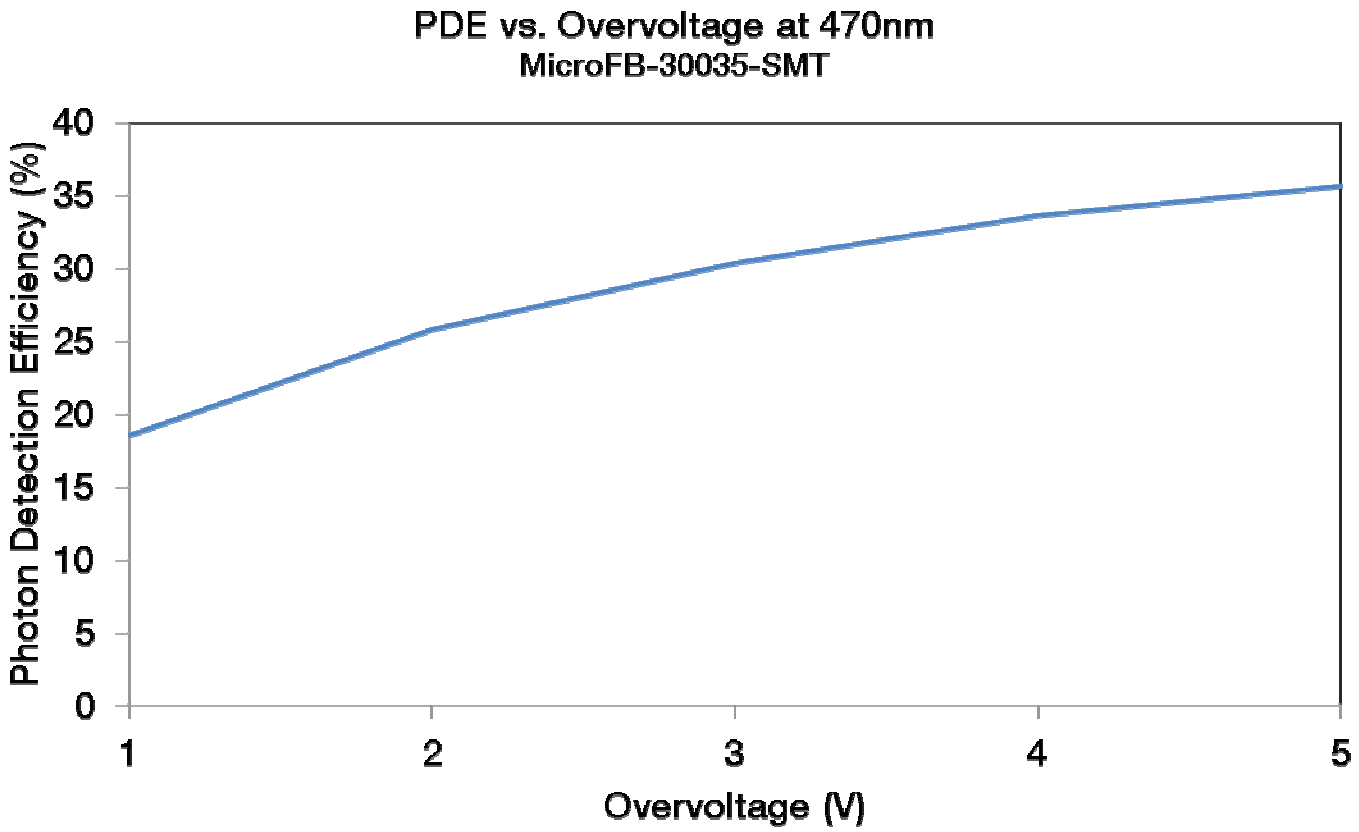
Low capacitance Fast Output Capable (35um cell shown)

PDE Vs. Wavelength



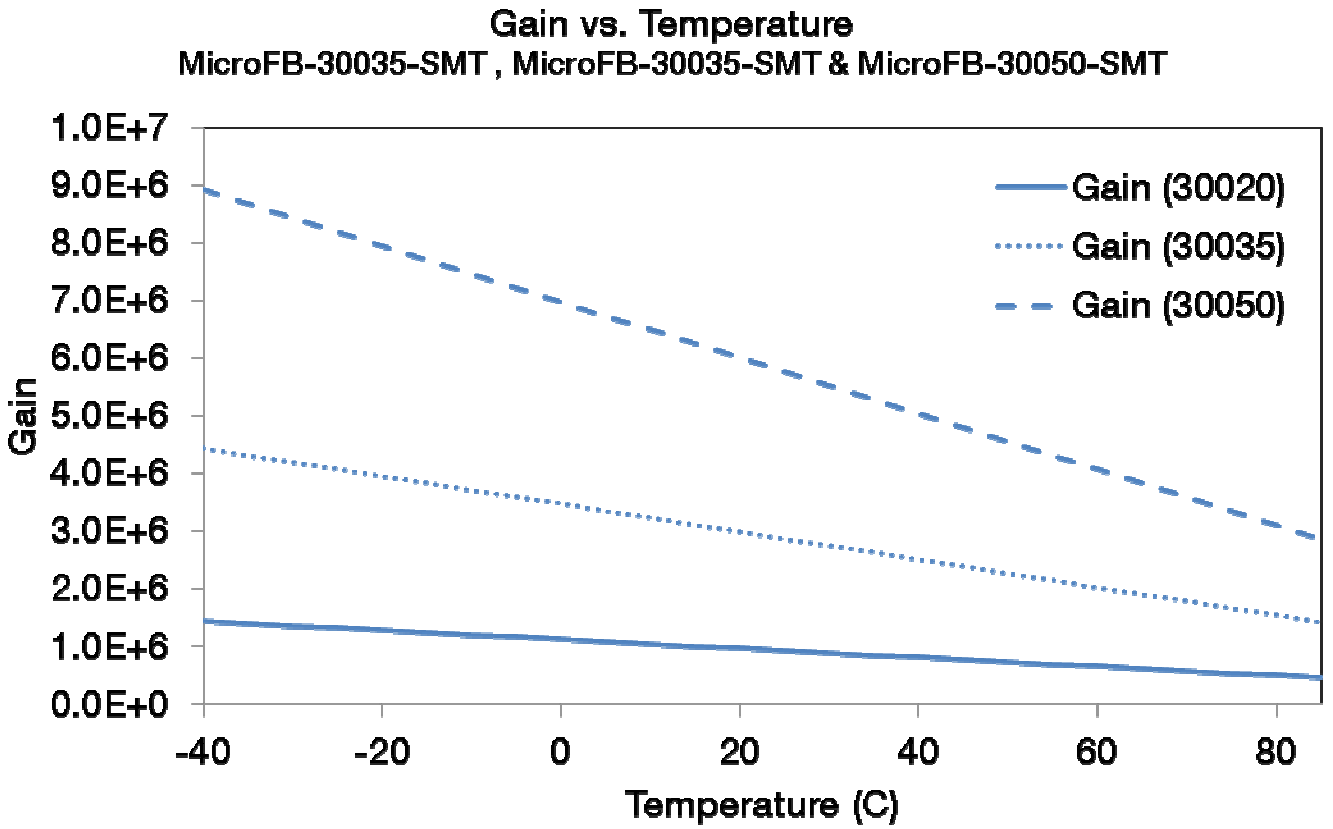
PDE optimised for fast blue/UV scintillators (35um cell shown)

PDE vs. Overvoltage



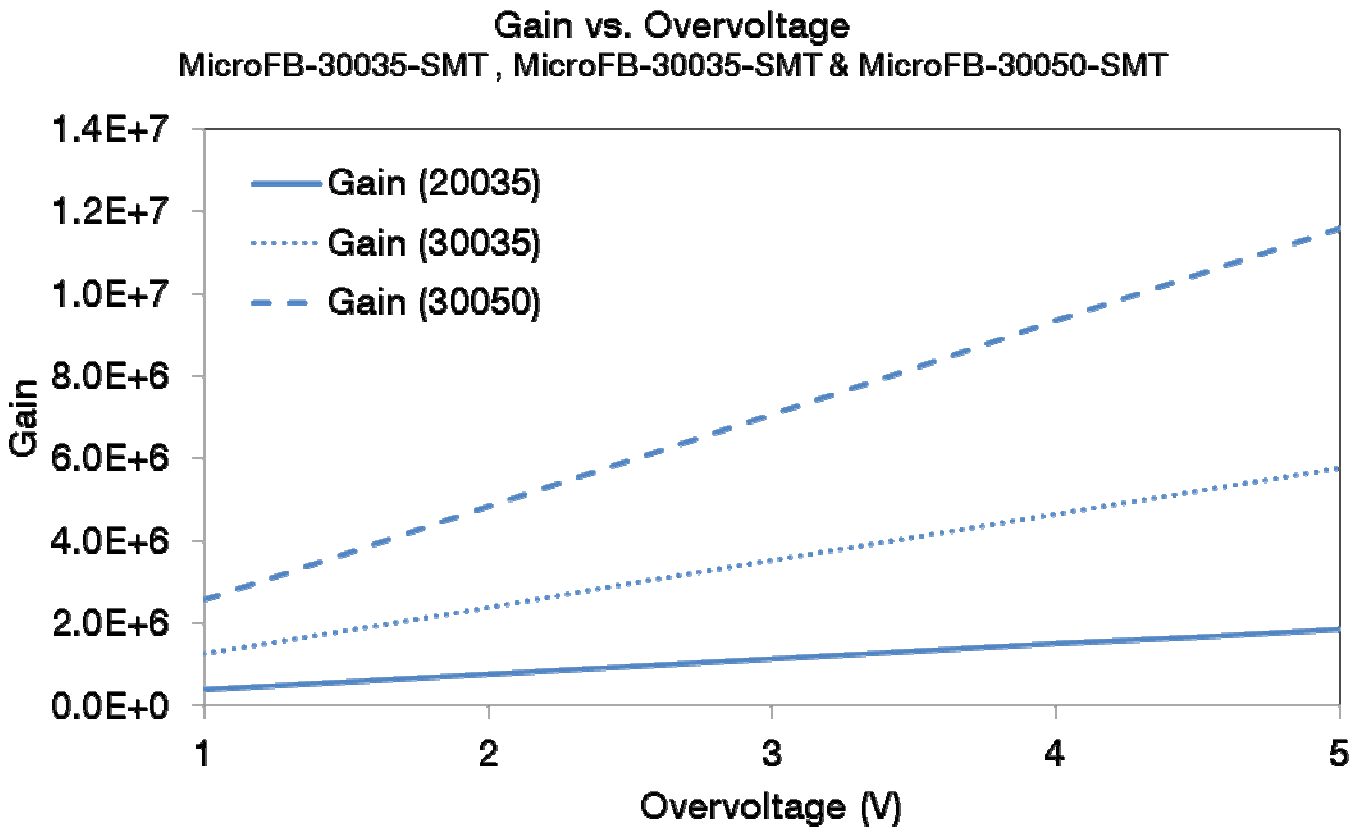
PDE optimisation with overvoltage (35um cell shown)

Gain vs. Temperature



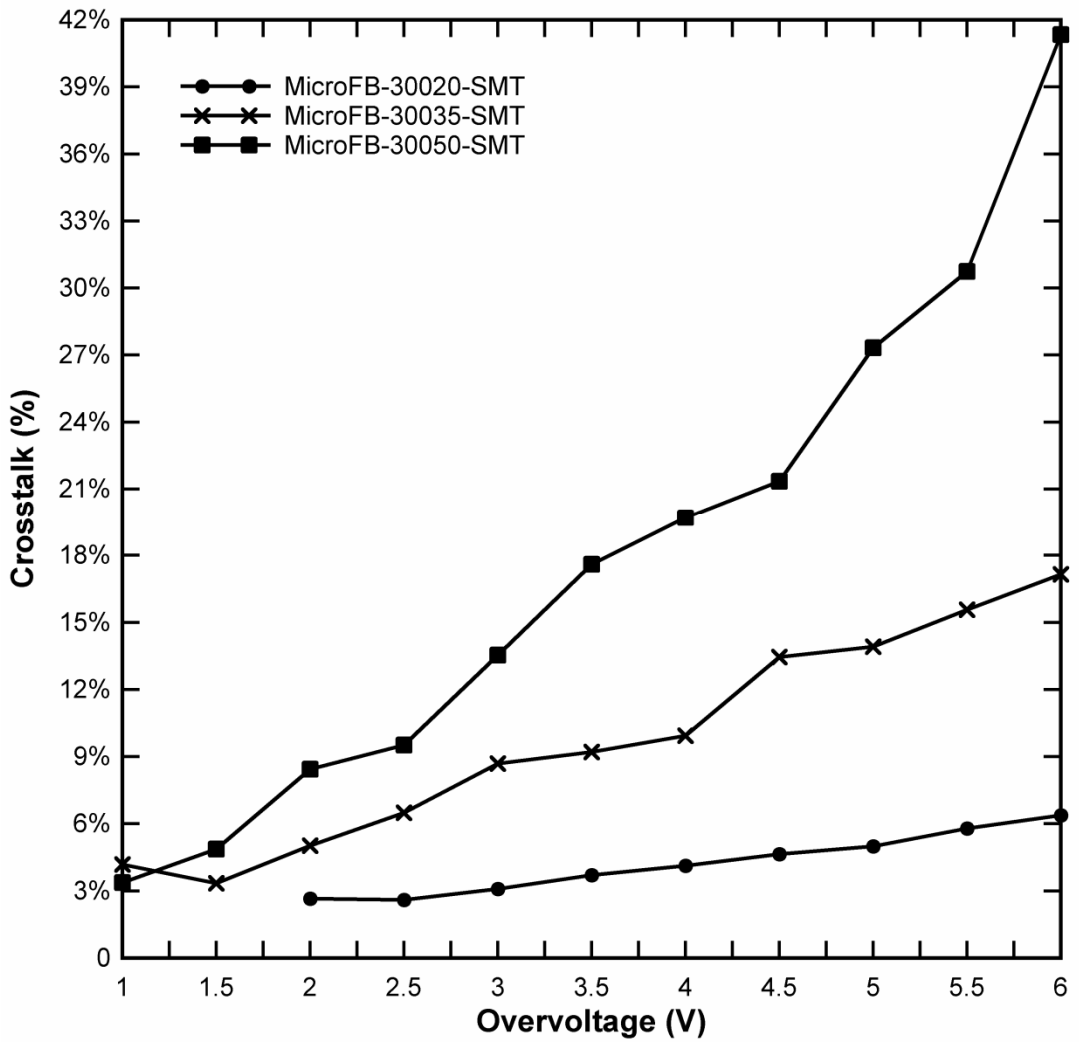
Low gain variation with temperature

Gain vs. Overvoltage

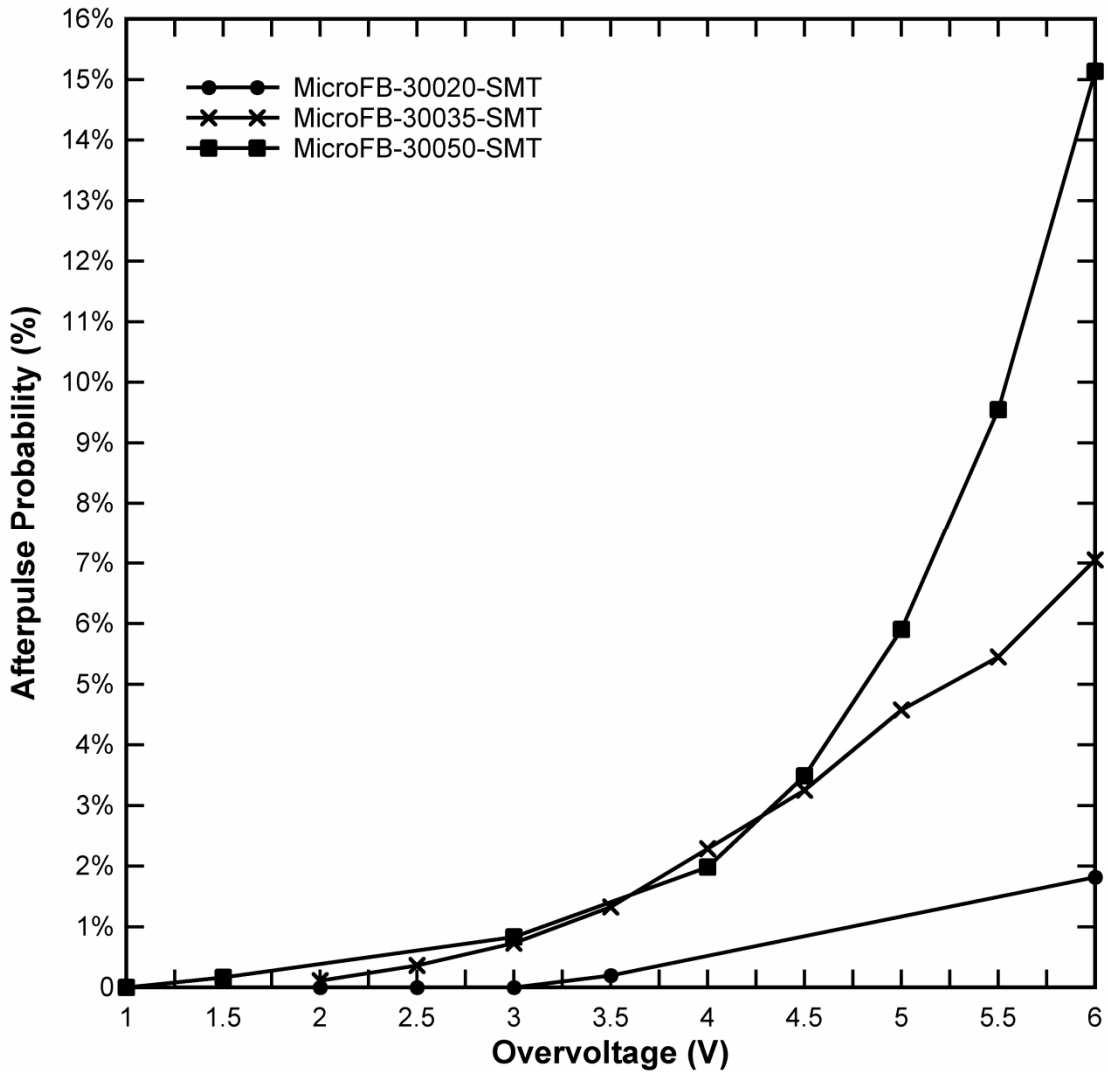


Low gain variation with overvoltage

Crosstalk vs. Overvoltage



After-pulsing vs. Overvoltage



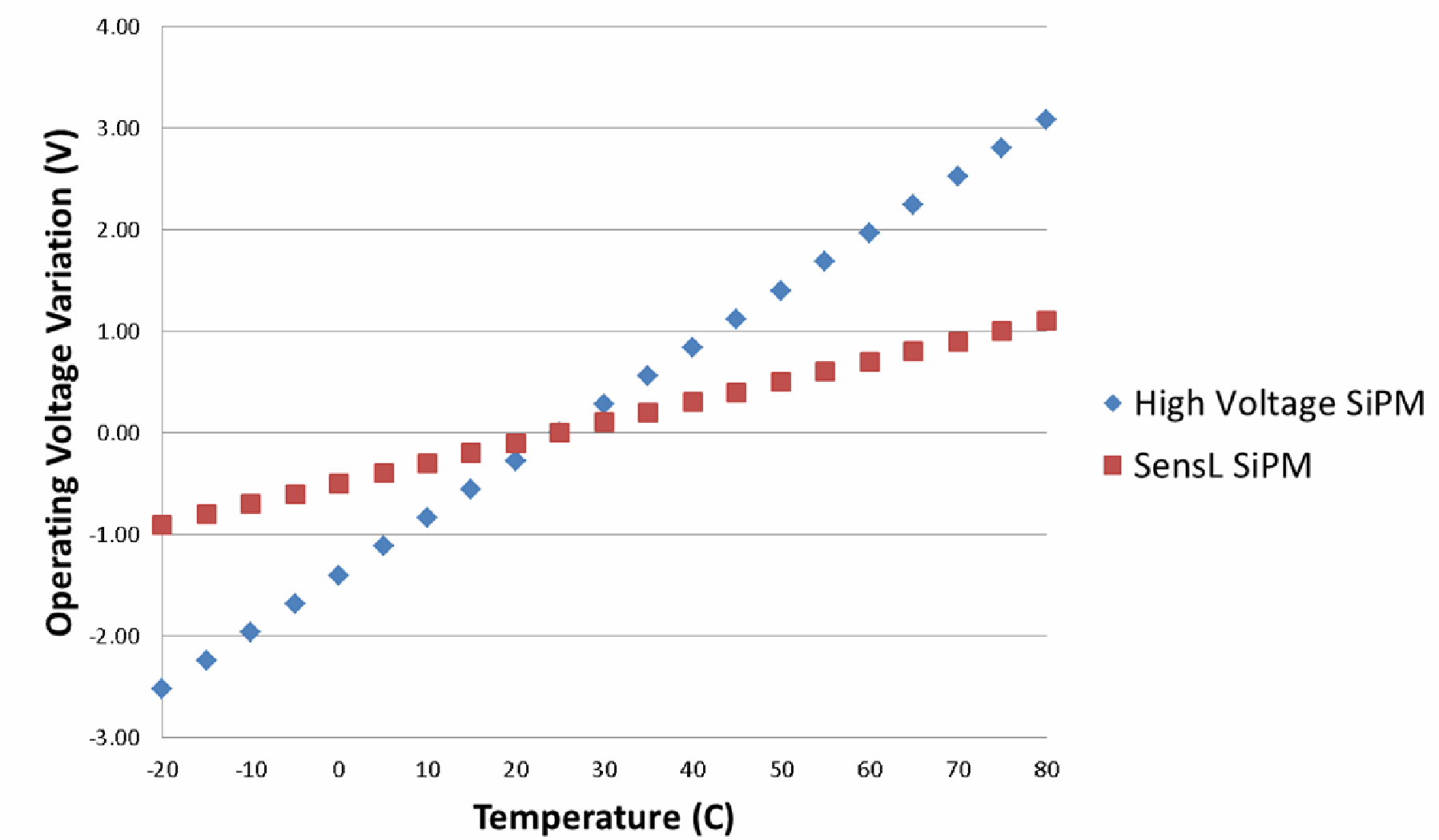
B-Series Dark Count Rate vs. Bias

Jan 2013 Datasheet(s)

