Thin-film Charged Particle Detectors

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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
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**

- Thin layers (nm to $\mu$m) 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

PECVD: an example of CVD

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

https://arxiv.org/abs/1411.1794
- **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**
Table 1. Potential charged particle detector materials and their properties [27–30].

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Band gap (eV)</th>
<th>Intrinsic carrier concentration (cm⁻³)</th>
<th>Average atomic number</th>
<th>Ionization energy (eV)</th>
<th>Drift Mobility (cm²/Vs)</th>
<th>Carrier lifetime</th>
<th>MIP in 10 µm (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electron</td>
<td>Hole</td>
<td></td>
</tr>
<tr>
<td>Diamond (SC)</td>
<td>3.51</td>
<td>5.48</td>
<td>&lt; 10³</td>
<td>6</td>
<td>13.1</td>
<td>1.800</td>
<td>1.200</td>
<td>~ 1 ns</td>
</tr>
<tr>
<td>Si</td>
<td>2.33</td>
<td>1.12</td>
<td>1.45 × 10¹⁰</td>
<td>14</td>
<td>3.61</td>
<td>1.415</td>
<td>480</td>
<td>~ 250 µs</td>
</tr>
<tr>
<td>a-Si</td>
<td>2.15</td>
<td>1.5 ~ 1.8</td>
<td></td>
<td>14</td>
<td>4.8 ~ 6</td>
<td>1 ~ 5</td>
<td>0.01</td>
<td>~ µs</td>
</tr>
<tr>
<td>Zn</td>
<td>7.13</td>
<td></td>
<td></td>
<td>30</td>
<td>8.1¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>6.1</td>
<td>1.44</td>
<td>10⁷</td>
<td>50</td>
<td>4.43</td>
<td>1.050</td>
<td>100</td>
<td>0.1–2 µs</td>
</tr>
<tr>
<td>CdS</td>
<td>4.8</td>
<td>2.42</td>
<td></td>
<td>32</td>
<td>6.3</td>
<td>340</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>CdSe</td>
<td>5.81</td>
<td>1.73</td>
<td></td>
<td>41</td>
<td>5.5⁴</td>
<td>720</td>
<td>75</td>
<td>~ µs</td>
</tr>
<tr>
<td>CdZnTe</td>
<td>6</td>
<td>~ 1.6</td>
<td>10⁷</td>
<td>43.3</td>
<td>4.6</td>
<td>~ 1,000</td>
<td>50–80</td>
<td>~ µs</td>
</tr>
<tr>
<td>InP</td>
<td>4.8</td>
<td>1.35</td>
<td>1.3 × 10⁷</td>
<td>32</td>
<td>4.2</td>
<td>4,600</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>InSb</td>
<td>5.8</td>
<td>0.17</td>
<td></td>
<td>50</td>
<td>1.5⁴</td>
<td>78,000</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td>PbS</td>
<td>7.6</td>
<td>0.41</td>
<td></td>
<td>49</td>
<td>1.9⁴</td>
<td>6,000</td>
<td>4,000</td>
<td></td>
</tr>
<tr>
<td>PbI₂</td>
<td>6.2</td>
<td>2.32</td>
<td></td>
<td>67.5</td>
<td>4.9</td>
<td>8</td>
<td>2</td>
<td>8 µs</td>
</tr>
<tr>
<td>TlBr</td>
<td>7.56</td>
<td>2.68</td>
<td></td>
<td>58</td>
<td>6.5</td>
<td>6</td>
<td>2.5 µs</td>
<td></td>
</tr>
<tr>
<td>TlI₃Br</td>
<td>7.5</td>
<td>2.2 ~ 2.8</td>
<td></td>
<td>56.3</td>
<td></td>
<td>~ 4.5</td>
<td></td>
<td>~ 2 µs</td>
</tr>
<tr>
<td>ZnO</td>
<td>5.6</td>
<td>3.37</td>
<td></td>
<td>19</td>
<td>8.25⁴</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnS</td>
<td>4.1</td>
<td>3.68</td>
<td></td>
<td>23</td>
<td>8.23</td>
<td>165</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>ZnTe</td>
<td>5.72</td>
<td>2.26</td>
<td></td>
<td>41</td>
<td>7.0⁴</td>
<td>340</td>
<td>100</td>
<td>4 µs</td>
</tr>
</tbody>
</table>

