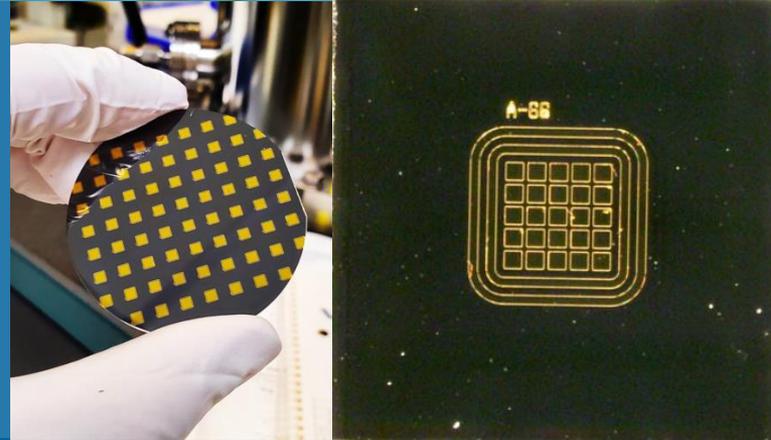


# Thin Film Detectors

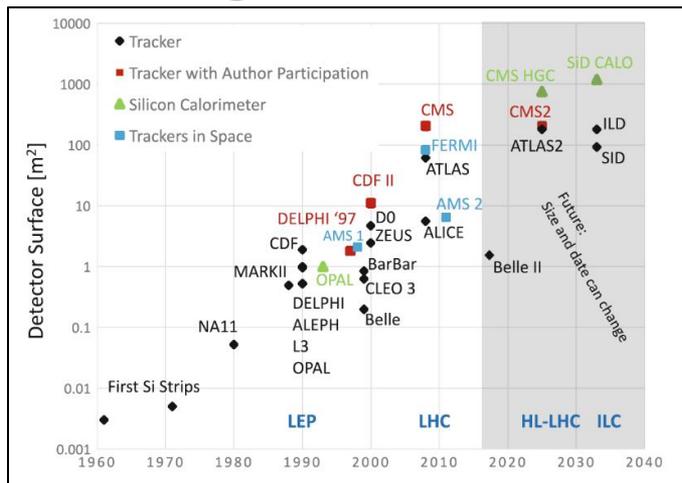


**Jessica Metcalfe**  
Argonne National Laboratory

**CPAD**  
October 9, 2025

On behalf of: A. Affolder, E.R. Almazan, I. Dyckes, V. Fadeyev, M. Hance, M. Jadhav, S. Kim, T. McCoy, J. Nielsen, J. Ott, L. Poley, T.(K.-W.) Shin, D. Sperlich, A. Sumant

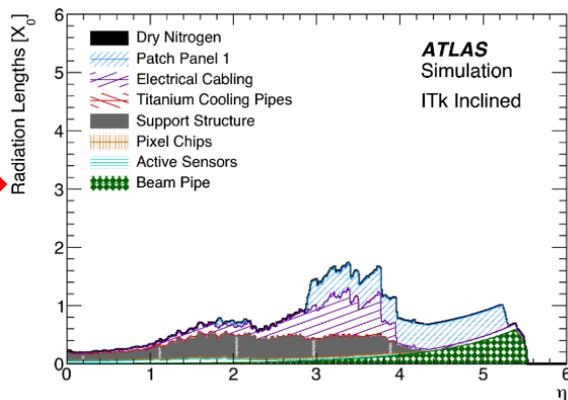
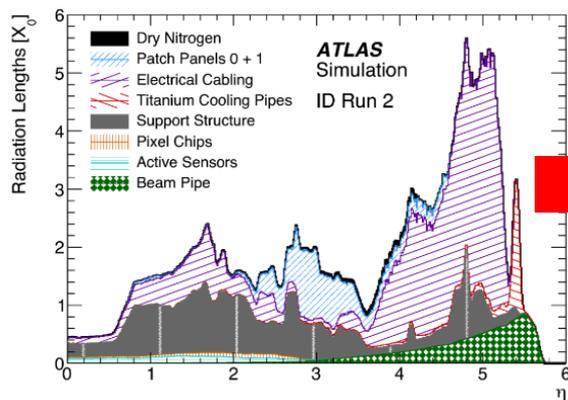
# Challenge



Evolution of silicon sensor technology in particle physics – Frank Hartmann, Springer

## Big Experiments

- Scale of detectors keeps increasing
- Continue to have optimal performance
- Pixel size
- Timing
- Calorimetry Imaging



Atlas technical design report, 10.17181/CERN.FOZZ.ZP3Q

## Unwanted Materials

- Low mass for better performance
- Monolithic/Integrated designs
- Minimize power, cooling, services

# Blue Sky

- Low Mass
  - Low power
  - High position resolution
  - Fast timing resolution
  - Monolithic
  - Radiation Tolerance
  
  - Energy resolution
  - Energy range: signal/noise
    - Low electron energies
- Low cost
  - Reduce services
  - Reduce cooling needs
  
  - All-in-one?
    - Fewer 'sub-systems'
      - Reduce cost
      - Optimize resources
  - Faster development cycle