B-Series Current vs. Bias

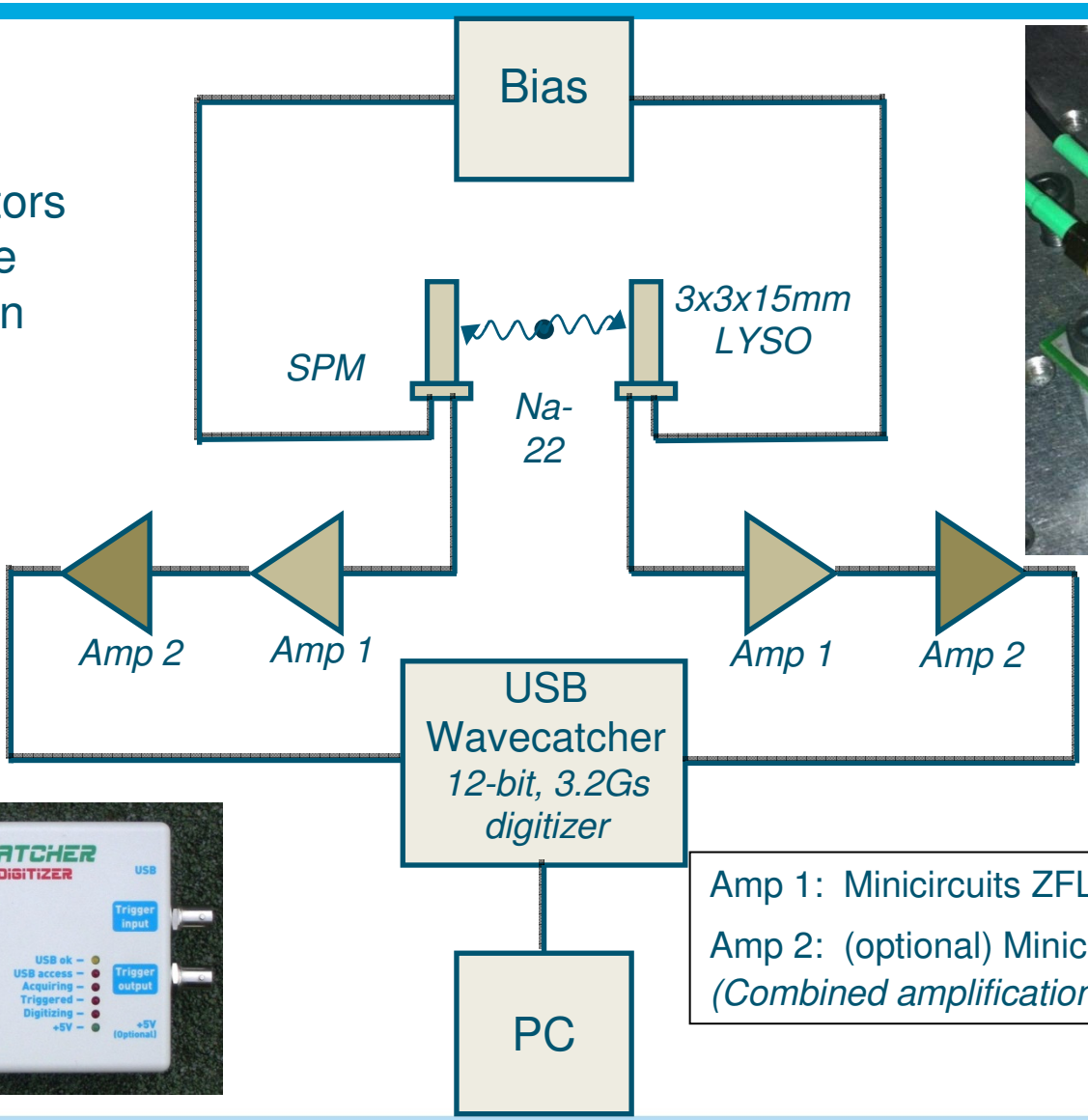
Jan 2013 Datasheet(s)

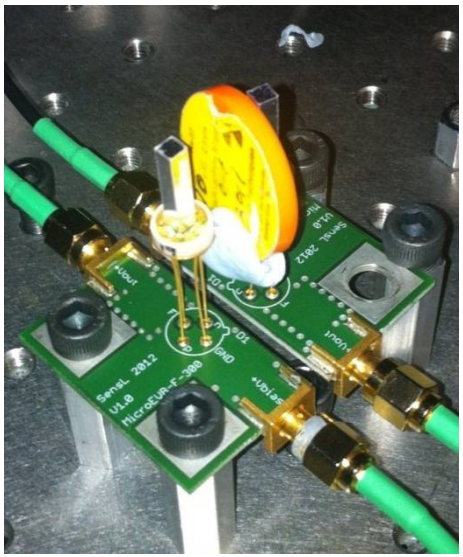
Low Temp. Dependence of Operating Voltage



Coincidence Resolving Time Measurement

- 3mm detectors
- Side-by-side configuration





Amp 1: Minicircuits ZFL-1000

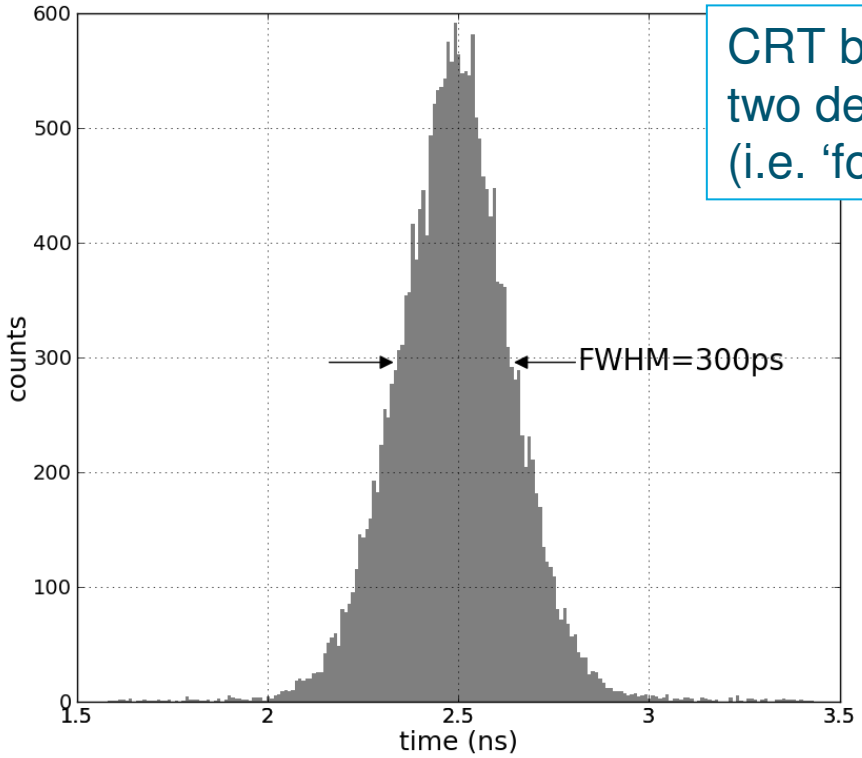
Amp 2: (optional) Minicircuits ZX60-43-S+
(Combined amplification of ~200x)

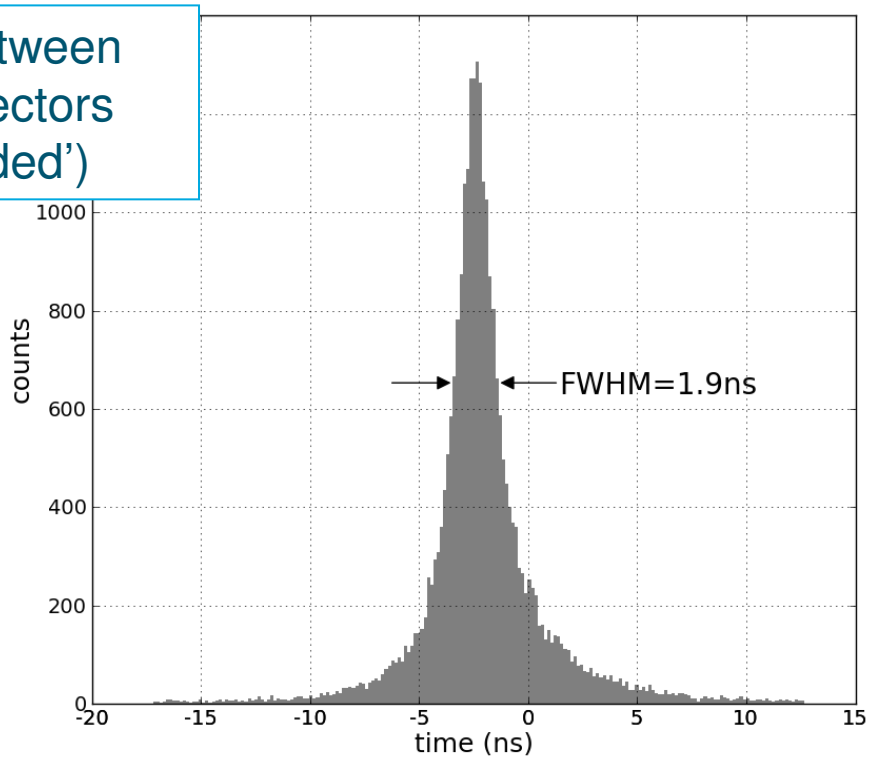
Coincidence Timing Resolution with FM

LYSO
3x3x15mm^3

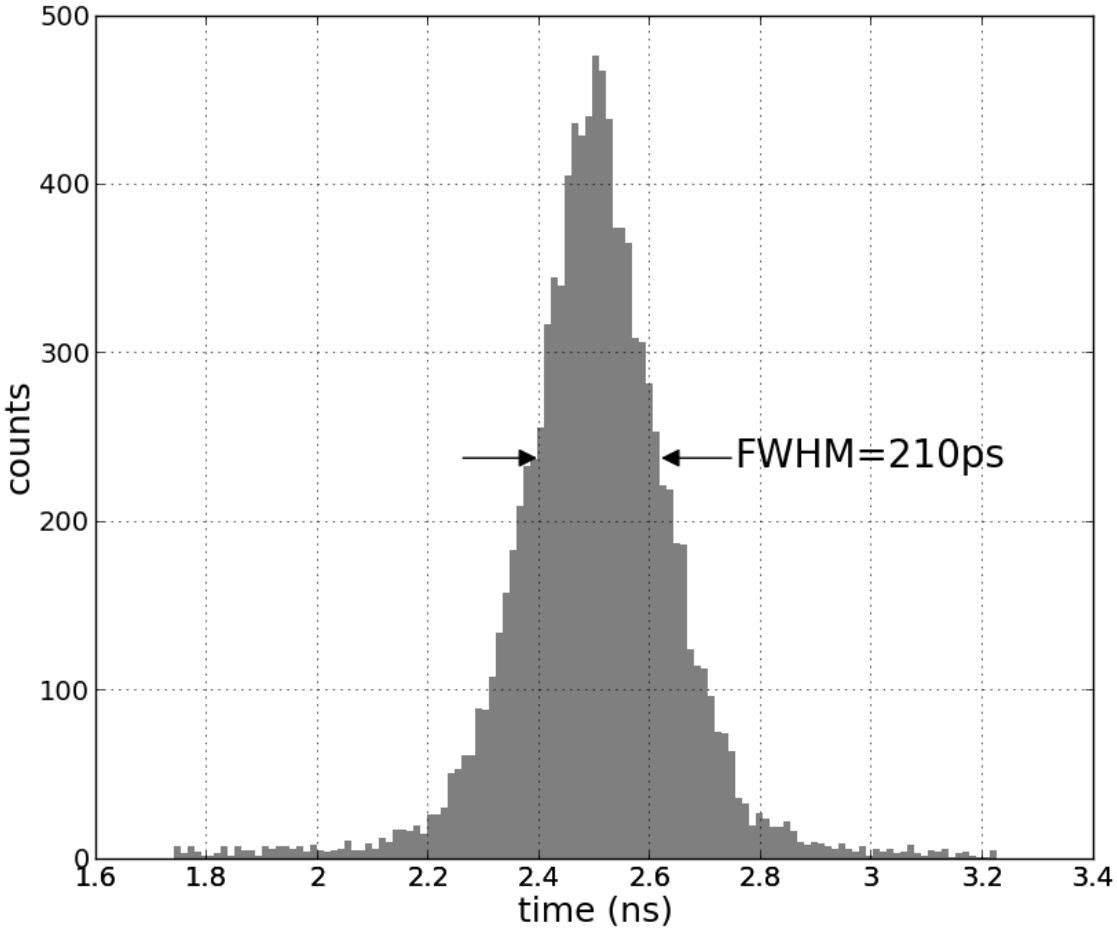
BGO
3x3x15mm^3

CRT between two detectors (i.e. 'folded')





FB - Coincidence Resolving Time
3mm Pixel Fast Output



- 3x3x15mm^3 LYSO
- Full coincidence of two 3mm SPM Pixels
- Na-22 source (511keV)

Additional publications are available on our website at www.sensl.com

Sensor Capacitance

		1mm	3mm	6mm
		10035	**30035**	**60035**
	Rise time Fast Output	0.3ns	0.6ns	1.0ns
	Signal pulse width Fast Output (FWHM)	0.6ns	1.5ns	3.2ns
Fast o/p	**Capacitance (Fast Terminal to Cathode)**	**1pF**	**12pF**	**48pF**
Std o/p	Capacitance (anode – cathode)	100pF	850pF	3400pF

Fast Output Provides Low Capacitance Output Capability

SiPM Reliability

- Extensive SiPM reliability tests carried out on standard packages & detectors
- All tests were made in accordance to the relevant JEDEC standards (below)

Test	Standard Reference	Required Condition	Lot size	Duration / Acceptance	Status
High Temperature Operating life	JESD22A 108	Ambient temperature = 125℃; bias>Vbr	3 lots of 77 units	1000 hours / no fail	Pass
High Temperature Operating life	JESD22A 108 higher endurance	Ambient temperature = 125℃; bias>Vbr	256 units	2000 hours / no fail	Pass
High Temperature Operating life	Product Specific	Ambient temperature = 85℃; bias>Vbr	1 lot of 77 units	1000 hours / no fail	Pass
Unbiased Highly Accelerated Stress	JESD22-A118	110℃, 85%RH	3 Lots of 25 units	264 hrs / no fail	Pass
Temperature Cycling	JESD22-A104	-40C to 85C, 15 sec transition, 15 min dwell time	3 Lots of 77 units	500 cycles / no fail	Pass
High Temperature Storage Test	JESD22-A103	504hrs @ 125℃	3 Lots of 25 units	504 hrs / no fail	Pass

JEDEC Standard JESD22-A108D, "Temperature, Bias, and Operating Life", http://www.jedec.org/standards-documents/results/jesd22a108, (2010)

In February 2013 SensL launched the B-Series

- 4th generation SiPM technology
- 40% PDE at 420nm
- Ultra fast rise time and recovery
- Exceptional gain and optical response uniformity
- Temperature stability of <20mV per degree C
- 30V operation
- Lower cost than PMT
- Shipping now in volume

sensL
sense light

Products & Pricing Overview

The SensL Advantage

- Designed for High Volume
- Designed for Lowest Cost
- Designed for Uniformity
- Excellent Customer Support

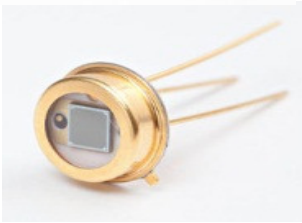
Products Introduction

- Discrete package-level sensors (SiPM and Photon Counting)
- Modules (SiPM and Photon counting)
- Arrays (small and large area)
- Readout electronics
- Nuclear medicine modules (& software)
- Measurement instruments

sensL
sense light

MicroSM & MicroSB – Discrete SPM Detectors

Standard mode (not high speed) detectors



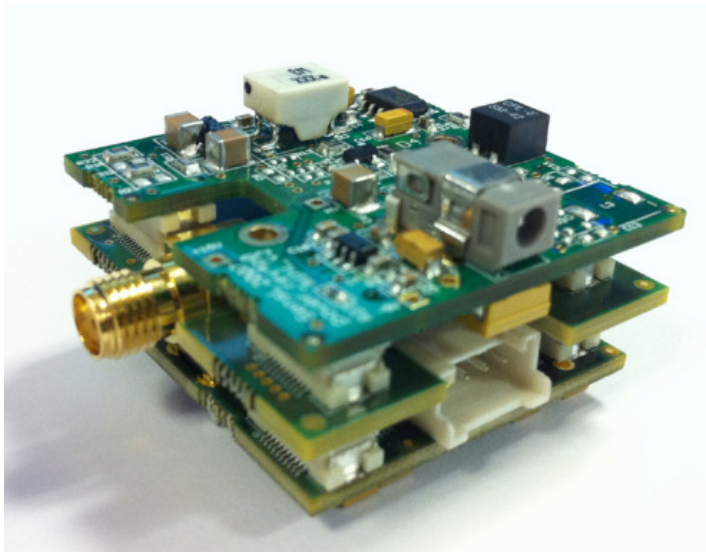
- The MicroSM & MicroSB family of detectors are available in a variety of miniature packages
- Designed to suit a wide range of applications
- 4 detector sizes available (0.25mm,1mm, 3mm and 6mm)
- Range of microcell sizes available representing different performance trade-offs
- Low power, low voltage operation
- Readout & power supply options available
- Cooled and uncooled options available
- Package styles include: TO18, X13, TO5, TO39 (cooled)

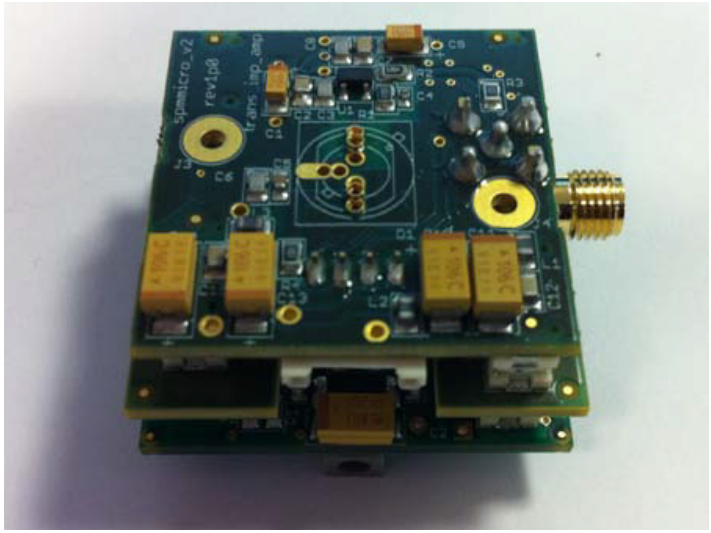
MicroSM-60035 & MicroSB-60035

Single channel 6mm pixel

- Low cost ceramic package
- Epoxy overfill 500µm
- Low voltage operation & low temperature dependency
- Electronic preamplifier boards available

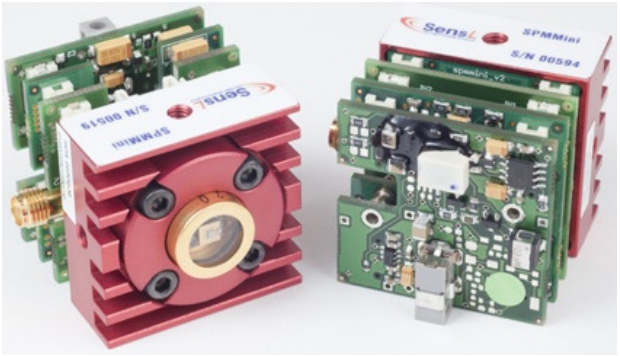
Micro-EVB (standard output only)

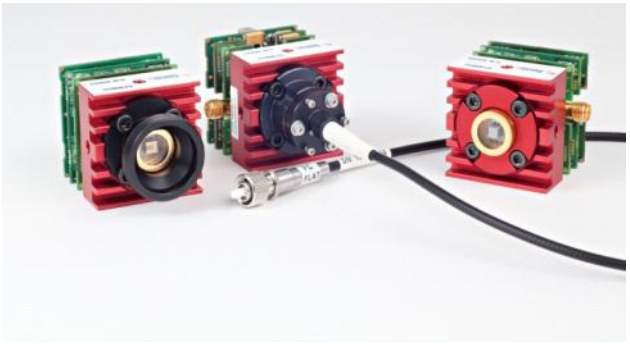




- The Micro-EVB is designed for use with all uncooled MicroSB and MicroSM series detectors (standard output only)
- Separate versions for 1mm and 3mm detectors available (6mm detectors operate with the EVB designed for 3mm detectors)
- Based on trans-impedance circuitry
- Includes power supply and shield boards
- Low power, low voltage operation
- SMA output connector (voltage output)
- Dual power supply options

MiniSM – Cooled SPM Module



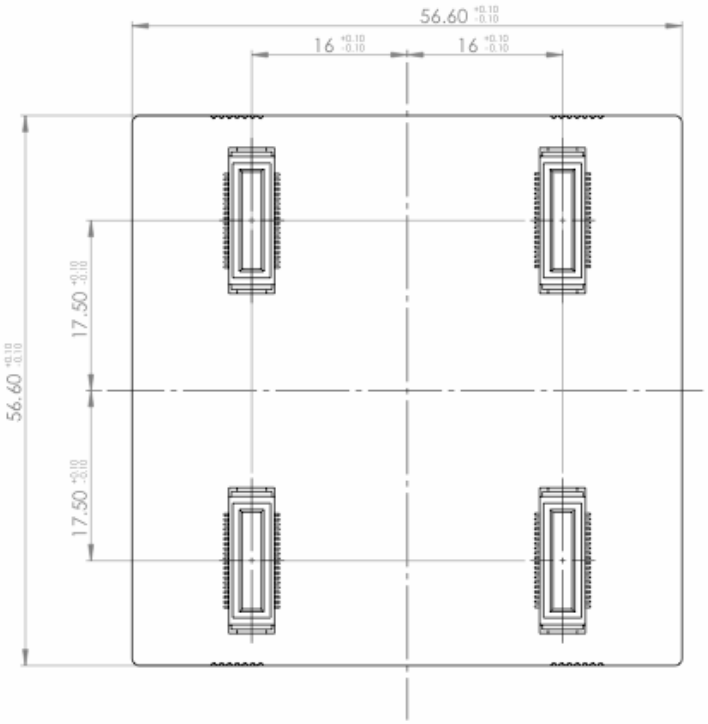


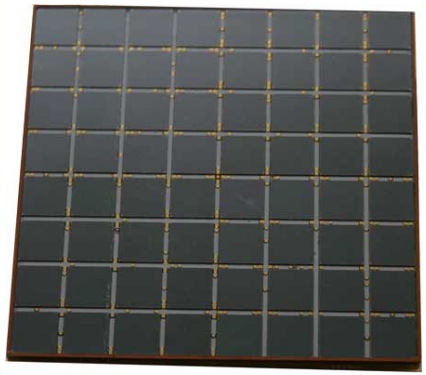
- The MiniSM is a family of detector modules that are designed as turnkey evaluation modules
- Thermoelectrically cooled (-15C)
- Designed to suit a wide range of applications, but particularly aimed at bio-photonics markets
- Two detector sizes available (1mm, 3mm)
- 35um microcells used
- Low power, low voltage operation
- Features integrated readout, cooling & power supply
- c-mount option available
- Fiber coupler option (FC) available