*Estimated values

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### Large library of promising / interesting materials

- **Extreme radiation hardness**
- **High atomic number (Z)**
- **Charge carrier mobility**
- **Large bandgap**

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### 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
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

### 2020
- COVID – Focused on Fundamentals & review of detector landscape

### 2021
- Project started on February 2020
- First device fabrication started in June 2021

### 2022
- Collaboration with UCSC started in April 2022
- New CVD system delivered & Second device fabricated in summer 2022
- Second device fabricated in summer 2022

### 2023
- Testing second devices

### 2024
- Coming soon: Additional publications + Thin film detector V.2 with in-house deposited thin films

**Affiliation**
- **UIC**
- **ANL**
- **UCSC**
- **NST/CNM**

CPAD Workshop 2023 – Sungjoon Kim
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)
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

- **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

**Optical image and data from UCSC team**

*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 architecture*
Organo-Metallic Chemical Vapor Deposition System

- Crystalline $\Rightarrow$ 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

Tri-methyl indium

$$\text{H}_3\text{C} \rightleftharpoons \text{In} \rightleftharpoons \text{CH}_3$$

Phosphine

$$\text{H}_3\text{P} \rightleftharpoons \text{H}$$

Chemical precursors for InP CVD

Located at Argonne Micro Assembly Facility
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**
Thank you for your attention!

### Acknowledgements

- This project was funded by **Argonne National Laboratory**
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- 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

- Evolution of silicon sensor technology in particle physics – Frank Hartmann, Springer
- Atlas technical design report, 10.17181/CERN.FOZZ.ZP3Q
- [https://www.mks.com/n/cvd-physics](https://www.mks.com/n/cvd-physics)

Interested? We are looking for collaborators!

golite31@gmail.com & jmetcalfe@anl.gov
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
### Table 1: The stack-up for a single detector layer made using thin film techniques.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>thickness [μm]</th>
<th>$X_0$ [cm]</th>
<th>$X/X_0$</th>
<th>$\lambda_0$ [cm]</th>
<th>$\lambda/\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>PET</td>
<td>250</td>
<td>29</td>
<td>0.088%</td>
<td>60.6</td>
<td>0.041%</td>
</tr>
<tr>
<td>Sensor</td>
<td>InSb</td>
<td>10</td>
<td>15</td>
<td>0.0065%</td>
<td>46.8</td>
<td>0.0021%</td>
</tr>
<tr>
<td>Electronics</td>
<td>InGaZnO</td>
<td>200</td>
<td>10</td>
<td>0.20%</td>
<td>45.0</td>
<td>0.044%</td>
</tr>
<tr>
<td>1st Via</td>
<td>Cu/dielectric</td>
<td>100</td>
<td>29</td>
<td>0.035%</td>
<td>60.2</td>
<td>0.017%</td>
</tr>
<tr>
<td>Electronics</td>
<td>InGaZnO</td>
<td>200</td>
<td>10</td>
<td>0.20%</td>
<td>45.0</td>
<td>0.044%</td>
</tr>
<tr>
<td>2nd Via</td>
<td>Cu/dielectric</td>
<td>100</td>
<td>25</td>
<td>0.04%</td>
<td>51.2</td>
<td>0.020%</td>
</tr>
<tr>
<td>Transmission</td>
<td>Cu/dielectric</td>
<td>250</td>
<td>20</td>
<td>0.13%</td>
<td>45.4</td>
<td>0.055%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.70%</strong></td>
<td></td>
<td><strong>0.22%</strong></td>
</tr>
</tbody>
</table>

A rough estimation of the radiation length, $X_0$, and the nuclear interaction length, $\lambda_0$, 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.
- **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**

