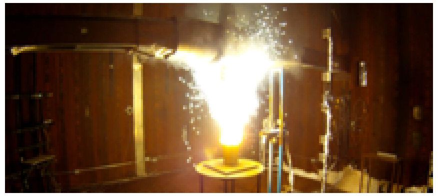
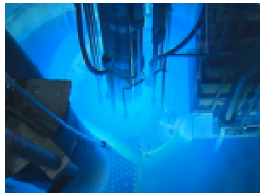
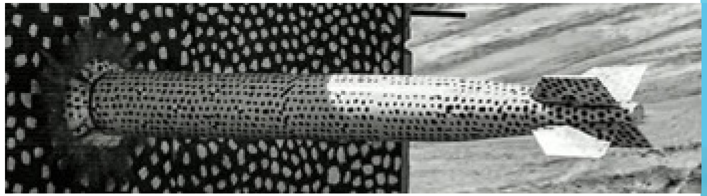
Sandia National Laboratories

SAND2020-11526C

Multi-Layered Solid-State Neutron Sensor

NSREC 2020 SANTA FE

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Motivation

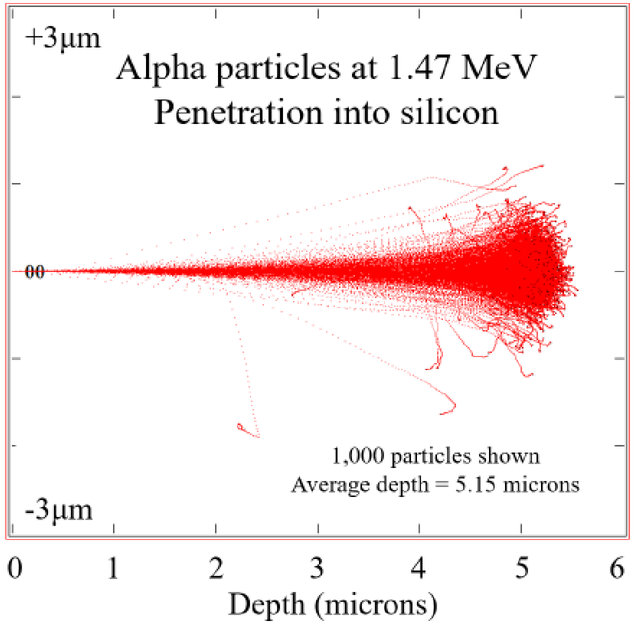
Neutron Detection is important for:
- Dosimetry for radiation experiments
- Radiation dose monitoring / Safety
- Non-proliferation
    - Identification and detection of special nuclear material
    - Discriminating neutrons from gamma radiation necessary

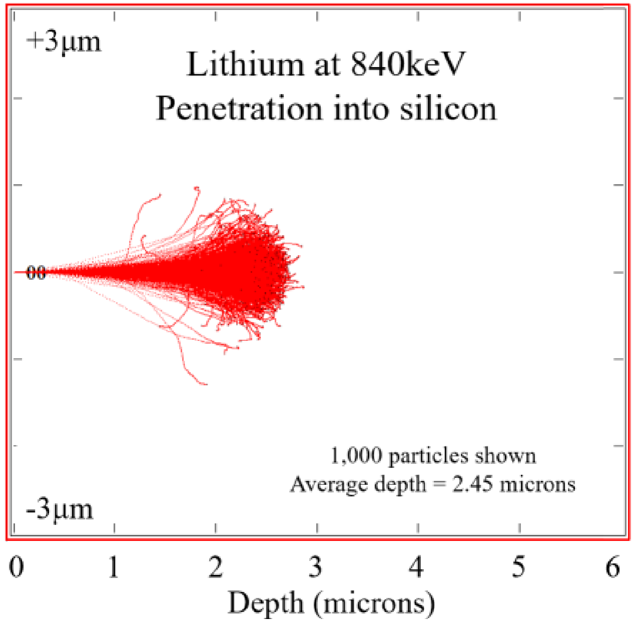
Current state-of-the-art:
- Radiation detectors are good for most radiation types except neutrons because of small interaction cross-sections
- Detection efficiencies are low (helium-3) requiring big volume detectors
- A small detector with size, weight and power advantages would provide an in-situ solution for experimentation dosimetry
- Solid-state neutron detectors exist, but designs have limitations.

Principle of Operation

Thermal neutron capture reaction by Boron-10 isotope:

- High reaction cross-section at ~3840 barns
- This reaction has historically been a problem. It's a well-known as a source of soft errors in microelectronics:
  - Boron is used as a p-type dopant in semiconductors
  - Boron-10 occurs in 20% of natural boron
  - Long and ongoing research effort (Auden, NSREC 2019)
- Many existing designs make use of the reaction for a sensor, including some commercial products





Advantages of Boron for sensing:

- Reaction products have high energies and penetrate into silicon (SRIM plots on right).
- 1.47 MeV alpha particle can generate >100,000 electron-hole pairs, which can be collected as electronic signal.