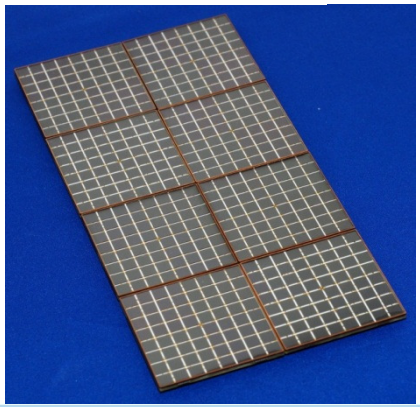
sensL
sense light

Array & Matrix Products

ArraySB-8 Large-Area 8x8 Array





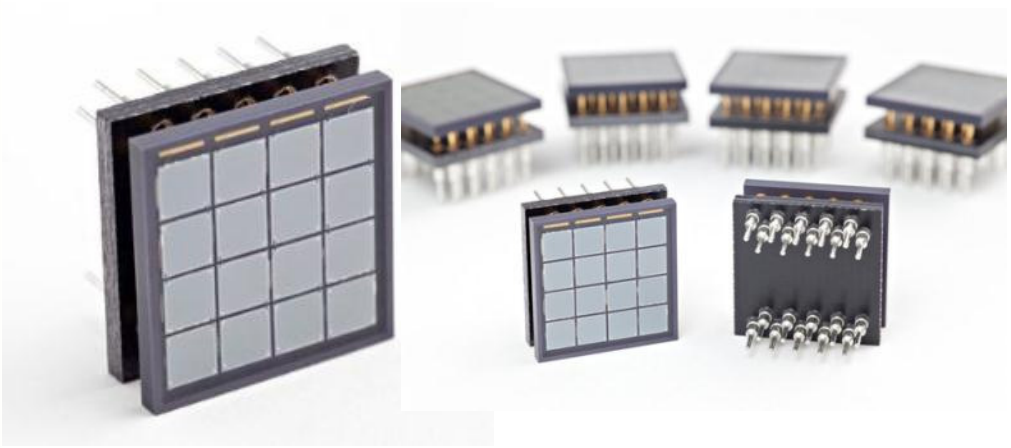


ArraySB-8

- 4-side scalable design, B-Series silicon
- 7mm pixel pitch
- 64 pixellated channels
- Single 30V power supply
- Optical Response Non-Uniformity <10%
- Replaces the H8500, R8900-C12 and H9500 position sensitive photomultiplier tubes
  - Better performance
  - Better uniformity
  - Lower cost

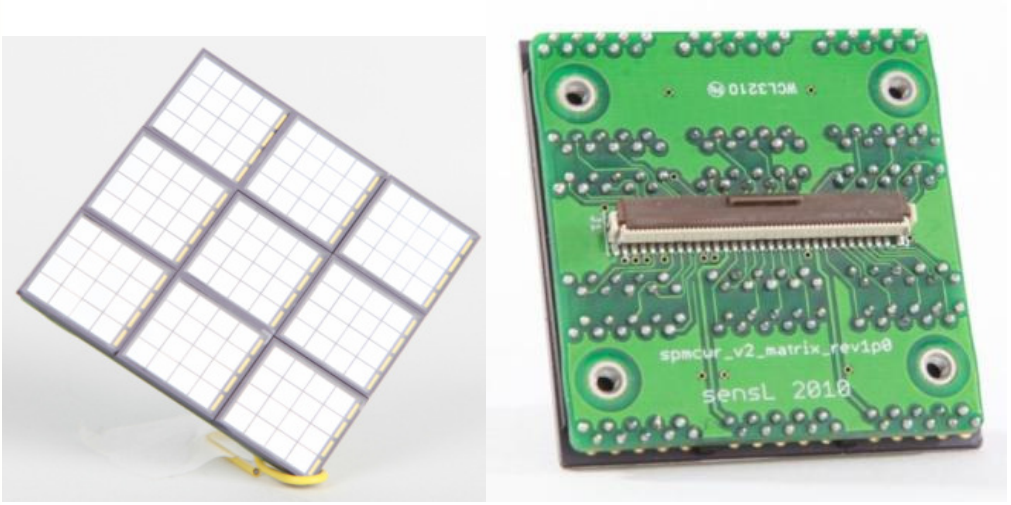
sensL
sense light

4x4 arrays: ArraySB-4 and ArraySB-4p9



ArraySM-4 & ArraySB-4

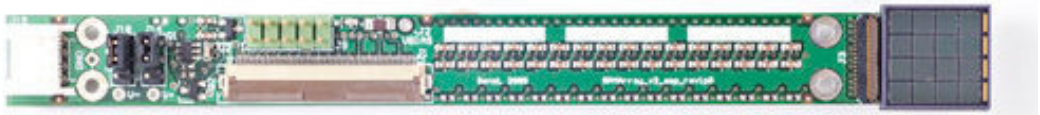
- 4-side scalable design
- 3.36mm pitch
- 16 pixellated channels
- Single 30V power supply
- Optical Response Non-Uniformity <10%
- Designed for simultaneous MRI compatibility
- Full system electronics available for bias control and pre-amplifier



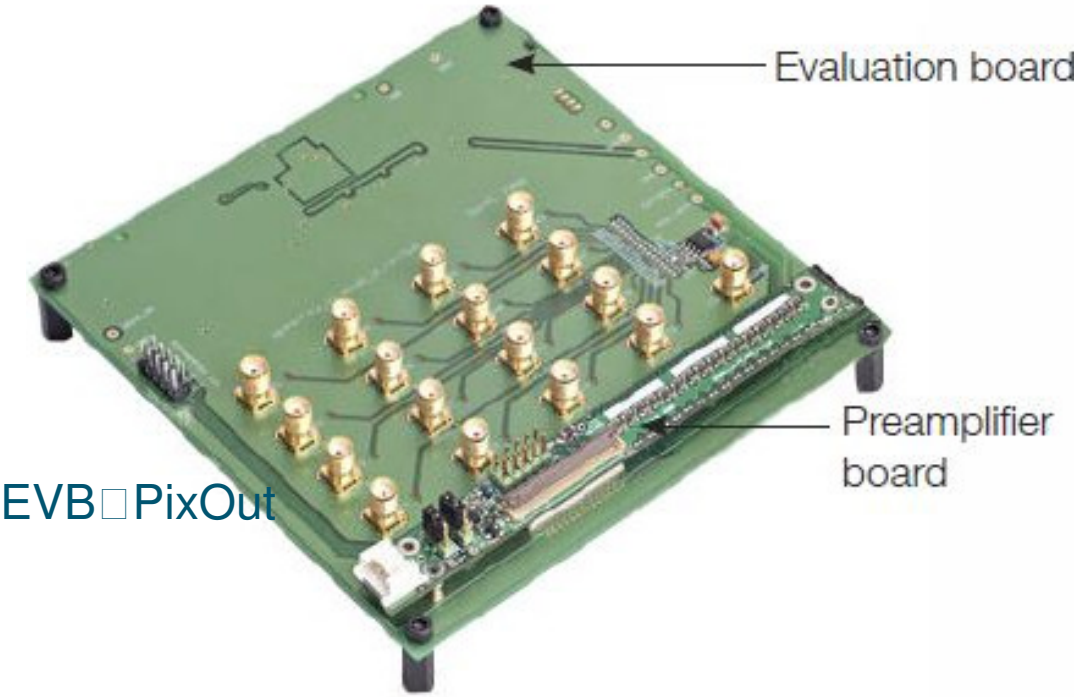
ArraySM-4P9 & ArraySB-4p9

- 4-side scalable design
- 144 channels
- Single 30 Volt power supply
- Optical response non-uniformity <10% (equivalent to a PMT max:min <1:1.2)
- Solid-state alternative to the H8500, R8900-C12 and H9500 position sensitive photomultiplier tubes

Array Readout Electronics

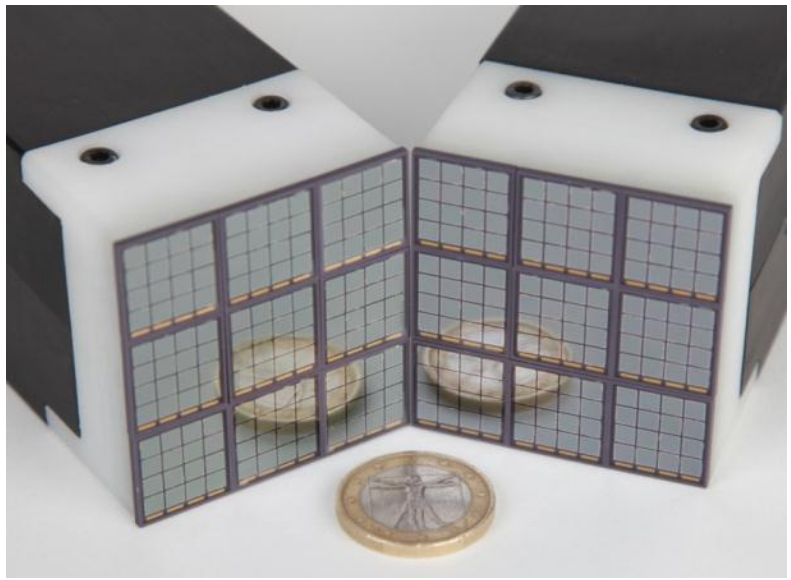


Array4□EVB□PreAmp



Array4□EVB□PixOut

MatrixSM-9



A Scalable, Large Area Module for Silicon Photomultiplier Integration

- Optimized for L(Y)SO readout
- 144 channels of 9mm^2 SPM
- Full digitization and coincidence processing for 2304 channels per board
- Temperature stabilization
- Available as research or OEM version
- 1x9 linear version in production
- Cable length options available

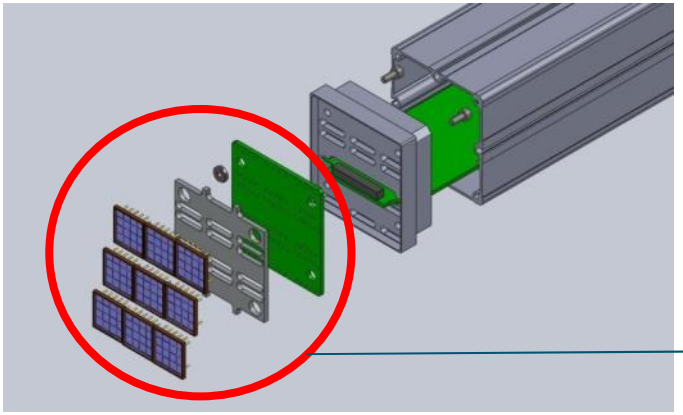
Electronics Partnership:

ANALOG DEVICES

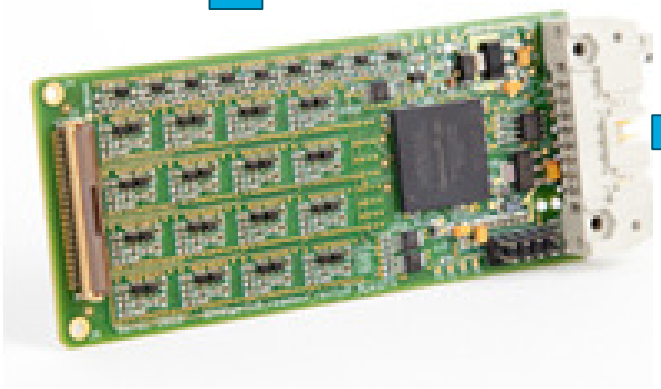
1x9 linear option

sensL sense light

MatrixSM-9

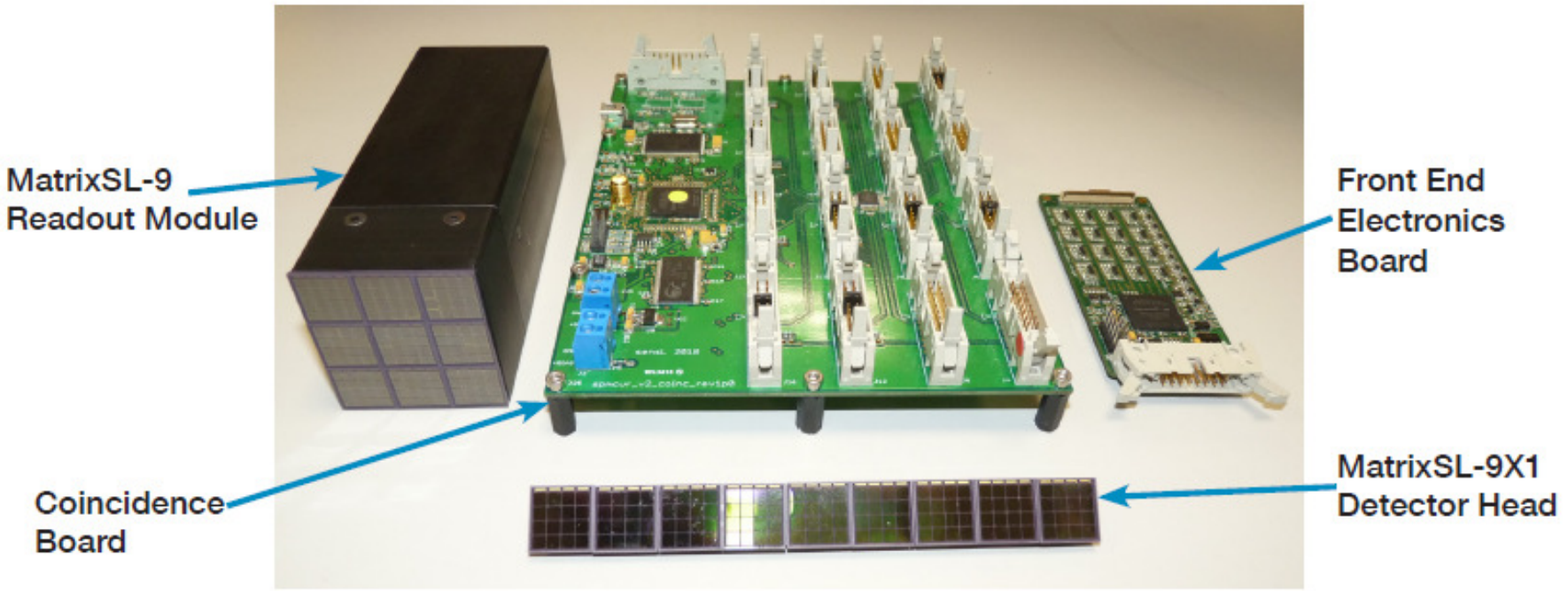


Array4p9



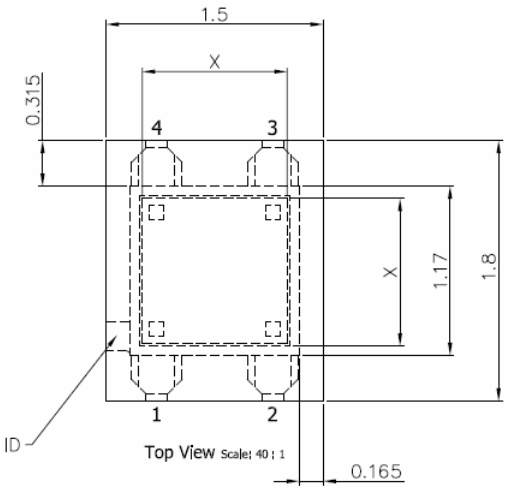
sensL
sense light

MatrixSL-9

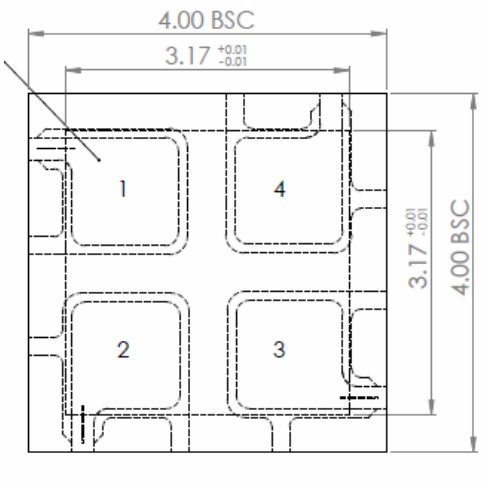

MatrixSL-9
Readout Module
Front End
Electronics
Board
Coincidence
Board
MatrixSL-9X1
Detector Head

Surface Mount (SMT) Products

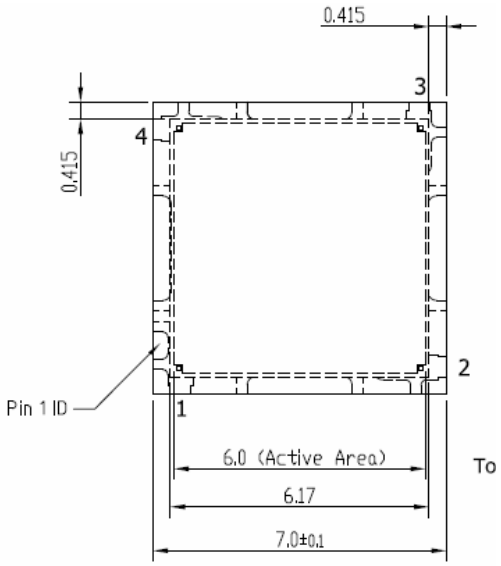
SMT Devices – Mechanical Specifications



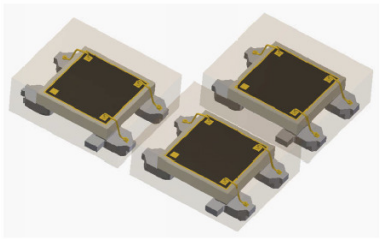
1mm SMT

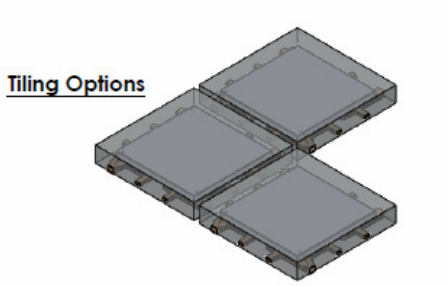


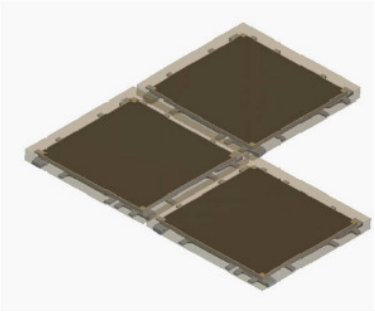
3mm SMT



6mm SMT

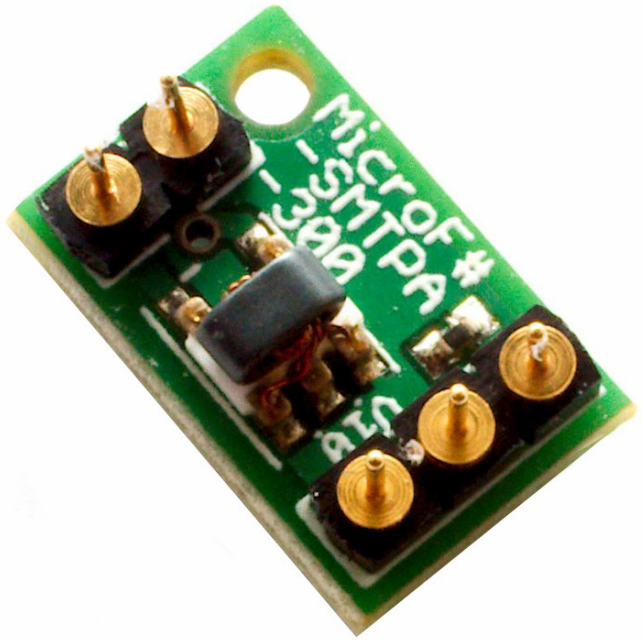




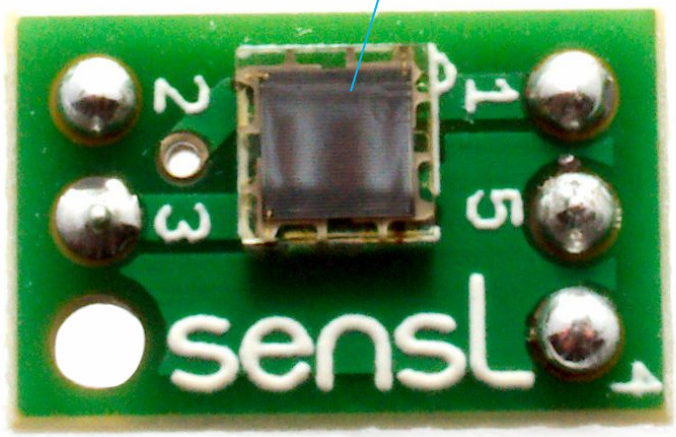


SMT Pin-Adapter Board (SMTPA)

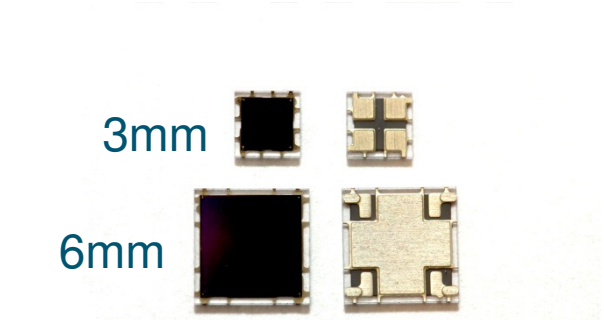
The SMTPA is a simple carrier board with pre-mounted SMT device giving users access to pins to facilitate easy testing.