**How many features can we combine into one detector technology?**

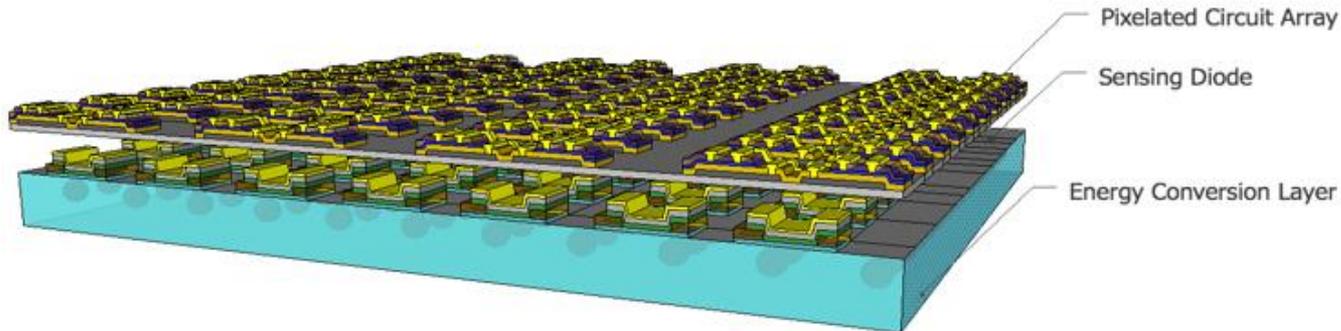
# Thin Film Particle Detectors

Thin Films: thin layers of materials ranging from nm to  $\mu\text{m}$

- Current popular applications
  - solar cells
  - LCD screens
- Thin Films for Particle Detectors:
  - Thin Film Diodes + Thin Film Transistors

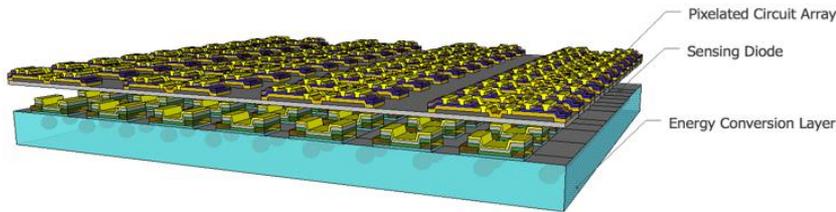
Potential:

- Large area 'printing'
- Low mass
- Low cost
- Pixelated
- Integrated/monolithic design
- Fast development cycle
- Easier system construction

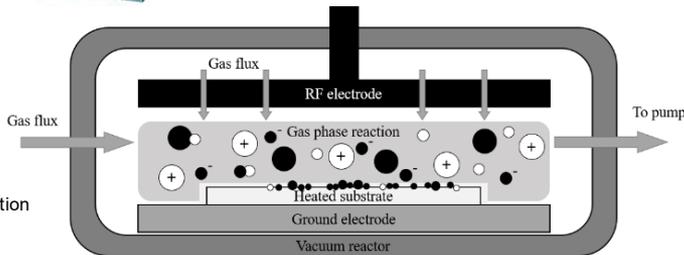


<https://arxiv.org/abs/1411.1794>

# Thin Film Deposition



PECVD:  
an example of **CVD**  
Plasma Enhanced Chemical Vapor Deposition



Wide range of techniques  
available depending on  
needs

- **CVD**
- **PECVD**
- **ALD**
- **MBE**
- **PVD**
- **CBD**



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

Scalable and robust process

- Large area deposition possible
- Compatible with **flexible substrates**

# Research Areas

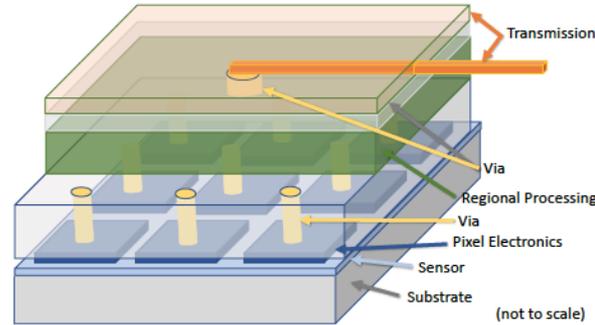
## 3 pillars:

### New materials

Material	Z	$\rho$ (g/cm <sup>3</sup> )	$\frac{-dE}{dx}$ [MeV/(g/cm <sup>2</sup> )]	MIP in 10 $\mu$ m (keV)	$E_i$ (eV)	$\langle N_{e-h \text{ pairs}} \rangle$ in 10 $\mu$ m
Diamond	6	3.51	1.78	6.25	13	0.5k
Si	14	2.329	1.664	3.9	3.62	1.1k
CdS	32	4.8	4.0*	19.08	6.49*	2.9k
PbS	49	7.6	6.2*	46.8	1.98*	23.6k
ZnO	19	5.6	4.4*	24.8	8.25*	3.0k
GaAs	32	5.32	1.4	7.45	4.2	1.8k
InP	32	4.97	4.0*	20.5	4.2	4.8k
HgI	66.5	6.4	5.6*	35.8	4.3	8.3k
InSb	50	5.78	4.9*	28.1	1.57*	17.9k
InAs	41	5.67	4.7*	26.8	1.94*	13.8k
HgTe	66	8.1	6.7*	54.7		
CdZnTe	43.3	6	5.0*	29.8	4.7	6.3k
IGZO	29.5	6			7.58*	

- Explore different material properties
- Optimize for specific applications: timing, charge collection, radiation hard, etc.
- Consider compatible fabrication techniques for vertically integrated and printable designs

### Electronics Integration



- Monolithic design
- Microelectronics in thin films
- Compatible processing, vertical integration
- Sensor, Readout, Data transmission, Regional processing in one
- Enables AI/ML on-detector

### Printable: large area, scalable



- Large-area fabrication
- Flexible substrates
- Printable fabrication processes
- Faster design cycles
- Faster detector construction

