CPAD Workshop – Plenary: Early Career Talks

Thin-film Charged Particle Detectors

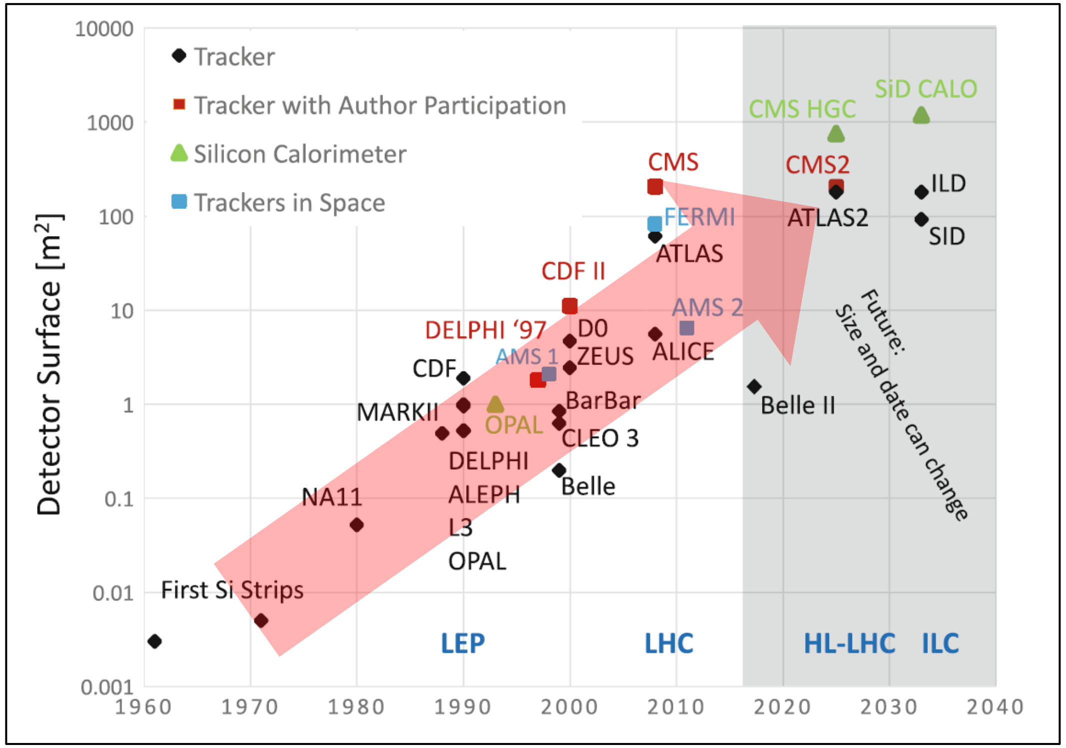
Sungjoon Kim

Department of Chemical Engineering
University of Illinois at Chicago, IL

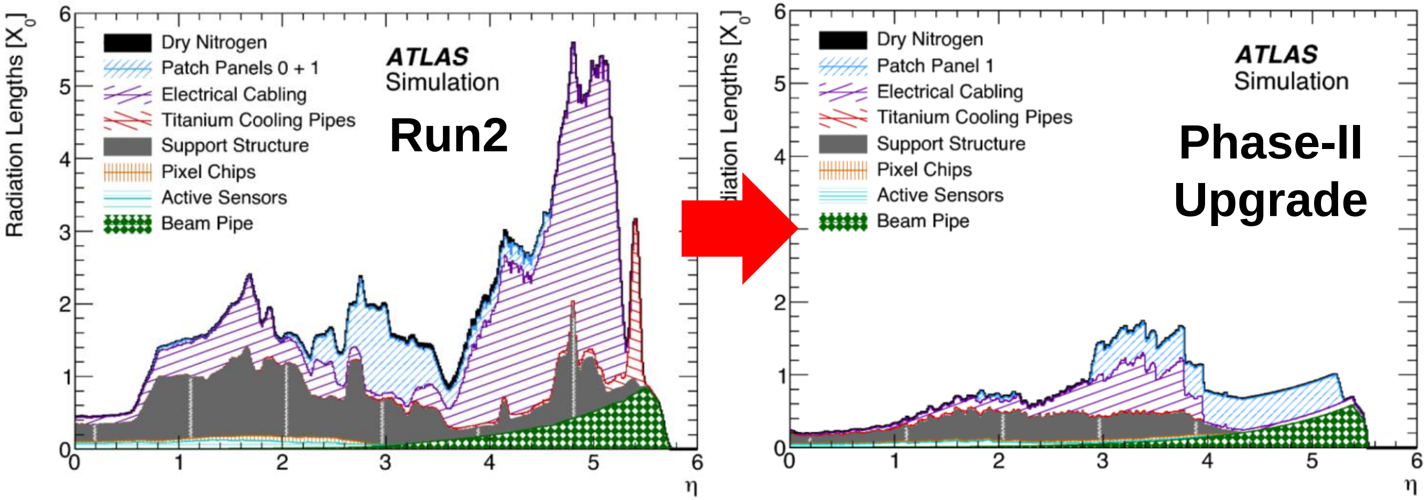
Anthony Affolder, Earl Russell Almazan, Vitaliy Fadeyev, Mike Hance, Manoj Jadhav, Jessica Metcalfe, Jason Nielsen, Jennifer Ott, Anirudha Sumant

Argonne NATIONAL LABORATORY
CHEMICAL ENGINEERING COLLEGE OF ENGINEERING
UIC
UNIVERSITY OF CALIFORNIA SANTA CRUZ

Particle Detection & Tracking – Silicon Detectors



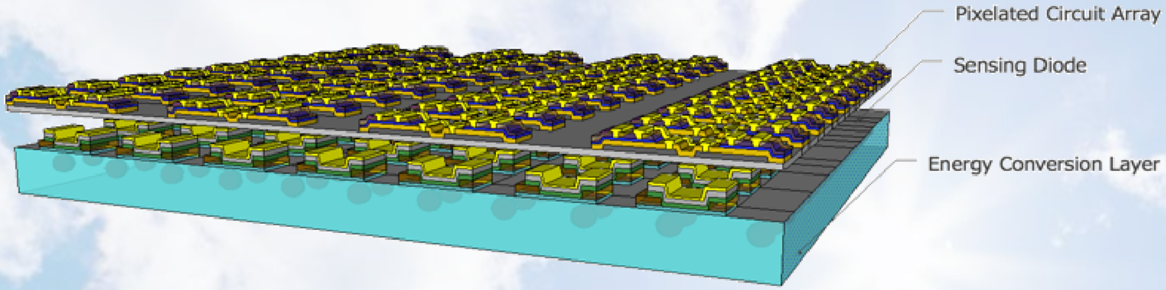
- ***Silicon detectors***
  - Covers **> 100 m²**
  - **Tracking** detector
  - Replace **sub-detectors** (calorimeters) due to superior performance
  - 1 m² in 2000, over **100 m² in 2010**

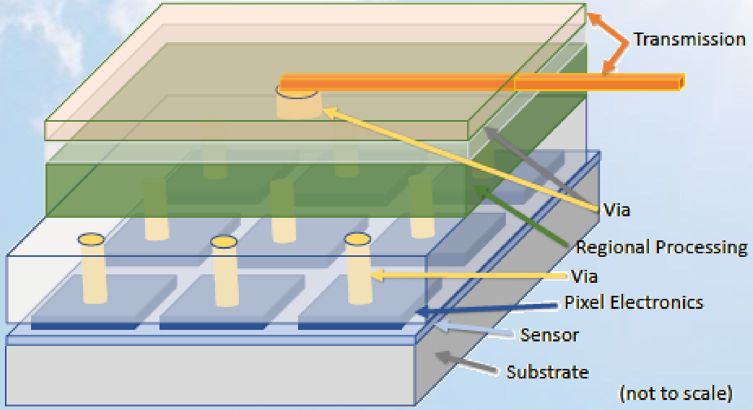


- ***Challenges & Limitations***
  - **Achieve low-mass**
  - **Cost** (material + labor)
  - **Long lead times**
  - Require large amounts of **supports & services**

Evolution of silicon sensor technology in particle physics
– Frank Hartmann, Springer
Atlas technical design report, 10.17181/CERN.FOZZ.ZP3Q

Thin Film Particle Detectors – Blue Sky R&D





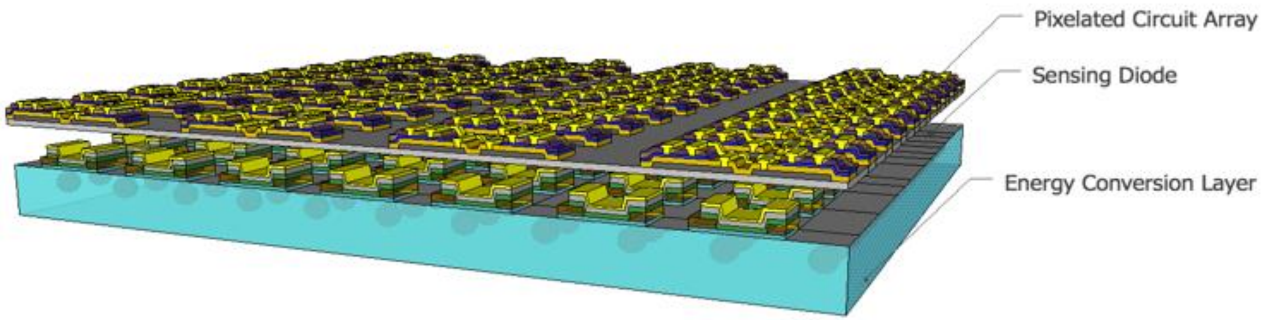
Advances in ***Device Technology*** & ***Materials Science***

