Microstructured Semiconductor Neutron Detectors (MSND) and Instrumentation


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1. **MSND Recap** – Benefits over thin-film-coated devices.


3. **Helium Replacement (HeRep)** – Direct replacement designs.

4. **Arrayed MSNDs** – Pixelated and large-area neutron detectors.


**Thin-Film Coated Neutron Detectors**

- Mass-producible, inexpensive, compact, rugged, low-voltage operation.

- **Limited Neutron Efficiency (4-5%)**

**Microstructured Semiconductor Neutron Detectors (MSNDs)**

- Mass-producible, inexpensive, compact, rugged, low-voltage operation.

- **Greater Neutron Efficiency (>45%)**
1. MSND Recap – Benefits over thin-film-coated devices.


3. Helium Replacement (HeRep) – Direct replacement designs.

4. Arrayed MSNDs – Pixelated and large-area neutron detectors.


6. DSMSNDs – Dual-sided Microstructured Semiconductor Neutron Detectors.
Diode fabrication

- **12** 4cm² MSNDs fabricated per single 4-inch (110)-oriented silicon wafer.
- **56** 1cm² MSNDs per 4-inch wafer.
- Up to **50** wafers can be processed simultaneously.
- Good diffusion in new furnace led to leakage current measurements of \(\sim 5 \text{nA/cm}^2\) at -3V bias.
- Current record for single, un-stacked, device: **30.1±0.5%**
Mounting Fabricated MSNDs

- MSND size has ranged from 0.25 cm$^2$ to 4 cm$^2$.
- Methods for mounting MSNDs to electronics has varied, but typically a disposable intermediate board is used.
Domino (2014)

• A standard modular device that is mass producible and houses one MSND.
• Individual Dominoes can be tiled together to form meter-long strings; strings can then be grouped together to form blades of detectors.
• Powered by a 1-3V input, draws ~3mW, weighs ~9 grams.
• Typically 20% intrinsic thermal neutron detection efficiency; 1:10^6 gamma-rejection ratio.

- IEEE 802.15.4 compliant
- Onboard Atmel 128 processor
- Modular and expandable
- 50,000 cps
- 20-30m indoor range
- 70-100m outdoor range
1. **MSND Recap** – Benefits over thin-film-coated devices.


3. **Helium Replacement (HeRep)** – Direct replacement designs.

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**3He Direct Replacement (HeRep Mk I and Mk II)**

- Designed to directly replace a standard $^3$He proportional counter:
  - 4 atm, 2-in. diameter by 6-in. long.
- Can contain moderator inside of device.
- Strips of MSNDs are arranged to eliminate streaming between strips.
HeRep Mk I (2011)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSND Area</td>
<td>1 cm²</td>
</tr>
<tr>
<td>Num. of MSNDs</td>
<td>64</td>
</tr>
<tr>
<td>Total Act. Area</td>
<td>64 cm²</td>
</tr>
<tr>
<td>Eff. Of MSNDs</td>
<td>7% @ ≥500keV LLD</td>
</tr>
<tr>
<td>Voltage</td>
<td>12V</td>
</tr>
</tbody>
</table>

- Comparing to a **4 atm** ³He tube (a **3800 ng** ²⁵²Cf source was placed **2 m** from the face of each detector and measured for 30 min.

- HeRep was only as good as its weakest diode; there were many diodes present, making setting the LLD difficult.

<table>
<thead>
<tr>
<th>Device</th>
<th>Relative to ³He</th>
</tr>
</thead>
<tbody>
<tr>
<td>³He Tube: HDPE</td>
<td>100.0%</td>
</tr>
<tr>
<td>HeRep Mk I: HDPE</td>
<td>~70 %</td>
</tr>
</tbody>
</table>
HeRep Mk II (2013)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSND Area</td>
<td>4 cm²</td>
</tr>
<tr>
<td>Num. of MSNDs</td>
<td>30</td>
</tr>
<tr>
<td>Total Act. Area</td>
<td>120 cm²</td>
</tr>
<tr>
<td>Eff. Of MSNDs</td>
<td>20% @ ≥500keV LLD</td>
</tr>
<tr>
<td>Voltage</td>
<td>12V</td>
</tr>
<tr>
<td>Power</td>
<td>30mA (Resting); ~130mA (Max)</td>
</tr>
</tbody>
</table>

- Comparing to a **4 atm** \(^3\)He tube (a **60 ng** \(^{252}\)Cf source was placed **1 m** from the face of each detector and measured for 30 min.