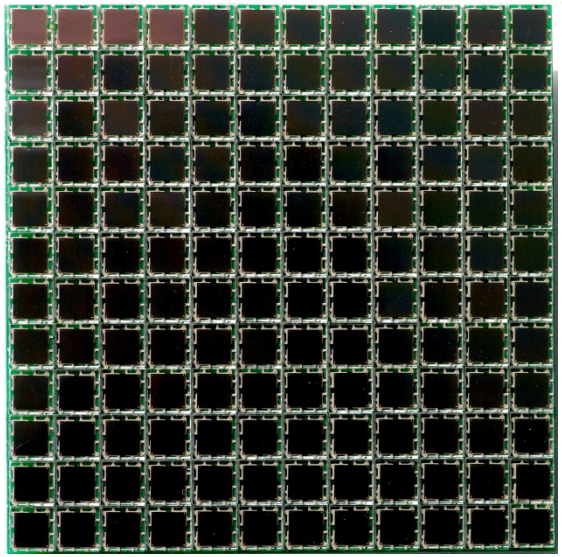


MicroFM-30035-SMT



.25mm, 1mm, 3mm & 6mm pixel 4 Side Tileable SMT Package





12x12 array of 3x3mm SMT parts shown. Arrays based on 6mm & 1mm SMTs are in design.

ArrayFM-30035-SMT

- 4 Side tileable
- <500µm from detector edge to package edge
- Clear molded top surface
- Low profile 0.6mm thickness
- Close coupling capable with 200µm from SPM to top of package
- Supply Options

–Tape and Reel (3k/reel)

–49 unit tray for prototyping

- 3mm & 6mm Available Now

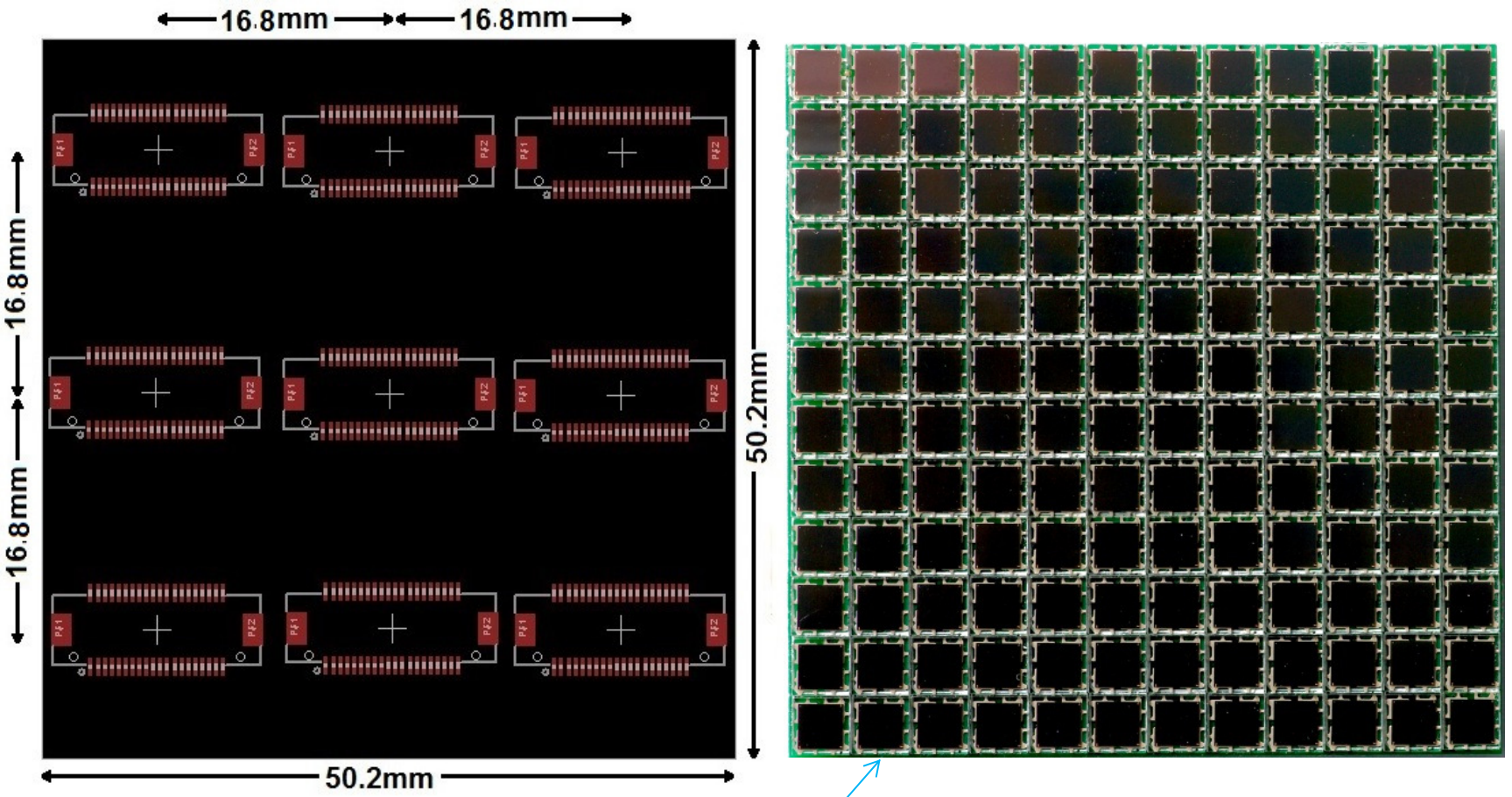
–1mm in development

3mm SMT Application Example

- 12x12 array of 3mm SMT
- 4.2mm pitch
- 200µm flatness on standard FR4 PCB
- Provides both standard and fast readouts

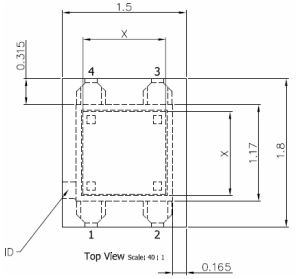
sensL sense light

SMT Arrays – 12x12 example of 3mm SMTs

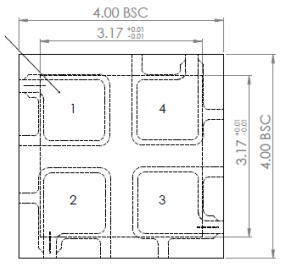


3mm x 3mm SMT

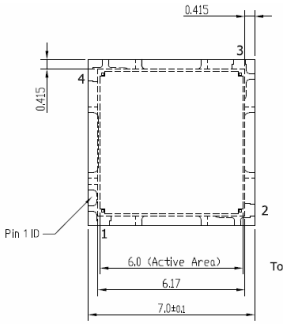
Volume SMT Shipment – Tape & Reel



1mm
SMT



3mm
SMT

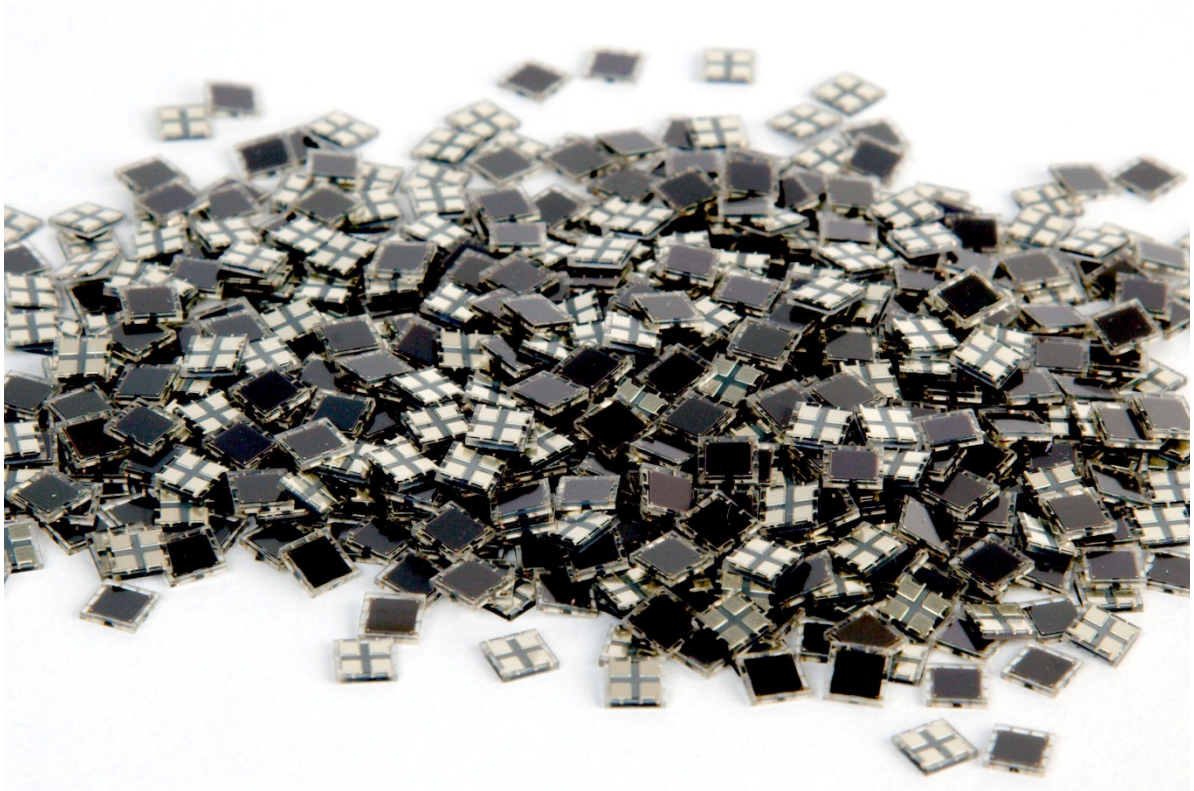


6mm
SMT

- All parts shipped as tape and reel in moisture barrier bag to J-ST 033
- **MSL=3** reflow solder compliant
- All parts ship 3000 units per tape
  - 1mm on 7” diameter (8mm width)
  - 3mm on 13” diameter (12mm width)
  - 6mm on 13” diameter (16mm width)

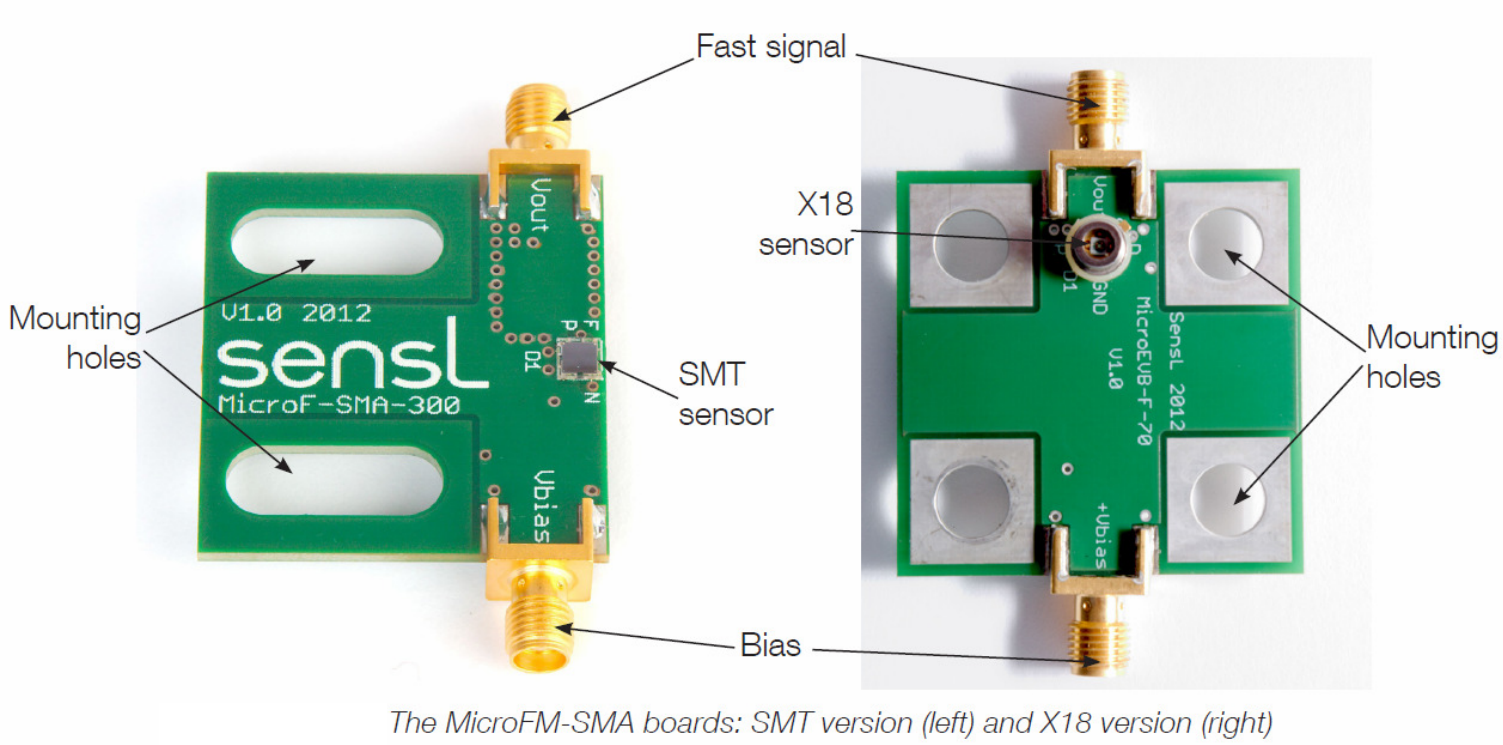
SMT detectors – High volume solution

- MSL3 compliant
- Simultaneous fast & standard readout possible
- Lead-free solder reflow compatible
- -40 to +85 Celsius operating range
- Low cost



sensL
sense light

Evaluation Boards – EVB's – for Fast SiPMs



The MicroFM-SMA boards: SMT version (left) and X18 version (right)

Fast-output detectors are available in all SMT packages and also in TO18 packaged die (1mm and 0.25mm SiPMs)

MicroFM-SMA boards are for fast mode readout of TO and SMA packaged 0.25mm, 1mm, 3mm and 6mm detectors

sensL
sense light

Measurement Instruments: TDC & CFD

Measurement Instruments – TDC & CFD

A detector's performance can be limited by the electronics which are used to read it and acquire the signal it produces.

SensL offers two products relevant to such applications:

HRM-TDC (Time to digital converter)

HRM-CFD (Constant fraction discriminator)

sensL
sense light

HRM-TDC

- Portable, highly functional timing system
- Flexible, easy-to-use timing functions
- Four channels, each with 27ps timing resolution
- Maximum data rate of 4.5MHz over USB
- Programmable TTL clock output
- Directly compatible with PCDMini & HRM-CFD
- User GUI, DLL's & Lab VIEW examples provided
- OEM versions available (with MOQ)

sensL
sense light

HRM-CFD

- Portable 2-channel CFD system
- Picosecond timing with ultra-fast detectors, low time walk/jitter
- Compact, rugged and low-power
- 0.75GHz amplifier per channel
- All settings programmed via USB & GUI
- Fully compatible with the SensL HRM-TDC
- Compatible with PMT, APD, MCP, PIN & SPM style detectors
- OEM versions available

sensL
sense light

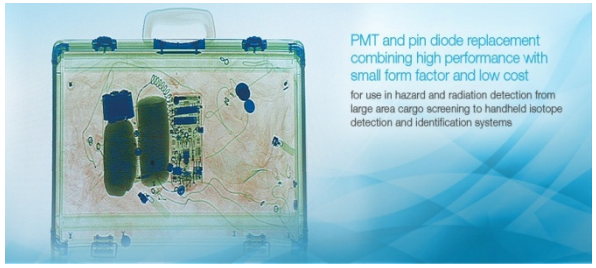
sensL
sense light

Markets & Application Areas

Large Diversified Markets and Applications

Medical Imaging

PET/CT, PET/MR, SPECT, Gamma Camera



Hazard and Threat Detection

Radiation Detection, Cargo Scanning

Automotive and Industrial

Advanced Driver Assistance, Laser Range Finding, Robotic Automation, Nucleonics, Process Inspection

Biophotonics

Hematology, Flow Cytometry, DNA Analysis, Flouresence, Spectroscopy

sensL
sense light

Academic Research & Other Applications

- Biophotonics (not covered in this presentation)

  - ATP monitoring
  - Flouresence analysis
  - Cytometry
  - Flouresence lifetime imaging (FLIM)
  - Time correlated single photon counting (TCSPC)
  - Confocal Microscopy
  - Retinal scanning
  - Blood analysis

- Data communications
- Space-related programs (ESA, civilian satellites, LiDAR)
- High-energy physics programs ongoing (CERN, DESY, GSI, PSI, LANL, INFN...)
- Cherenkov radiation detection (CTA)
- Turbine temperature monitoring
- Multiple photon counting applications (particle sizing, scientific…)
- Dark matter experiments

sensL
sense light

Recent Academic Papers on our Website

www.sensl.com

- Stanford
  - Fast Readout
- UC Davis
  - Matrix 9
- U Manitoba
  - HDMI Cable
- GE/SensL
  - Fast Readout
- McGill University
  - Highly Pixelated Readout

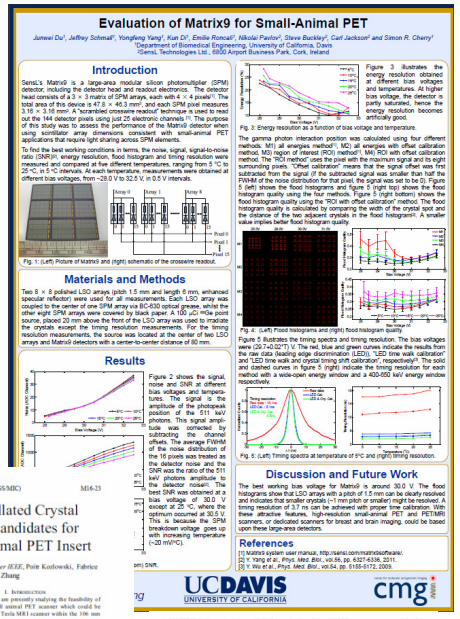

Timing Performance of Fast Timing Silicon Photomultipliers

Jung-Yeol Yeom[1], Ruud Vinke[1], Nikolai Pavlov[2], Stephen Bellis[2], Kevin O'Neill[2], Carl Jackson[2] and Craig Levin[1,3,4,5]

Molecular Imaging Program at Stanford, Dept. of Radiology[1], Physics[3], Bioengineering[4] and Electrical Eng.[5], Stanford University, Stanford, CA 94305, USA
SensL Technologies Ltd., 6800 Airport Business Park, Cork, Ireland[2]

MIPS Molecular Imaging Program at Stanford

Stanford University School of Medicine Department of Radiology


Evaluation of Matrix9 for Small-Animal PET

Introduction

Materials and Methods

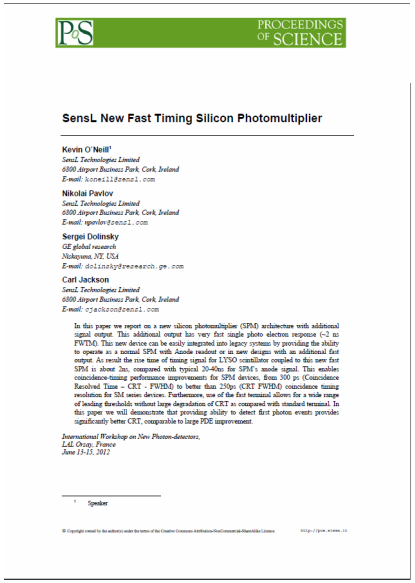
Results

Discussion and Future Work

References

UCDAVIS UNIVERSITY OF CALIFORNIA

cmg


PROCEEDINGS OF SCIENCE

SensL New Fast Timing Silicon Photomultiplier

Kevin O'Neill
Nikolai Pavlov
Sergei Dolinsky
Carl Jackson


Evaluation of Very Highly Pixellated Crystal Blocks with SiPM Readout as Candidates for PET/MR Detectors in a Small Animal PET Insert


Application of HDMI® Cables as an MRI Compatible Single Cable Solution for Readout and Power Supply of SiPM Based PET Detectors

70+ publications on SensL.com

sensL sense light

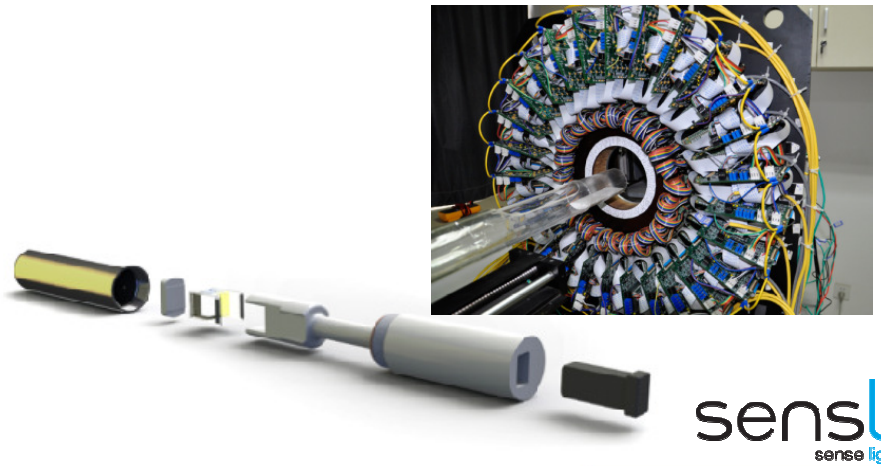
Select Medical Imaging Design Wins

Commercial Customers

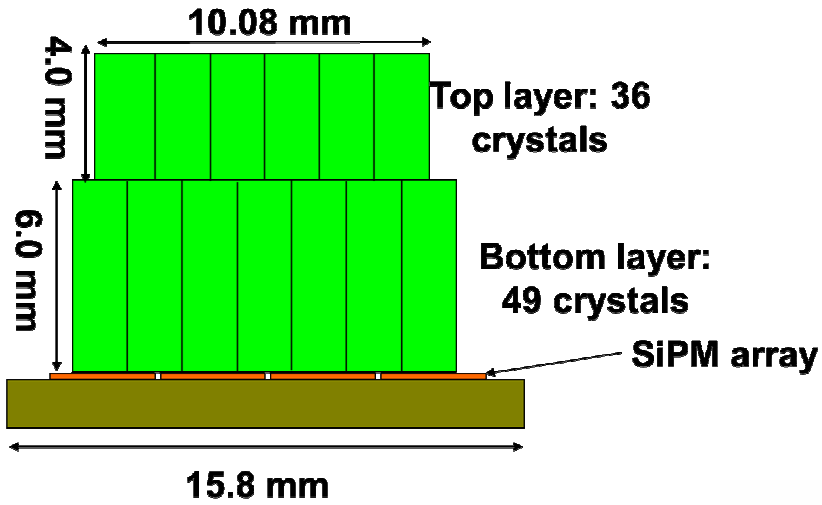
- Brain PET/CT System (US)
  - FDA Trials now @ 2 hospitals
  - First commercial system results Published SNM-June-2012
- Full Body PET/CT System (US)
  - Active development
- Small Animal PET (Asia)
  - Field Trials

