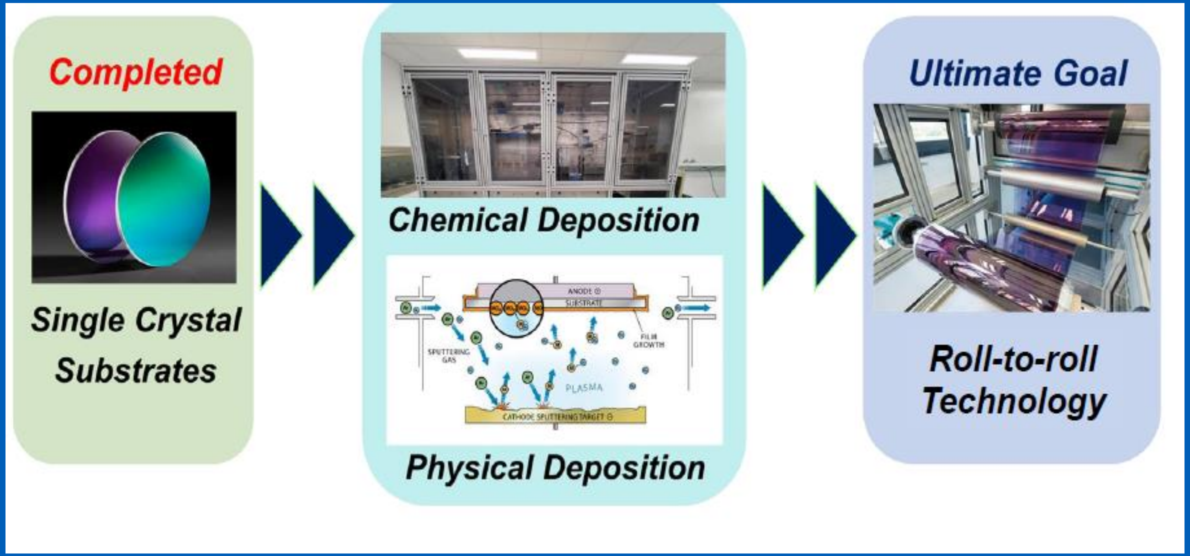
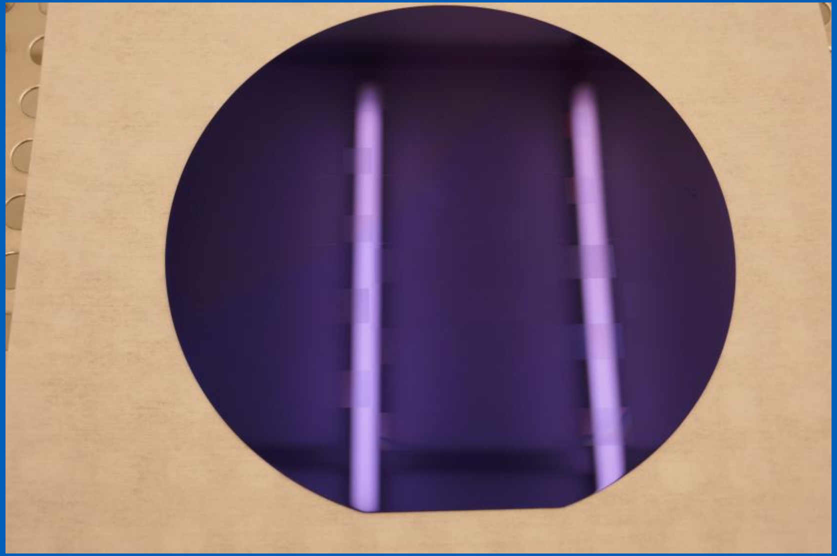




Thin-film detectors

Jennifer Ott
jeott@ucsc.edu

November 7, 2024
4D Tracking workshop

Thin-film detectors

Motivation and potential:

- Low mass
- Low material budget
- Large scale manufacturing
- ‘3D integration’ or monolithic detector: avoid hybridization for small pixels, keep low interconnect capacitance
- Different semiconductor materials

Thin-film growth methods are already used in detectors!

- High-resistivity epitaxial Si on low-res substrate, e.g. for LGADs: deposition is done as a thin film onto a substrate (of identical material and crystal structure), but result is a a ‘thick’ substrate for hybrid detector
- CVD polycrystalline diamond: used for ‘bulk’ material deposition
- Thick Si detectors which are ground down (ALICE ITS3) are not thin films in this sense…

Examples on the path towards thin film particle tracking detectors shown here:

- Crystalline material (InP) as test case and reference for thin film sensors
- aSe thermal evaporation onto active ASIC

S. Kim et al, CPAD 2023, https://indico.slac.stanford.edu/event/8288/contributions/7503/

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

Deposition methods & availability

Physical

- (Spin coating, dip coating)
- Sputtering
- Thermal evaporation
- E-beam evaporation
- Molecular beam epitaxy
- Ion- / laser beam assisted deposition

Chemical

- (Oxidation)
- Plating
- CVD
  - Plasma-enhanced CVD
- (MO)Vapour-phase epitaxy
- Atomic layer deposition

Facilities

- Individual labs or groups – often in Chemistry or Engineering departments
- Micro- / nanofabrication facilities at universities or national labs: e.g. Stanford, SLAC, ANL, BNL, LBNL
- Research institutes or semi-commercial centers, e.g. FBK, CNM, Sintef
- Commercial vendors

Thin film materials as charged particle detectors?