- Gamma-ray rejection ratio: ~2-7x10\(^{-5}\), 14 mR/hr

<table>
<thead>
<tr>
<th>Device</th>
<th>Count Rate (cps)</th>
<th>Relative to (^3)He</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^3)He Tube: HDPE</td>
<td>17.13±0.099</td>
<td>100.0%</td>
</tr>
<tr>
<td>He-Rep: HDPE</td>
<td>17.60±0.102</td>
<td>102.74 ± 2.65%</td>
</tr>
<tr>
<td>(^3)He Tube: Bare</td>
<td>3.35±0.046</td>
<td>100.0%</td>
</tr>
<tr>
<td>He-Rep: Bare</td>
<td>3.19±0.050</td>
<td>95.15 ± 9.04%</td>
</tr>
</tbody>
</table>
1. **MSND Recap** – Benefits over thin-film-coated devices.


3. **Helium Replacement (HeRep)** – Direct replacement designs.

4. **Arrayed MSNDs** – Pixelated and large-area neutron detectors.


2-Dimensional Array (2011)

- Comprised of 25 thin-film-coated neutron detectors.
  - Used for calibration of diffracted thermal neutron beam.
**Arrayed 6x6 Dual-Stacked Design (2011)**

- Arrays can be linked together to function as a single larger unit.
  - Devices can read out individually or sum together as a single detector.
  - If one unit becomes inoperable, it can be easily replaced.
Panel Array Mk I (2012)

- 4x4 Array Elements are tiled together to form a modular large-area neutron detector.
- Tested using a $^{252}$Cf source with an applied voltage of $\pm 8\text{V}$.
  - Reported count rate of 0.2 cts/s per ng of $^{252}$Cf at 2 meters. (215 kcts Per 5 minutes)
Panel Array Mk II (2013)

- Contains 480 4cm$^2$ Dominoes, each with $\epsilon_{th} \approx 15\%$
- Total area, including moderator: 3 ft. x 3 ft.
- Total Thickness: 3 in.
  - HDPE Thickness: 1 in. front, 1.5 in. back (internal).
- Each string is read out individually; summed via software.
## Gen. 2 Panel Array – Testing

* Denotes testing in hallway; likely leading to artificial increase in count-rate

<table>
<thead>
<tr>
<th>Distance</th>
<th>Count Rate (s⁻¹)</th>
<th>Count Rate (s⁻¹ ng⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Meter</td>
<td>172.48 ± 0.76</td>
<td>3.15 ± 0.014</td>
</tr>
<tr>
<td>2 Meters</td>
<td>79.57 ± 0.52</td>
<td>1.45 ± 0.009</td>
</tr>
<tr>
<td>5* Meters</td>
<td>24.60 ± 0.21</td>
<td>0.45 ± 0.004</td>
</tr>
<tr>
<td>10* Meters</td>
<td>6.098 ± 0.066</td>
<td>0.111 ± 0.001</td>
</tr>
<tr>
<td>Background Rm2 / Hallway</td>
<td>0.811 ± 0.021</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>0.893 ± 0.022</td>
<td></td>
</tr>
</tbody>
</table>

**Panel Array Static Absolute Efficiency**

- Detector Response (cps ng⁻¹)
- Source Distance from Detector (m)

![Diagram of panel array and testing setup]
Gen. 2 Panel Array – Testing

- **Angle Test**
  - Panel Array was kept in place and rotated for each test; distance to source was 2 meters.
  - Area corrections were not made.