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

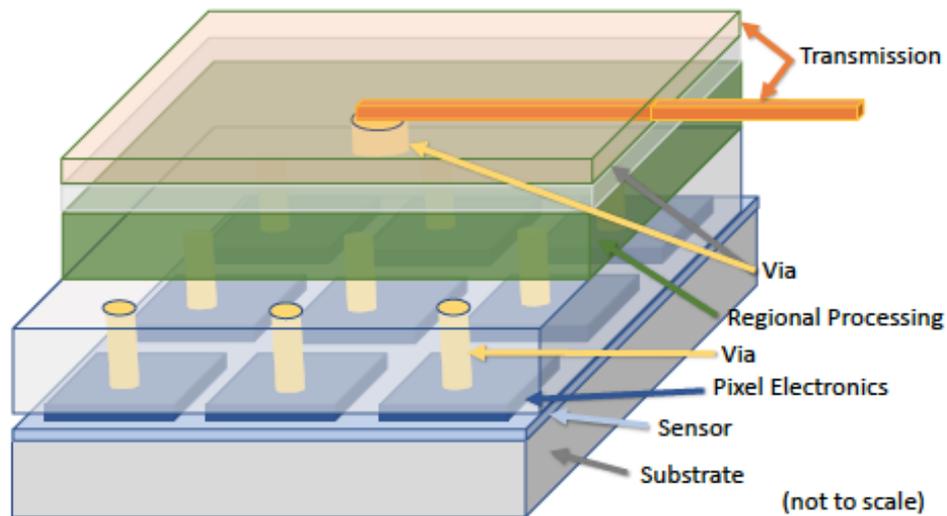
Material	Density (g/cm <sup>3</sup> )	Band gap (eV)	Intrinsic carrier concentration (cm <sup>-3</sup> )	Average atomic number	Ionization energy (eV)	Drift Mobility (cm <sup>2</sup> /(Vs))		Carrier lifetime	MIP in 10 μm (keV)
						Electron	Hole		
Diamond (SC)	3.51	5.48	< 10 <sup>3</sup>	6	13.1	1,800	1,200	~ 1 ns	6.25
Si	2.33	1.12	1.45 × 10 <sup>10</sup>	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 <sup>7</sup>	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 <sup>7</sup>	43.3	4.6	~ 1,000	50–80	~ μs	29.8
InP	4.8	1.35	1.3 × 10 <sup>7</sup>	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 <sub>2</sub>	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

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

- **Large library** of promising / interesting materials
  - Extreme radiation hardness
  - High atomic number (Z)
  - Charge carrier mobility / lifetime
  - 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
  - Safety, Price

# Electronics Integration



## Monolithic concept:

- Flexible substrate
- Sensor with on-pixel electronics
- Vertically integrated into local pixel readout electronics
- Vertically integrated into large area regional processing
- Vertically integrated into transmission/off-detector lines

## Low Mass

- Minimize services
- Reduce dead material
- $X/X_0 < 1\%$

## Robust Construction

- Monolithic
- Vertical integration
- Fully integrated

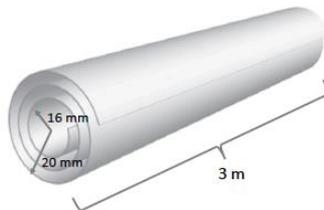
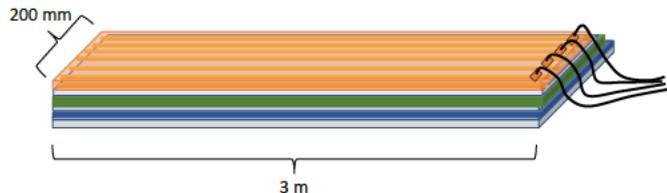
## Performance

- Pixelated
- Low power
- Fast timing
- Energy resolution/range

## Regional Processing

- Enable AI/ML

# Scalable: Printable Large Area



## Printable Designs:

- Requires scalable processes
- Requires compatible processes
- Low temperature

## Large area design possibilities:

- Fabricate on a single flexible substrate
- Creative detector geometries like spiral cylinder roll
- Simplify detector construction process
- Move toward a single active detector system

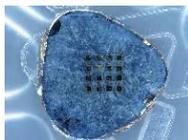
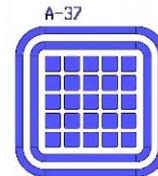
# InP Results