Detectors with …

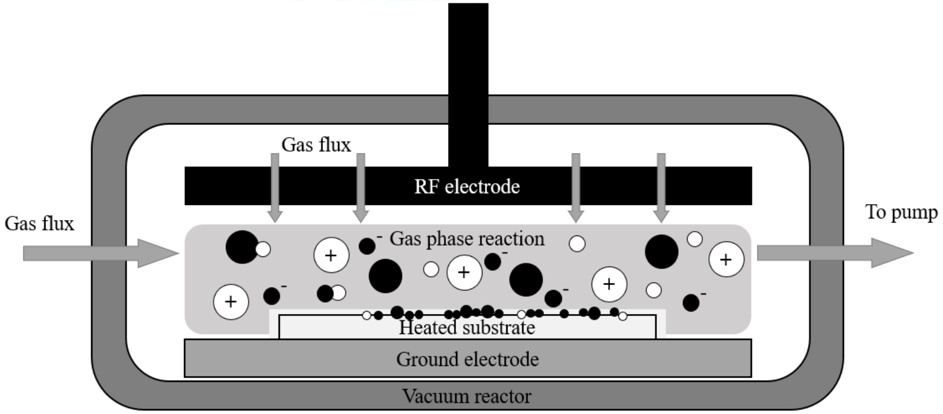
- ***Low mass***
- ***High energy resolution***
- ***Fast response***
- ***Room temperature operation***
- ***Compatible w/ Scalable processes***

Thin film charged particle detectors:
a ***promising candidate*** to push the
boundary of physics discovery

Thin Film Deposition Techniques



PECVD:
an example of **CVD**

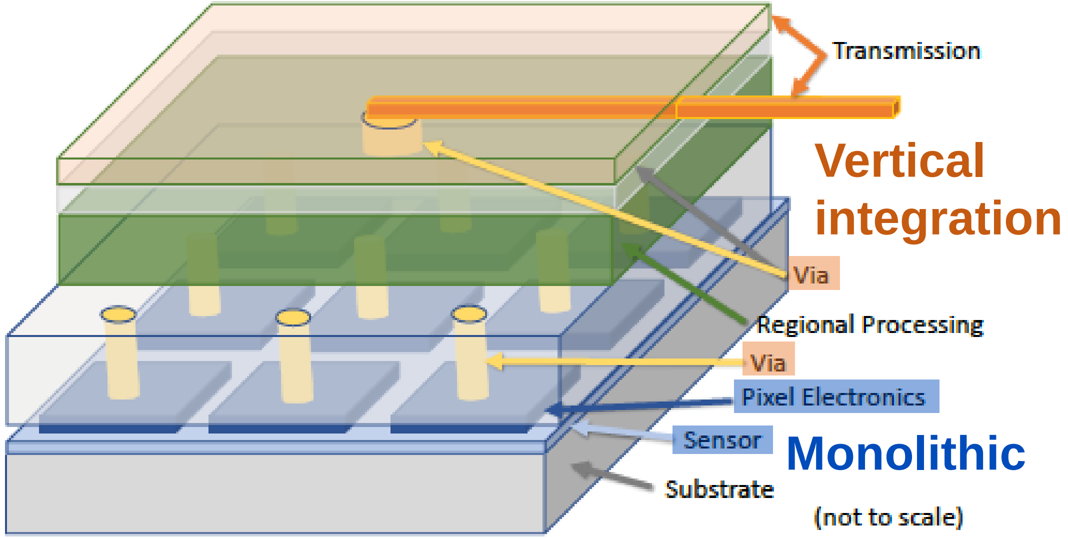


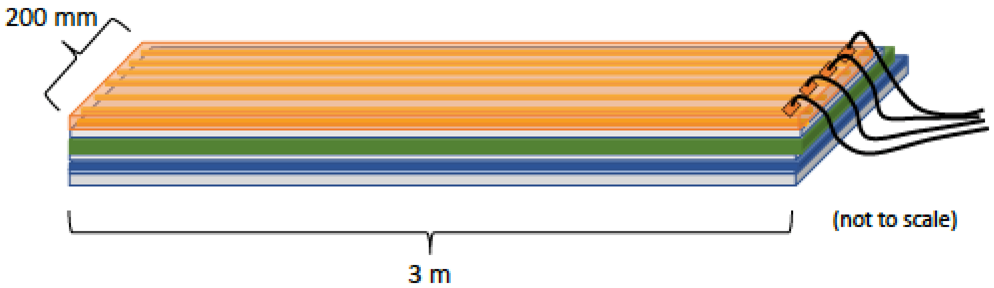
Large scale “roll-to-roll”
deposition/fabrication

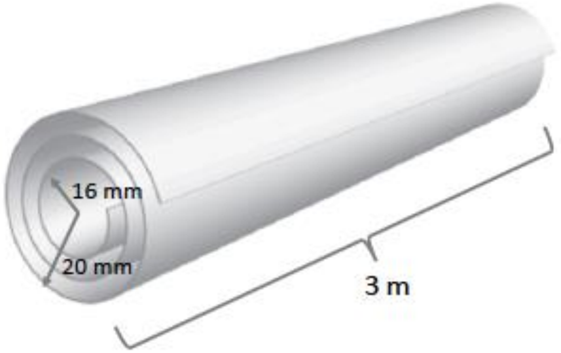
- **Thin layers (nm to μm)** of semiconductor / metal / insulator deposited on choice substrate
- **Wide range of techniques available** depending on needs
  - **CVD**
  - **PECVD**
  - **ALD**
  - **MBE**
  - **PVD**
  - **CBD**
- **Scalable** and **robust** process
  - **Large area** deposition possible
  - Compatible with **flexible substrates**

https://arxiv.org/abs/1411.1794

Thin Film Detectors – Benefits for Design and Production







- **Services** is a large part of the dead material
  - **Vertical integration**
  - **Monolithic designs**

- **Printing**
  - **Large area** deposition
  - Drastic reduction in **time & cost**
  - **Novel geometries** possible
  - Roll-to-roll production
  - **Easy to replace / repair**

https://arxiv.org/abs/1411.1794

Thin Film Detector Materials

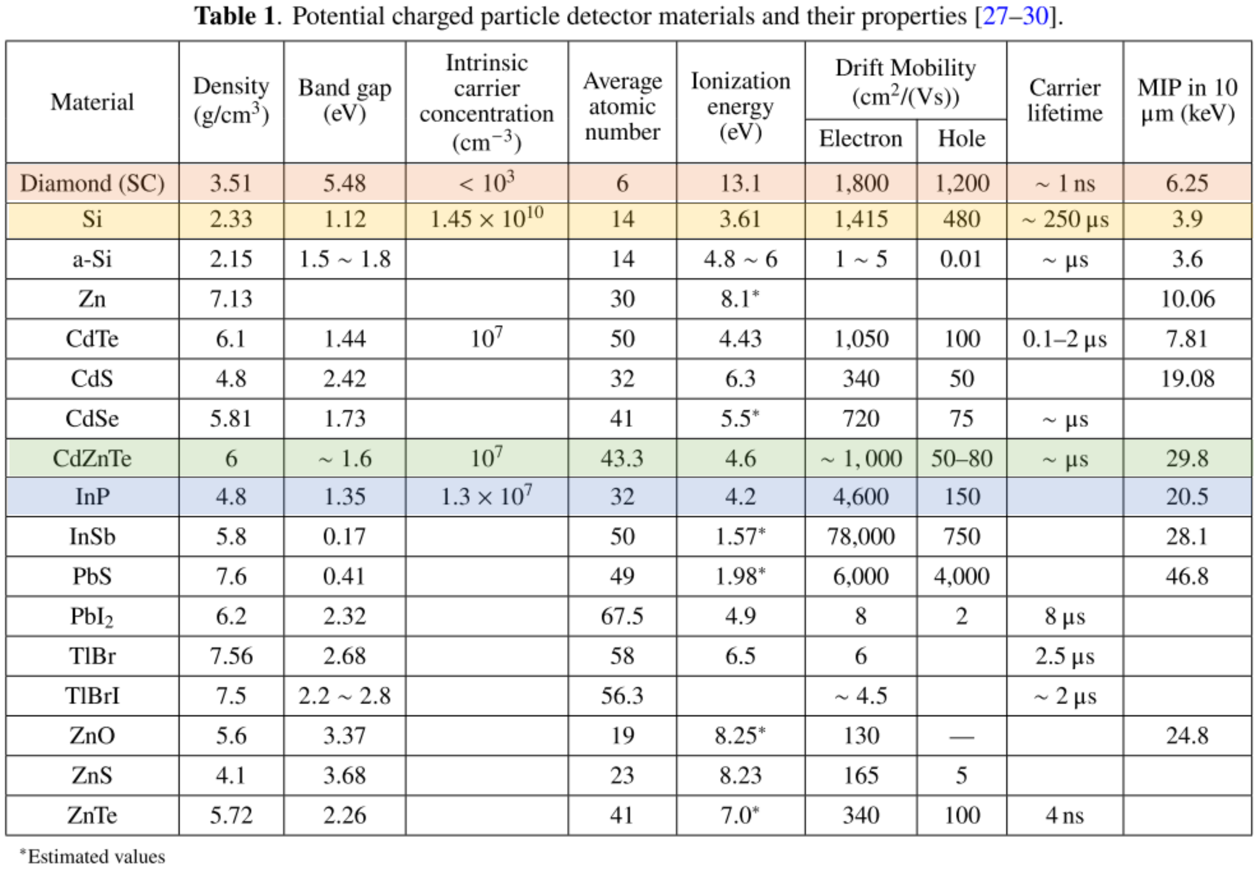


Table 1. Potential charged particle detector materials and their properties [27–30].