### Panel Array Angular Dependence

<table>
<thead>
<tr>
<th>Angle</th>
<th>Percent of 2 meter measurement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>100 %</td>
</tr>
<tr>
<td>30°</td>
<td>98.70 %</td>
</tr>
<tr>
<td>45°</td>
<td>94.52 %</td>
</tr>
<tr>
<td>60°</td>
<td>75.65 %</td>
</tr>
<tr>
<td>90°</td>
<td>55.73 %</td>
</tr>
</tbody>
</table>
Briefcase Detector

- The briefcase is powered with 12V.
- The current design weighs **21 lbs**. Contains **84 Dominoes** at ~15% efficiency each.
- Data is output via a 5V TTL pulse.
<table>
<thead>
<tr>
<th>Distance</th>
<th>Count Rate (s⁻¹)</th>
<th>Count Rate (s⁻¹ ng⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Meter</td>
<td>29.76±1.16 cps</td>
<td>~0.54</td>
</tr>
<tr>
<td>2 Meters</td>
<td>14.65±0.57 cps</td>
<td>~0.27</td>
</tr>
<tr>
<td>5* Meters</td>
<td>4.39±0.17 cps</td>
<td>~0.08</td>
</tr>
</tbody>
</table>

* Denotes testing in hallway; likely leading to artificial increase in count-rate.
1. **MSND Recap** – Benefits over thin-film-coated devices.


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4. **Arrayed MSNDs** – Pixelated and large-area neutron detectors.


Portable Spectrometer

• Light weight (~10 lbs.) portable neutron spectrometer that is populated with 9-11 Dominoes.
• Spectrometer interrogates a source until a $FOM$ is reduced to where identification can be made.
• $FOM$ is found by comparing response to onboard template matching.
• Efficiency of current design can be greatly improved by implementing more Dominoes.
• Designed For S.A.N.S.
  – Extremely fine resolution
  – 32 Channels
  – >10% Efficient
  – <10^6 Dead-time (sensors)
• Prototype of larger array
  – 32, 64, 1024 Channel
  – Demonstrated: SNS-ORNL
1. **MSND Recap** – Benefits over thin-film-coated devices.


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Double-stacking MSNDs

- Neutrons streaming through silicon sidewalls are made incident on a second MSND.
- Thermal neutron absorption efficiency ~93% (53% for single device).
- **42.0±0.25%** intrinsic thermal neutron detection efficiency achieved. (300 keV LLD)

- Difficult to stack properly (misalignment, off rotationally, etc.).
- Device mismatching leads to poor signal integration.
- Double the capacitance, double the leakage current.
Dual-Side Etched MSND Devices (DSMSNDs)

- **Dual-Sided Device Characteristics**
  - Devices are fabricated exactly as single-sided devices.
  - Capable of batch processing; +50 per wafer, 50 wafers per batch capable.
  - High detection efficiency is possible with opposing DSMSND design; >79% intrinsic detection efficiency.
  - Fast charge-collection is possible with some designs; < 100 ns integration time.

Dual-Sided MSND Prototype Future Improvements

- Charge-collection efficiency must be improved
- Device mass-fabrication must be perfected
  - Etching imperfections on front and/or backside can render the diode useless.
- Device depletion is not entirely understood; depletion region may not reach backside contact.
- 4 cm² diodes must be fabricated to increase absolute sensitivity and reduce complexity.

<table>
<thead>
<tr>
<th>Off-Set Dual-Sided MSND, Straight Trench, 6-LiF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{T}{W_{\text{Cell}}}$</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Trench depth $H = 500$ um</td>
</tr>
<tr>
<td>0.10</td>
</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.30</td>
</tr>
<tr>
<td>0.40</td>
</tr>
<tr>
<td>0.50</td>
</tr>
<tr>
<td>0.60</td>
</tr>
<tr>
<td>0.70</td>
</tr>
<tr>
<td>0.80</td>
</tr>
<tr>
<td>0.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Off-Set Dual-Sided MSND, Straight Trench, 10-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{T}{W_{\text{Cell}}}$</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Trench depth $H = 60$ um</td>
</tr>
<tr>
<td>0.10</td>
</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.30</td>
</tr>
<tr>
<td>0.40</td>
</tr>
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<td>0.50</td>
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<tr>
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</tr>
<tr>
<td>0.80</td>
</tr>
<tr>
<td>0.90</td>
</tr>
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</table>
Thank you for your attention.
Questions?