# Thin Film Detectors: Project History

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

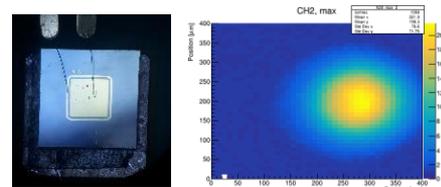


Project started on February 2020

Early idea concept: ~2014

Collaboration with UCSC started in April 2022

Testing second devices



Device studies:  
Irradiation, test beam, charge collection efficiency

Affiliation

UIC/  
ANL

ANL

UCSC

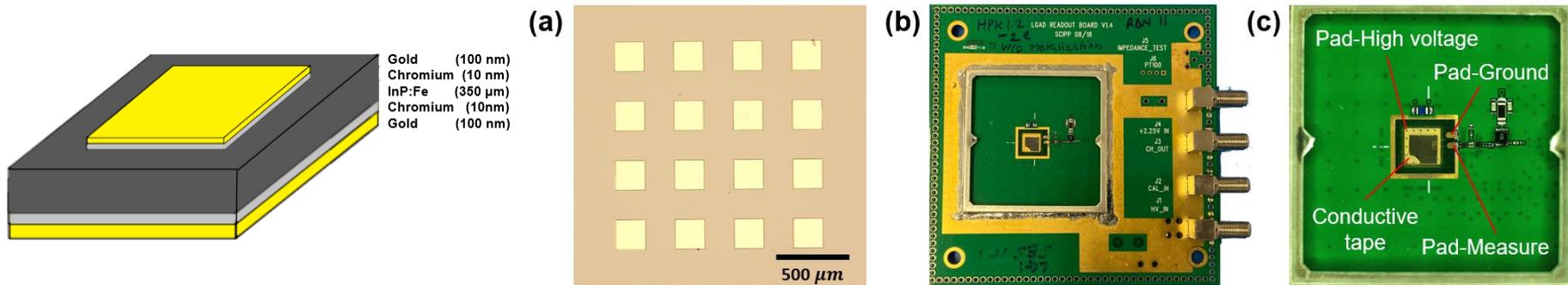
NST/CNM



# Sensor Fabrication

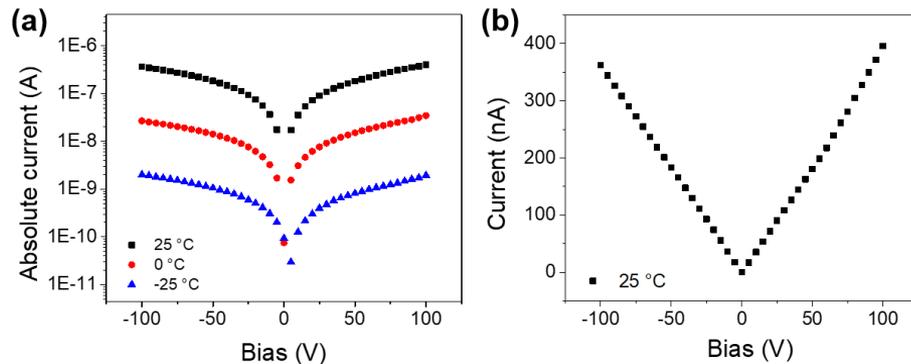
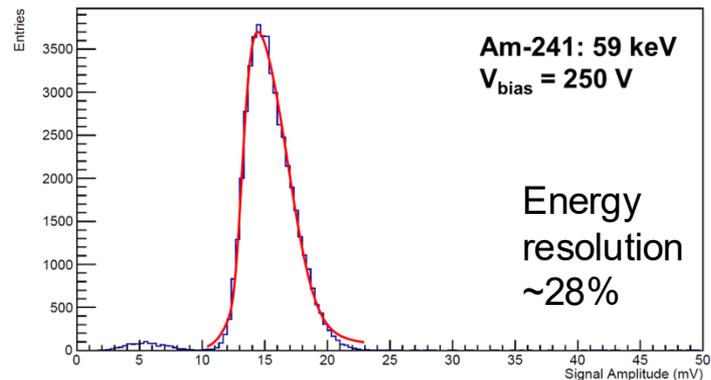
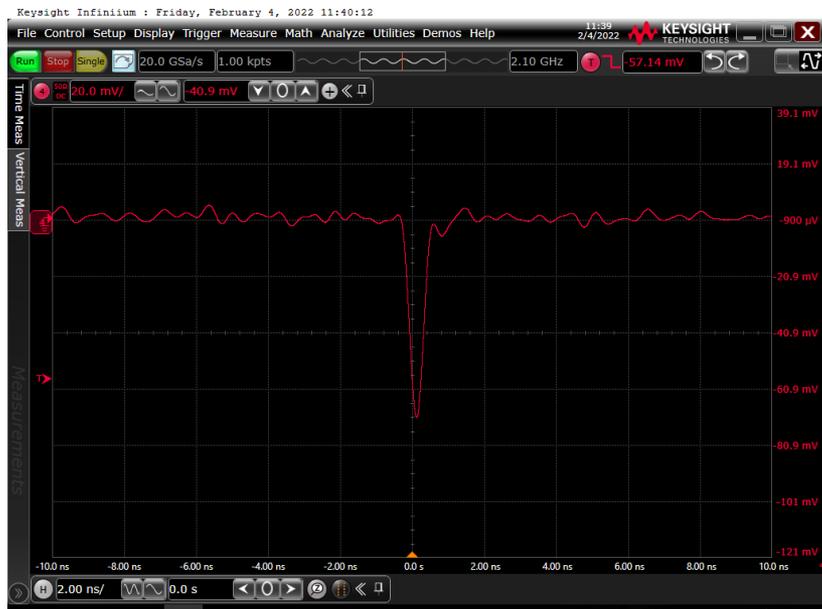
## Crystalline InP Devices

- First devices were chosen from InP:Fe crystalline wafer → bandgap, charge generation, electron mobility, wafer availability
- Fabrication by Sungjoon Kim (UIC, now ANL) at the Center for Nanoscale Materials (CNM) at Argonne
- Experience with electrode deposition techniques, lab setups
- Additional devices from Diamond and CdZnTe (not shown)
- → Baseline performance



# INP:Fe First Sample Results

- First signals observed with oscilloscope readout
- IV curves indicate ohmic response  $\rightarrow$  due to semi-insulating properties of InP:Fe
- Good Signal/Noise