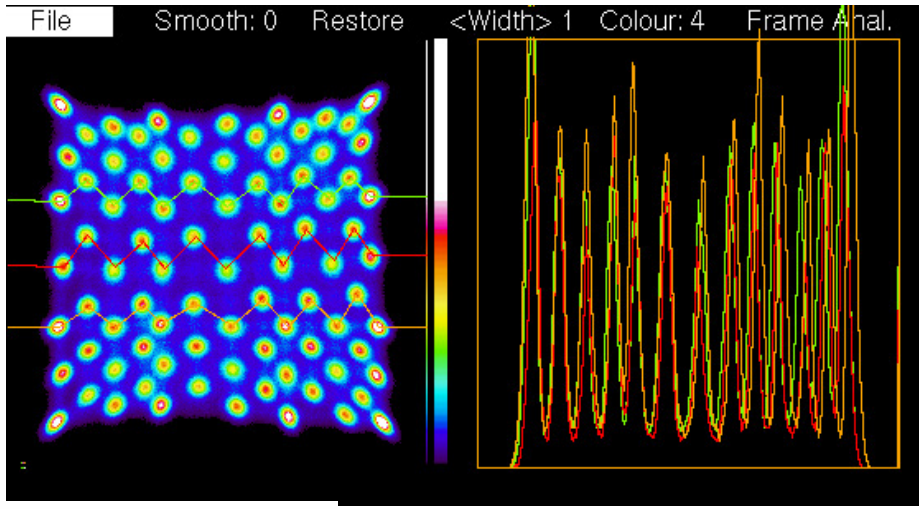
Research Customers

- Brain PET/MRI Scanner (Samsung Research)
- Brain PET/MRI (Stanford)
- Prostate Probe (WVU)
- High Resolution Breast PET (MD Anderson)
- Preclinical PET (Large Chinese University)
- 80 Research papers available on SensL website

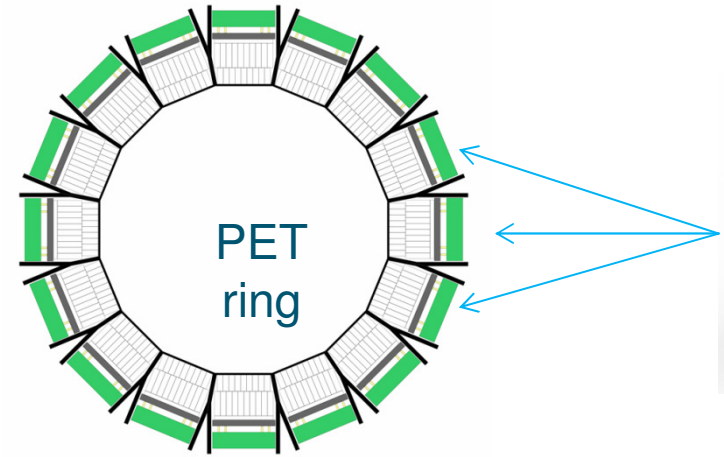


High Density LYSO Crystal Block Readout



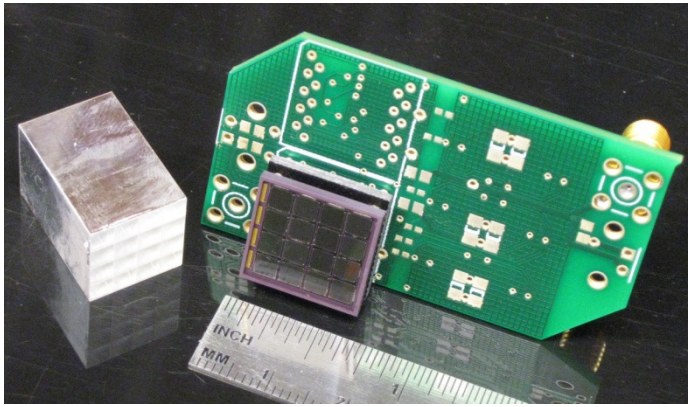


- Designed for 7T PET/MIR
- 1.67x1.67 LYSO crystals
- Dual crystal layers
- SensL products
  - ArraySL-4-30035-CER
  - ArraySL-4-PIXOUT
  - ArraySL-4-EVB

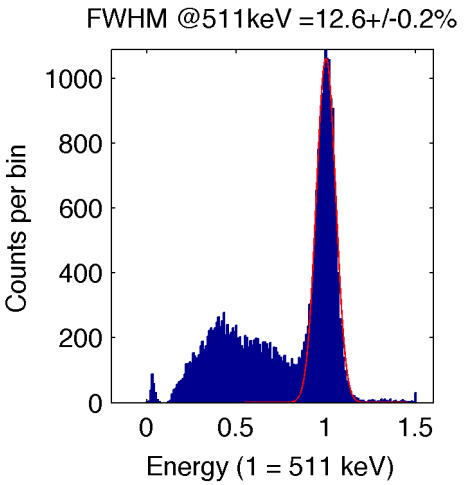


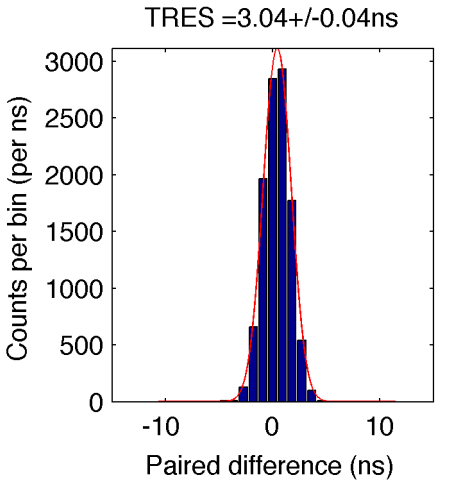
* Images courtesy of Chris Thompson

PET/MRI
Molecular Imaging Program at Stanford

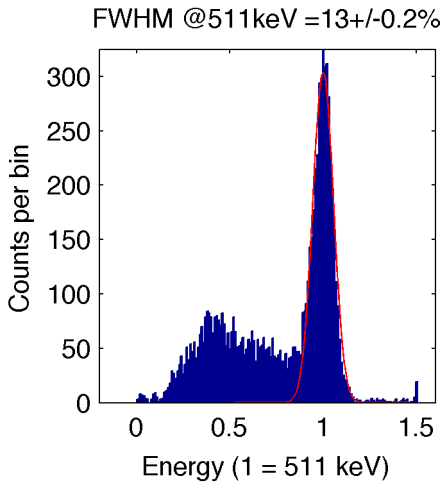


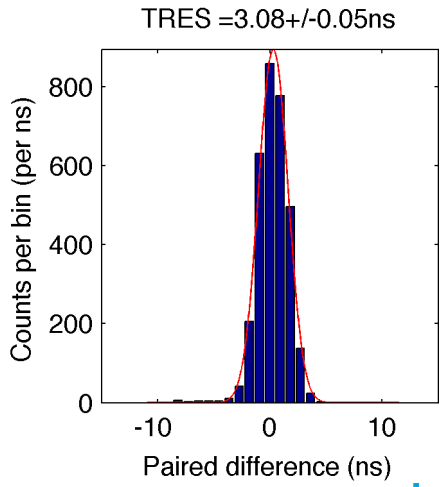
1.5T RF OFF





1.5T RF ON



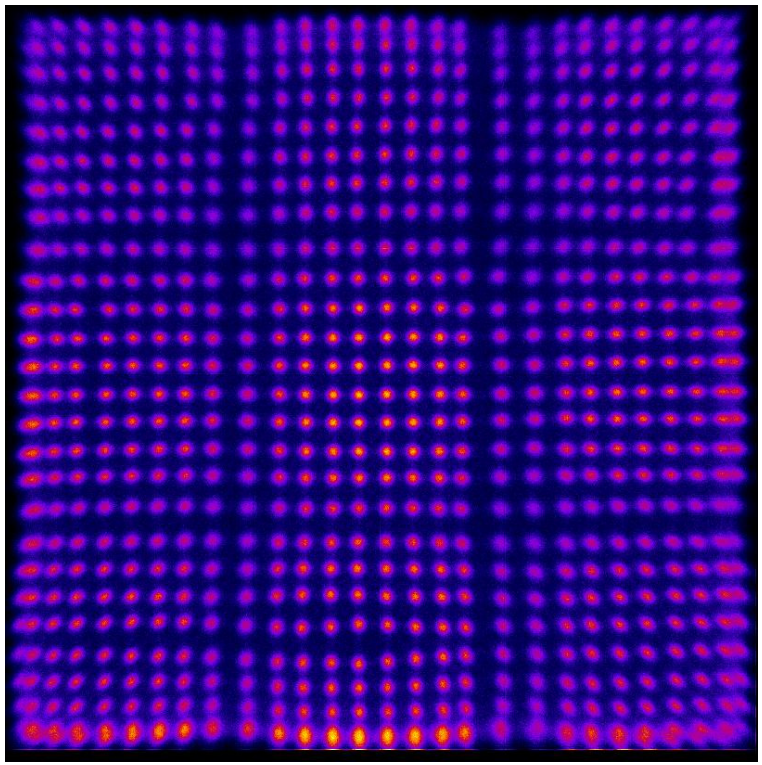


PET/MRI
- Readout through SPM modulated VCSEL over fibre
- 2.14x2.14x20mm^3 LYSO
- All components selected for magnetic field compatibility

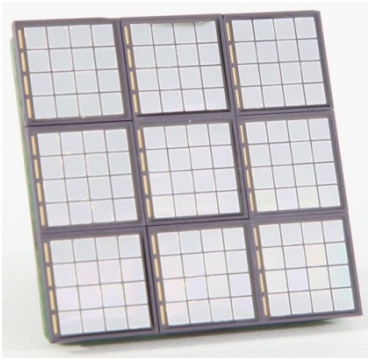
* Images courtesy of Peter Olcott and Craig Levin Poster (MIC 14-8)

sensL sense light

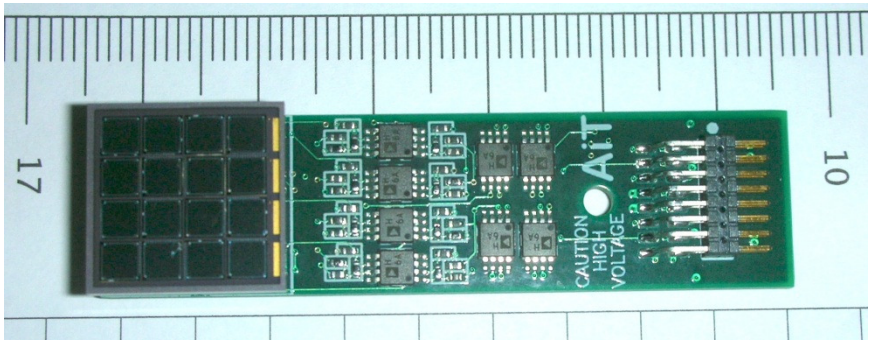
PET - High Density Signal Multiplexing
West Virginia – Center for Advanced Imaging



A 1.5mm LYSO Array flood map
DOI and MR compatibility
Multiplexing from 144:4 channels



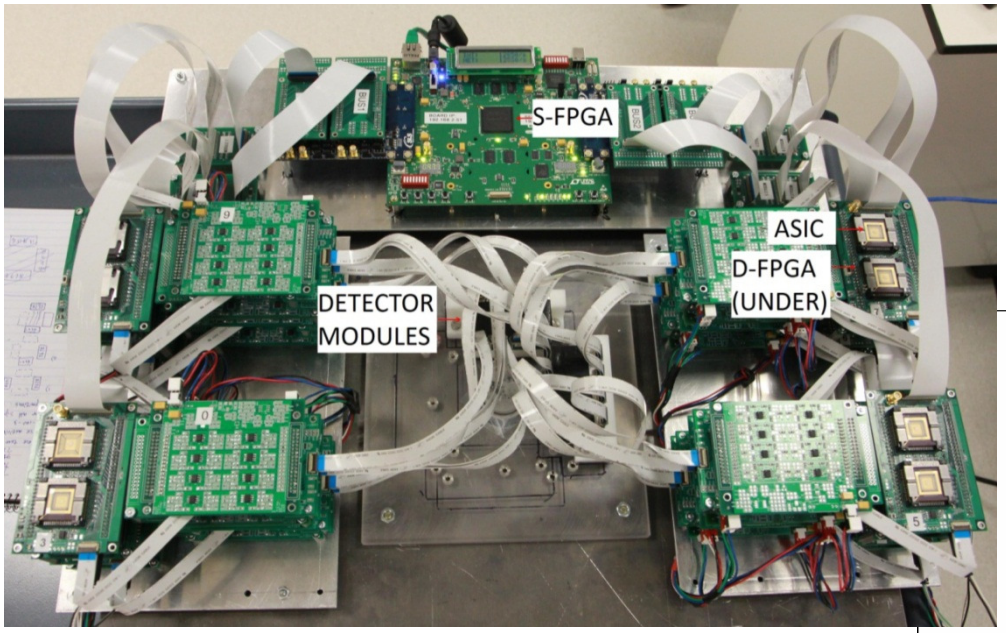
SensL Array4p9

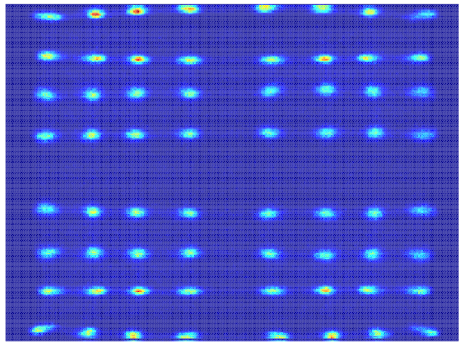


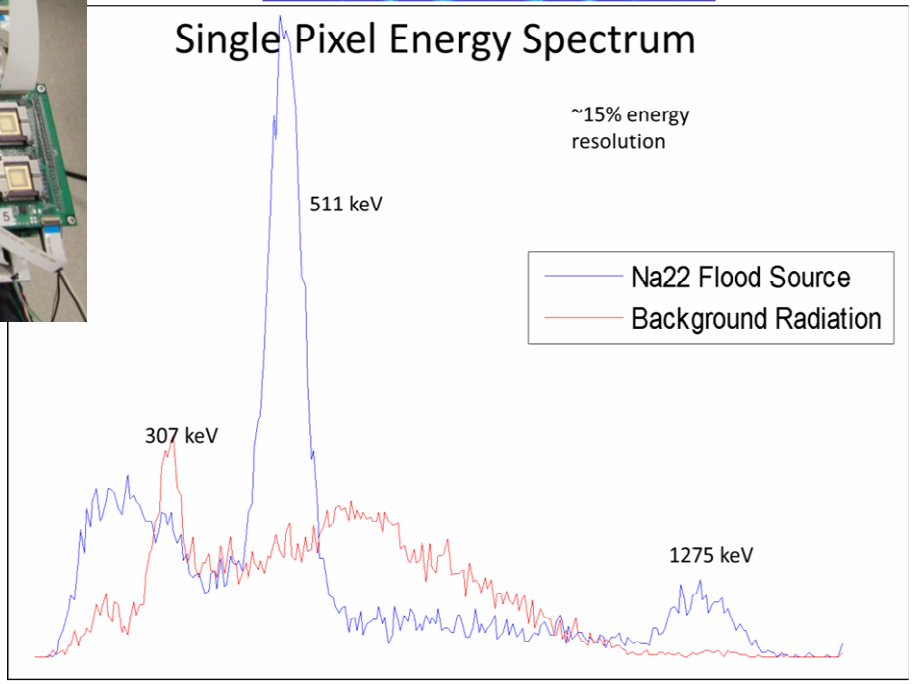
144:4 channel readout by AiT

* Images courtesy of Stan Majewski

High Resolution PET System
MD Anderson







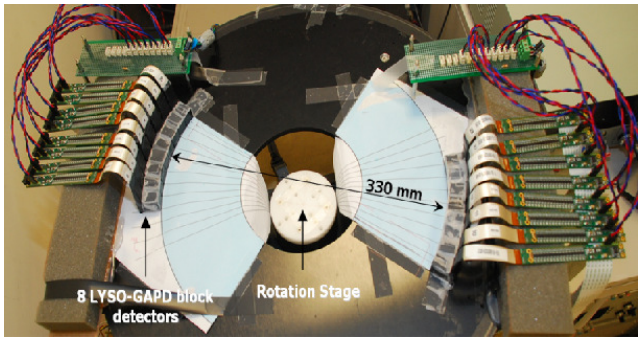
Custom ASIC readout
2mm pitch, 30mm length LYSO array
2ns timing
14% energy resolution
3-4 Depth of Interaction

* Images courtesy of Chad Birchner and Yiping Shao

sensL
sense light

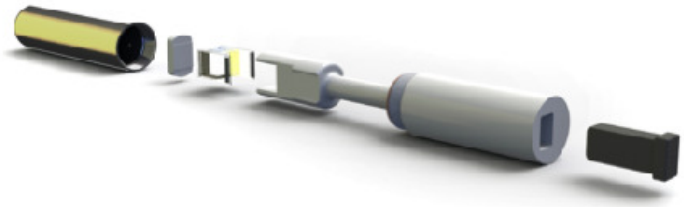
SensL Multi-Modality
Nuclear Medical Imaging

SAMSUNG SAMSUNG MEDICAL CENTER



World's first PET/MRI Ring

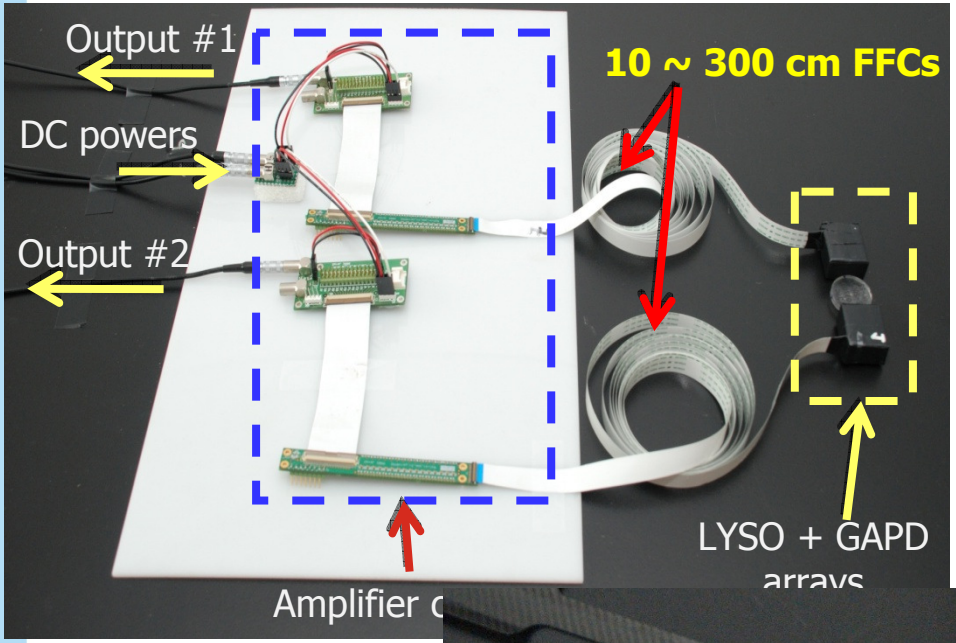
WestVirginiaUniversity.
ROBERT C. BYRD HEALTH SCIENCES CENTER