rfronk@ksu.edu

http://www.ksu.edu/smartlab
Discussion Slides
1. The $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction – inexpensive, good $\sigma$, short ranges
   
   $Q = 2.34 \text{ MeV (94%)} - 1.47 \text{ MeV } \alpha$, 840 keV Li ion
   $Q = 2.78 \text{ MeV (6%)} - 1.78 \text{ MeV } \alpha$, 1.02 MeV Li ion
   $\sigma_{th} = 3840 \text{ barns}$

2. The $^6\text{Li}(n,\alpha)^3\text{H}$ reaction – inexpensive, lower $\sigma$, longer ranges
   
   $Q = 4.78 \text{ MeV (100%)} - 2.05 \text{ MeV } \alpha$, 2.7 MeV $^3\text{H}$ ion
   $\sigma_{th} = 940 \text{ barns}$

3. The $^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$ reaction – expensive, high $\sigma$, short ranges
   
   Energetic conversion electrons, emits only low energies between 70 keV - 220 keV (low particle yield)
   $\sigma_{th} = 250,000 \text{ barns}$
For Si, the cross over for Compton scattering to dominate interactions above photoelectric is at approximately 60 keV. We usually set the lower level discriminator at or above 5 times this value (> 300 keV) to reduce gamma ray background.

Photoelectrons or Compton electrons with energies above 65 keV have transit lengths in Si >40 microns, a dimension larger than the lateral dimensions of the $^6$LiF filled trench devices!
Thin-Film Coated Neutron Detectors

- Neutron-converter material converts neutrons into charged reaction products.
- Mass-producible, inexpensive, compact, rugged, low-voltage operation.
- Poor neutron absorption efficiency (<15%).
- Poor charged-particle counting efficiency.

- Limited Neutron Efficiency (4-5%)
Microstructured Semiconductor Neutron Detectors (MSNDs)

- Mass-producible, inexpensive, compact, rugged, low-voltage operation.
- Better neutron absorption efficiency (>52%).
- Better charged-particle counting efficiency.
- **Greater Neutron Efficiency (>45%)**

**Energy Deposition**
- Increased likelihood of energy deposition by reaction products; increases signal-to-noise ratio.

**Neutron Absorption**
- Increased neutron absorption increases count rate and therefore detection efficiency.
**Anisotropic Chemical (KOH) Wet Etching of (110) Si**

- **Benefits**
  - Better Uniformity Across Large Wafers
    - This Leads to Uniform Responses From Each Device in an Array!
  - Batch Wafer Processing (No Limit!)
    - Less Mechanical Damage than ICP RIE
  - 3 Different perforation designs
    - Straight Trench
    - Chevron Trench
    - Rhombus Hole/Pillar
Dual-Sided MSND Prototype Characterization

- Devices are tested for pass/fail prior to $^6$LiF backfilling based on diode characteristics
  - Leakage current vs. voltage (IV) curves are measured; $\leq 5 \text{nA cm}^{-2}$ at -3 V bias.
  - Capacitance vs. voltage (CV) curves are measured. $\leq 95 \text{pF}$ at -3 V bias.

CV-Testing

- Capacitance leads to weaker output signal as well as poor pre-amp coupling.
- Capacitance $< 150 \text{pF}$ is acceptable.