Sensor prototypes in InP: favorable properties, especially electron mobility, which is higher than in Si

Chosen as a commercially available small wafer material and crystalline reference to (amorphous) future thin film devices

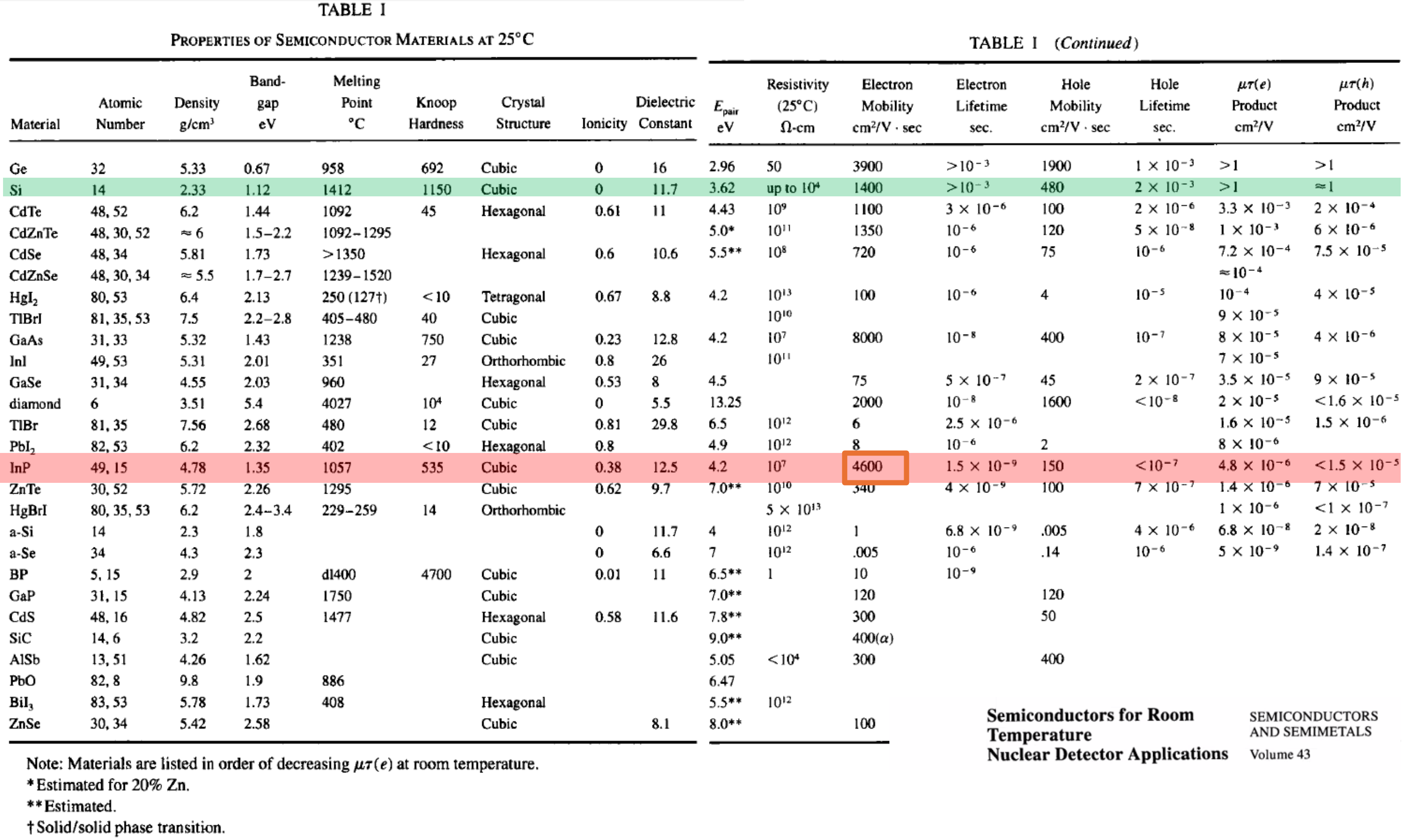


TABLE I

PROPERTIES OF SEMICONDUCTOR MATERIALS AT 25°C

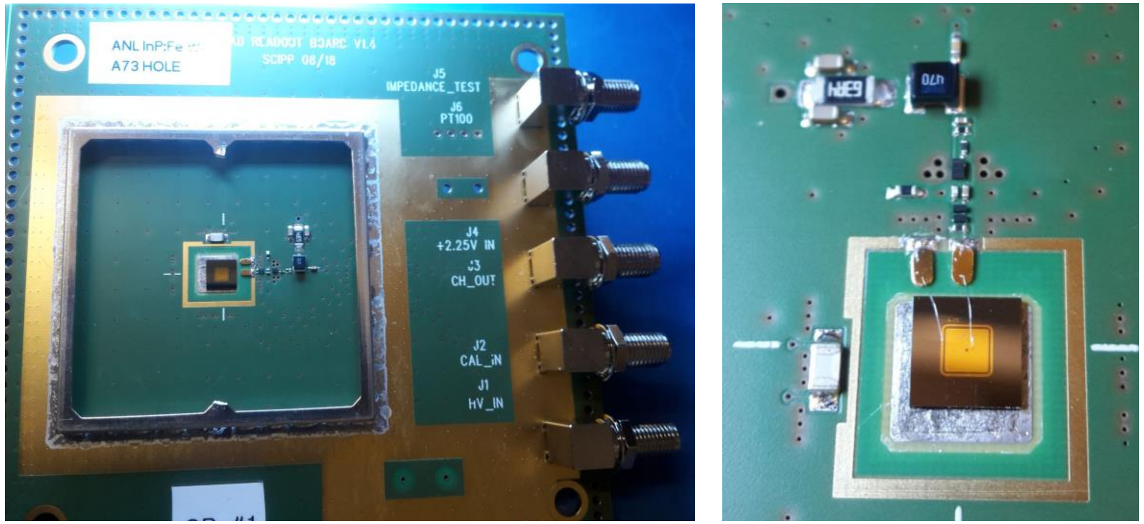
TABLE I (*Continued*)