Neutron Capture Reaction

94%:

$^{10}B + \eta \rightarrow {}^{11}B \rightarrow {}^{7}Li + \alpha + \gamma$ (480keV)

E_α = 1.47 MeV

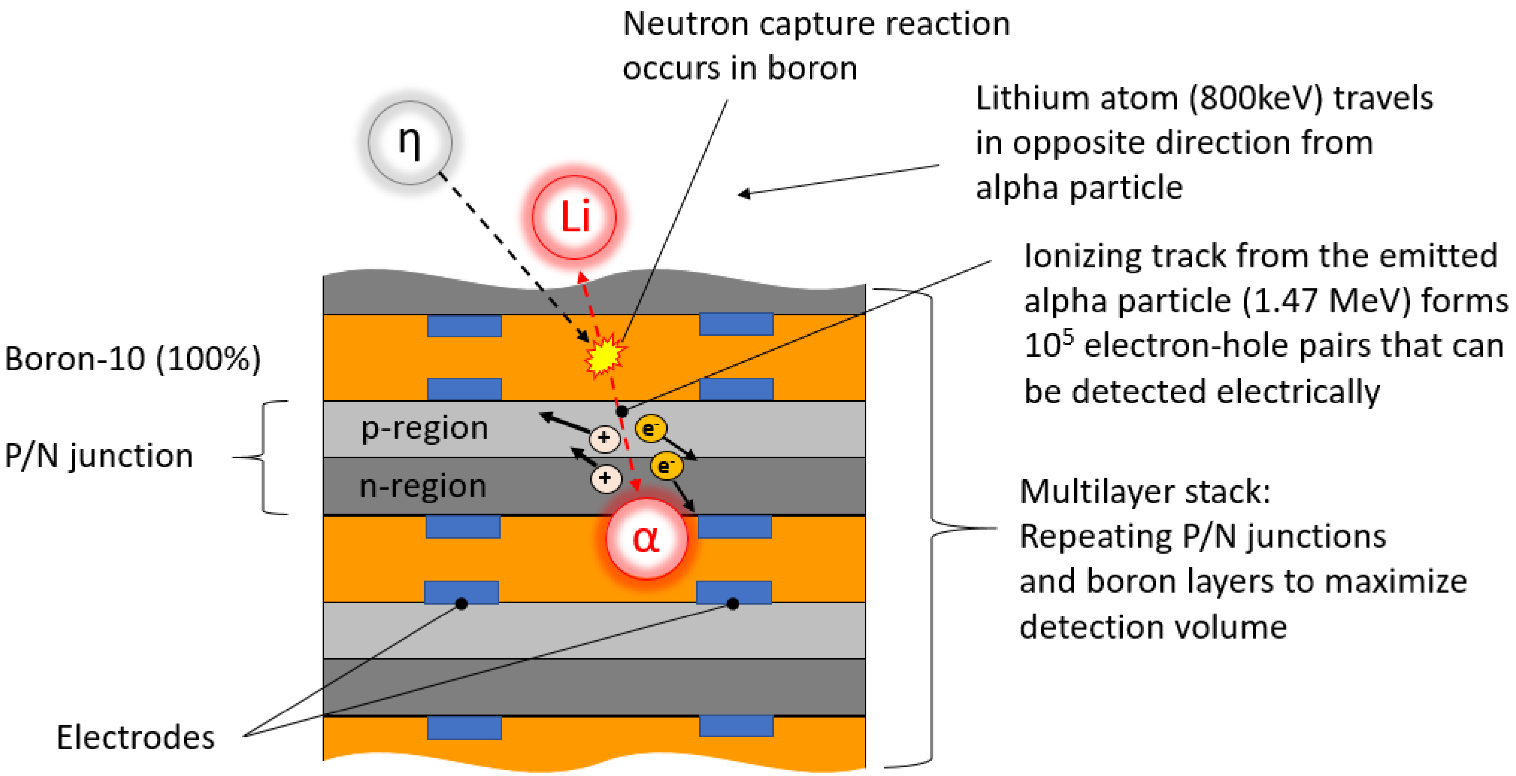
6%:

$^{10}B + \eta \rightarrow {}^{11}B \rightarrow {}^{7}Li + \alpha$

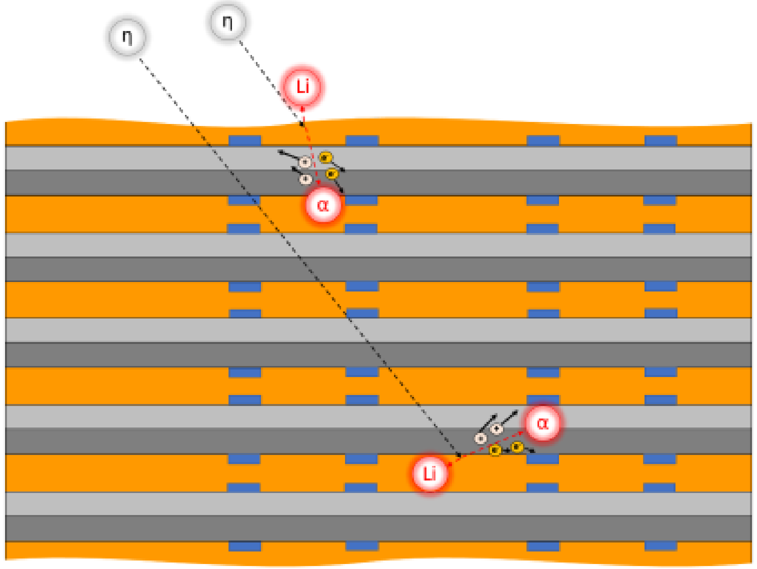
E_α = 1.78 MeV

Multi-Layered Stack Design

Layers alternating between:
Converter material (boron-10) and collector material (Si photodiode)



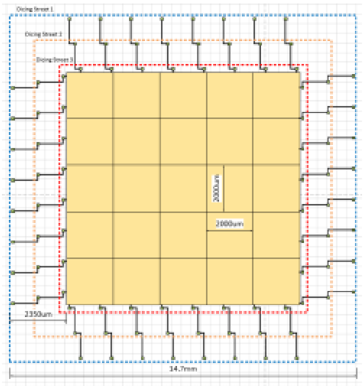
As the stack gets thicker, eventually all thermal neutrons are absorbed. at 40 layers, > 90% absorbed.