IV-Testing

- LC leads to high noise levels; difficulty in resolving signal.
- LC $< 50 \text{nA cm}^{-2}$ is typically acceptable.
### Sidewall Width vs Trench Width

**400 um Trenches, 40 um Pitch**

<table>
<thead>
<tr>
<th>Sidewall Width</th>
<th>10 um</th>
<th>12 um</th>
<th>14 um</th>
<th>16 um</th>
<th>18 um</th>
<th>20 um</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trench Width</td>
<td>30 um</td>
<td>28 um</td>
<td>26 um</td>
<td>24 um</td>
<td>22 um</td>
<td>20 um</td>
</tr>
<tr>
<td>Total Eff.</td>
<td>36.33%</td>
<td>35.29%</td>
<td>34.05%</td>
<td>32.61%</td>
<td>30.98%</td>
<td>29.19%</td>
</tr>
<tr>
<td>0.3 MeV LLD</td>
<td>34.04%</td>
<td>33.27%</td>
<td>32.27%</td>
<td>31.09%</td>
<td>29.66%</td>
<td>28.07%</td>
</tr>
<tr>
<td>0.5 MeV LLD</td>
<td>32.29%</td>
<td>31.94%</td>
<td>31.13%</td>
<td>30.12%</td>
<td>28.82%</td>
<td>27.36%</td>
</tr>
</tbody>
</table>

**Diagram:**
- **400 um Trenches, 40 um Pitch**
- Number of Source Particles (NPS) vs Energy (MeV)
- Lines represent different Sidewall Widths and Trench Widths.

**Legend:**
- 10 um Sidewall
- 12 um Sidewall
- 14 um Sidewall
- 16 um Sidewall
- 18 um Sidewall
- 20 um Sidewall
MSND Angular Efficiency Comparisons

Uniform parallel neutron beam

Neutron converter material

Semiconductor volume

Graph showing thermal neutron detection efficiency as a function of incident angle (degrees) for area-corrected and intrinsic efficiencies.
DSMSND Angular Efficiency Comparisons

400-um Deep Trenches, 40-um Pitch, 20-um Sidewalls

- MSND Eff.
- DSMSND Eff.
- DSMSND Avg. Eff.

Intrinsic Neutron Detection Efficiency

Incident Beam Angle

0 10 20 30 40 50 60 70 80 90

25% 30% 35% 40% 45% 50% 55% 60% 65% 70% 75%
**MSND Neutron Testing**

- Diffracted thermal neutron beam at KSU TRIGA Mark II Nuclear Reactor
  - Reactor Power – 0 to 500 kW
  - Thermal (0.0253 eV) Neutron Flux: $1.72 \times 10^2 \text{ n cm}^{-2} \text{ s}^{-1} \text{ kW}^{-1}$
  - Calibrated against $^3$He-Gas Detector

**MSND Gamma-ray Sensitivity**

- $^{137}$Cs source
  - γ-ray Energy: 662 keV
  - 1 meter from MSND
  - Assay: 68.27 mCi
  - Exposure: 21.8 mR hr$^{-1}$
  - 0.08 γ-ray μs$^{-1}$ (per 4-cm$^2$ area)
**Neutron Efficiency of 4-cm² MSND Detector**

- 4 cm² MSND, 440-µm deep trenches, 10-µs charge integration time.
  - \(30.1 \pm 0.5\%\) at a 650 keV LLD with normal beam incidence.
  - \(37.6 \pm 0.7\%\) at a 650 keV LLD with 45 deg. beam incidence.
**Stacked Perforation Design**: 10 µs preAmp integration time

Pulse height spectrum taken with a $^6$LiF-filled microstructured semiconductor neutron detector formed from stacked 1cm$^2$ devices. $42.0 \pm 0.25\%$ at a 300 keV LLD.
Gen. 2 Panel Array – Issues

- **Broken/Weak Wire-bonds**
  - Stresses on wire-bonds led to intermittent noise issues.
  - Could induce problem with heater gun or squeezing device near bond pad.
- **Cause:** Improper wire-bonding technique.
Gen. 2 Panel Array – Issues

- **Solder Pins**
  - Pins were soldered onto DDBs using low-cost lead-free solder.
  - Heating the pin while soldering the DDB to the Domino melted the low-cost solder, lifting the DDB from the board.
  - Pins and low-cost solder were removed and replaced with a ‘solder bump’.
- **Cause:** Poor materials quality.