Material	Density (g/cm^3)	Band gap (eV)	Intrinsic carrier concentration (cm^{-3})	Average atomic number	Ionization energy (eV)	Drift Mobility ($cm^2/(Vs)$)		Carrier lifetime	MIP in 10 μm (keV)
						Electron	Hole		
Diamond (SC)	3.51	5.48	$< 10^3$	6	13.1	1,800	1,200	~ 1 ns	6.25
Si	2.33	1.12	1.45×10^{10}	14	3.61	1,415	480	~ 250 μs	3.9
a-Si	2.15	1.5 ~ 1.8		14	4.8 ~ 6	1 ~ 5	0.01	~ μs	3.6
Zn	7.13			30	8.1*				10.06
CdTe	6.1	1.44	10^7	50	4.43	1,050	100	0.1–2 μs	7.81
CdS	4.8	2.42		32	6.3	340	50		19.08
CdSe	5.81	1.73		41	5.5*	720	75	~ μs	
CdZnTe	6	~ 1.6	10^7	43.3	4.6	~ 1,000	50–80	~ μs	29.8
InP	4.8	1.35	1.3×10^7	32	4.2	4,600	150		20.5
InSb	5.8	0.17		50	1.57*	78,000	750		28.1
PbS	7.6	0.41		49	1.98*	6,000	4,000		46.8
PbI_2	6.2	2.32		67.5	4.9	8	2	8 μs	
TlBr	7.56	2.68		58	6.5	6		2.5 μs	
TlBrI	7.5	2.2 ~ 2.8		56.3		~ 4.5		~ 2 μs	
ZnO	5.6	3.37		19	8.25*	130	—		24.8
ZnS	4.1	3.68		23	8.23	165	5		
ZnTe	5.72	2.26		41	7.0*	340	100	4 ns	

*Estimated values

- **Large library** of promising / interesting materials
  - **Extreme radiation hardness**
  - **High atomic number (Z)**
  - **Charge carrier mobility**
  - Large bandgap
- For candidacy, must consider …
  - Theoretical material properties
    - Expected performance
  - **Actual material properties**
    - **Existence of deposition techniques**
    - **Process compatibility**
  - **Optimized material** based on the **physics application**
  - Price

Kim, S., Berry, V., Metcalfe, J. & Sumant, A. V. Thin film charged particle detectors. *Journal of Instrumentation* **18**, (2023)

The Challenges & Risks

Material-level understanding *to* ***design and optimize***
a given detector design for a ***specific application***

- ***Sensor performance***
    - Match silicon sensor performance
    - Tracking efficiency
    - Timing resolution
    - Energy resolution
    - Occupancy
    - Radiation damage
- ***Transistor designs***
    - Transistor performance
        - Low power
        - Fast switching
    - Compatible fabrication processes
    - Transistor footprint

- ***Vertical integration***
    - How to reliably stack layers
    - Alignment

- ***Transmission signal integrity***
    - Regional relays (if needed)

Numerous unknowns & High-risk
Until full potential is realized

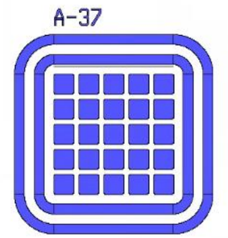
→ **Suitable** as a
Long-term blue-sky R&D

Project History & Timeline

COVID – Focused on Fundamentals & review of detector landscape

First device fabrication started in June 2021

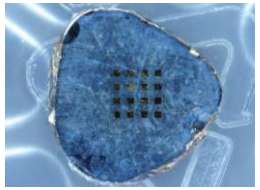
New CVD system Delivered & **Second device fabricated in summer 2022**



2020 | **2021** | **2022** | **2023** | **2024**

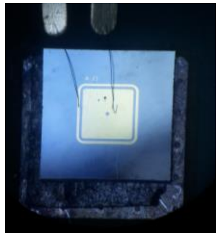
Argonne NATIONAL LABORATORY

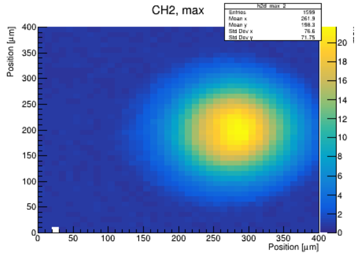
Project started on February 2020



Collaboration with UCSC started in April 2022

Testing second devices





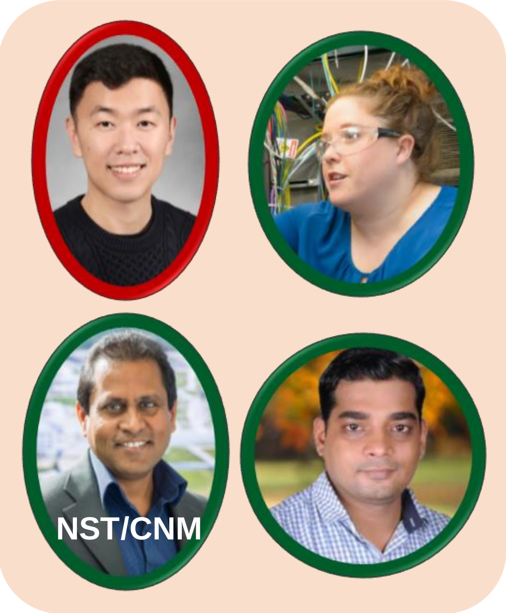
Coming soon:
Additional publications
+
Thin film detector V.2
with **in-house deposited thin films**

Affiliation

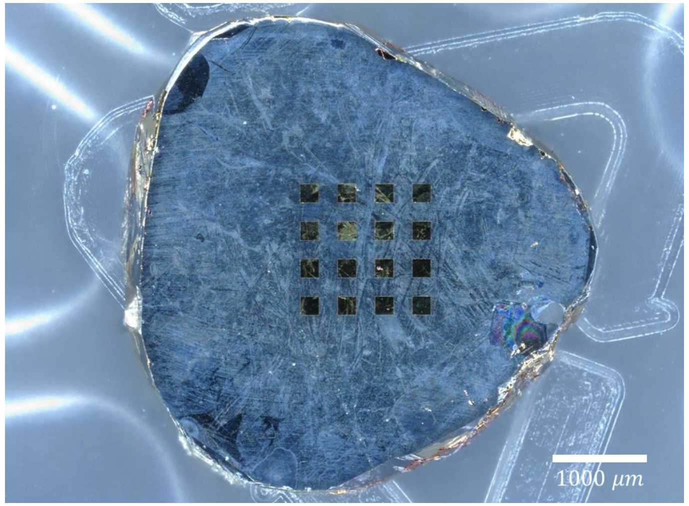
UIC

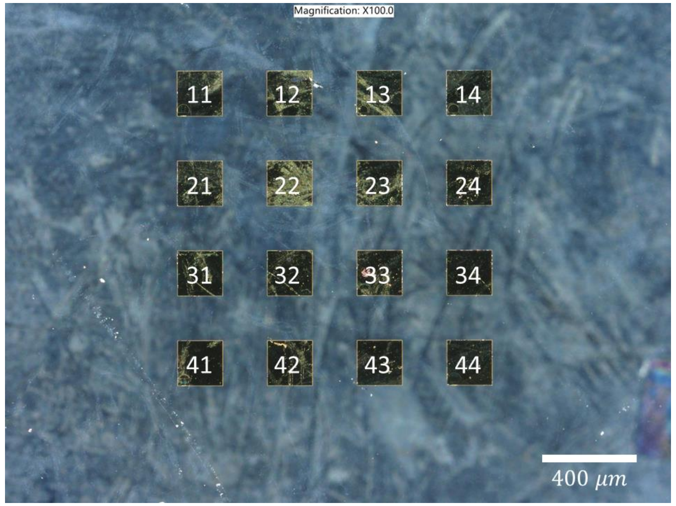
ANL

UCSC



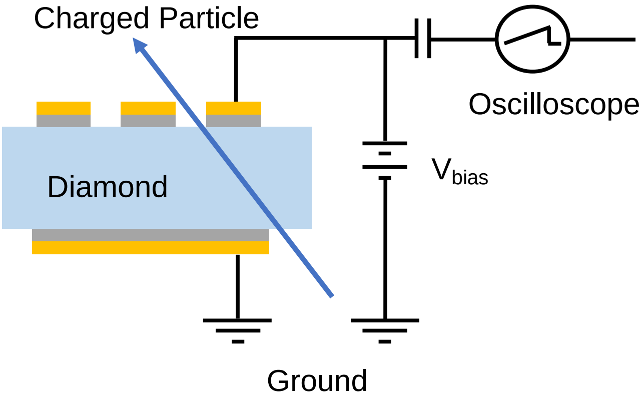
Pilot Study – Detector Fabrication

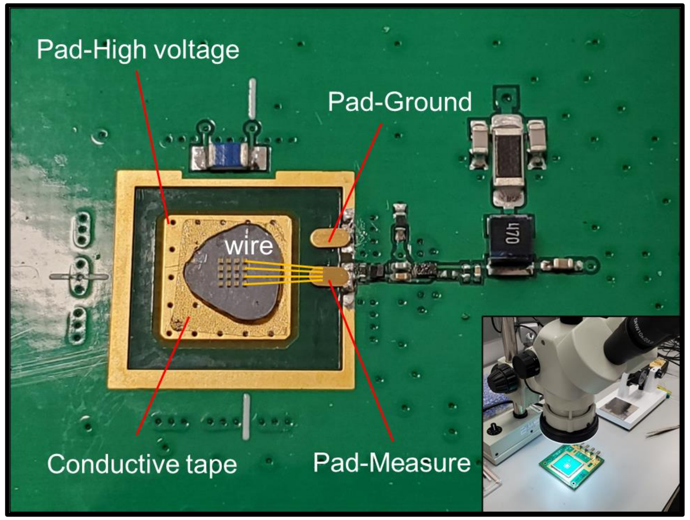




Began with diamond (June 2021) :