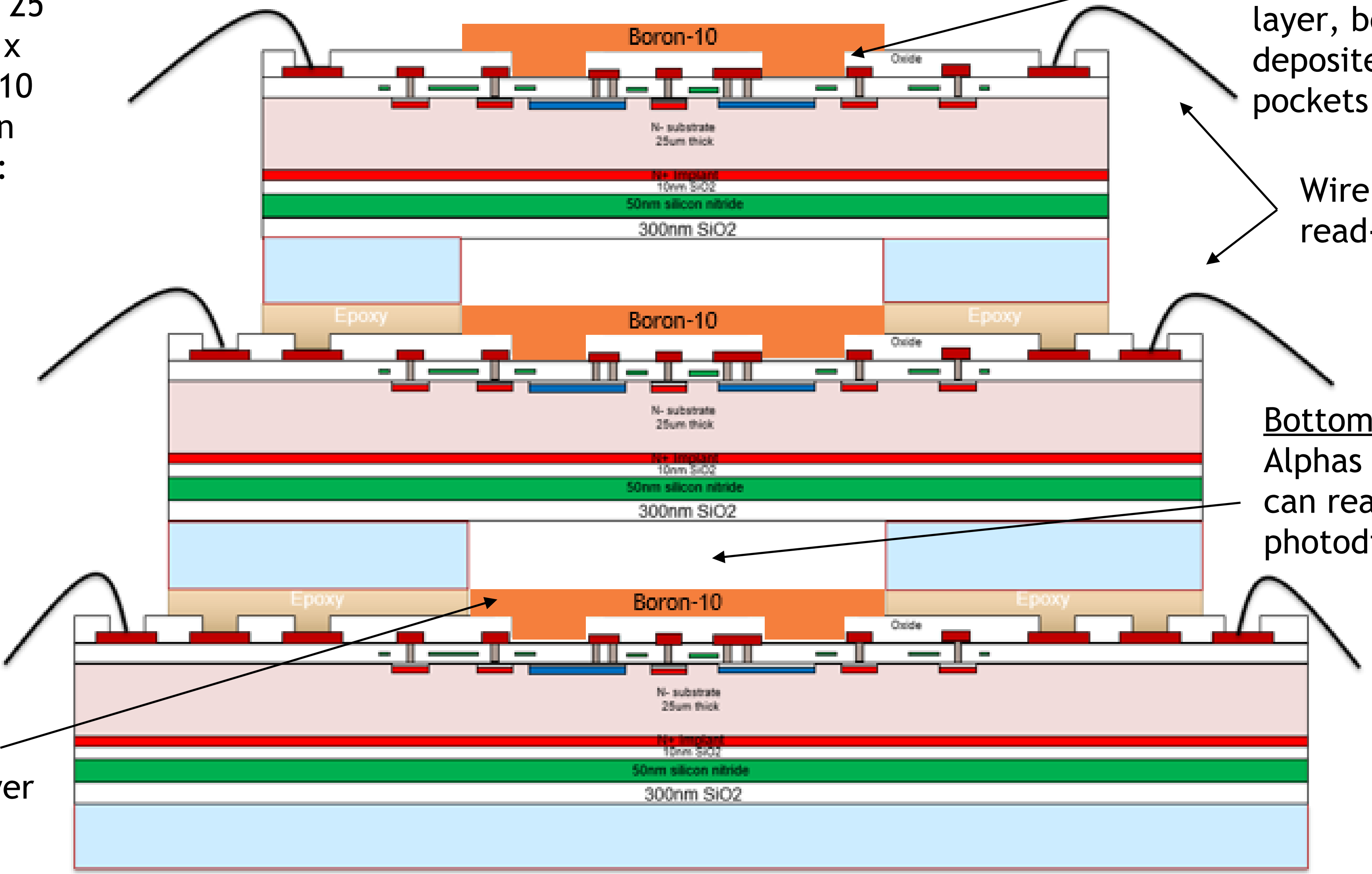
Objective: Make use of recent advances in die processing: heterogenous integration, die stacking, through silicon vias to make the stack as many layers as possible.

Prototype: Wedding Cake

Each 1 cm^2 layer has 25 photodiodes (200um x 200um), with boron-10 deposited in between the layers. Top view:



Photodiode array with staggered bond-out pattern for the layers.



Frontside pocket etches made into the oxide layer, boron-10 deposited into the pockets