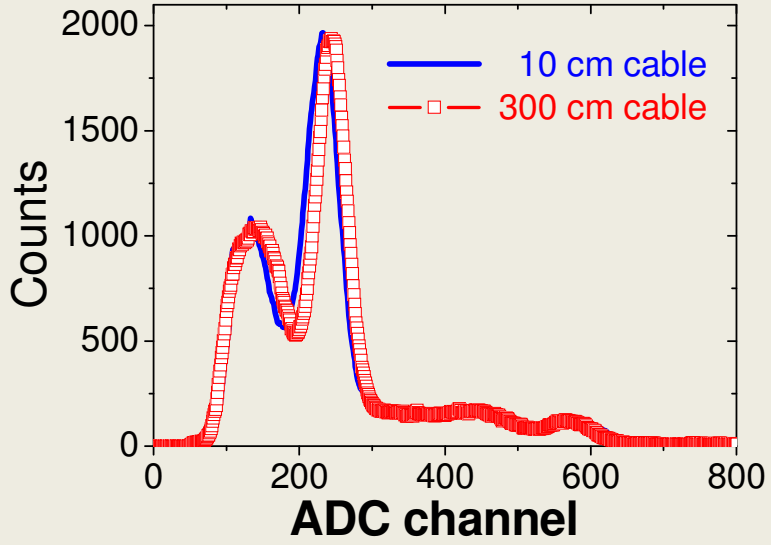


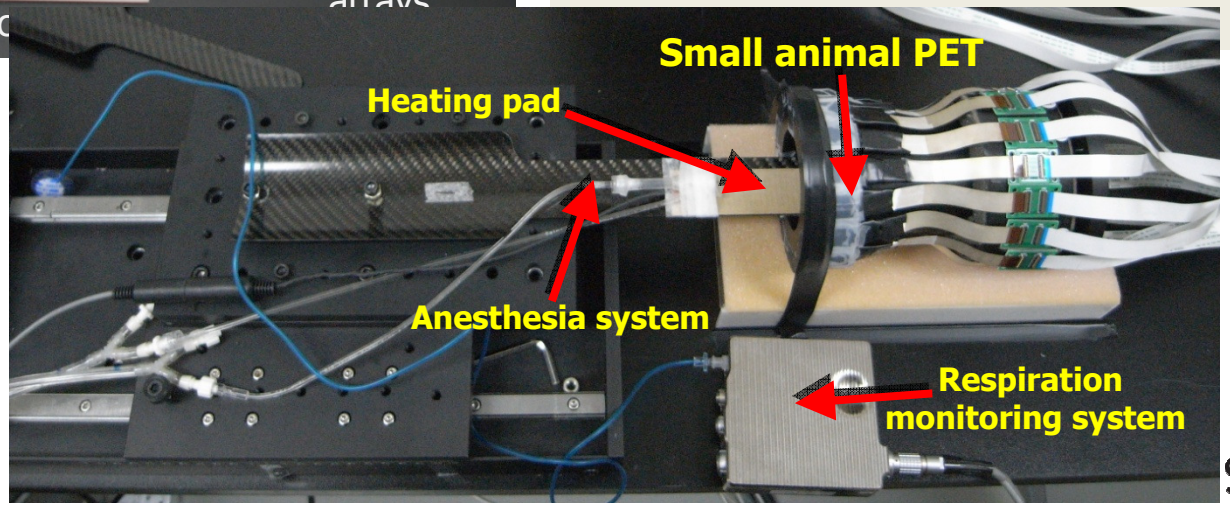
Prostate Imager

sensL
sense light

PET / MR



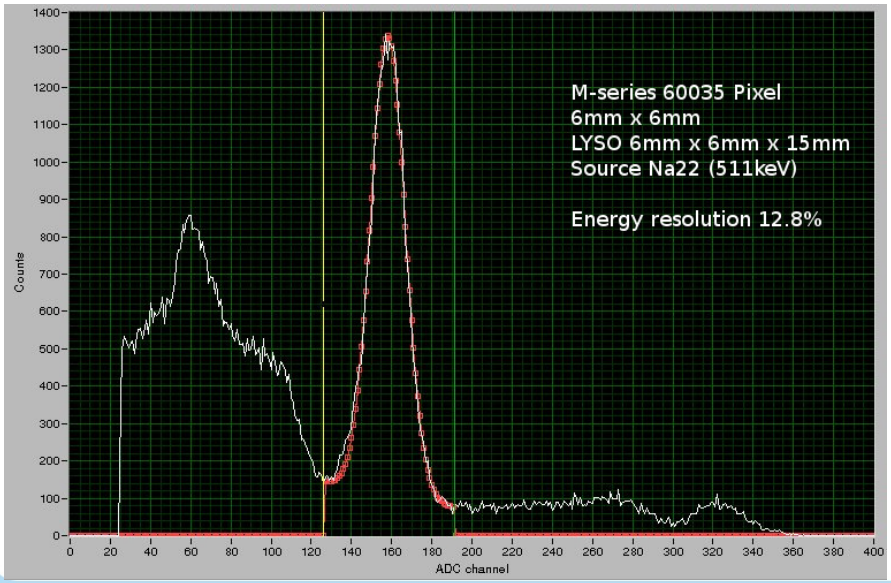


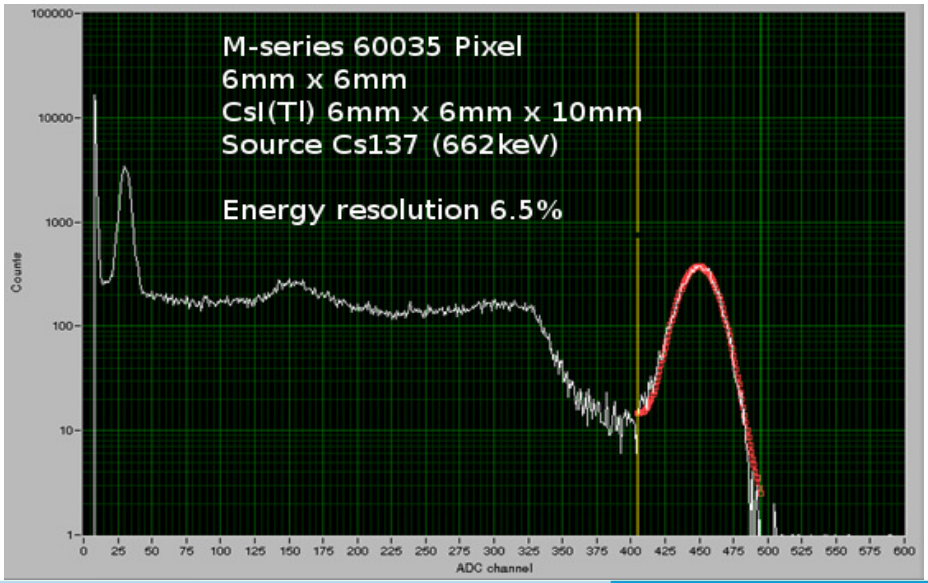


**All images Ref J. Kang, Y. Choi, et al.*

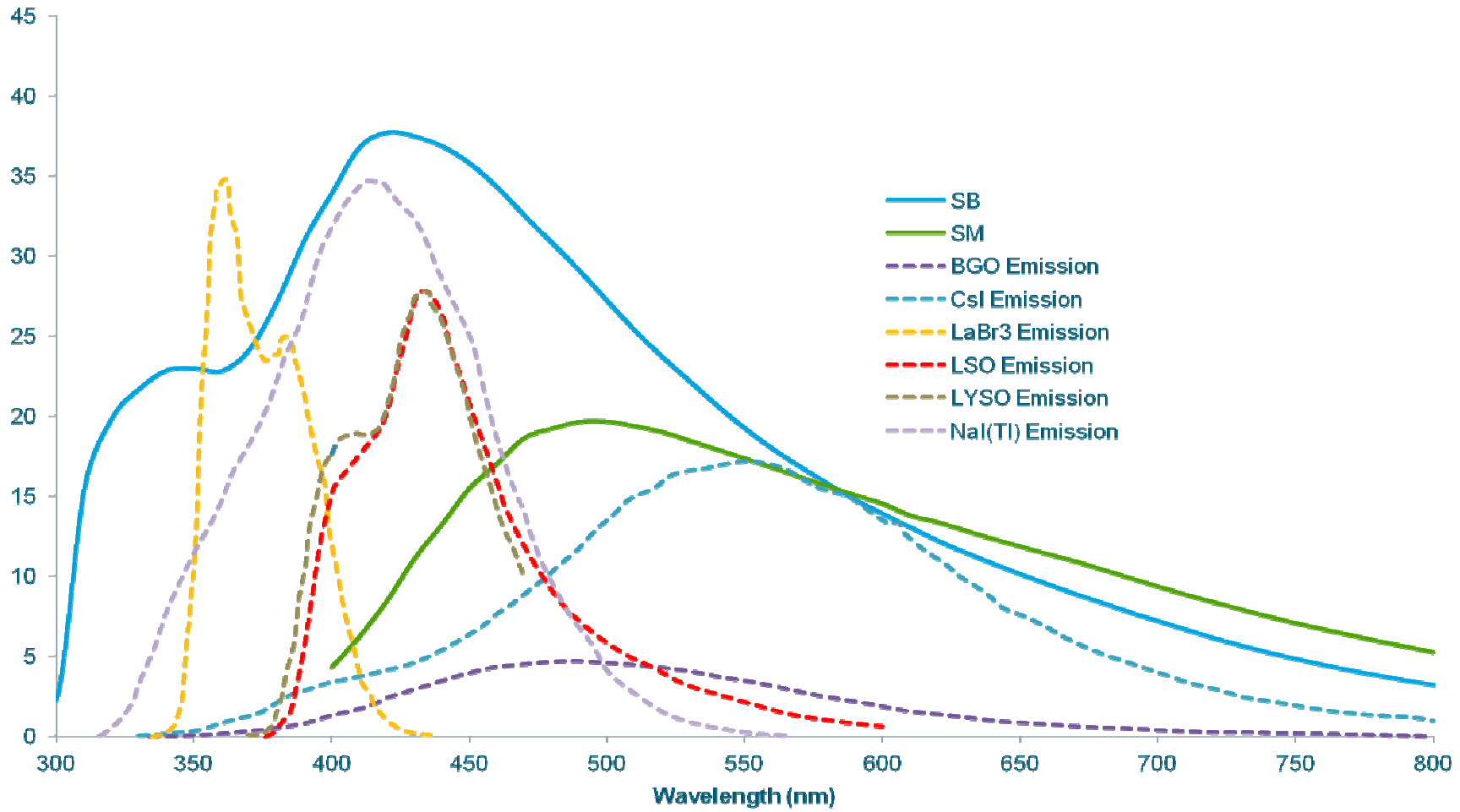
Nuclear Detection / Spectroscopy

- SensL detectors have need designed into numerous radiation detection systems:
  - Handheld dosimeters & counters
  - Large portal/truck scanning systems (neutron & gamma)
  - Handheld spectroscopy (isotope identification) systems
  - Customers are currently investigating SiPM-based neutron detection
  - Hazardous waste storage monitoring
  - Industrial scrap metal sorting
  - Nucleonic level measurement





Common Scintillators & SensL SiPMs



LIDAR Requirements

- LIDAR Requirements
  - Wide detection range
  - High range accuracy
  - Temperature stability
  - Miniaturized
  - Rugged
  - Low power
  - Low cost
  - High Speed

- SensL SiPM Benefits
  - Dynamic range
  - Ambient light rejection
  - Temperature stability

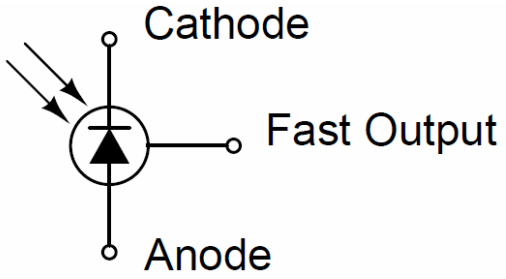
- Benefits of SiPM Technology
  - High signal to noise
  - High gain
  - High uniformity
  - Multi-sensor capable
  - Low power
  - Low cost

SiPM sensors are a superior alternative to the APD and PIN Photodiode

sensL
sense light

Example - SensL SiPM for Automotive LIDAR

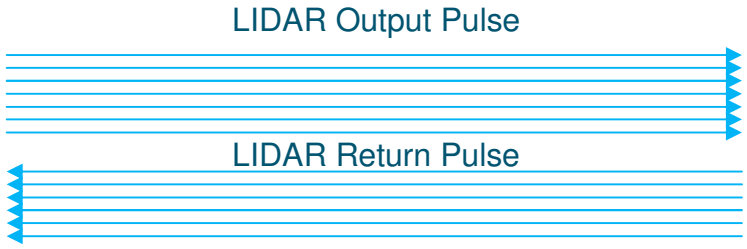
- Advantages of SiPM over PIN or APD
  - Gain of SiPM is >1M
  - Output response is picoseconds
  - Temperature stability
  - Uniformity of output response
  - Wide dynamic range
  - Large area array compatible
  - CMOS compatible
- Advantages of SensL SiPM for Automotive
  - Patented Fast Output terminal provides extremely fast output response
  - Picosecond response times provide the highest range accuracy possible

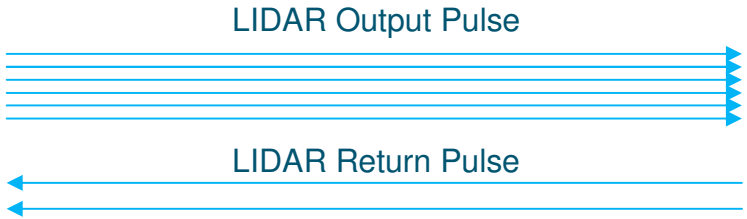


Circuit Designator

SiPM Dynamic Range & Automotive LiDAR?

- Reflected light intensity varies by orders of dynamic range
- SensL SiPM provides wide dynamic range accuracy
- Benefits of a wide dynamic range sensor
  - Ability to sense high photon flux signals
  - Ability to sense low photon flux signals



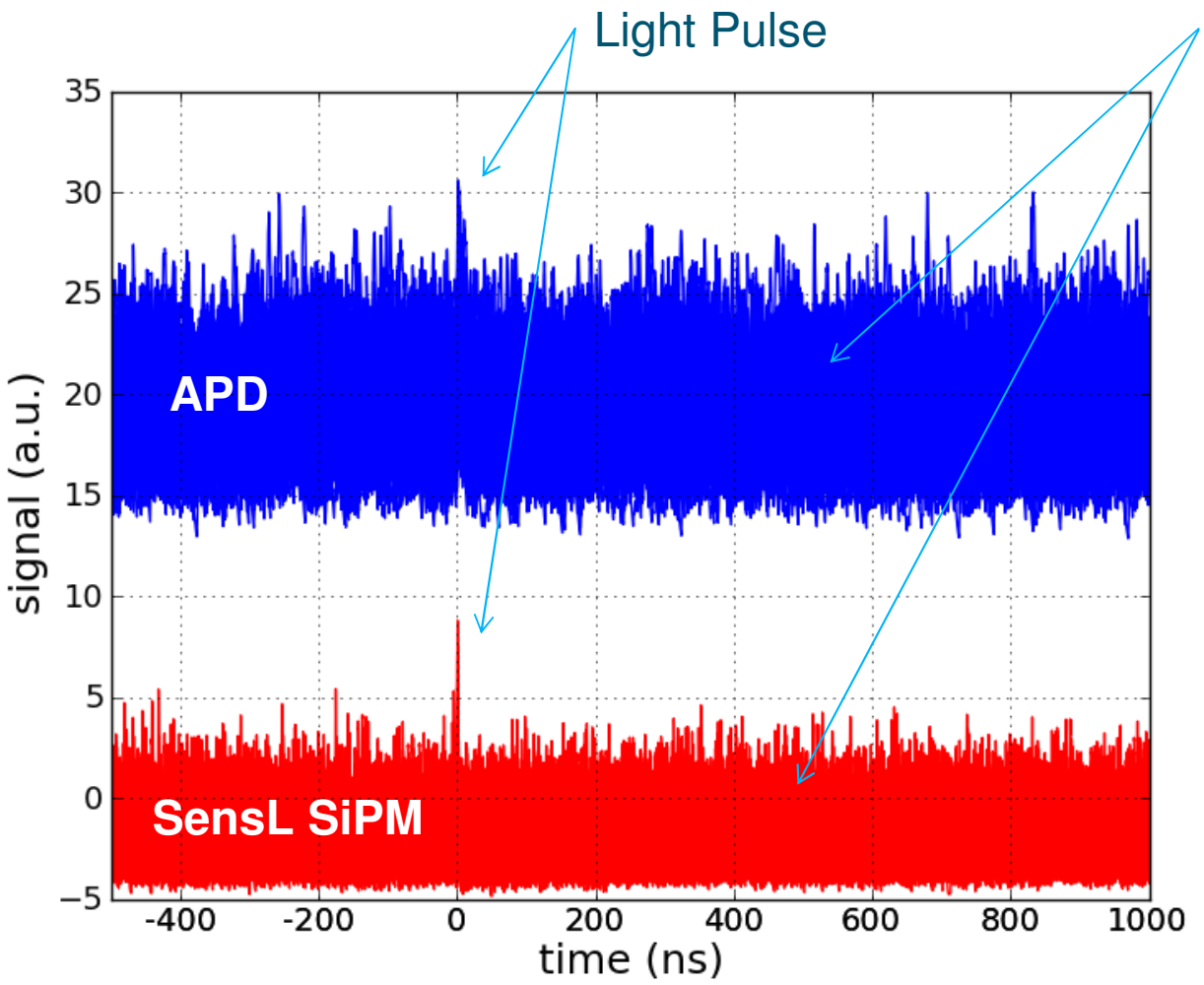


sensL
sense light

Ambient Light Rejection in Automotive LiDAR

- Automotive LIDAR systems must deal with reflected ambient light from the environment
  - Sunlight
  - Environmental lighting
- Ambient light can be rejected through system design
  - Reduction in field of view
  - Filters
  - Sensor with better ambient light rejection
- Benefits of ambient light rejection at the Sensor
  - Improved range accuracy
  - Wider dynamic range
  - Reduced system cost

Ambient Light Rejection Example



- This is an example of a low photon LIDAR signal pulse in a high ambient background
- Amplifier noise excluded
- SiPM provides superior background suppression

SiPM Temperature Stability & Automotive LiDAR

- Temperature stability is required to maximise range accuracy over the operating temperature range
- Benefits of a temperature insensitive sensor
  - Minimal need to adjust bias voltage with temperature
  - No need for a variable gain amplifier
  - Reduction in calibration requirements
  - Increased system stability over operating lifetime
  - Ability to have multi-sensor or arrays for Imaging LIDAR

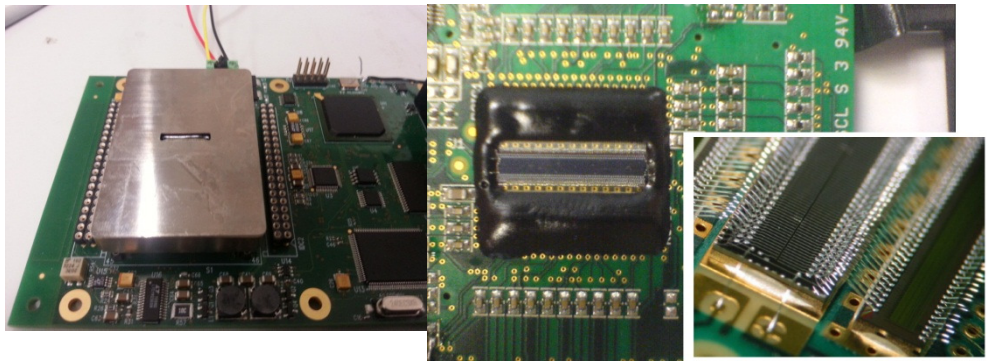
	APD	SiPM
Operating Voltage Variation	50V	0.5V
Temperature Stability	0.65V/˚C	0.02V/˚C

sensL
sense light

Advanced Imaging LIDAR

LIDAR ranging and Imaging System for MARS Lander

256x1 linear array with a dual ASIC packaged with TEC controller and interface board.



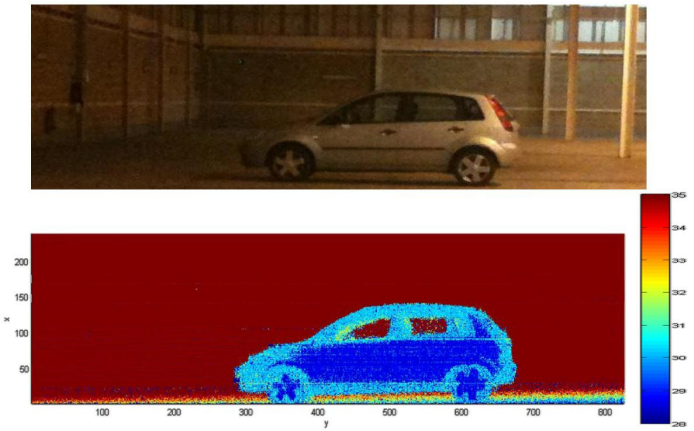


Image taken using SensL's detector head for ESA Imaging LIDAR program

Detector head and interface electronics provides high resolution LIDAR ranging and imaging.