- Inventory
- Simple **MIM structure**
- Refine **lithography techniques**
- Measurements on probe station
- Mount on PCBs Wire bond
- Testing

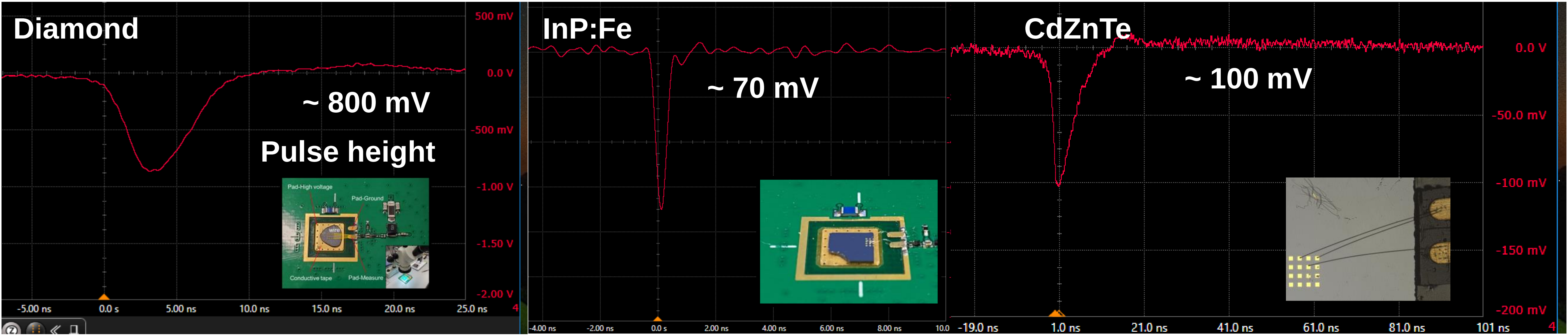




Added InP:Fe & CdZnTe:

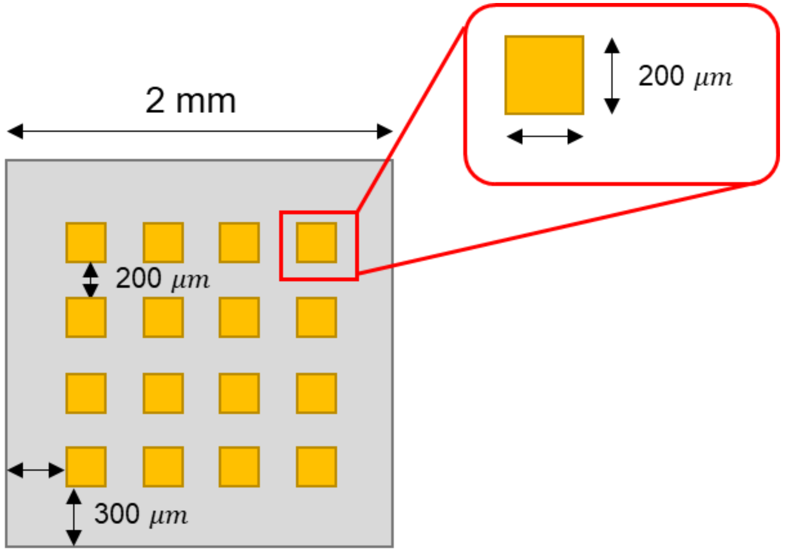
- Promising mat. properties
- Start from **crystalline wafer**
- Lithography, etc. processing at **CNM**
- Practice measurements
- Use in **120 GeV test beam (FNAL)**

Pilot Study – Initial Oscilloscope Measurements

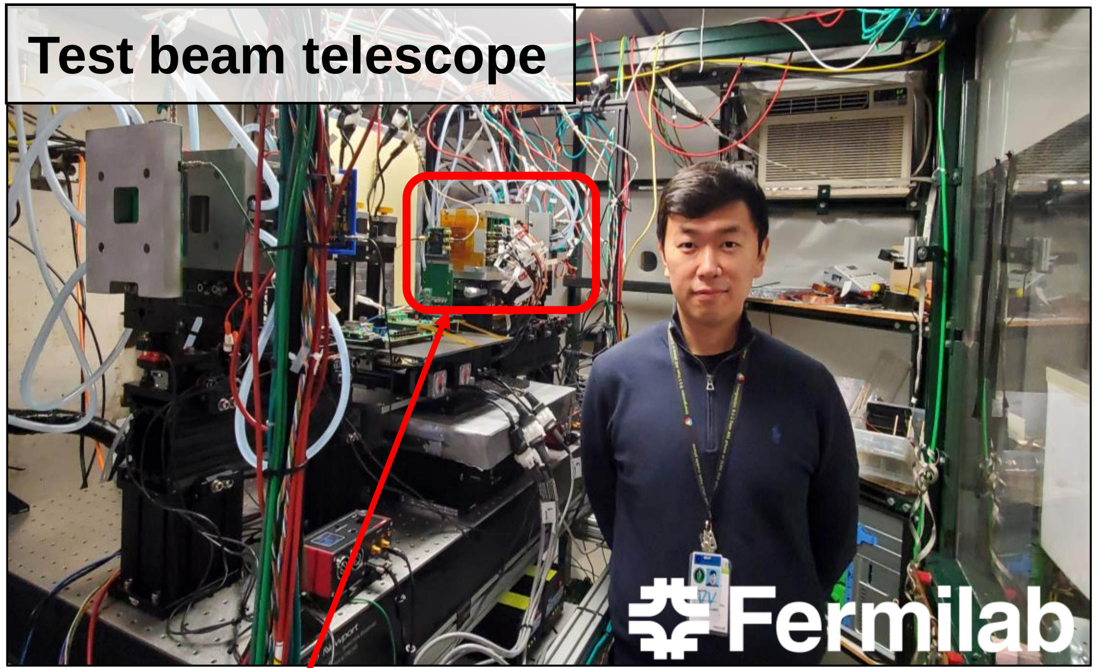


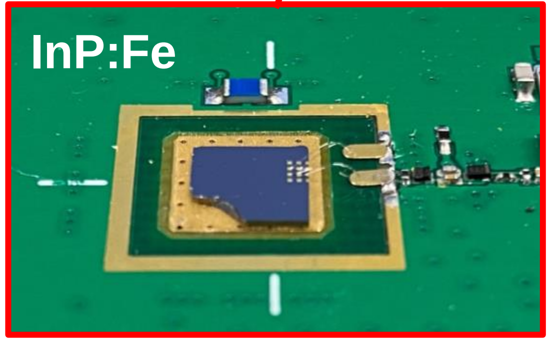
- ❖ All devices **successfully detect** and **generate electric pulses** when exposed to radiation source
- ❖ Measured on probe station

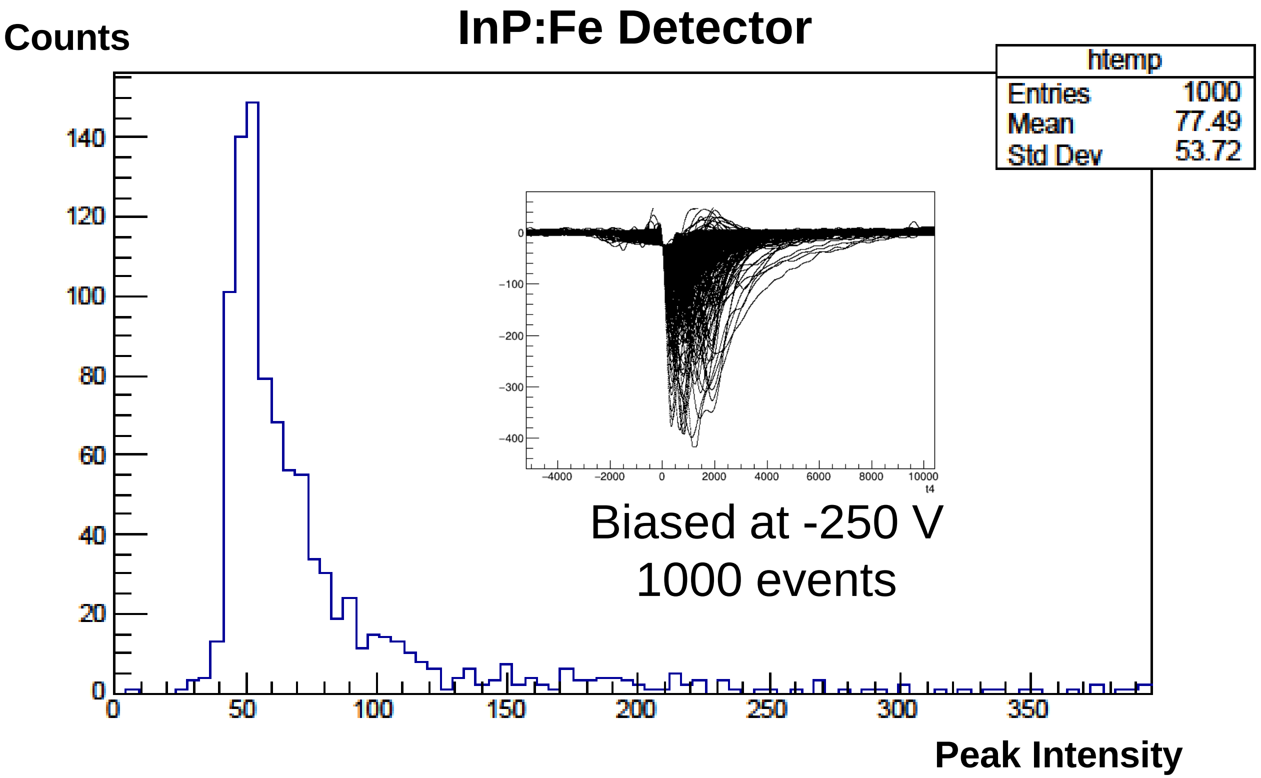
- Radiation type: **Electron** (Beta decay, Sr-90)
- Particle energy: 546 keV
- Pad size: (200 × 200 μm)