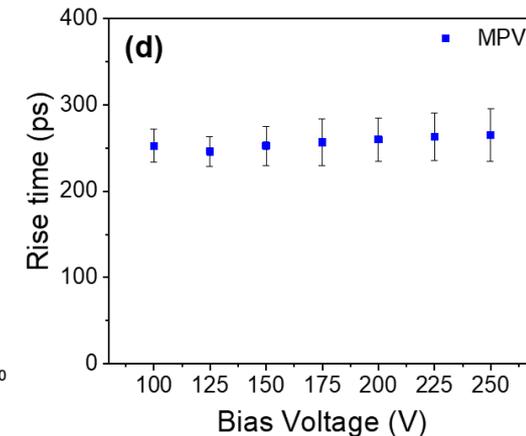
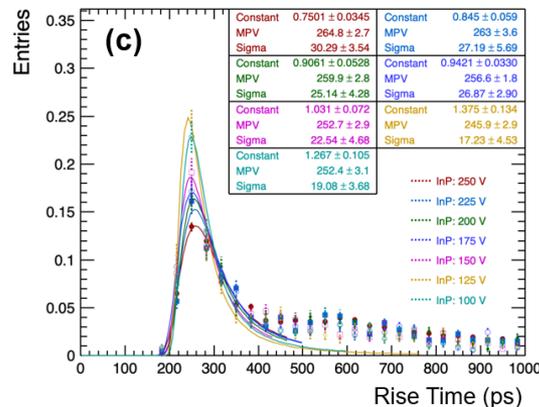
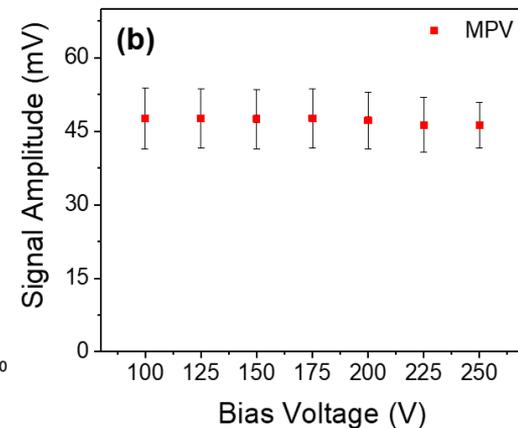
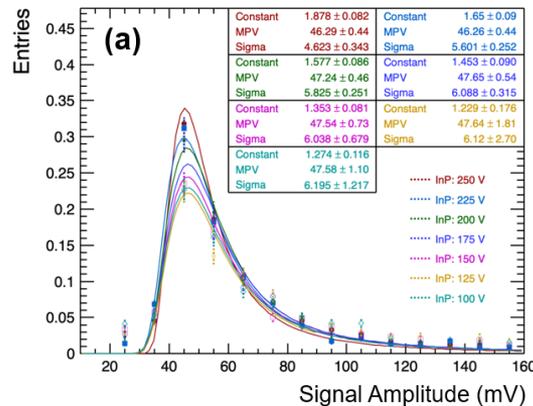


# Fermilab Test Beam

- 120 GeV proton beam
- Individual device readout with oscilloscope
- Fully biased devices > 100 V show similar signal amplitude

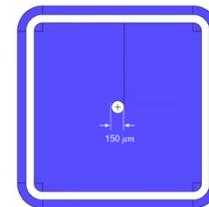
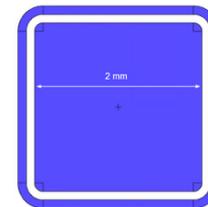
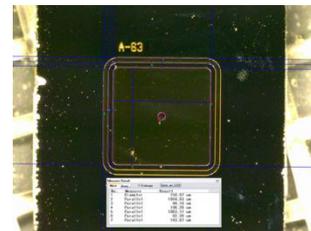
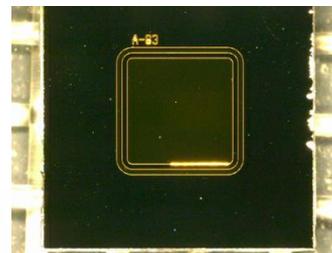
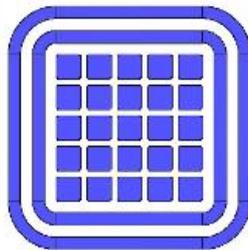
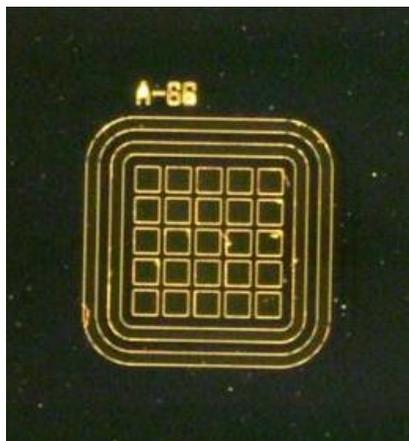
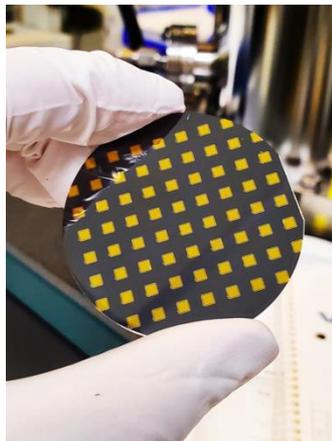
## Rise time on the order of 250 ps

- 350  $\mu\text{m}$  thick device
- No special amplification region
- Electron mobility 4,600  $\text{cm}^2/(\text{Vs})$
- (Silicon electron mobility 1,415  $\text{cm}^2/(\text{Vs})$ )