20Km accurate to +/- 1.5m for ranging

•Coarse ranging clock = 100MHz.
•Return Time = Count x 10 x 10^{-9}
Distance = 0.5 x Return Time x 3 x 10^{8}
•Distance = 1.5 x Count Metres
•Accuracy is +/- 0.75 metres

5Km accurate to +/- 1.5cm for imaging

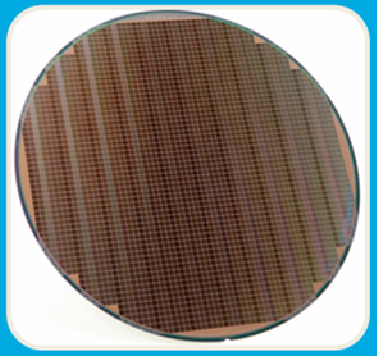
High resolution required over < 5Km
High resolution uses interpolators for sub 10ns resolution
Interpolator accuracy is +/-50ps
Imaging accuracy = 3 x 10^{8} x 50 x 10^{-12} = +/- 1.5cm

See **http://www.esa.int/Our_Activities/Technology/Laser_radar_illuminates_the_way_to_deep_space**

sensL
sense light

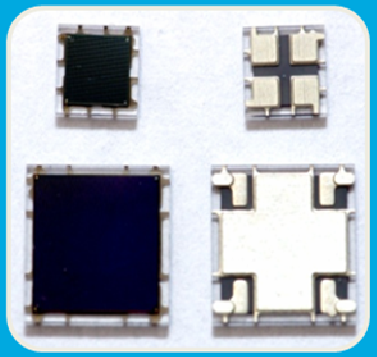
Quality Assurance & Testing

Product Level Test Plan



Wafer Level Test (at foundry)

- Process Control Monitor - PCM (5 site)
- Product (all die)
  - Electrical test below and above breakdown voltage
  - Optical test (blue light) below and above breakdown voltage
  - All parts binned and failing parts removed from supply chain



SMT Product Test (at vendor)

- Visual Inspection (all die)
- Electrical end of line test (all die)
- Failing parts are removed from supply chain and destroyed
- All passing parts are supplied on tape and reel

sensL
sense light

Wafer Level Product Test

PROBE OPERATION	TEST NUMBER	TEST DESCRIPTION	Units
P1 (DARK)	01025	OPEN TEST (PROBE QUALITY CHECK)	nA
P1 (DARK)	01035	SPM OPEN_SHORT TEST (DIE CHECK)	V
P1 (DARK)	01085	BREAKDOWN VOLTAGE VBR SPM	V
P1 (DARK)	01105	DARK CURRENT AT 26V REVERSE BIAS	nA
P1 (DARK)	01115	DARK CURRENT AT 27V REVERSE BIAS	nA
P1 (DARK)	01125	DARK CURRENT AT 28V REVERSE BIAS	nA
P1 (DARK)	01135	DARK CURRENT AT 29V REVERSE BIAS	uA
P1 (DARK)	01145	DARK CURRENT AT 30V REVERSE BIAS	uA
P2 (LIGHT)	01535	SPM OPEN_SHORT TEST (DIE CHECK)	nA
P2 (LIGHT)	01615	CURRENT AT 27V REVERSE BIAS	uA
P2 (LIGHT)	01625	CURRENT AT 28V REVERSE BIAS	uA
P2 (LIGHT)	01635	CURRENT AT 29V REVERSE BIAS	uA
P2 (LIGHT)	01645	CURRENT AT 30V REVERSE BIAS	uA

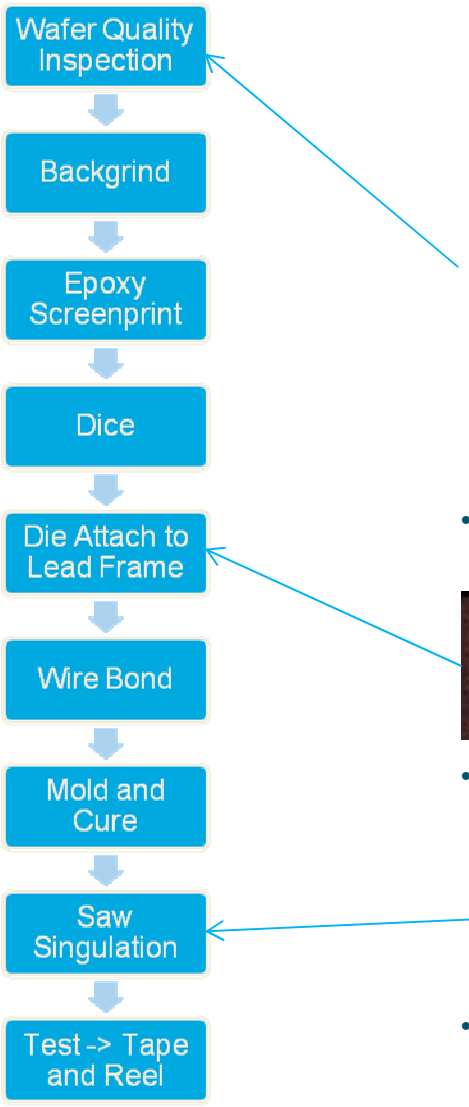
Image Sensor Tester

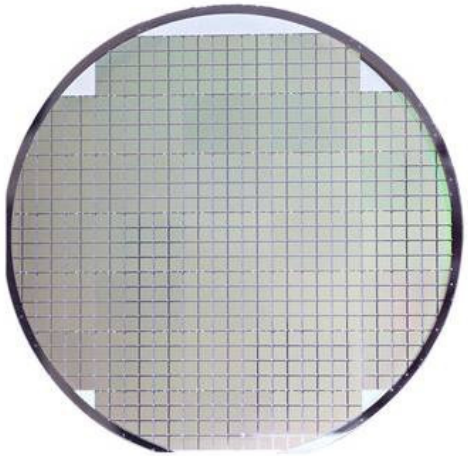
- Industry standard wafer level image sensor test equipment with custom SensL probe card
- Automatic batch processing of 25 wafers at a time
- Test conditions
  - In Dark - electrical tests
  - In Light - optical tests using filtered blue illumination
  - Tests temperature controlled to 25˚C
- Parts are binned to SensL specification with failing parts electronically “inked”
- Data files are shipped encrypted via FTP for processing and storage at SensL

Temperature Controlled Wafer Chuck

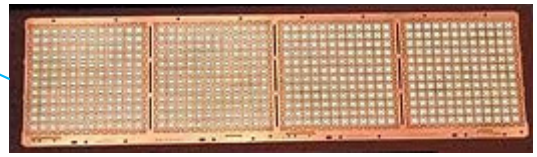
sensL sense light

Surface Mount Package Assembly Process

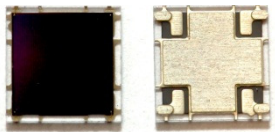




- 200mm wafer – 6mm die



- Lead frame strip



- Final product – MicroFB-60035-SMT

- All parts tested to SensL specification
- Data verified against wafer level data at the batch level
- 3000 parts per tape and reel (1mm, 3mm & 6mm)
- MSL=3 status achieved for reflow solder and mass production of arrays

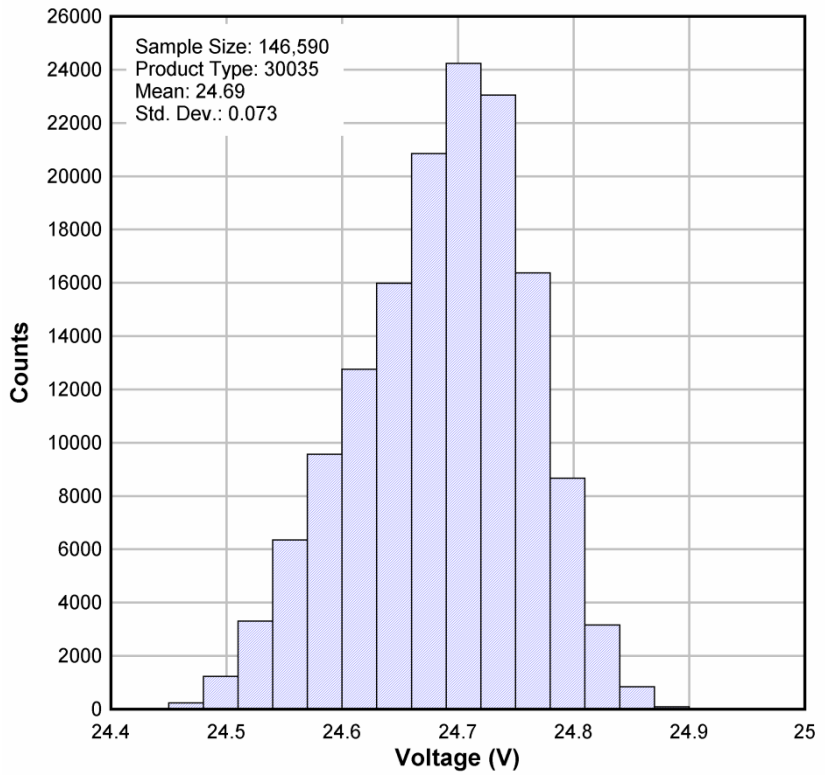
SMT Devices -- End of Line Test

Test Name	Unit	Electrical Test Conditions
Open Check	mA	Apply forward bias @ 1V Measure Current Test in dark
I_DRK_26V	nA	Apply 26.00V Measure current Test in dark
VBR_100NA	V	Force 100nA Measure voltage Test in dark
I_DRK_VBR_1V	µA	Apply Voltage of V1 = (VBR_100NA + 1.00V) Measure current Test in dark
I_DRK_VBR_2V	µA	Apply Voltage of V2 = (VBR_100NA + 2.00V) Measure current Test in dark
I_DRK_30V	µA	Apply 30.00V Measure current Test in dark
F_Test_Vrms	mV	Apply 100kHz, 10.0V peak to peak sinusoidal signal across PN terminals. Measure the output RMS voltage at the F terminal.

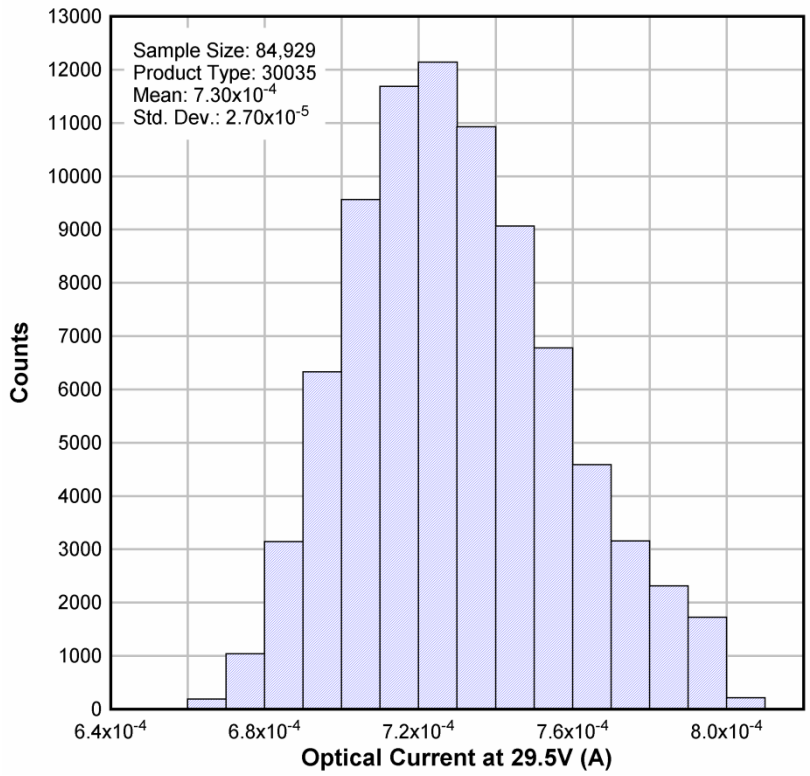
- Standard test handler modified to satisfy SensL test specifications
- All parts tested electrically
- All parts optically inspected prior to tape and reel

Electrical and Optical Uniformity

- With high volume CMOS processing capabilities, SensL has the best uniformity in the industry.
- Data is from >150k 3x3mm Pixels (un-binned data)



+/-250 mV Operating Voltage Uniformity



±10% Optical Response Uniformity

sensL
sense light

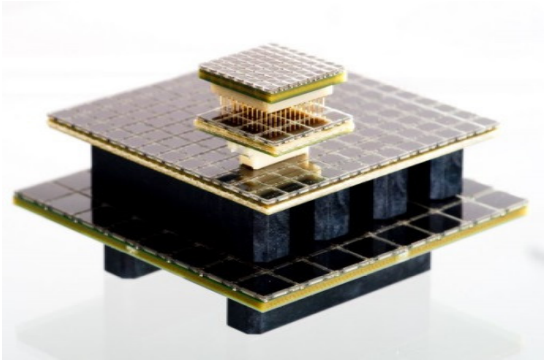
design | detect | today

The Leaders in Silicon Photomultipliers Since 2004

SensL – New Developments in Silicon Photomultipliers

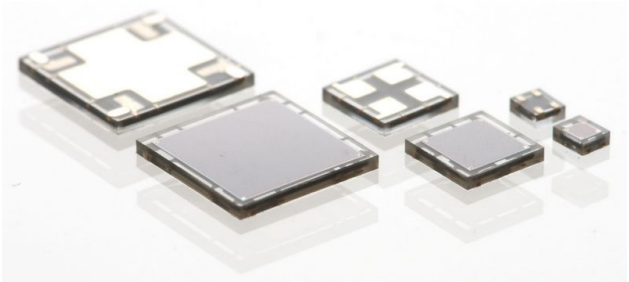
April 2014

SensL SiPM Product Portfolio

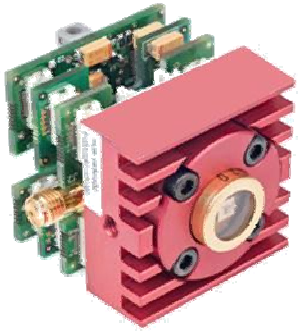


Arrays

PET Readout Matrix



SMT



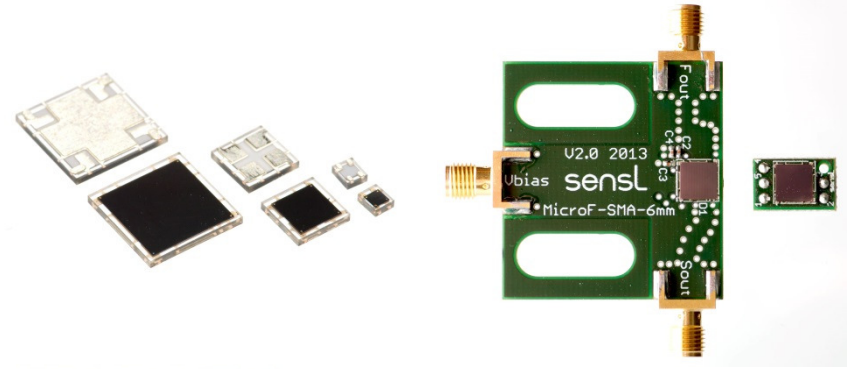
Mini

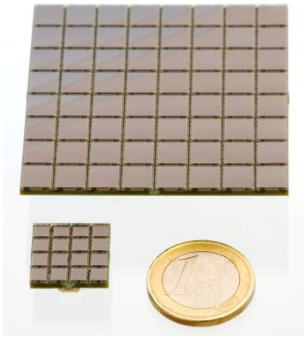
Micro

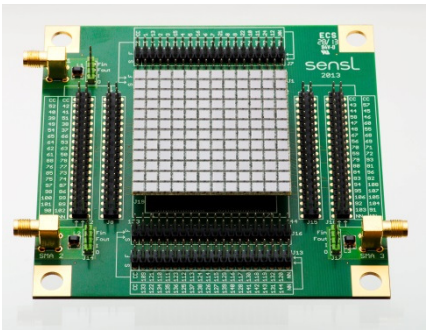
sensL
sense light

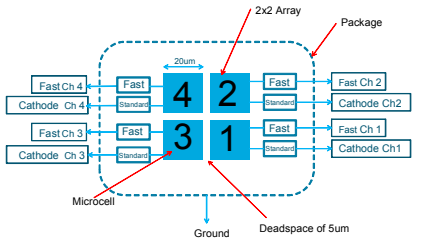
Recent Product Introductions & Contracts

- B Series Released for Production
  - Version 2.0 of Datasheet Available
- SMT Devices & Test Boards
  - .25mm & 1mm (M Series)
  - 3mm & 6mm (M & B Series)
- SMT Arrays & Test Boards
  - 4x4 of MicroFB-30035-SMT
  - 12x12 of MicroFB-30035-SMT
  - 8x8 of MicroFB-60035-SMT
- Photon Counting Arrays
  - 2 x 2 microcell 20u Array
  - 20u single cell sensor
- Program Partner in FP-7 “Mindview”
  - Brain PET Imager









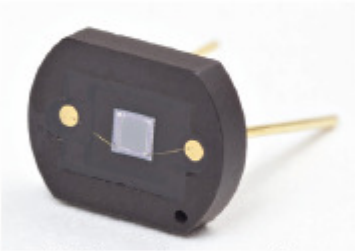
sensL
sense light

B Series Performance Overview

B-Series Summary Performance Parameters (See Datasheet for full details)

		10000 series	30000 series		60000 series
		10035 [d]	30035 [d]	30050 [d]	60035 [d]
Typical breakdown voltage (VBr) [b]		24.5V ± 0.5V			
Bias range (above VBr)		1V - 5V			
Spectral range		300nm - 800nm			
Peak wavelength (λ_p)		420nm			
PDE at λ_p	@ VBr +2.5V [a]	31%	31%	35% [g]	31%
	@ VBr +5V	41%	41%	47%	41%
Gain [a] [e]		$3x10^6$	$3x10^6$	$6x10^6$	$3x10^6$
Dark current - Typical [a]		0.3µA	3.2µA	7.2µA	10µA
Dark current - Max. [a]		0.6µA	6.0µA	13.5µA	24µA
Rise Time (Fast Output) [a] [f]		<0.3ns	0.6ns		1ns
Signal pulse width - Fast Output (FWHM) [a]		<0.6ns	1.2ns		3.2ns
Microcell recovery time [a] [b]		180ns	180ns	350ns	210ns
Temperature dependence of VBr		21.5mV/°C			

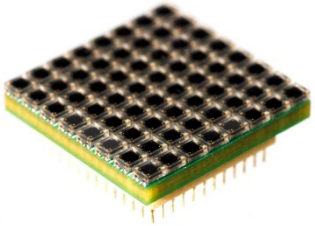
X18 package option



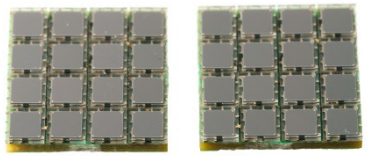
X13 package option

SMT package option

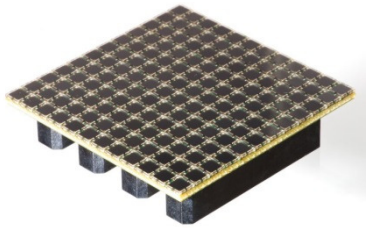
4 SMT Array Variants Available Now



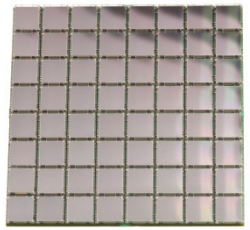
8x8 of 1mm
(2.49 cm^2)



4x4 of 3mm
(2.74 cm^2)



12x12 of 3mm
(25.2 cm^2)



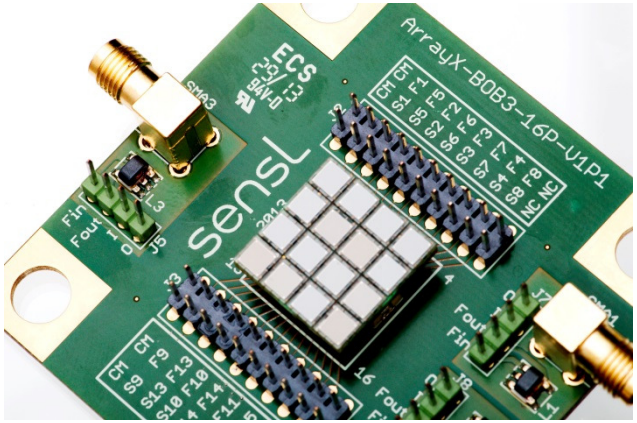
8x8 of 6mm
(32.94 cm^2)

- Available for rapid testing
  - 8x8 of 1mm SMT
    - 1.7mm pitch
  - 4x4 of 3mm SMT
    - 4.2mm pitch
  - 12x12 of 3mm SMT
    - 4.2mm pitch
  - 8x8 of 6mm SMT
    - 7.2mm pitch
- Passive Breakout Board (BoB)
  - Ability to readout any pixel (no amp)
  - 3 SMA connection options
- Full Reference Design Available

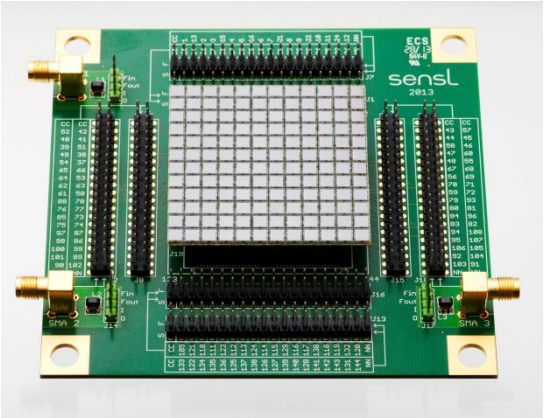
sensL
sense light

SMT Array Breakout Boards

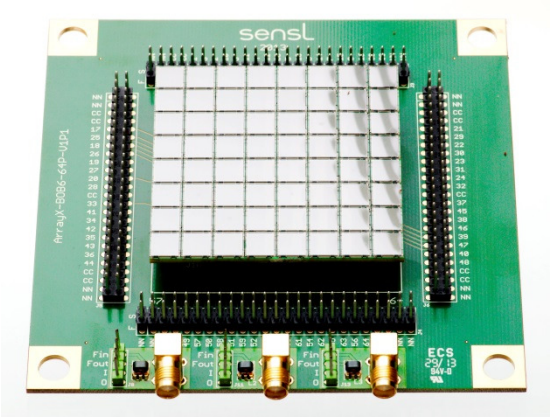
8x8 of 1mm (2.49 cm^2)



4x4 of 3mm (2.74 cm^2)



12x12 of 3mm (25.2 cm^2)



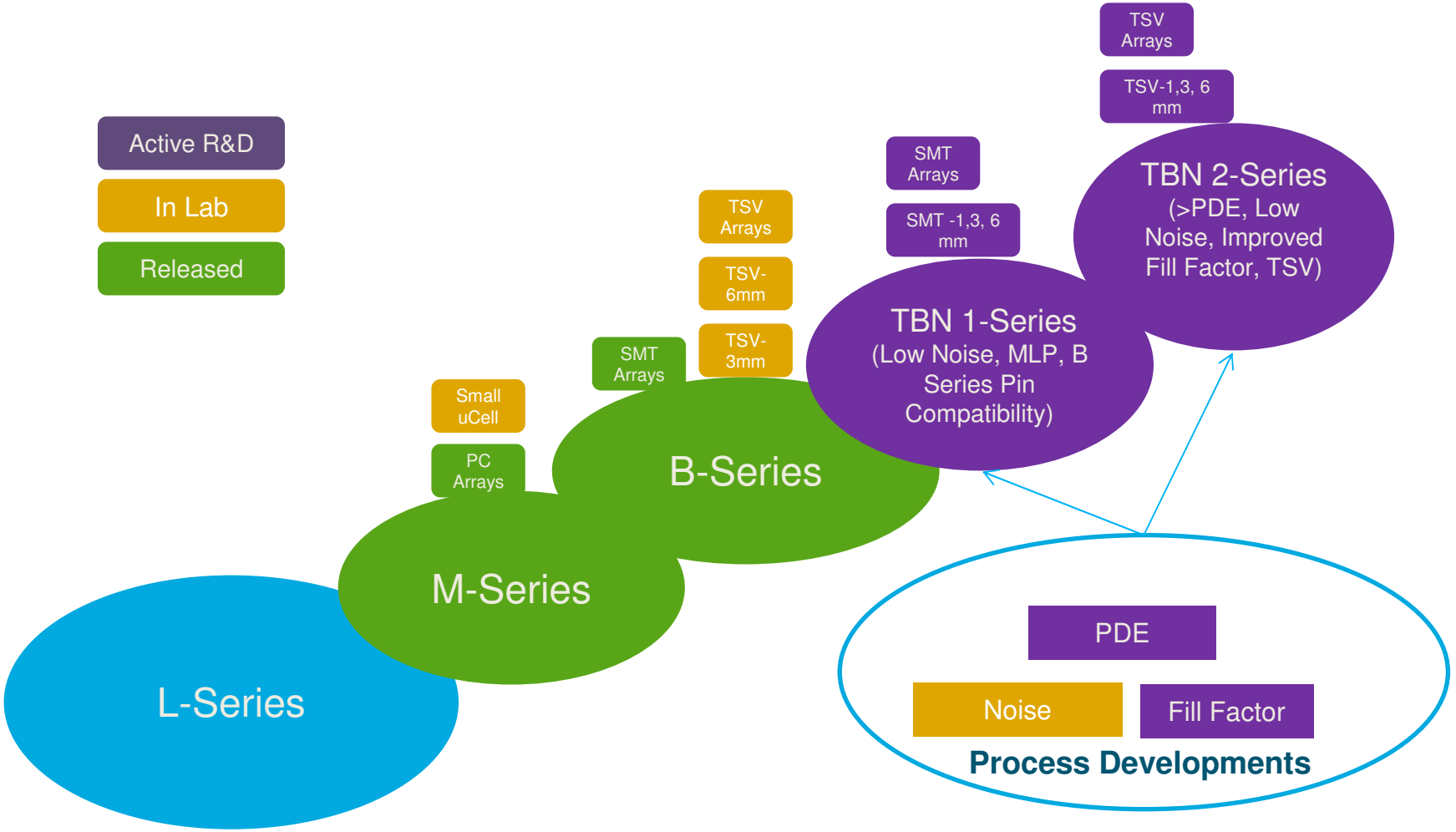
8x8 of 6mm (32.94 cm^2)

sensL
sense light

Roadmap

- Low Noise
- TSV

SiPM Product Roadmap and R&D Plan



Roadmap Summary -- At Glance

TBN-1 Series (Low Noise)