Wire-bonds out to the read-out electronics

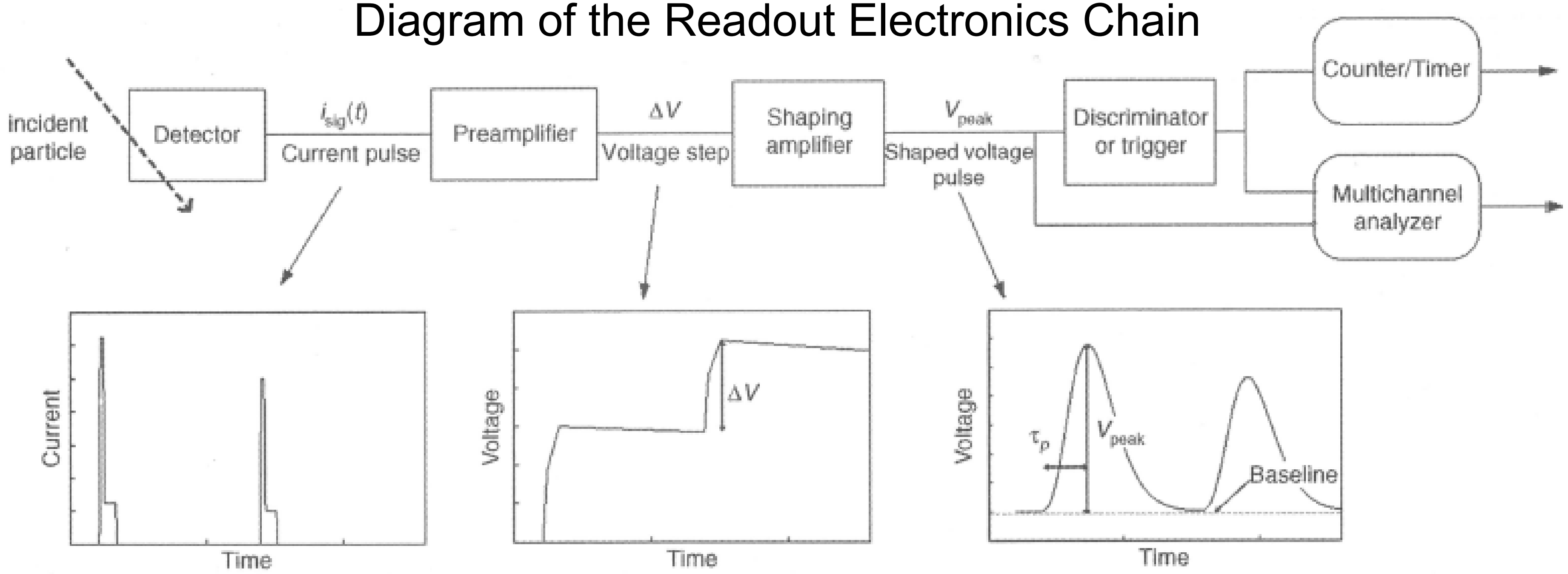
Bottom window etch: Alphas generated below can reach active photodiode layer above