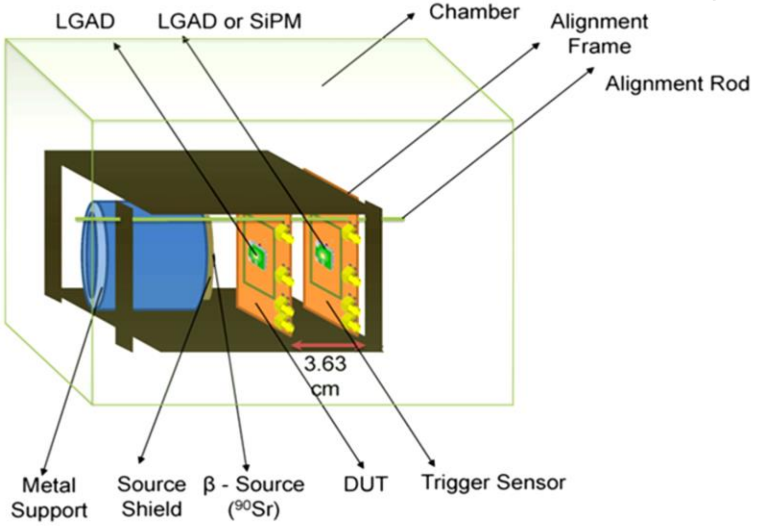
Material	Atomic Number	Density g/cm³	Band-gap eV	Melting Point °C	Knoop Hardness	Crystal Structure	Ionicity	Dielectric Constant	E_{pair} eV	Resistivity (25°C) Ω-cm	Electron Mobility cm²/V · sec	Electron Lifetime sec.	Hole Mobility cm²/V · sec	Hole Lifetime sec.	$\mu\tau(e)$ Product cm²/V	$\mu\tau(h)$ Product cm²/V
Ge	32	5.33	0.67	958	692	Cubic	0	16	2.96	50	3900	$>10^{-3}$	1900	1×10^{-3}	>1	>1
Si	14	2.33	1.12	1412	1150	Cubic	0	11.7	3.62	up to 10^4	1400	$>10^{-3}$	480	2×10^{-3}	>1	≈ 1
CdTe	48, 52	6.2	1.44	1092	45	Hexagonal	0.61	11	4.43	10^9	1100	3×10^{-6}	100	2×10^{-6}	3.3×10^{-3}	2×10^{-4}
CdZnTe	48, 30, 52	≈ 6	1.5–2.2	1092–1295					5.0*	10^{11}	1350	10^{-6}	120	5×10^{-8}	1×10^{-3}	6×10^{-6}
CdSe	48, 34	5.81	1.73	>1350		Hexagonal	0.6	10.6	5.5**	10^8	720	10^{-6}	75	10^{-6}	7.2×10^{-4}	7.5×10^{-5}
CdZnSe	48, 30, 34	≈ 5.5	1.7–2.7	1239–1520											$\approx 10^{-4}$	
HgI_2	80, 53	6.4	2.13	250 (127†)	<10	Tetragonal	0.67	8.8	4.2	10^{13}	100	10^{-6}	4	10^{-5}	10^{-4}	4×10^{-5}
TlBrI	81, 35, 53	7.5	2.2–2.8	405–480	40	Cubic				10^{10}					9×10^{-5}	
GaAs	31, 33	5.32	1.43	1238	750	Cubic	0.23	12.8	4.2	10^7	8000	10^{-8}	400	10^{-7}	8×10^{-5}	4×10^{-6}
InI	49, 53	5.31	2.01	351	27	Orthorhombic	0.8	26		10^{11}					7×10^{-5}	
GaSe	31, 34	4.55	2.03	960		Hexagonal	0.53	8	4.5		75	5×10^{-7}	45	2×10^{-7}	3.5×10^{-5}	9×10^{-5}
diamond	6	3.51	5.4	4027	10^4	Cubic	0	5.5	13.25		2000	10^{-8}	1600	$<10^{-8}$	2×10^{-5}	$<1.6 \times 10^{-5}$
TlBr	81, 35	7.56	2.68	480	12	Cubic	0.81	29.8	6.5	10^{12}	6	2.5×10^{-6}			1.6×10^{-5}	1.5×10^{-6}
PbI_2	82, 53	6.2	2.32	402	<10	Hexagonal	0.8		4.9	10^{12}	8	10^{-6}	2		8×10^{-6}	
InP	49, 15	4.78	1.35	1057	535	Cubic	0.38	12.5	4.2	10^7	4600	1.5×10^{-9}	150	$<10^{-7}$	4.8×10^{-6}	$<1.5 \times 10^{-5}$
ZnTe	30, 52	5.72	2.26	1295		Cubic	0.62	9.7	7.0**	10^{10}	340	4×10^{-9}	100	7×10^{-7}	1.4×10^{-6}	7×10^{-5}
HgBrI	80, 35, 53	6.2	2.4–3.4	229–259	14	Orthorhombic				5×10^{13}					1×10^{-6}	$<1 \times 10^{-7}$
a-Si	14	2.3	1.8				0	11.7	4	10^{12}	1	6.8×10^{-9}	.005	4×10^{-6}	6.8×10^{-8}	2×10^{-8}
a-Se	34	4.3	2.3				0	6.6	7	10^{12}	.005	10^{-6}	.14	10^{-6}	5×10^{-9}	1.4×10^{-7}
BP	5, 15	2.9	2	dl400	4700	Cubic	0.01	11	6.5**	1	10	10^{-9}				
GaP	31, 15	4.13	2.24	1750		Cubic			7.0**		120		120			
CdS	48, 16	4.82	2.5	1477		Hexagonal	0.58	11.6	7.8**		300		50			
SiC	14, 6	3.2	2.2			Cubic			9.0**		400(α)					
AlSb	13, 51	4.26	1.62			Cubic			5.05	$<10^4$	300		400			
PbO	82, 8	9.8	1.9	886					6.47							
BiI_3	83, 53	5.78	1.73	408		Hexagonal			5.5**	10^{12}						
ZnSe	30, 34	5.42	2.58			Cubic		8.1	8.0**		100					

Note: Materials are listed in order of decreasing $\mu\tau(e)$ at room temperature.
*Estimated for 20% Zn.
**Estimated.
†Solid/solid phase transition.