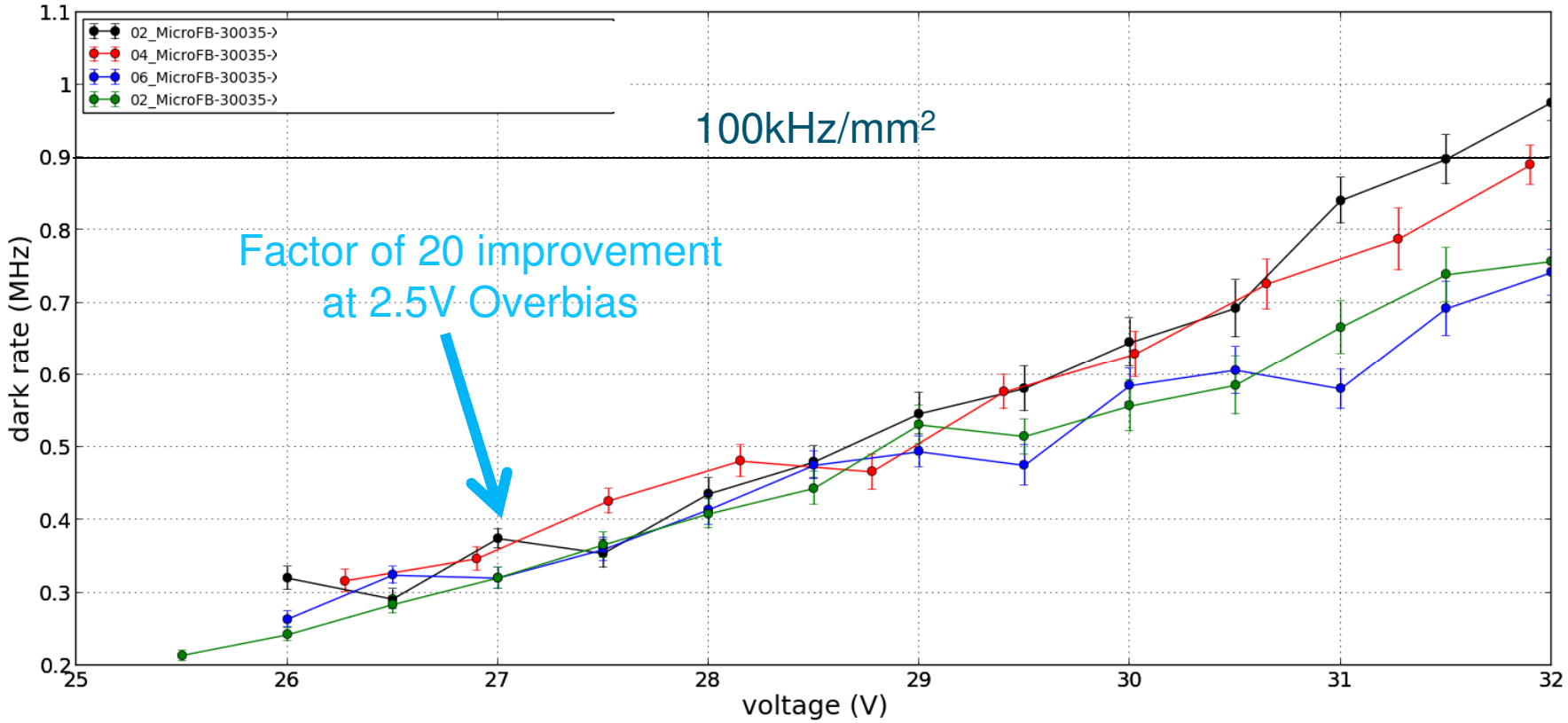
- MLP/SMT 100% pin & package compatible with B Series
- 100kHz dark rate/mm^2 dark noise (20x reduction over B-Series)
- Slight shift in Vbr for optimum PDE but otherwise all other B Series attributes
- Availability:
  - Samples to select customers now (TO Package on SMA board)
  - Volume release in MLP/SMT in summer 2014

TBN-2 Series (↑PDE, ↑FF, ↓noise)

- Improved PDE (~50% target) over B Series
- Improved fill factor with microcell pitch change
- TSV/SMT package
  - Improved array pitch
  - MSL-1
- Availability:
  - Samples of TSV/SMT package on SMA board in April (B Series process)
  - Beta samples in Q4 2014
  - General release (Volume) Q1 2015

Dark Rate (Measured Lab Results)

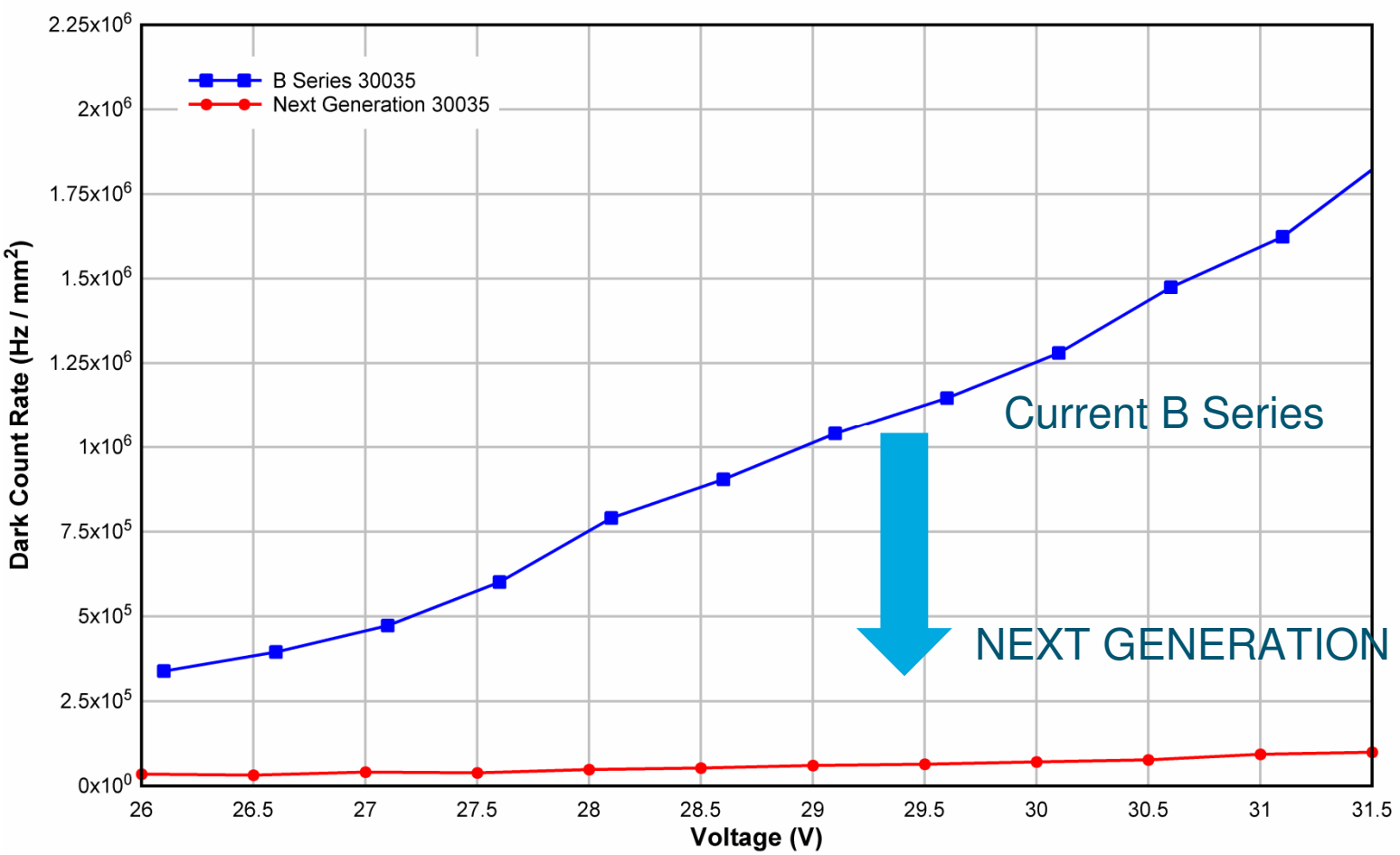
February 2014 Process



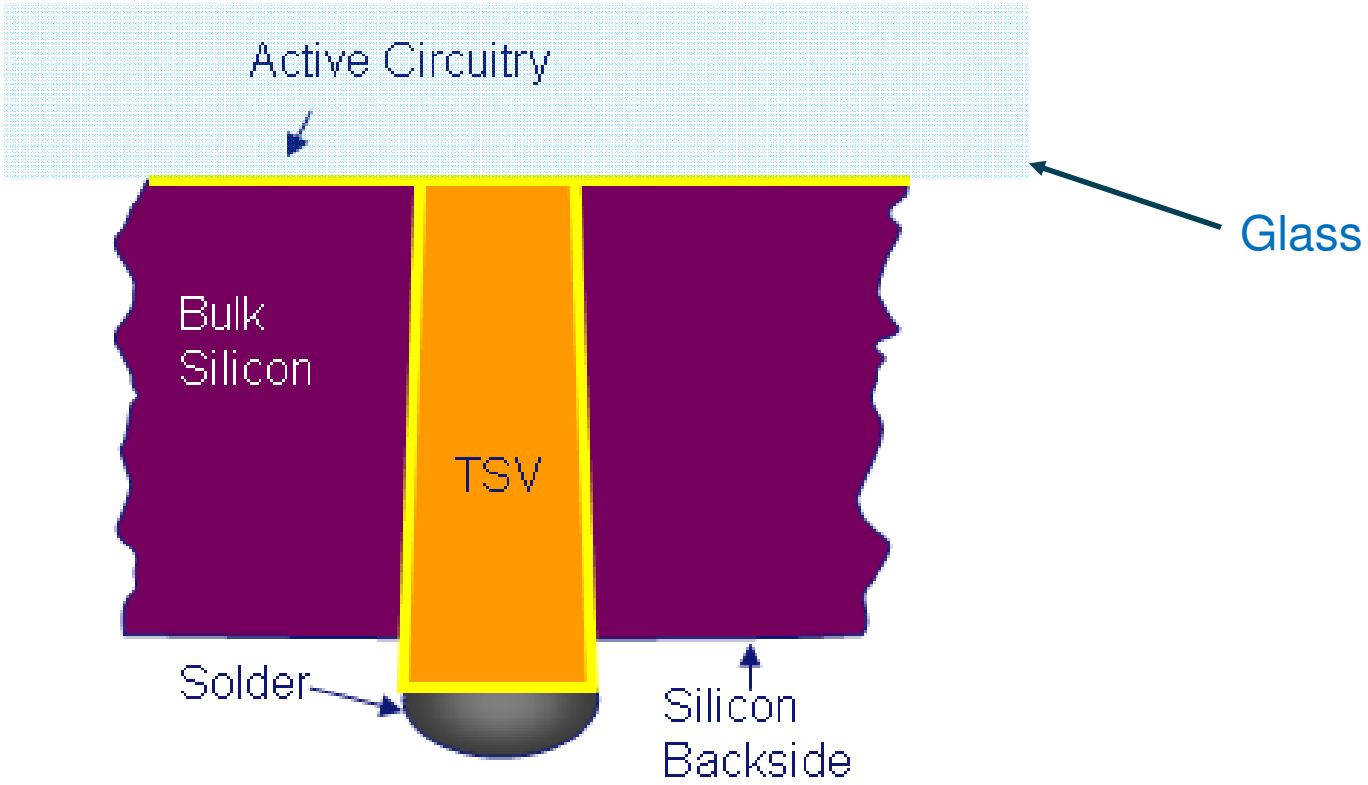
OVB up to ~7.5V

VBR2=~24.5V

Dark Count - 30035 Engineering Samples



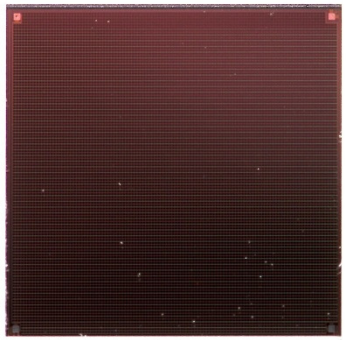
Through Silicon Via (TSV)

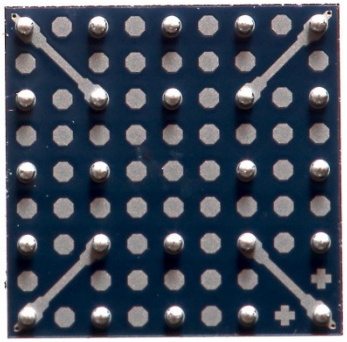


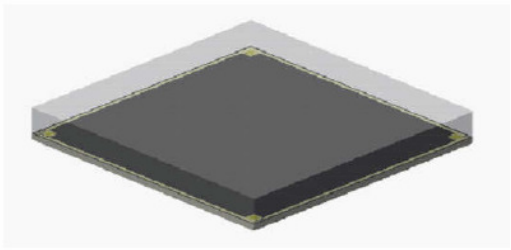
Silicon wafer is attached to glass, thinned to <0.10mm, contact vias are etched, filled and solder balls attached

TSV Package

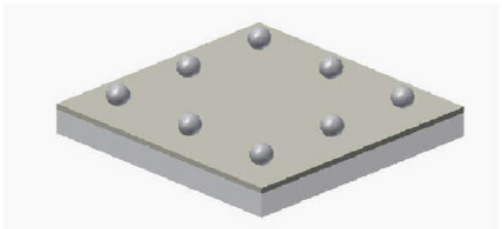
- Advantages
  - High volume
  - Medium cost
  - Reliability (no wire bonds)
  - Reproducibility
  - Long service life
  - Yield
  - Operating temperature range (-40C to 95C)
  - MR compatible
  - Glass enables best low wavelength PDE
  - Suitable for arrays
  - Large area packages are possible
  - Optimum fill factor
  - MSL1
- Disadvantages
  - Cost of product development
  - Higher unit cost than SMT







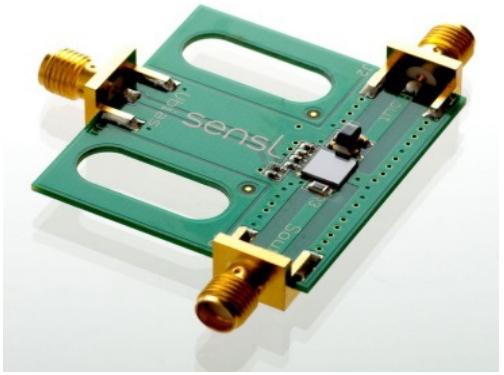
Top View

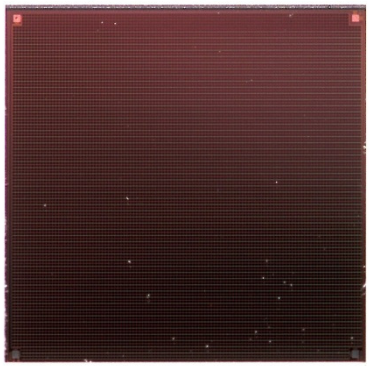


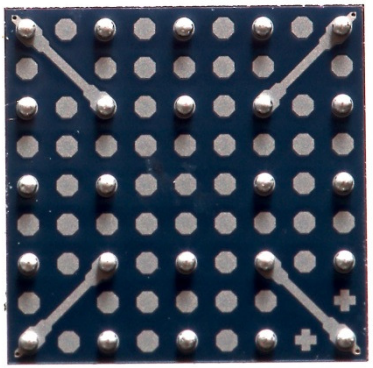
Bottom View

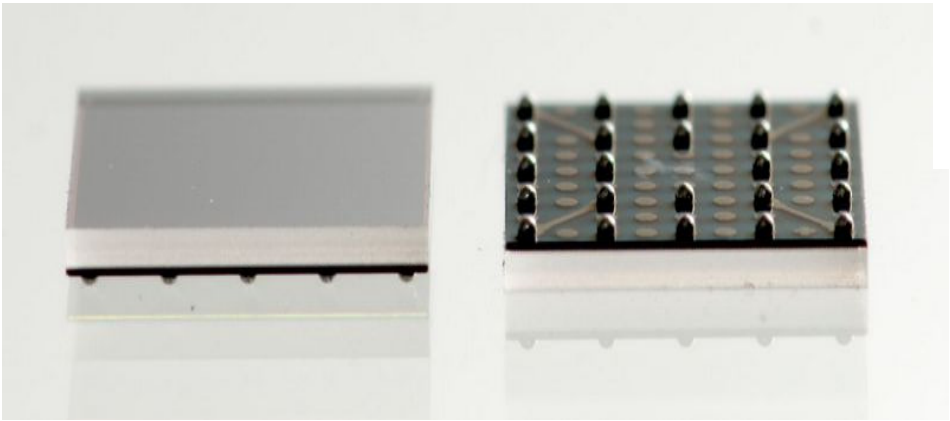
TSV Package Development Status @ SensL

- Devices Currently in lab (B Series Process)
  - 1mm
  - 3mm
  - 6mm
- Demonstrates package concept and reduces risk to TBN-2 Series significantly



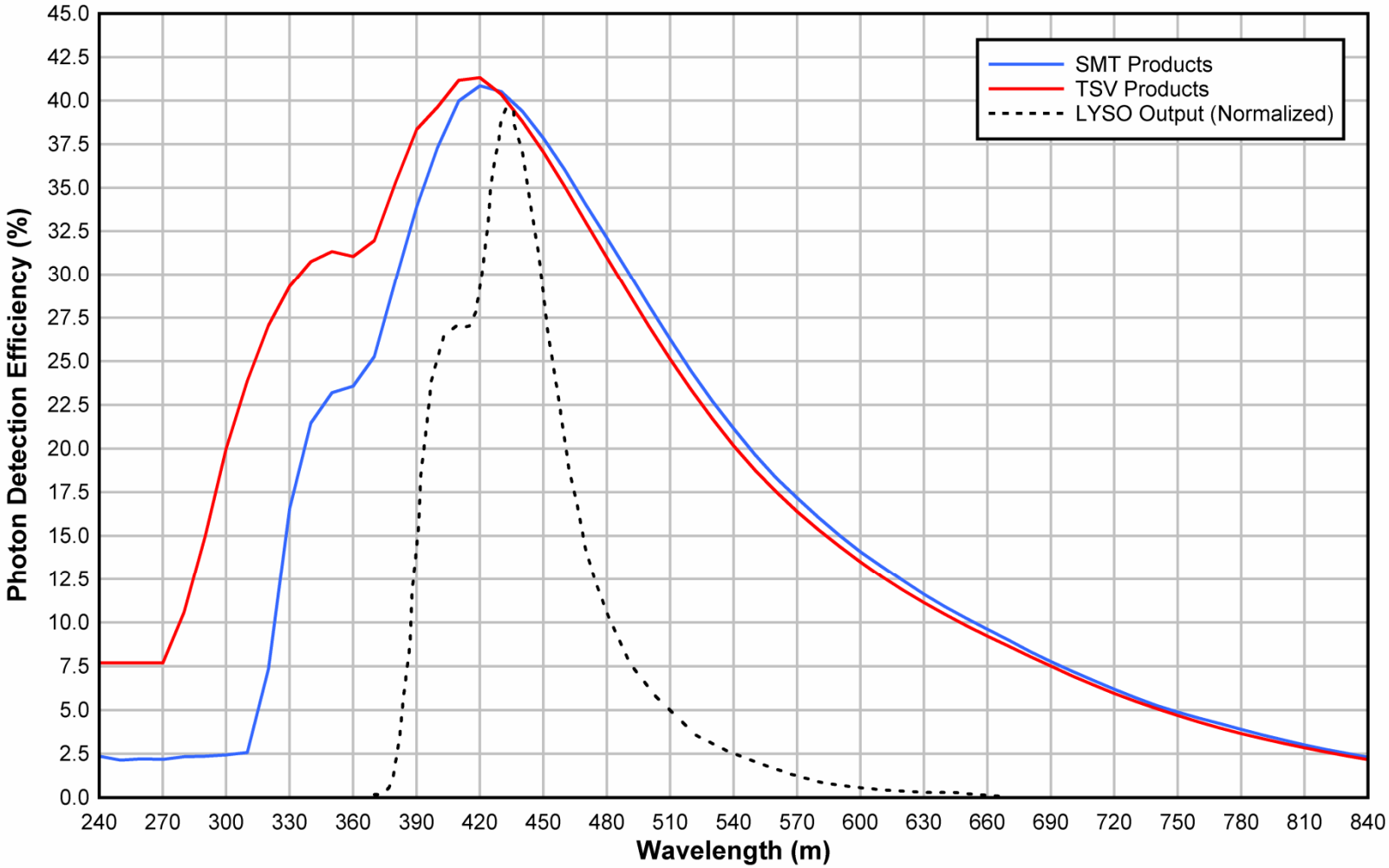






SensL TSV Devices

TSV B-Series PDE (35um Microcell)



NOTE – TBN-2 silicon targets PDE > 45%

Спасибо!