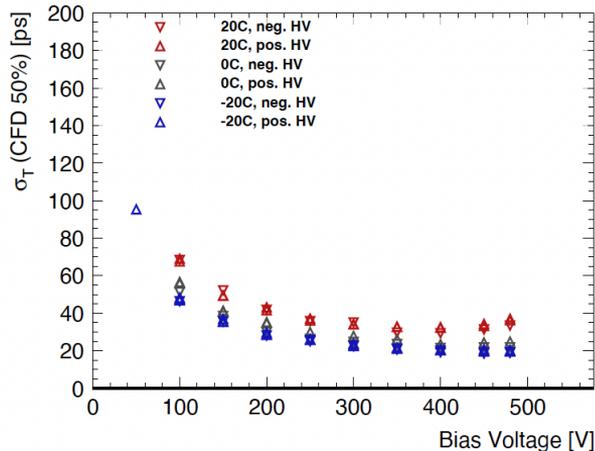
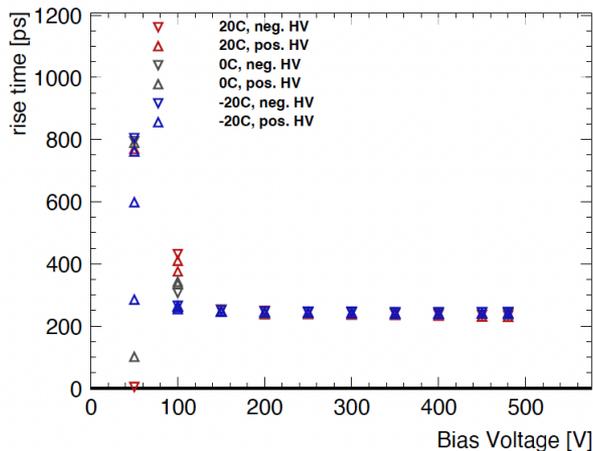
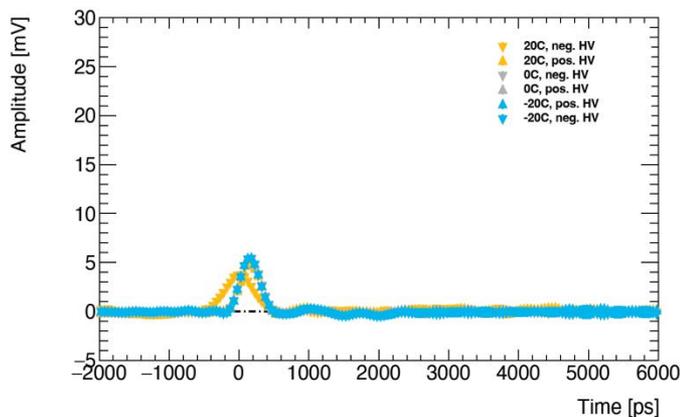
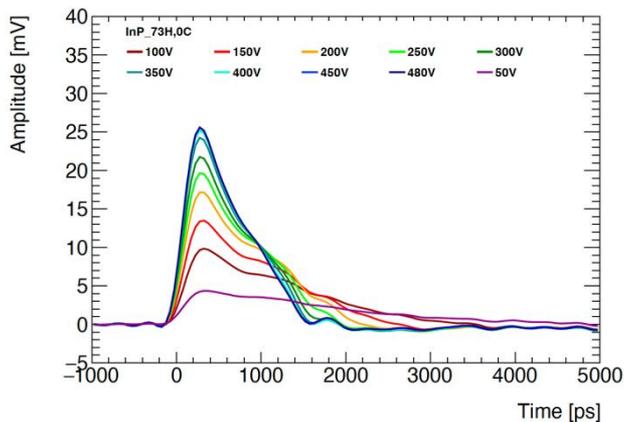


## InP Crystalline Wafers: Pads & Guard Ring Structures

- Fabrication by Sungjoon Kim (UIC, now ANL) at the Center for Nanoscale Materials (CNM) at Argonne
- Guard ring structures added for better edge field behavior
- 3 device types: single pad, single pad with opening for charge collection measurements, multi-pad sensors



# InP:Fe Single Pad Device

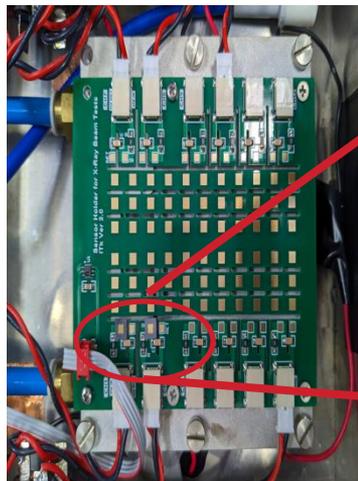
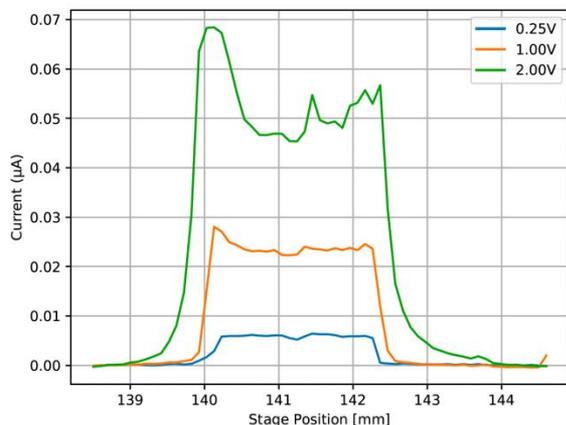


Additional studies on single pad devices

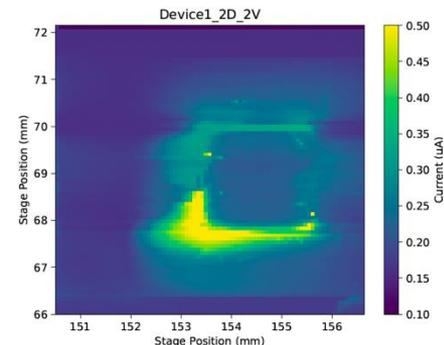
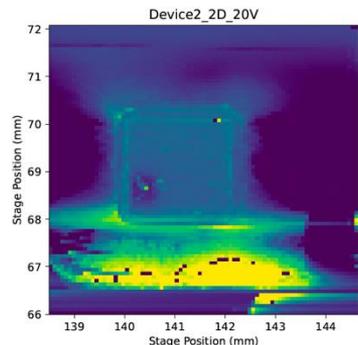
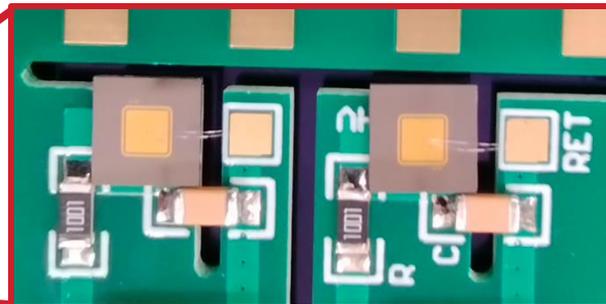
- Verify timing
- Rise time  $\sim$ 250 ps
- Temperature dependence
- Timing resolution  $\sim$ 20-40 ps