<table>
<thead>
<tr>
<th>Material</th>
<th>Carrier type and mobility [cm^2/\text{V} \cdot \text{s}]</th>
<th>Thickness [\mu\text{m}]</th>
<th>Applied bias [\text{V}]</th>
<th>Front side electrode dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP</td>
<td>$e^-$, 2650</td>
<td>350</td>
<td>-250</td>
<td>$200 \times 200 \mu\text{m}$</td>
</tr>
<tr>
<td>Cd$<em>{0.96}$Zn$</em>{0.04}$Te</td>
<td>$e^-$, 1350$^*$</td>
<td>1000</td>
<td>-650</td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>$h^+$, 1600$^*$</td>
<td>500</td>
<td>700</td>
<td></td>
</tr>
</tbody>
</table>

*Literature values
# QUALITY TEST REPORT

**Description:** 2" InP wafers  
**Customer:** ARGONNE NATIONAL LABORATORY  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Customer's Requirements</th>
<th>Guaranteed / Actual Values</th>
<th>UOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>InP</td>
<td>InP</td>
<td></td>
</tr>
<tr>
<td>Conduct Type/Dopant</td>
<td>Si/Fe</td>
<td>Si/Fe</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>60.8±0.2</td>
<td>60.8±0.2</td>
<td>mm</td>
</tr>
<tr>
<td>Orientation</td>
<td>(100)±0.5°</td>
<td>(100)±0.5°</td>
<td></td>
</tr>
<tr>
<td>Flat Option</td>
<td>EJ</td>
<td>EJ</td>
<td></td>
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<tr>
<td>Primary Flat Orientation:</td>
<td>(0-1-1)</td>
<td>(0-1-1)</td>
<td></td>
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<tr>
<td>Primary Flat Length</td>
<td>16±1</td>
<td>16±1</td>
<td>mm</td>
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<tr>
<td>Secondary Flat Orientation:</td>
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<tr>
<td>Secondary Flat Length:</td>
<td>7±1</td>
<td>7±1</td>
<td>mm</td>
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<tr>
<td>Resistivity</td>
<td>Min: 1E7</td>
<td>Min: 1.96E7</td>
<td>cm²</td>
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<tr>
<td>Mobility</td>
<td>Min: 2000</td>
<td>Min: 2650</td>
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<tr>
<td>EPD</td>
<td>Ave: &lt;5000</td>
<td>Ave: &lt;2251</td>
<td>cm²</td>
</tr>
<tr>
<td>Laser Marking</td>
<td>Back side major flat</td>
<td>Back side major flat</td>
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</tr>
<tr>
<td>Edge Rounding</td>
<td>0.25 (Conform to SEMI Standards)</td>
<td>0.25 (Conform to SEMI Standards)</td>
<td>mmR</td>
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<tr>
<td>Thickness</td>
<td>Min: 325</td>
<td>Min: 325</td>
<td>um</td>
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<tr>
<td>TTV</td>
<td>Max: 10</td>
<td>Max: 10</td>
<td>um</td>
</tr>
<tr>
<td>BOW</td>
<td>Max: 10</td>
<td>Max: 10</td>
<td>um</td>
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<tr>
<td>Warp</td>
<td>Max: 15</td>
<td>Max: 15</td>
<td>um</td>
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<tr>
<td>Surface</td>
<td>Side 1 Polished Side 2 etched</td>
<td>Side 1 Polished Side 2 etched</td>
<td></td>
</tr>
<tr>
<td>Package</td>
<td>individual container filled with N₂</td>
<td>individual container filled with N₂</td>
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</tr>
<tr>
<td>Epi-ready</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Quantity</td>
<td>5</td>
<td>5</td>
<td>pcs</td>
</tr>
</tbody>
</table>


Prepared by Ximing Zhang  
Checked by Wenyuan Liu (ID 00401)  
SEP 03, 2021  
Approved by Shipeng Wang  
SEP 03, 2021
Supplementary – Effects of Cooling on Current – Voltage (I-V) Curves

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

Absolute current (A) vs Bias (V) for different temperatures: 25 °C, 0 °C, -25 °C.
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

[Supplementary - Thin film synthesis]

- 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