Boron deposition: Problem of single-layer adhesion solved

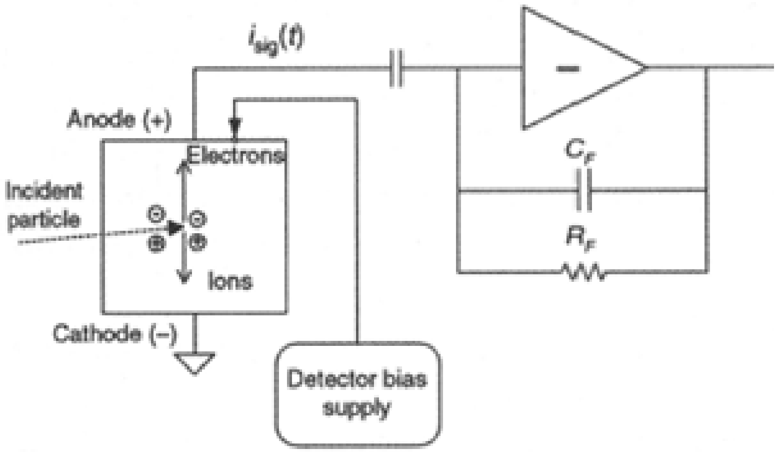
not to scale

Read-Out Electronics

Diagram of the Readout Electronics Chain



Detector Charge Sensitive PreAmplifier

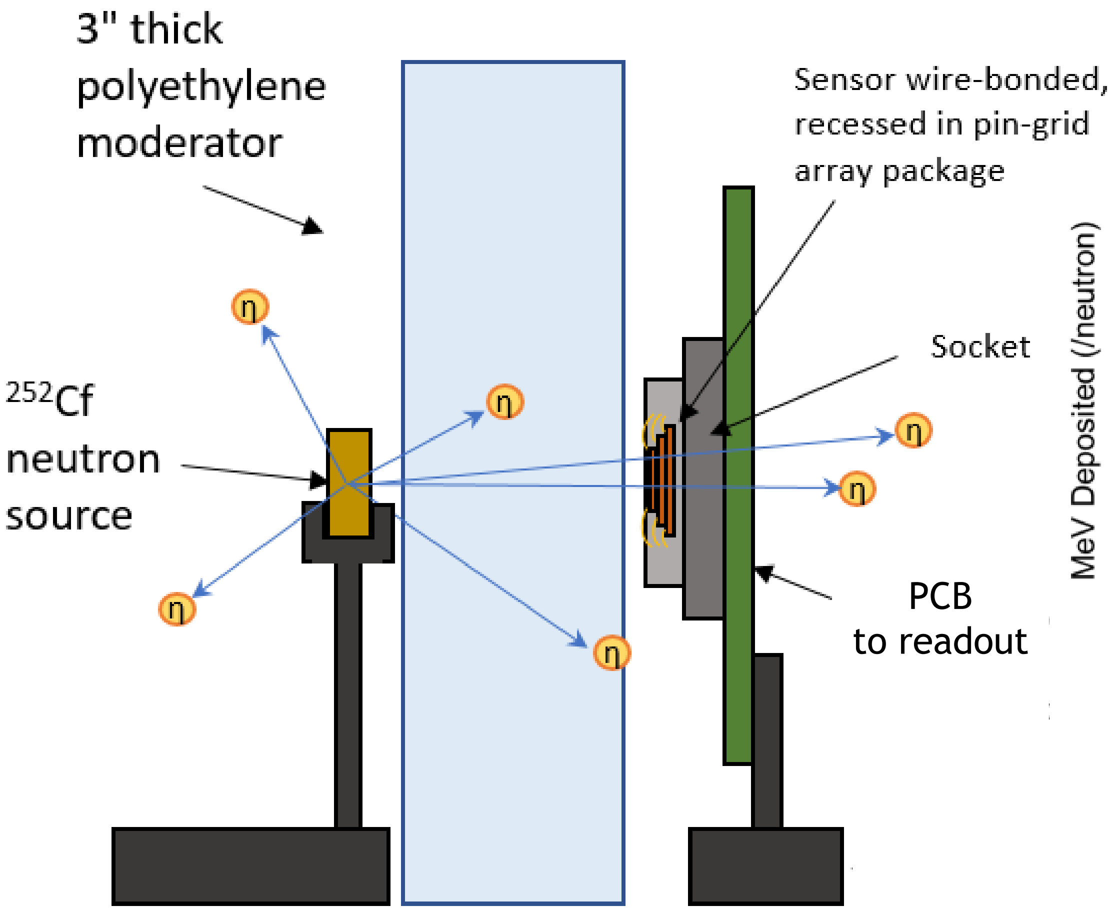


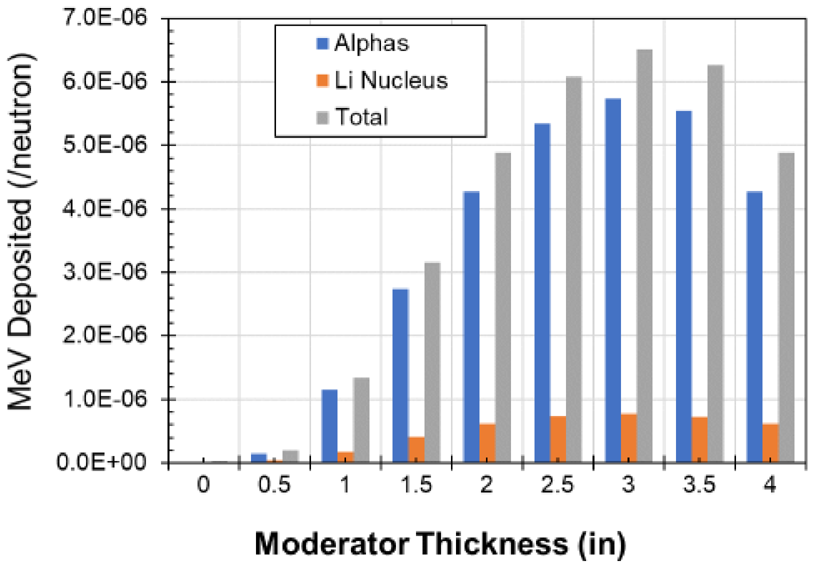
- A charge sensitive amplifier (CSA), shaping amplifier, and a Multi-channel Analyzer (MCA) were used for spectral analysis.
- CSA output voltage amplitude is tied to input signal via the transfer function $Vout \cong -Qin/Cf$ where V_{out} is the output voltage of the CSA, Q_{in} is the input charge, and C_f is the feedback capacitance.

G. F. Knoll, "Overview of Pulse Processing," in *Radiation Detection and Measurement*

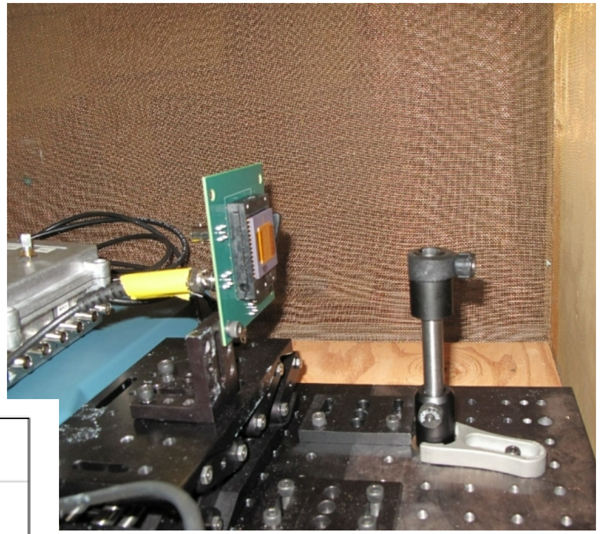
Experimental Set-Up

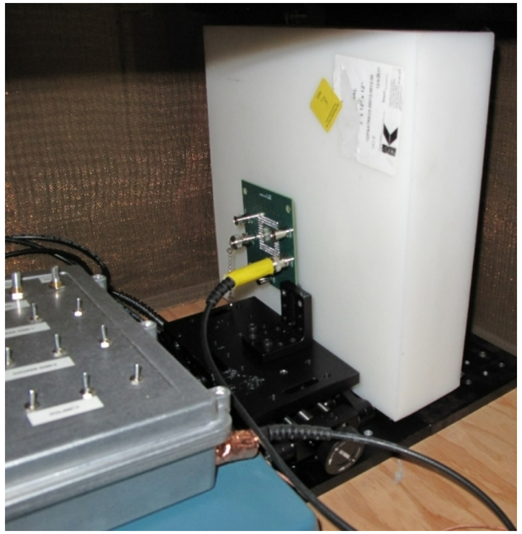
Two prototypes, a two-layer and a three-layer, were tested with a Cf-252 pellet neutron source.



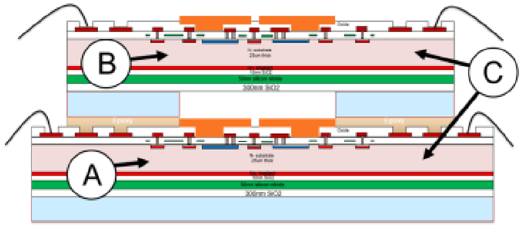


Energy deposition in silicon active layer of the sensor as a function of moderator thickness. Optimized at 3 inches thick (MCNP calculation).