# X-Ray Test Beams

- Response measured at two x-ray beam lines
  - Canadian Light Source (CLS)
  - Diamond Light Source (DLS)
- Scan a focused x-ray beam across devices
  - X-ray energy: 15 keV
  - Unexplained current spikes
- Magnitude and width increase with bias voltage → likely due to faster charge carriers in higher field resulting in smaller effective trapping



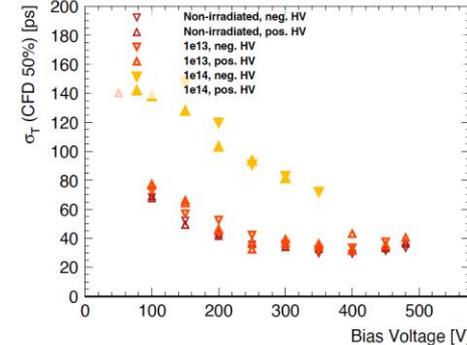
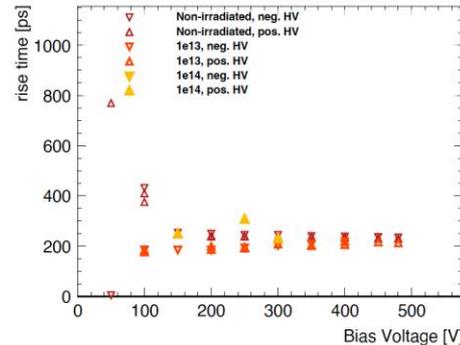
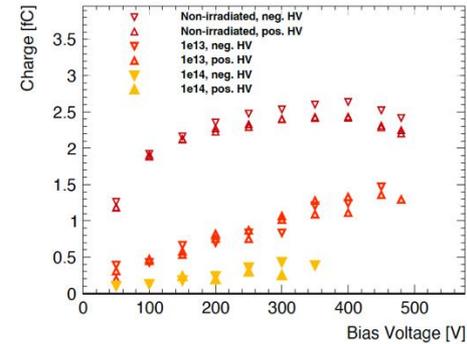
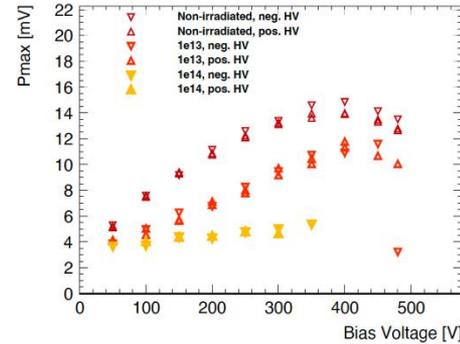
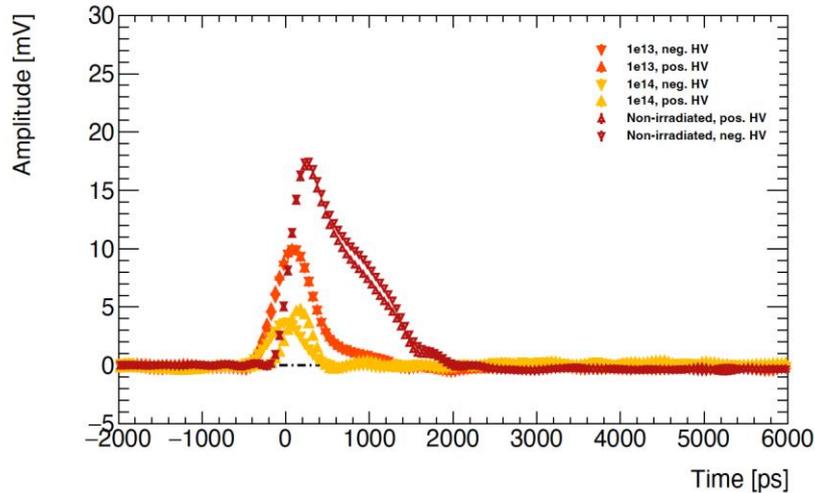
CLS board with single pad devices



Studies led by Earl Almazan (UCSC), recent GIRA Award recipient. See his presentation tomorrow.

# Irradiation: neutrons

- 1 MeV neutron irradiations @JSI/Ljubljana
- $1e13$ ,  $1e14$ ,  $1e15$  (very high currents at room temp)
- Relatively strong degradation with neutron irradiation displacement damage



# Summary

- The Thin Film Particle Detector concept is a Blue Sky R&D project
- Goal: meet future particle detector needs across a plethora of applications
- →Low mass, timing resolution, fine pixels, large-scale printing, fast mass construction
- Research Areas: New Materials, Microelectronics, Printable technologies
  
- Start: new material sensor substrate InP
- Baseline InP with crystalline wafer sensor devices
- Device characterization: charge response, IV, CV, timing resolution, energy resolution, x-ray beam response, charge collection efficiency, irradiation response