Semiconductors for Room Temperature Nuclear Detector Applications
SEMICONDUCTORS AND SEMIMETALS
Volume 43

Crystalline InP sensors





Z. Galloway et al 2019

350 µm single-pad sensor bonded to 1-ch UCSC fast readout board with 470 Ω transimpedance amplifier, second stage external 20dB RF amplifier

- Beta source: Sr-90
- Known HPK Silicon LGAD as trigger and reference

Radiation hardness:

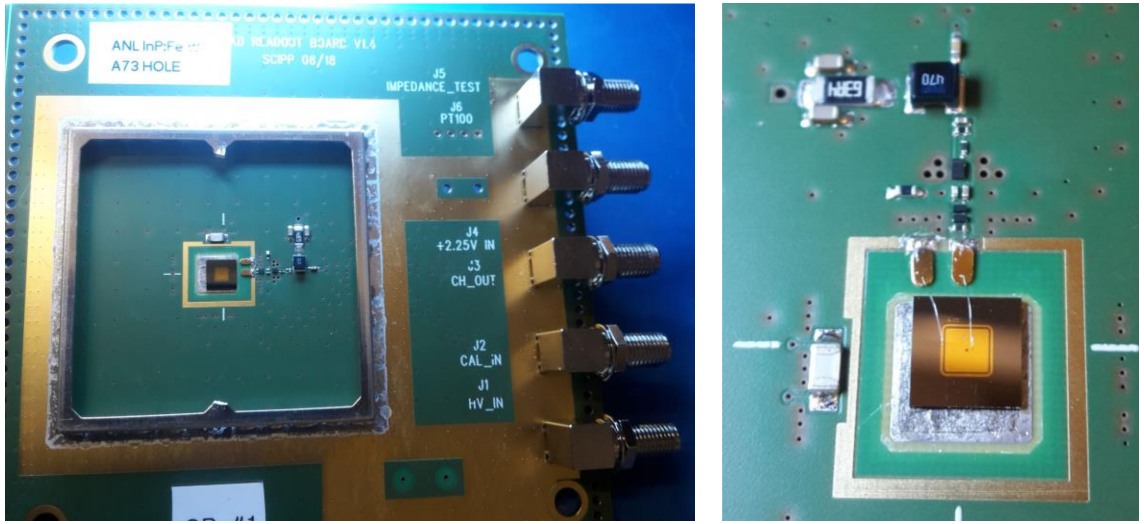
- **Investigated with single-pad sensors irradiated to 1e13, 1e14, 1e15, 1e16 n/cm^2 at JSI/Ljubljana with 1 MeV neutrons**
  - High activation with In-114m in higher fluences

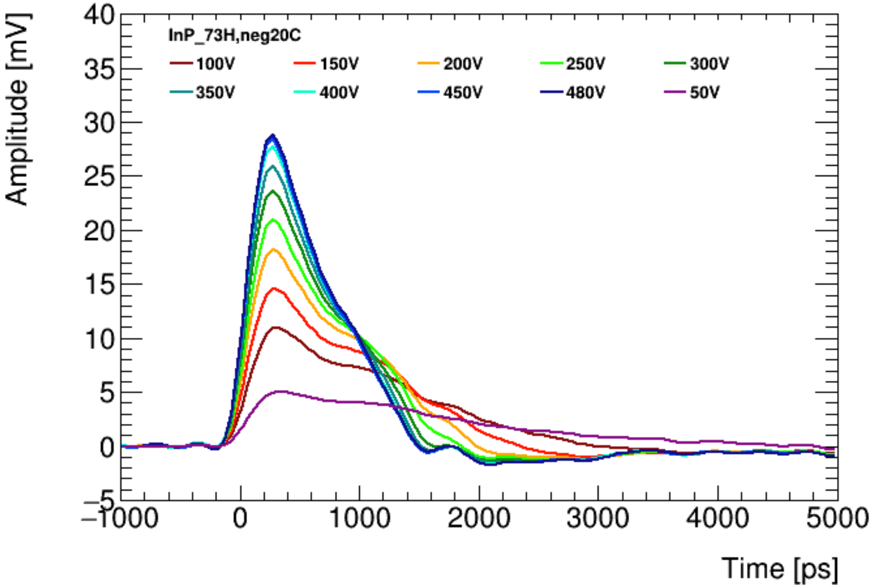
J. Ott, oral presentation, *Characterization of InP sensors for future thin film detectors*, 42nd RD50 Workshop

---

Manuscript in preparation

Crystalline InP sensors





350 µm single-pad sensor bonded to 1-ch UCSC fast readout board with 470 Ω transimpedance amplifier, second stage external 20dB RF amplifier