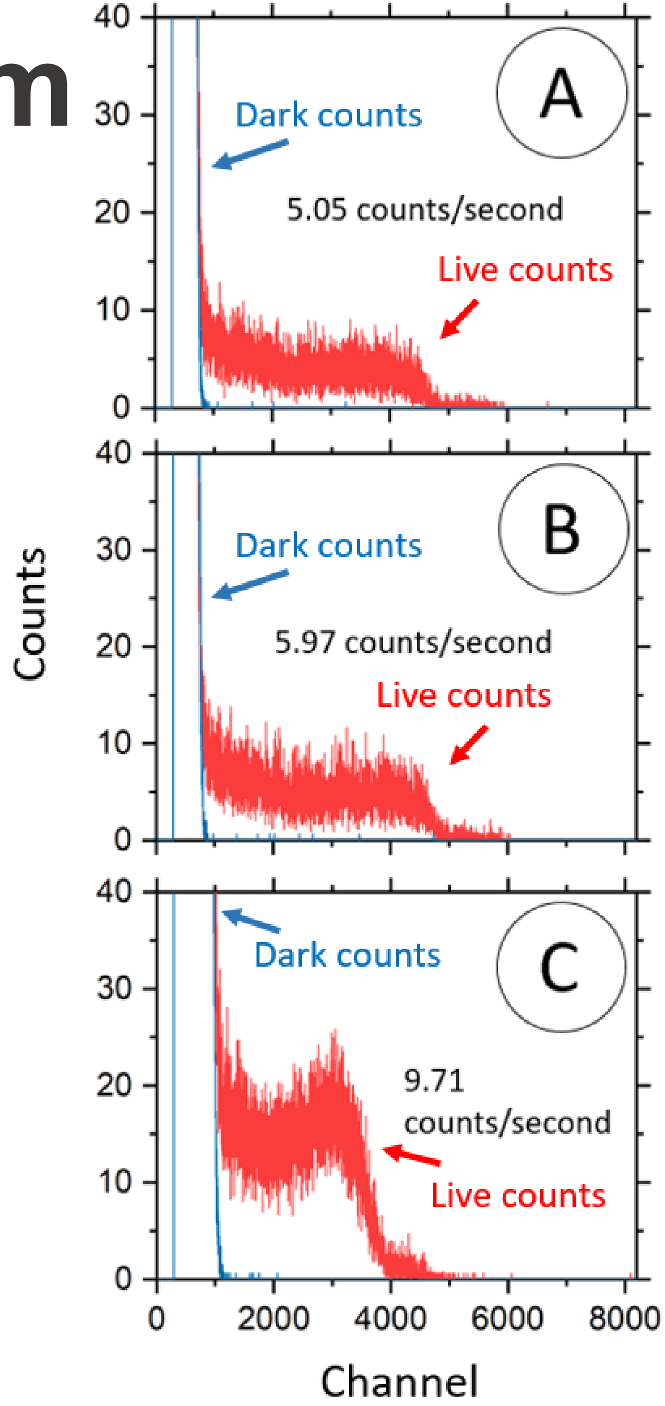


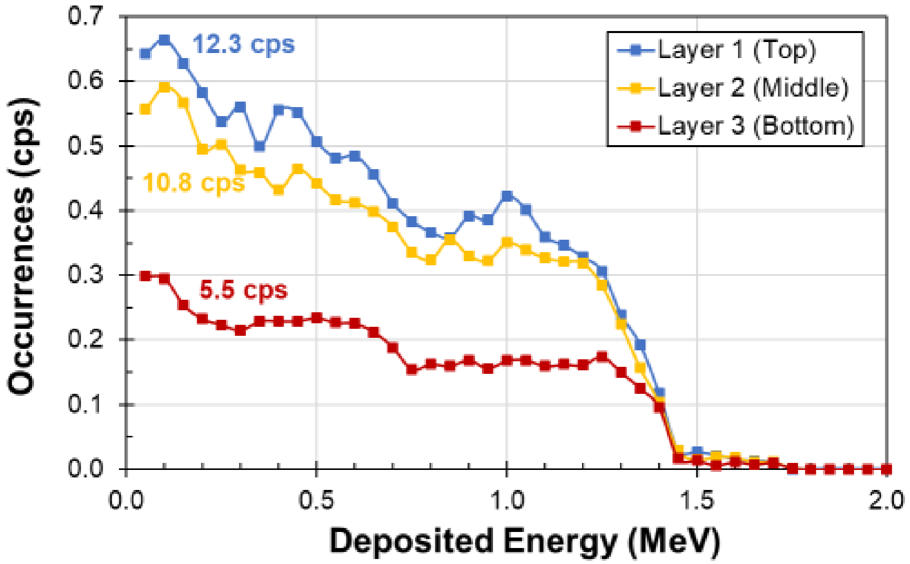


Results from 2-Layer Stack



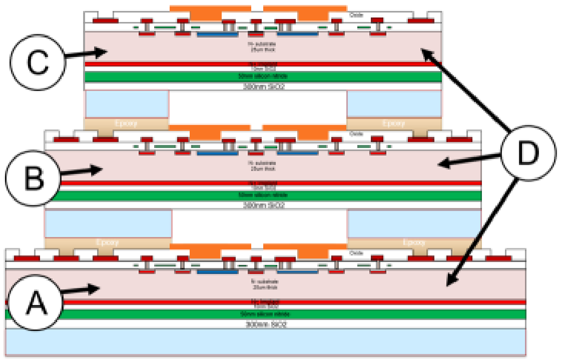
- Photodiodes were ***unbiased***.
- Dark counts were collected with no source present for one hour. Live counts collected with source present, also one hour.
- Dark counts are all below a certain threshold and go off the scale in plots (blue line). Live counts are detected neutrons and are shown in red.
- Top layer (B) has highest counts per second (cps) observed
- Combined measurement (C) produced 9.71 cps.