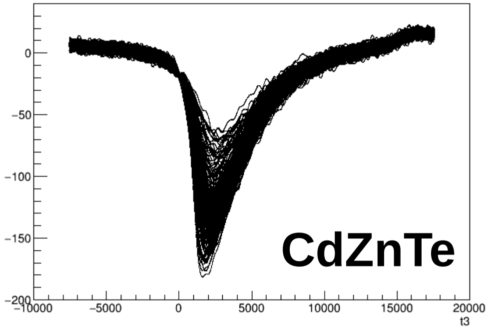
Pilot Study – 120 GeV Proton Beam at FNAL





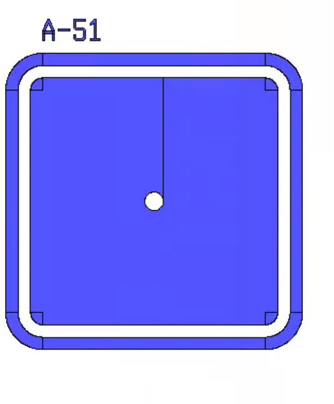


- Exposed to **120 GeV Proton Beam**
- **Particle detection & Signal generation successful**
- Room for improvement in device layout, guard rings, etc.

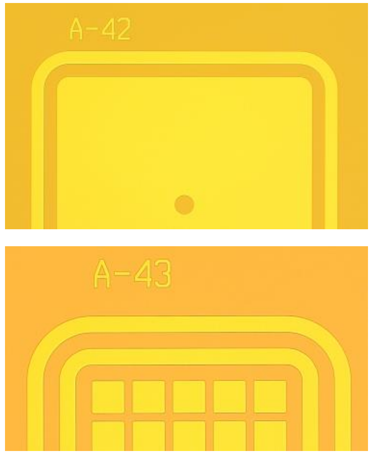


Follow-up Study – Improved Device Design + Additional Analysis

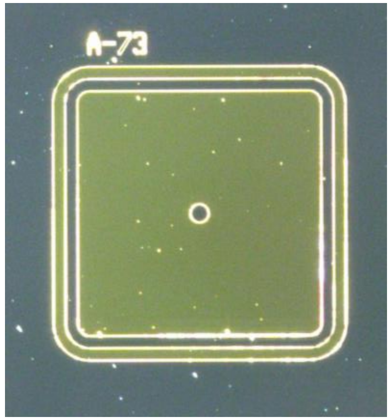
Computer design



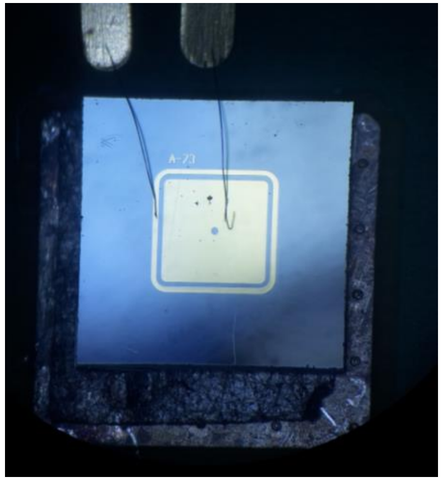
Photolithography

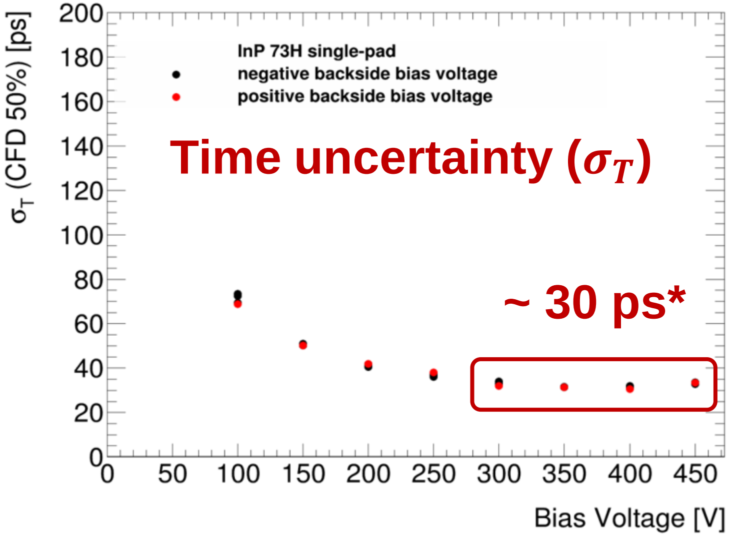


Fabricated device



Optical image and data from UCSC team





Time uncertainty (σ_T)

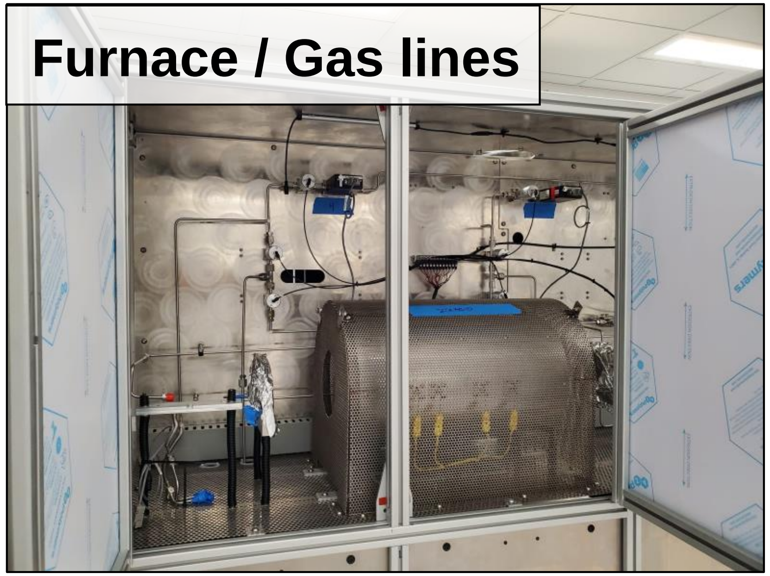
~ 30 ps*

- **New device pad designs**
  - Guard rings
  - Rounded corners
  - More pixels
  - Optical opening for measurements
  - Crystalline InP
- **Collaboration with UCSC**
  - Laser response
  - Betascope
  - X-ray beam tests

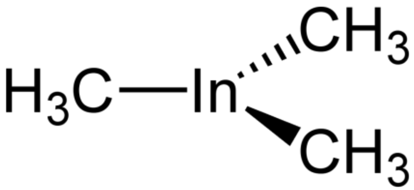
Studies of InP as a sensor material for tracking system based on thin film technology, Nov 7, 2023, 4:40 PM, by ***Earl Russell Almazan***

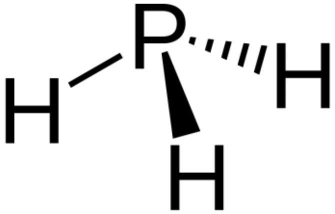
***Unoptimized device architechture**

Organo-Metallic Chemical Vapor Deposition System



- **Crystalline ⇒ polycrystalline/amorphous thin films**
- **The CVD system**
  - For **in-house thin film synthesis**
  - Designed for **future expansion** (additional thin film materials)
  - Working on **documentation & safety**



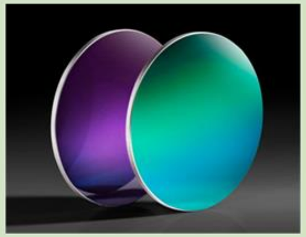


Chemical precursors for InP CVD

Located at Argonne Micro Assembly Facility

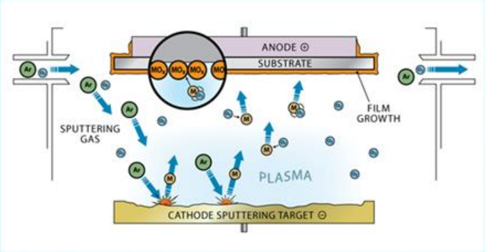
Summary & Our Vision

Completed



Single Crystal Substrates

Chemical Deposition



Physical Deposition

Ultimate Goal

Roll-to-roll Technology

Pilot Study

- **Screen/test candidate crystalline materials**
- **Test and analyze detector performance (source/test beam)**

Phase-II

- **In-house thin film InP**
- **Optimize deposition process**
- **Fabricate detectors, repeat testing and analysis**

The Vision & Goal

- **Quick & easy** to manufacture
- **Inexpensive**
- **Easy assembly** into large-scale detector
- Similar ‘sensor’ performance to **Silicon technologies**

R&D Direction

- ***Different materials***
- ***Monolithic detector design***
- ***Large-area production***

⇒ ***US groups are in a position** to **lead the solid-state detector R&D efforts***

https://www.mks.com/n/cvd-physics

Acknowledgements & References

Thank you for your attention!