- Beta source: Sr-90
- Known HPK Silicon LGAD as trigger and reference

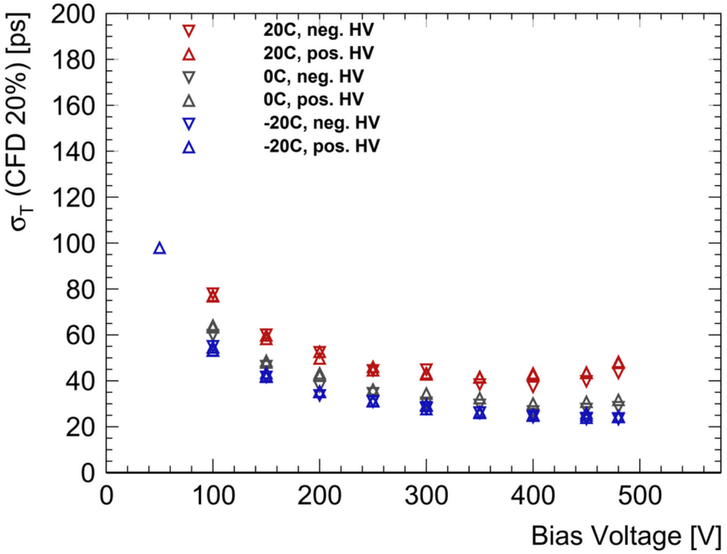
Radiation hardness:

- **Investigated with single-pad sensors irradiated to 1e13, 1e14, 1e15, 1e16 n/cm^2 at JSI/Ljubljana with 1 MeV neutrons**
  - High activation with In-114m in higher fluences

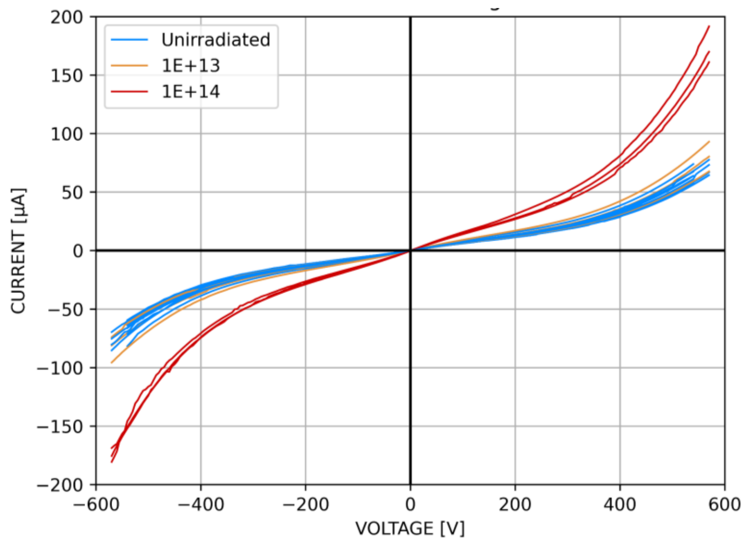
J. Ott, oral presentation, *Characterization of InP sensors for future thin film detectors*, 42nd RD50 Workshop

Manuscript in preparation

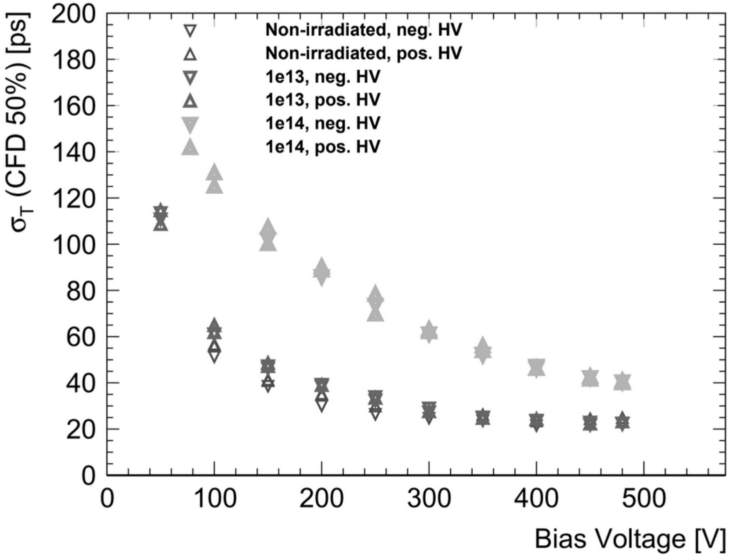
Crystalline InP sensors



I-V at room temperature



Sr-90 source, 0 C



Performance:

- Comparatively small signal, around 15 mV at RT, but fast! Lower leakage/noise, larger signal at lower temperatures
- Rise time independent of bias voltage, down to 250 ps after 150 V. Excellent timing resolution: 33 ps reached between 300 and 400 V

Radiation hardness:

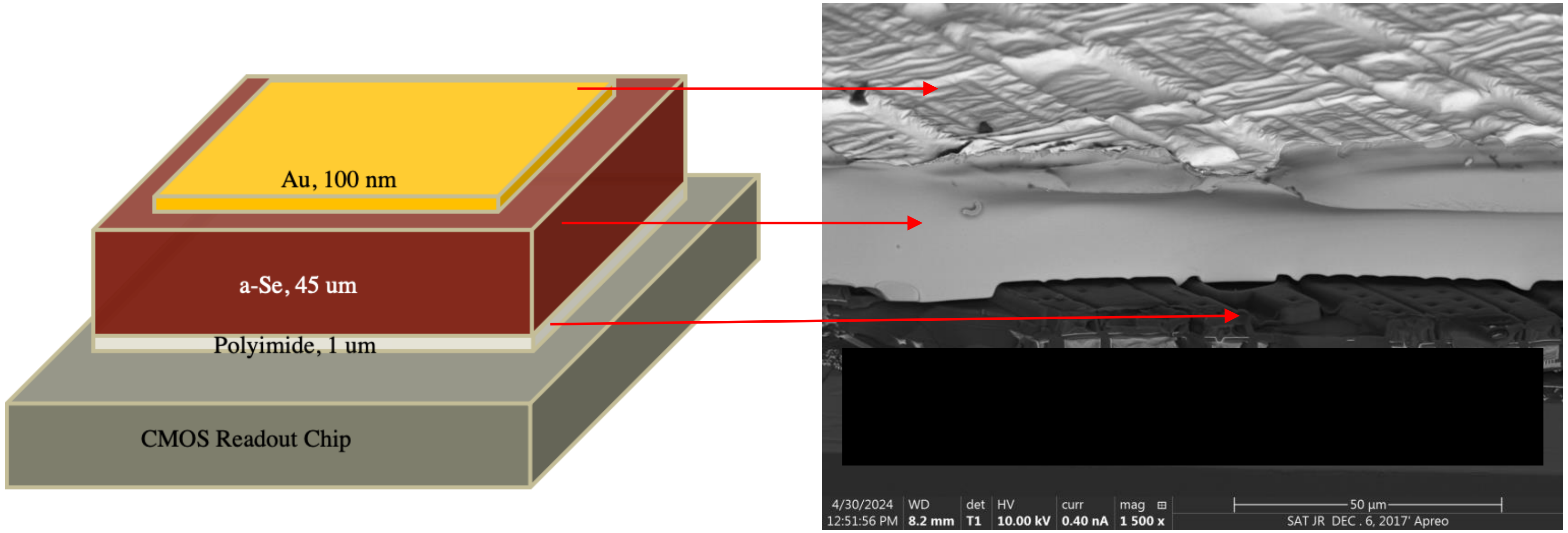
- Leakage current increases; collected charge, pmax decrease – as expected, but already at low fluences. Significant trapping in 350 μm bulk?
- Rise time and timing resolution are still fast at sufficient bias voltage and/or when cooled
- 1e15 samples have high leakage current and early breakdown, 1e16 not received yet

Amorphous Selenium; deposition on ASIC (ITkPix)

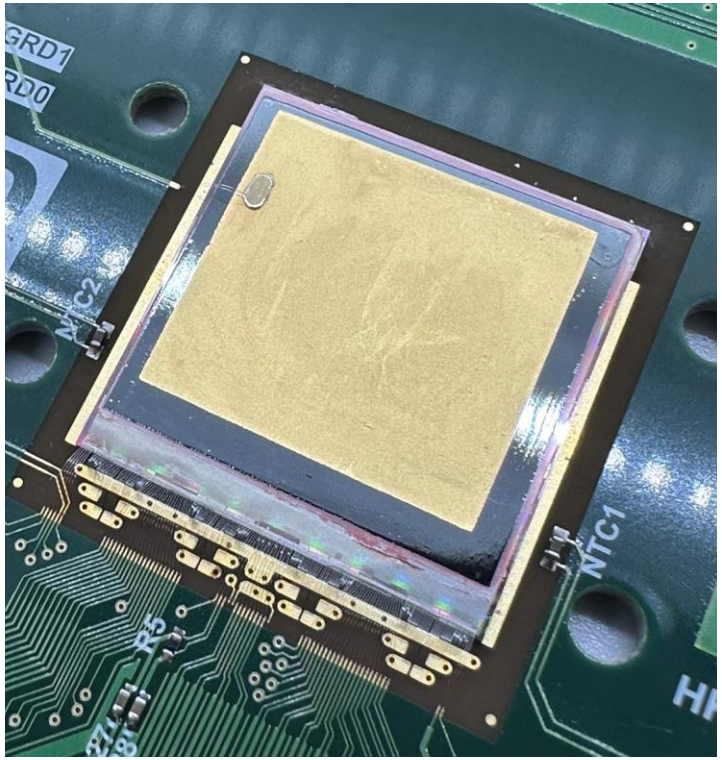
aSe is most established as x-ray detector for e.g. mammography panels

Approach here: utilize pixelated ASIC developed for HEP, deposit active sensor material directly on top by relatively low-temperature thermal evaporation

- Using ITkpixV1.0 (RD53B), V2.0 (recent)
- Leveraging expertise with ATLAS pixel modules to set up DAQ, perform chip calibrations and tuning before scans with radioactive source



[redacted]



A. Swaby, **J. Ott**, K. Hellier, M. Garcia-Sciveres, S. Abbaszadeh, *Hybrid a-Se/RD53B CMOS Detector: Initial Results*, Proceedings of SPIE Medical Imaging (2023), 12463, https://doi.org/10.1117/12.2654519

Amorphous Selenium; deposition on ASIC (ITkPix)

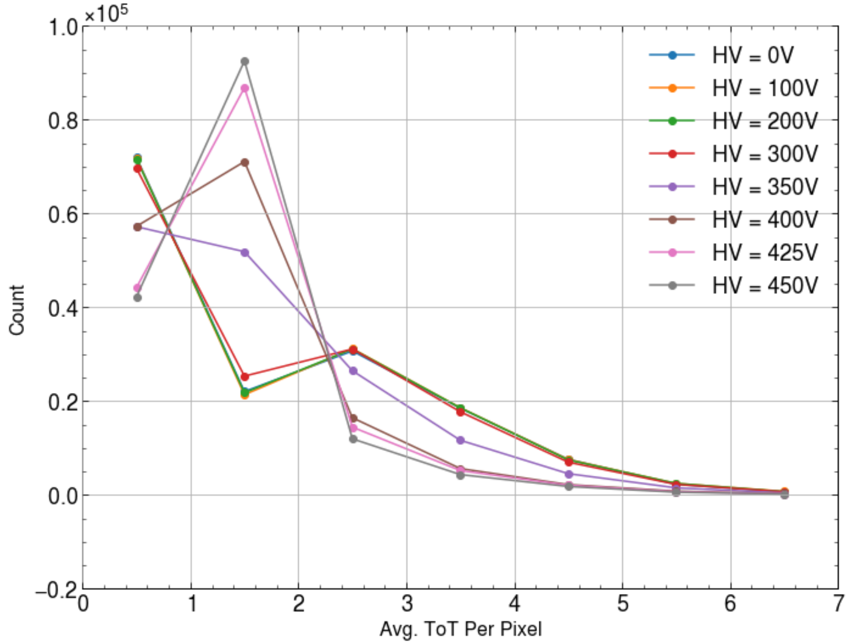
First prototype of ITkPix v2 chip with aSe film tested this summer