MCNP calculation of detectable events from a three-layer device. Plot is qualitatively similar to data collected, implying energy information can be determined with calibration.

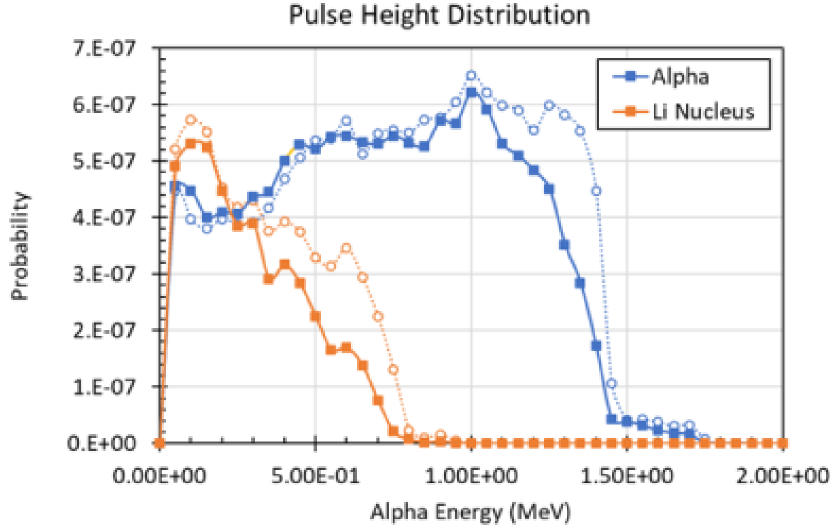
Results from 3-Layer Stack



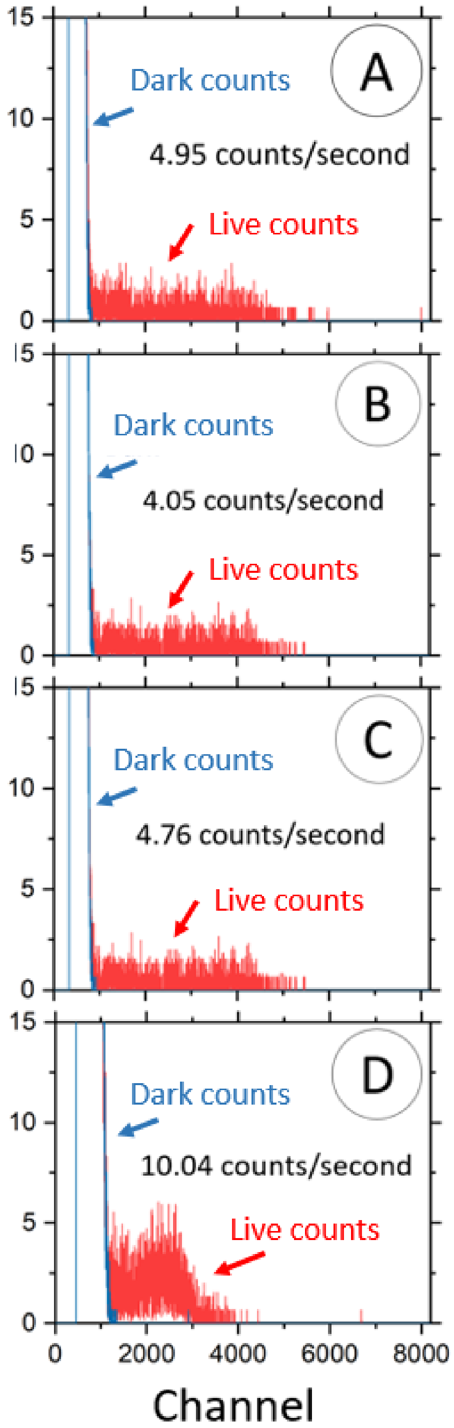
- Photodiodes were ***unbiased***.
- Dark counts were collected with no source present for 6 minutes. Live counts collected with source present, also for 6 minutes

Table 1: Radiation-induced deposition events above a threshold level for 1, 2, and 3 layer devices.