Interested?
We are looking for collaborators!
golite31@gmail.com & jmetcalfe@anl.gov

- **Acknowledgements**

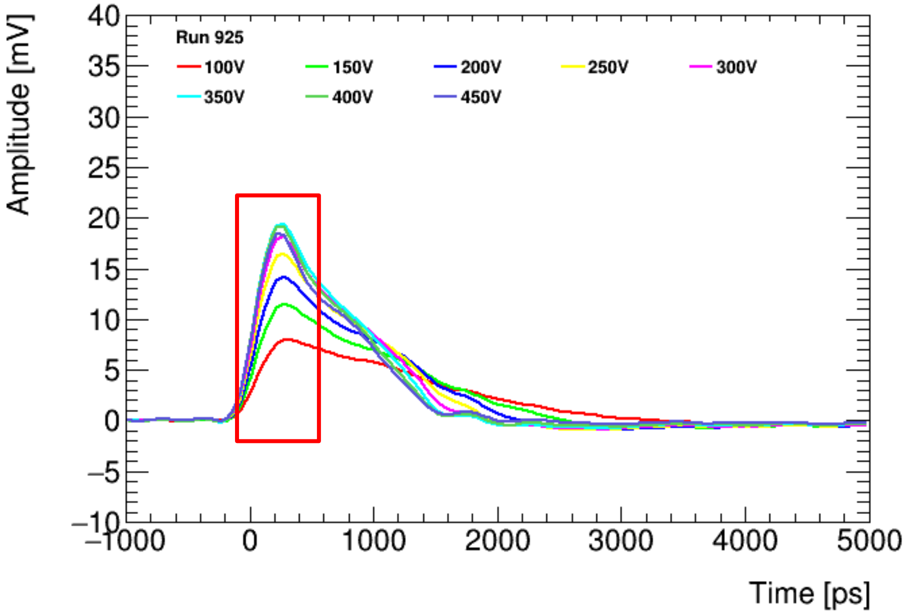
  - This project was funded by **Argonne National Laboratory**
  - Work performed at the **Center for Nanoscale Materials**, U.S. Department of Energy Office of Science User Facilities, was supported by the U.S. DOE, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
  - This document is prepared using the resources of the **Fermi National Accelerator Laboratory** (Fermilab), a U.S. Department of Energy, Office of Science, Fermi Lab Test Beam Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DEAC02-07CH11359.
  - Detector laser response results were provided by the **University of California Santa Cruz** and the **Santa Cruz Institute for Particle Physics**

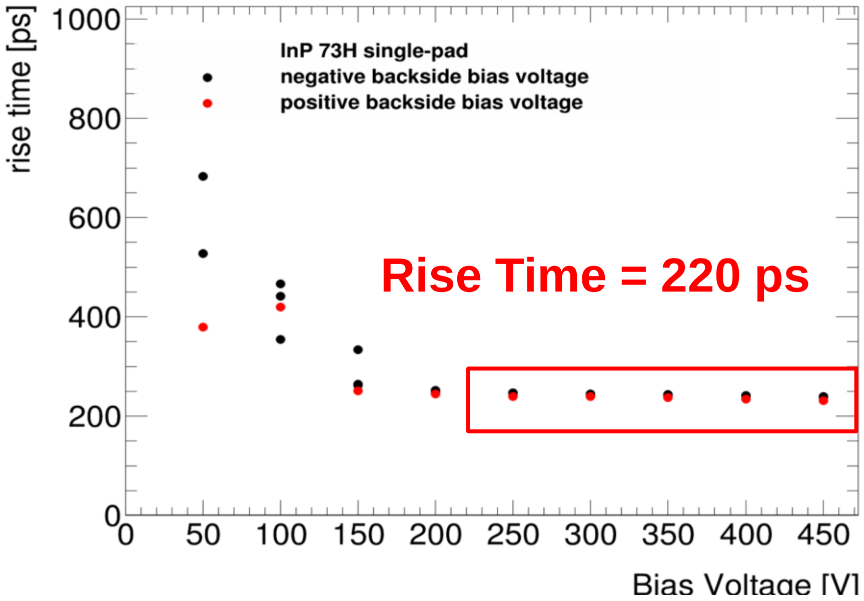
- **References**

  - **Kim, S.**, Berry, V., Metcalfe, J. & Sumant, A. V. Thin film charged particle detectors. *Journal of Instrumentation* **18**, (2023) [LINK]
  - Evolution of silicon sensor technology in particle physics – Frank Hartmann, Springer
  - Atlas technical design report, 10.17181/CERN.FOZZ.ZP3Q
  - https://arxiv.org/abs/1411.1794
  - https://www.mks.com/n/cvd-physics

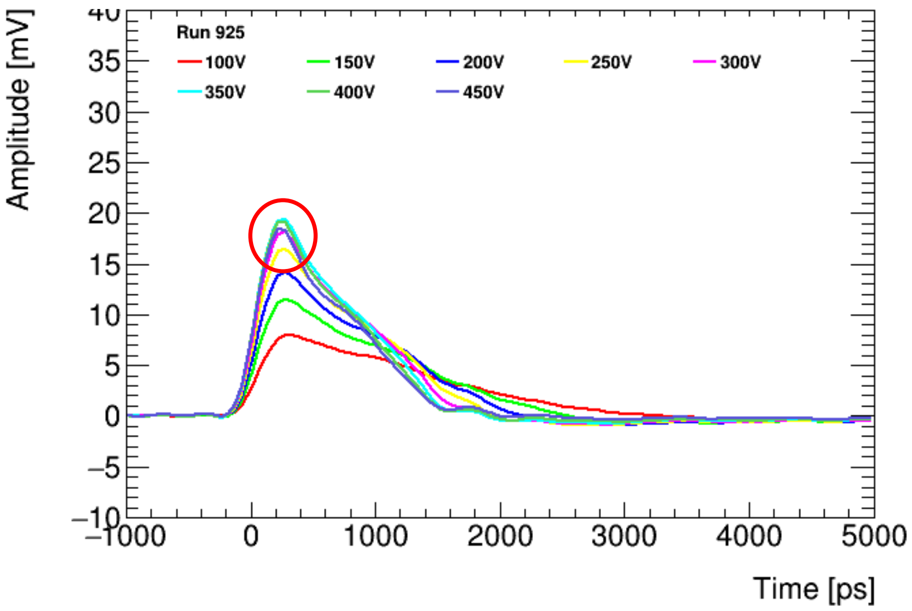
Supplementary - Detector Rise Time & Pulse Amplitude

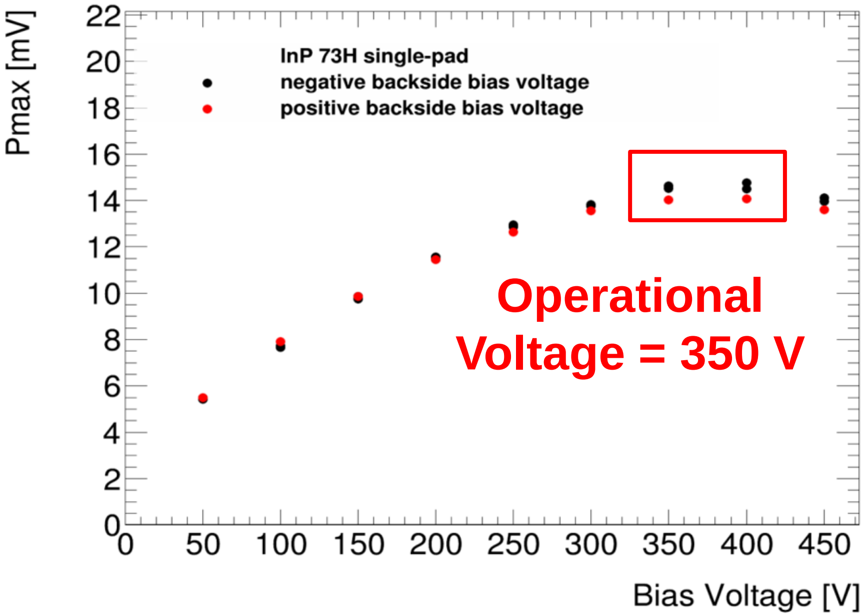
Reproduced from "SLAC-CPAD Workshop 2023, Studies of InP as a sensor material for tracking system based on thin film technology, by ***Earl Russell Almazan"***





Rise Time = 220 ps

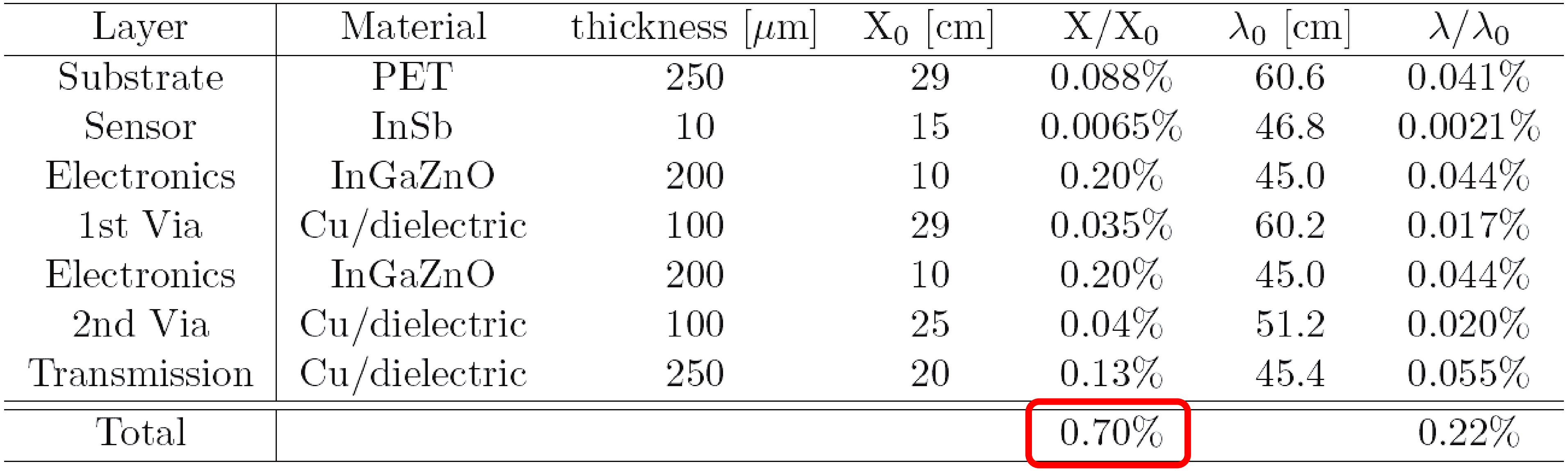




Operational Voltage = 350 V

Supplementary - Overall Radiation Length Estimation

Table 1: The stack-up for a single detector layer made using thin film techniques.