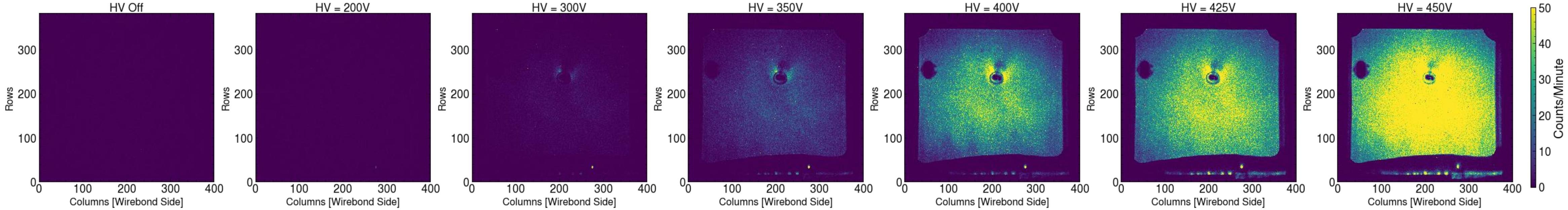
Regular testing routine (communication/eye diagram), digital & analog scan, tuning of threshold

- Deactivation of some edge columns was needed

Source scans with Kr-85 low-energy beta source and tabletop x-ray gun: effect of sensor bias voltage on hit rate and ToT well visible

Next steps: evaluation of aSe thickness, tuning of preamplifier feedback → ToT response





Materials of interest for charged particle tracking?

- (Si)
- InP
- CdTe, CZT?
- GaAs?
- Thin diamond?
- SiC?
- *Others?*

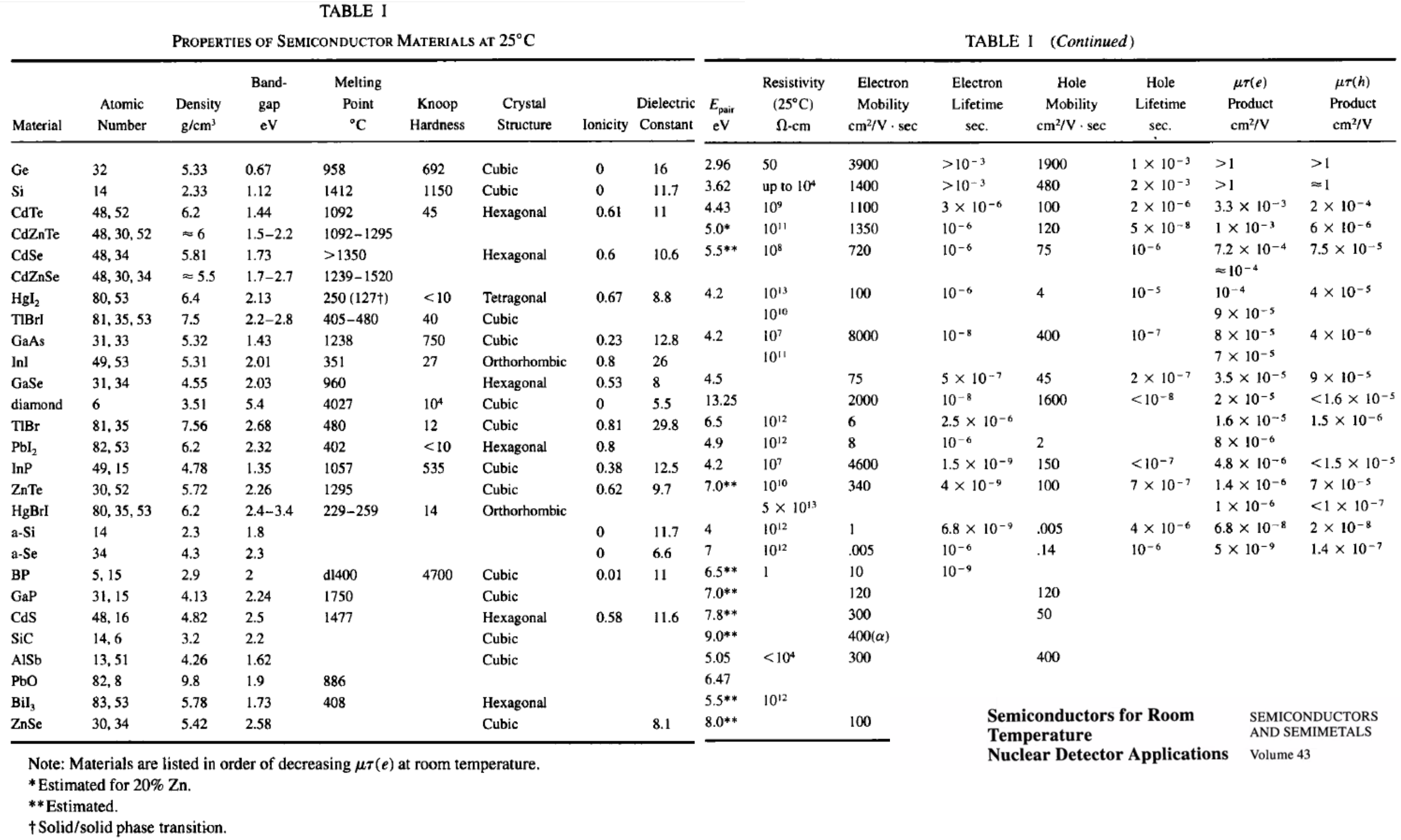


TABLE I

PROPERTIES OF SEMICONDUCTOR MATERIALS AT 25°C

TABLE I (*Continued*)