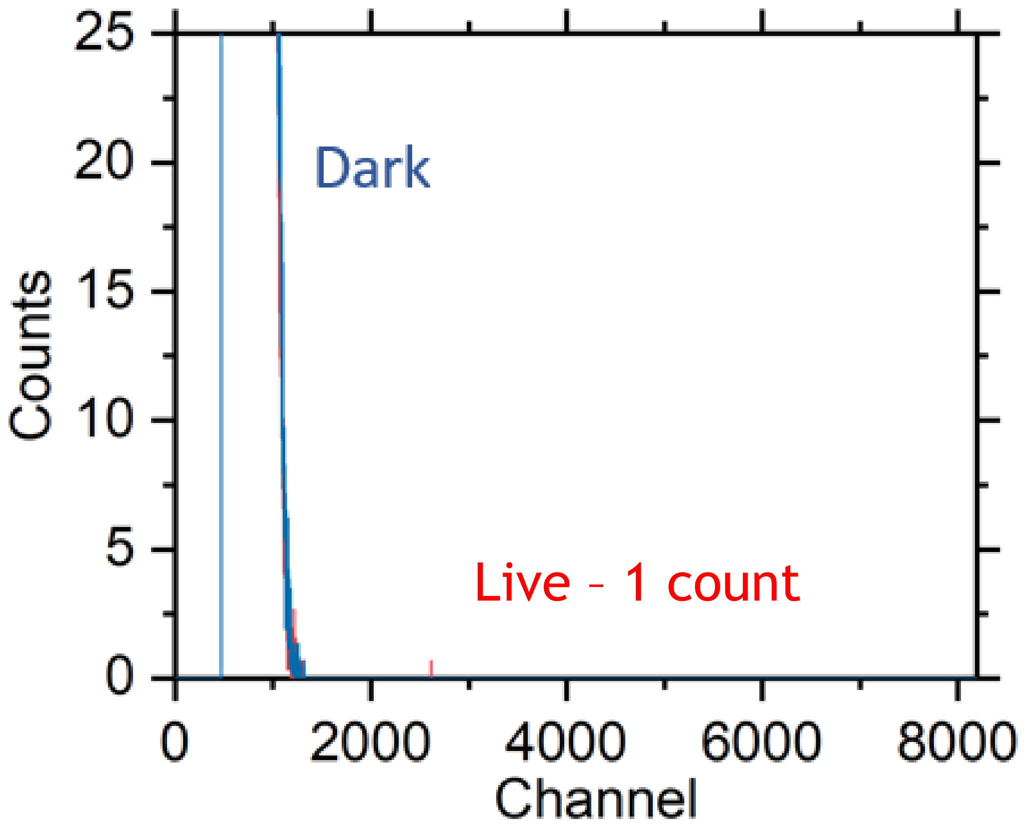
	1 Layer Device	2 Layer Device	3 Layer Device
Energy Cutoff	Events (cps)	Events (cps)	Events (cps)
Total	7.3	18.6	28.6
>100 keV	6.6	16.7	25.5
>250 keV	5.6	14.1	21.5
>500 keV	4.0	10.1	15.4
>1 MeV	1.6	3.8	5.9



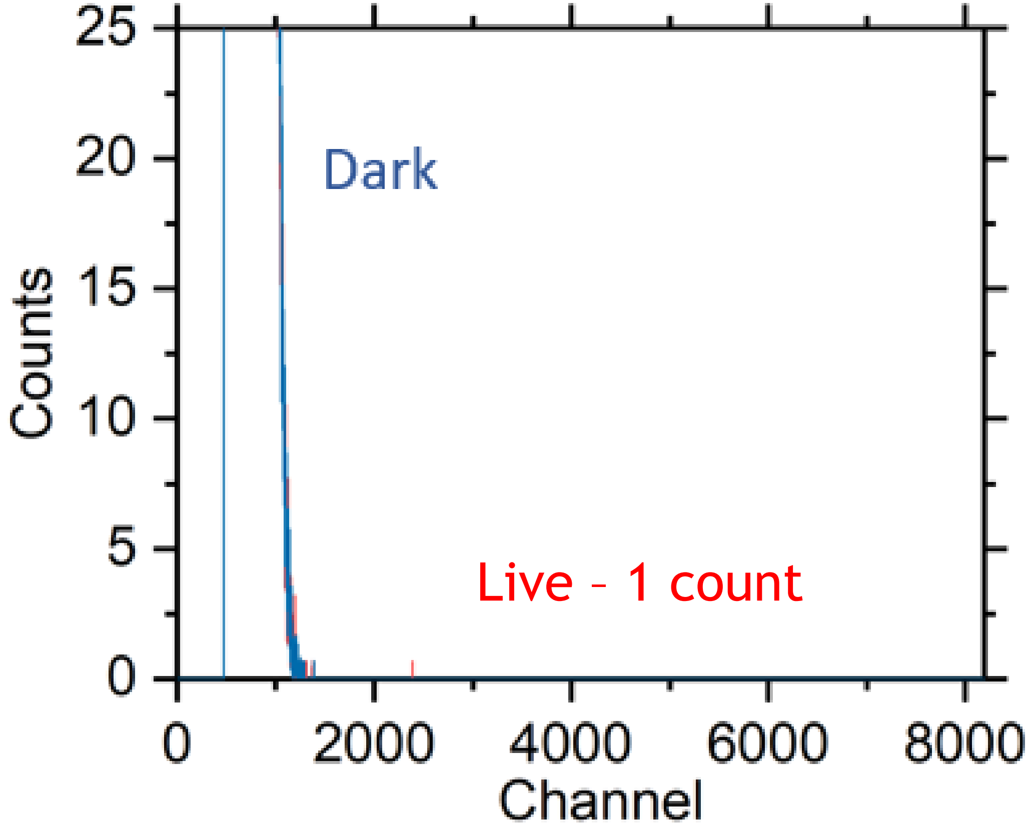
Energy distribution of reaction products shows potential to differentiate between alpha particles and lithium nuclei.



Gamma Insensitivity



124 µCi Ba-133 1” away for 6 minutes



87.3 µCi Cs-137 1” away for 6 minutes

Sensor demonstrates good insensitivity to gamma radiation (a single count was observed for two separate gamma sources using same test set-up but with moderator removed).

Summary

- The as-built 3-layer prototype of the multi-layered solid-state neutron sensor demonstrated a *21% efficiency* for detection of thermal neutrons entering the sensor. This is comparable to He-3 neutron detectors.
- Sensor has good gamma insensitivity.
- A stack that is heterogeneously integrated to form a 3-D array structure could be as large as a wafer and will have potential for directionality measurement. Efficiency greater than 70% is feasible for a 2mm device with low power requirements.
- These improvements will increase efficiency:
  - Reverse-biasing the diodes
  - Reduce pixel size to lower capacitance
  - On-chip processing of signals
  - Lowering the silicon photodiode active volume thickness from 25 microns to 7 microns (max. travel of alpha particle at normal incidence)