Layer	Material	thickness [μm]	X_0 [cm]	X/X_0	λ_0 [cm]	λ/λ_0
Substrate	PET	250	29	0.088%	60.6	0.041%
Sensor	InSb	10	15	0.0065%	46.8	0.0021%
Electronics	InGaZnO	200	10	0.20%	45.0	0.044%
1st Via	Cu/dielectric	100	29	0.035%	60.2	0.017%
Electronics	InGaZnO	200	10	0.20%	45.0	0.044%
2nd Via	Cu/dielectric	100	25	0.04%	51.2	0.020%
Transmission	Cu/dielectric	250	20	0.13%	45.4	0.055%
Total				0.70%		0.22%

A rough estimation of the radiation length, X_0, and the nuclear interaction length, λ_0, is based on the individual elements in each layer. A pixel size of 50 µm x 50 µm is assumed for this exercise although it would need to be optimized based on pixel capacitance (noise) and a final layout choice. The first via layer assumes a via column of 10 µm per pixel array of approximately 1,000 pixels. The second via layer assumes a 10 µm via column per 100 pixel arrays. The transmission layer assumes one 30 AWG line (power) and one 34 AWG (data) line (comparable to ITk Pixel wire gauges) per pixel array with an average length of half of the full length of a 1 m long sheet for a total of 40 lines. Clock, command and other transmission lines are ignored in the calculation and will have a negligible impact. Radiation length and nuclear interaction length of polyimide film is used for the dielectric materials.

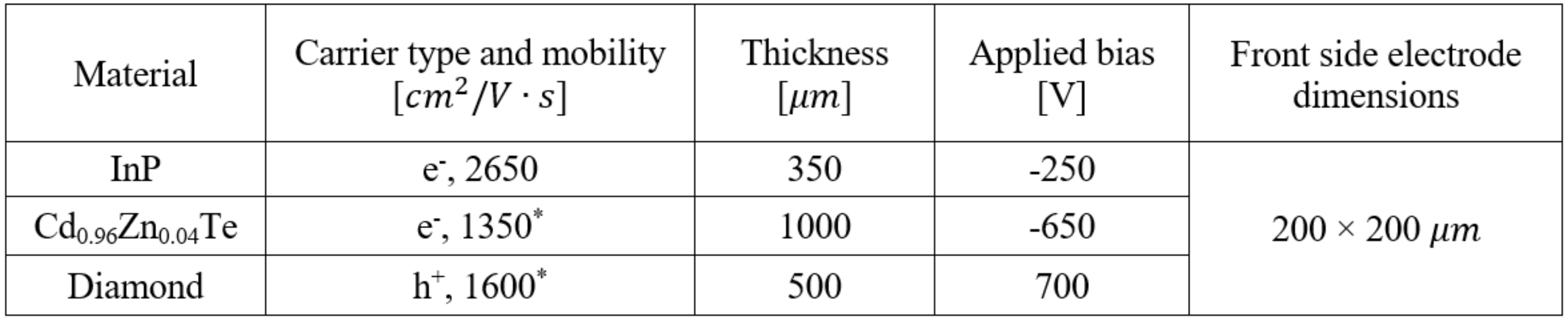
Supplementary - Device Structure & Material Properties

Au/Cr (100/10 nm)
InP:Fe (350 µm)
Au/Cr (100/10 nm)

	InP	Silicon
e$^-$ Mobility (cm^2/Vs)	4600*	1400
N$_{e\text{-}h}$ pairs in 10 µm from MIP	4.8k	1.1k
Bulk Resistivity (Ω cm)	10^7	10^4

- **Simple capacitor structure**
  - No implantation/transition layers
- Thick sensing layer: can be made **thinner** for **better performance**
  - Lower operating bias
  - Faster rise time

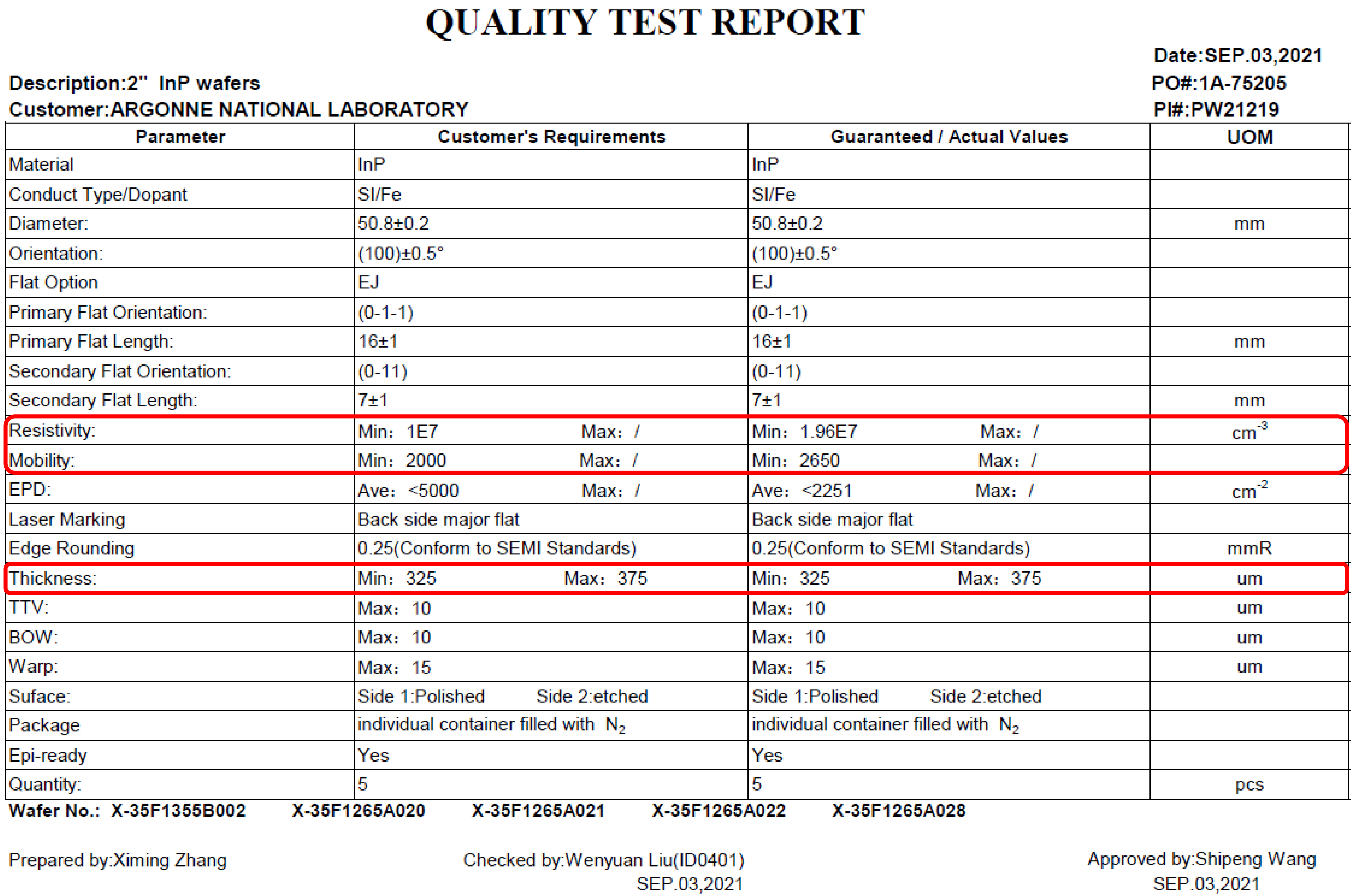
Table 1. *Material properties of fabricated detectors*



Material	Carrier type and mobility $[cm^2/V\cdot s]$	Thickness $[\mu m]$	Applied bias [V]	Front side electrode dimensions
InP	e$^-$, 2650	350	-250	$200 \times 200\ \mu m$
$Cd_{0.96}Zn_{0.04}Te$	e$^-$, 1350*	1000	-650	
Diamond	h$^+$, 1600*	500	700	

*Literature values

Supplementary - Material Report



QUALITY TEST REPORT

Date:SEP.03,2021

Description:2" InP wafers **PO#:1A-75205**

Customer:ARGONNE NATIONAL LABORATORY **PI#:PW21219**

Parameter	Customer's Requirements	Guaranteed / Actual Values	UOM
Material	InP	InP	
Conduct Type/Dopant	SI/Fe	SI/Fe	
Diameter:	50.8±0.2	50.8±0.2	mm
Orientation:	(100)±0.5°	(100)±0.5°	
Flat Option	EJ	EJ	
Primary Flat Orientation:	(0-1-1)	(0-1-1)	
Primary Flat Length:	16±1	16±1	mm
Secondary Flat Orientation:	(0-11)	(0-11)	
Secondary Flat Length:	7±1	7±1	mm
Resistivity:	Min: 1E7 Max: /	Min: 1.96E7 Max: /	cm^{-3}
Mobility:	Min: 2000 Max: /	Min: 2650 Max: /	
EPD:	Ave: <5000 Max: /	Ave: <2251 Max: /	cm^{-2}
Laser Marking	Back side major flat	Back side major flat	
Edge Rounding	0.25(Conform to SEMI Standards)	0.25(Conform to SEMI Standards)	mmR
Thickness:	Min: 325 Max: 375	Min: 325 Max: 375	um
TTV:	Max: 10	Max: 10	um
BOW:	Max: 10	Max: 10	um
Warp:	Max: 15	Max: 15	um
Suface:	Side 1:Polished Side 2:etched	Side 1:Polished Side 2:etched	
Package	individual container filled with N_2	individual container filled with N_2	
Epi-ready	Yes	Yes	
Quantity:	5	5	pcs