Material	Atomic Number	Density g/cm^3	Band-gap eV	Melting Point °C	Knoop Hardness	Crystal Structure	Ionicity	Dielectric Constant	E_{pair} eV	Resistivity (25°C) Ω-cm	Electron Mobility cm^2/V · sec	Electron Lifetime sec.	Hole Mobility cm^2/V · sec	Hole Lifetime sec.	$\mu\tau(e)$ Product cm^2/V	$\mu\tau(h)$ Product cm^2/V
Ge	32	5.33	0.67	958	692	Cubic	0	16	2.96	50	3900	$>10^{-3}$	1900	1×10^{-3}	>1	>1
Si	14	2.33	1.12	1412	1150	Cubic	0	11.7	3.62	up to 10^4	1400	$>10^{-3}$	480	2×10^{-3}	>1	≈ 1
CdTe	48, 52	6.2	1.44	1092	45	Hexagonal	0.61	11	4.43	10^9	1100	3×10^{-6}	100	2×10^{-6}	3.3×10^{-3}	2×10^{-4}
CdZnTe	48, 30, 52	≈ 6	1.5–2.2	1092–1295					5.0*	10^{11}	1350	10^{-6}	120	5×10^{-8}	1×10^{-3}	6×10^{-6}
CdSe	48, 34	5.81	1.73	>1350		Hexagonal	0.6	10.6	5.5**	10^8	720	10^{-6}	75	10^{-6}	7.2×10^{-4}	7.5×10^{-5}
CdZnSe	48, 30, 34	≈ 5.5	1.7–2.7	1239–1520											$\approx 10^{-4}$	
HgI$_2$	80, 53	6.4	2.13	250 (127†)	<10	Tetragonal	0.67	8.8	4.2	10^{13}	100	10^{-6}	4	10^{-5}	10^{-4}	4×10^{-5}
TlBrI	81, 35, 53	7.5	2.2–2.8	405–480	40	Cubic				10^{10}					9×10^{-5}	
GaAs	31, 33	5.32	1.43	1238	750	Cubic	0.23	12.8	4.2	10^7	8000	10^{-8}	400	10^{-7}	8×10^{-5}	4×10^{-6}
InI	49, 53	5.31	2.01	351	27	Orthorhombic	0.8	26		10^{11}					7×10^{-5}	
GaSe	31, 34	4.55	2.03	960		Hexagonal	0.53	8	4.5		75	5×10^{-7}	45	2×10^{-7}	3.5×10^{-5}	9×10^{-5}
diamond	6	3.51	5.4	4027	10^4	Cubic	0	5.5	13.25		2000	10^{-8}	1600	$<10^{-8}$	2×10^{-5}	$<1.6 \times 10^{-5}$
TlBr	81, 35	7.56	2.68	480	12	Cubic	0.81	29.8	6.5	10^{12}	6	2.5×10^{-6}			1.6×10^{-5}	1.5×10^{-6}
PbI$_2$	82, 53	6.2	2.32	402	<10	Hexagonal	0.8		4.9	10^{12}	8	10^{-6}	2		8×10^{-6}	
InP	49, 15	4.78	1.35	1057	535	Cubic	0.38	12.5	4.2	10^7	4600	1.5×10^{-9}	150	$<10^{-7}$	4.8×10^{-6}	$<1.5 \times 10^{-5}$
ZnTe	30, 52	5.72	2.26	1295		Cubic	0.62	9.7	7.0**	10^{10}	340	4×10^{-9}	100	7×10^{-7}	1.4×10^{-6}	7×10^{-5}
HgBrI	80, 35, 53	6.2	2.4–3.4	229–259	14	Orthorhombic				5×10^{13}					1×10^{-6}	$<1 \times 10^{-7}$
a-Si	14	2.3	1.8				0	11.7	4	10^{12}	1	6.8×10^{-9}	.005	4×10^{-6}	6.8×10^{-8}	2×10^{-8}
a-Se	34	4.3	2.3				0	6.6	7	10^{12}	.005	10^{-6}	.14	10^{-6}	5×10^{-9}	1.4×10^{-7}
BP	5, 15	2.9	2	d1400	4700	Cubic	0.01	11	6.5**	1	10	10^{-9}				
GaP	31, 15	4.13	2.24	1750		Cubic			7.0**		120		120			
CdS	48, 16	4.82	2.5	1477		Hexagonal	0.58	11.6	7.8**		300		50			
SiC	14, 6	3.2	2.2			Cubic			9.0**		400(α)					
AlSb	13, 51	4.26	1.62			Cubic			5.05	$<10^4$	300		400			
PbO	82, 8	9.8	1.9	886					6.47							
BiI$_3$	83, 53	5.78	1.73	408		Hexagonal			5.5**	10^{12}						
ZnSe	30, 34	5.42	2.58			Cubic		8.1	8.0**		100					

Note: Materials are listed in order of decreasing $\mu\tau(e)$ at room temperature.
*Estimated for 20% Zn.
**Estimated.
†Solid/solid phase transition.

Semiconductors for Room Temperature Nuclear Detector Applications

SEMICONDUCTORS AND SEMIMETALS
Volume 43