## Next:

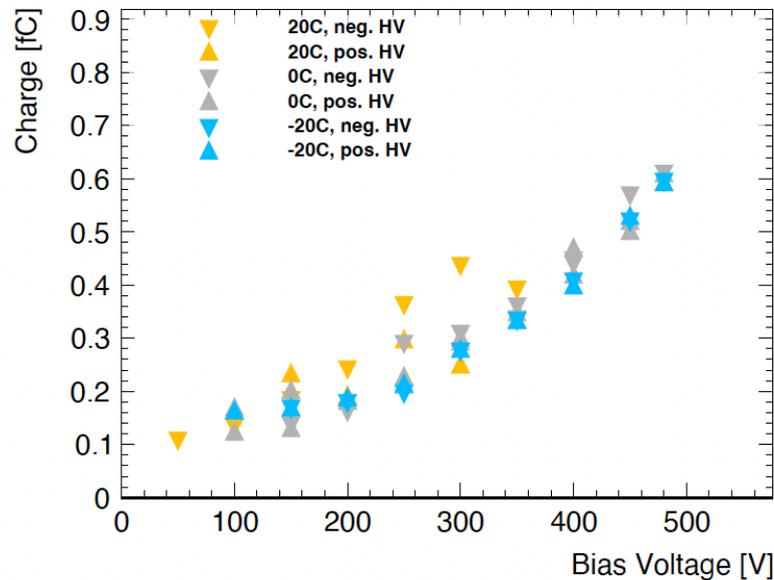
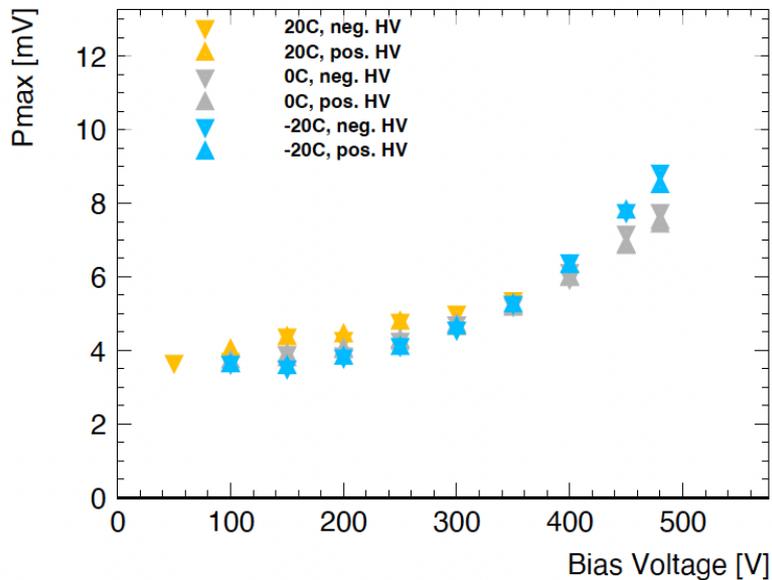
- Compare to crystalline baseline to thin film samples
- Explore new materials

# Backup

- **J. Metcalfe**, et al., Potential of Thin Films for use in Charged Particle Tracking Detectors, <https://arxiv.org/abs/1411.1794>, Nov 2014.
- **Kim, S.**, Berry, V., Metcalfe, J. & Sumant, A. V. Thin film charged particle detectors. *Journal of Instrumentation* **18**, (2023) [LINK](#)
- **S. Kim**, et al., Novel indium phosphide charged particle detector characterization with a 120 GeV proton beam, JINST, Aug 2024. [Link](#)
- **E.R. Almazan**, et al., Characterizing novel Indium Phosphide pad detectors with focused X-ray beams and laboratory tests, JINST, Nov 2024. [Link](#)
- In progress: 'Characterization of Indium Phosphide Detectors with Red Laser Transient Current Technique and Minimum-Ionizing Charged Particles' by J. Ott et al.

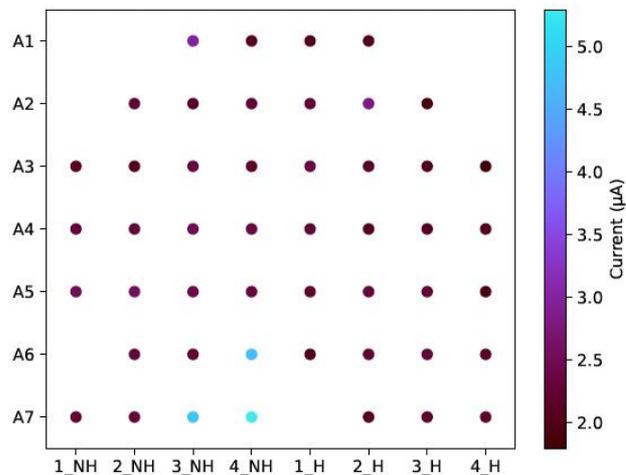
# InP:Fe Single Pad Device

## Charge Collection

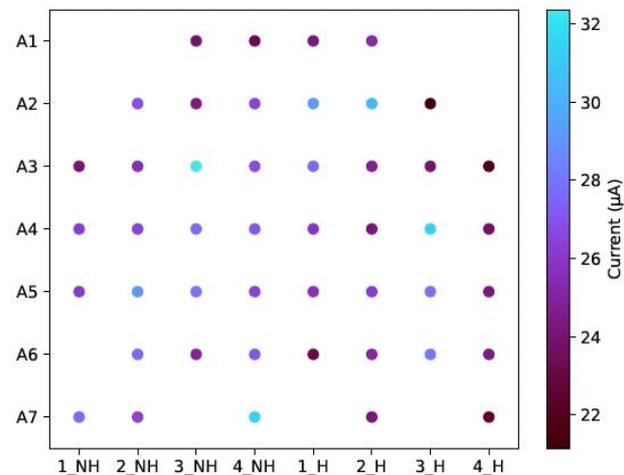


# InP:Fe Single Pad Devices

## Leakage Current



(a)  $V = +30$  V.



(b)  $V = +350$  V.