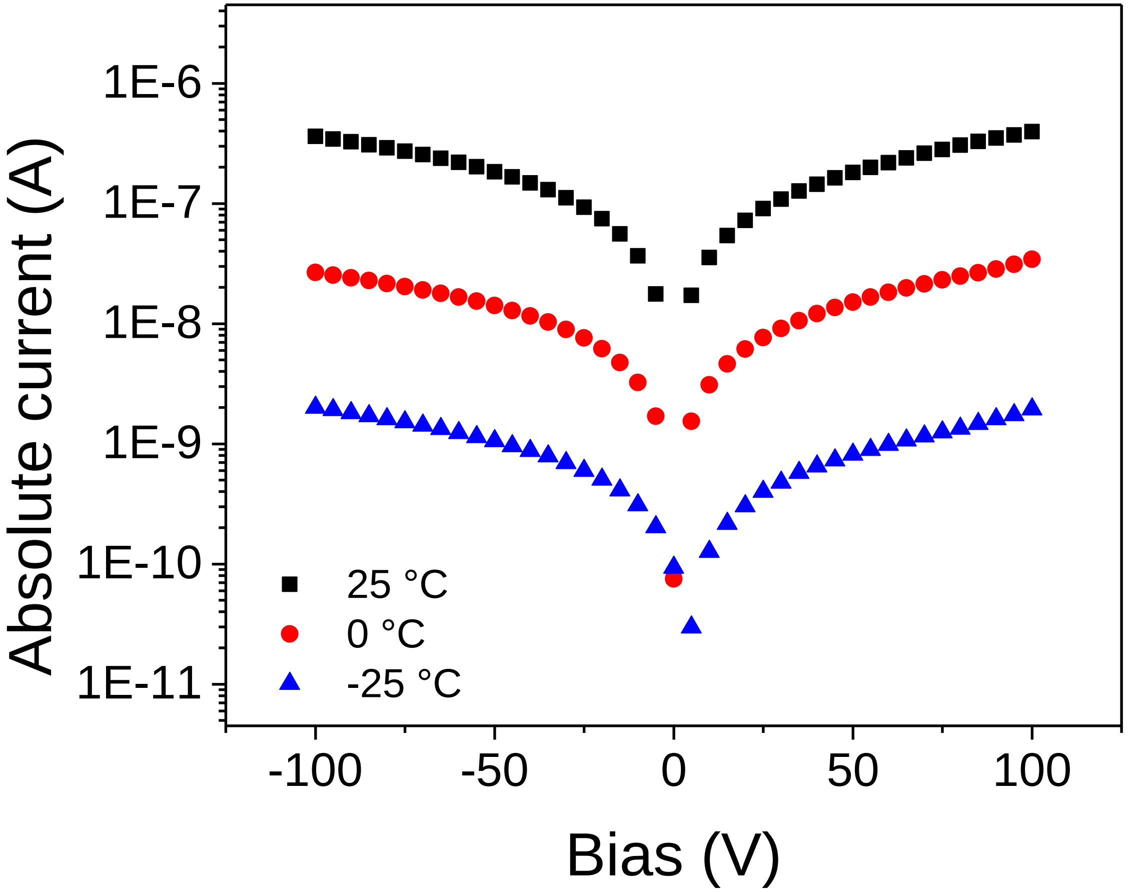
Wafer No.: X-35F1355B002 X-35F1265A020 X-35F1265A021 X-35F1265A022 X-35F1265A028

Prepared by:Ximing Zhang

Checked by:Wenyuan Liu(ID0401)
SEP.03,2021

Approved by:Shipeng Wang
SEP.03,2021

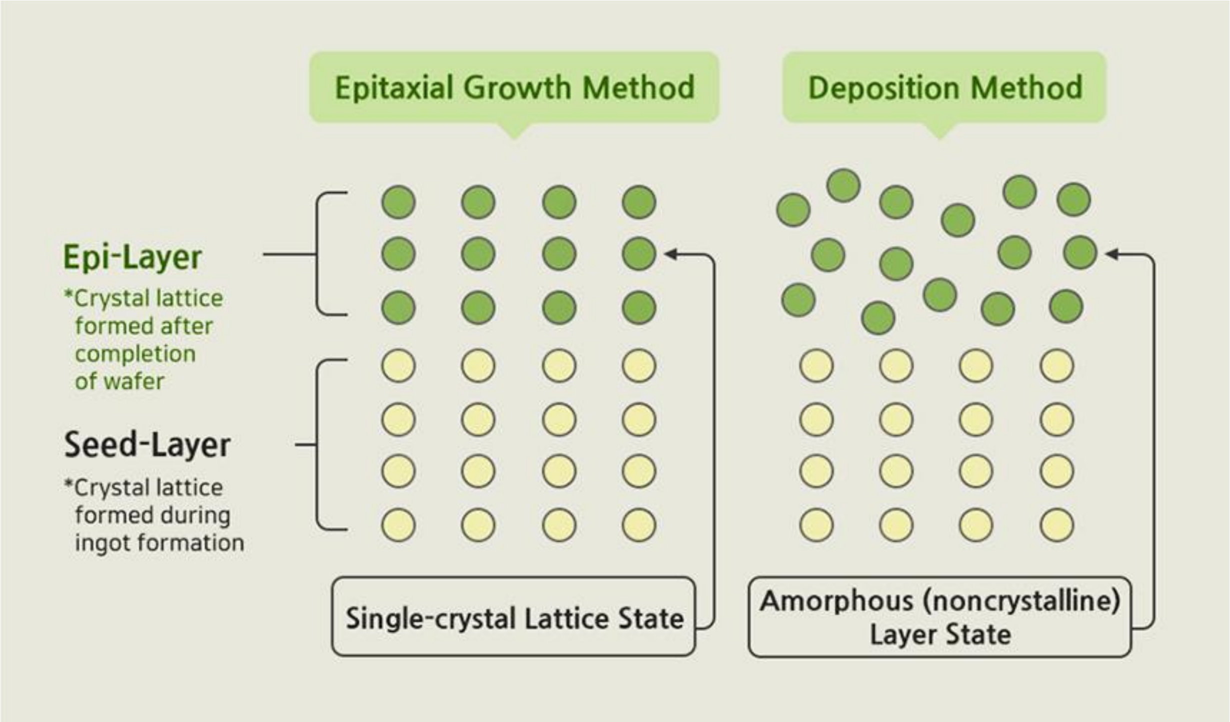
Supplementary – Effects of Cooling on Current – Voltage (I-V) Curves



Temperature	Current at 100 V [A]	Current density at 100 V [A/cm²]
25 °C	3.95×10^{-7}	9.88×10^{-4}
0 °C	3.43×10^{-8}	8.57×10^{-5}
-25 °C	1.94×10^{-9}	4.84×10^{-6}

Supplementary - Thin film synthesis

Focus: ***Epitaxial growth***



Candidate methods

- ***Physical***
  - Molecular beam epitaxy
  - Pulsed laser deposition
- ***Chemical***
  - Low energy plasma enhanced chemical vapor deposition
  - Vapor phase epitaxy

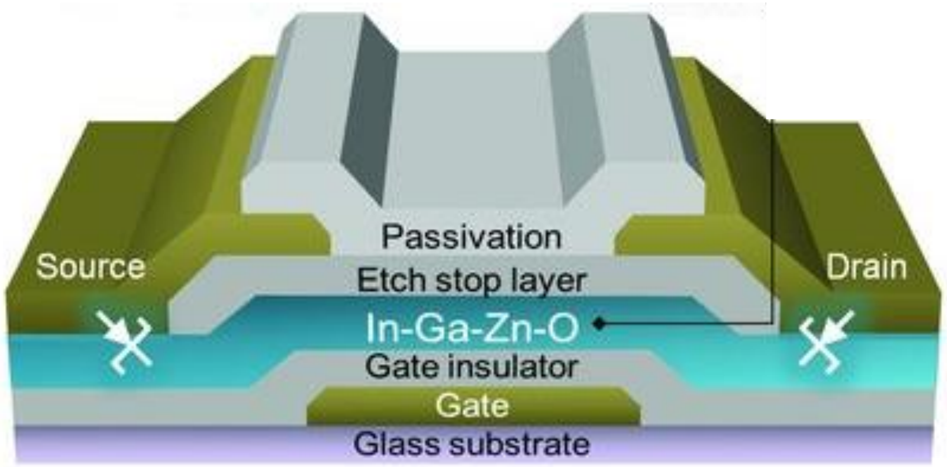
∵ increased crystallinity → higher carrier mobility → ***Better detector performance***

Toward amorphous / polycrystalline thin films

- Focus on **epitaxial growth methods** that provide some crystallinity, but more toward an amorphous thin film
- In 2024: Identify method/material, fabricate new devices this summer, test in lab/test beam, and repeat as time allows

https://news.skhynix.com/stacking-ultra-hyper-pure-layer-over-ultra-pure-wafer-epitaxy-technology/

Supplementary – Low Power Thin Film Detectors



- **Low power electronics** can help
  - **Thin Film Transistors** is a large area of nanoscience development

- Explore options for HEP
  - Example:
    - **High gains** > 400
    - **Low power** < 1 nW
    - Potential integration in thin film detectors

https://arxiv.org/abs/1411.1794

Sungsik Lee, Arokia Nathan, Subthreshold Schottky-barrier thin-film transistors with ultralow power and high intrinsic gain.*Science* **354**,302-304(2016).