Lawrence Livermore National Laboratory

Si Based Pillar Structured Thermal Neutron Detectors

Funded by DHS/DNDO

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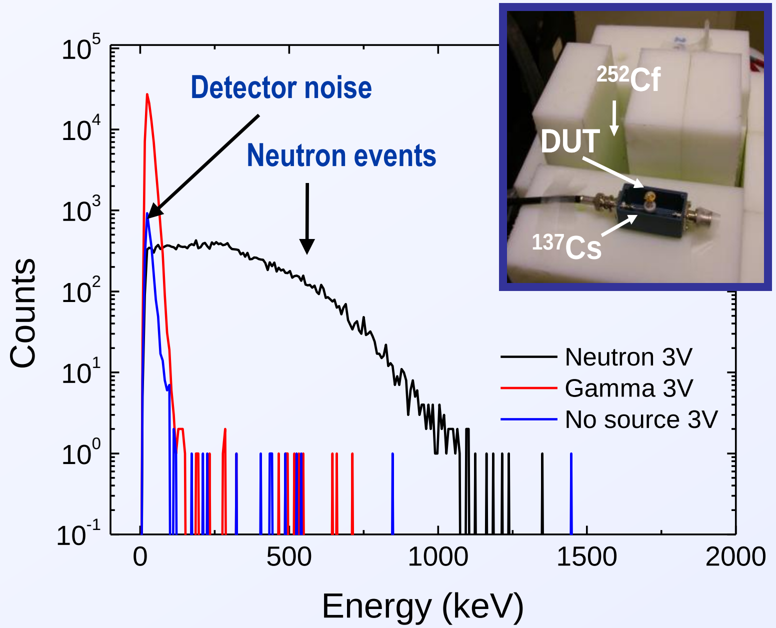
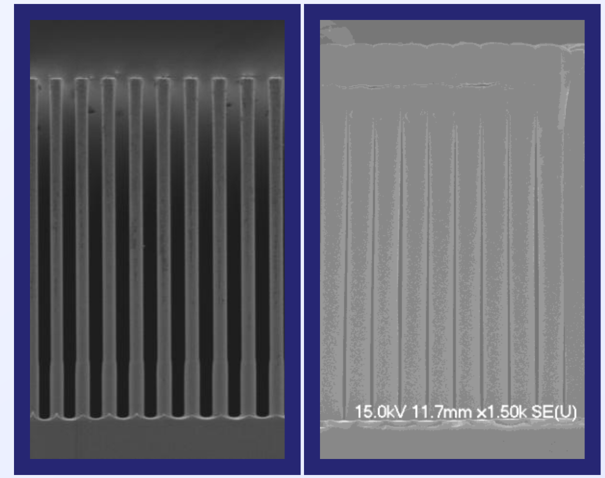
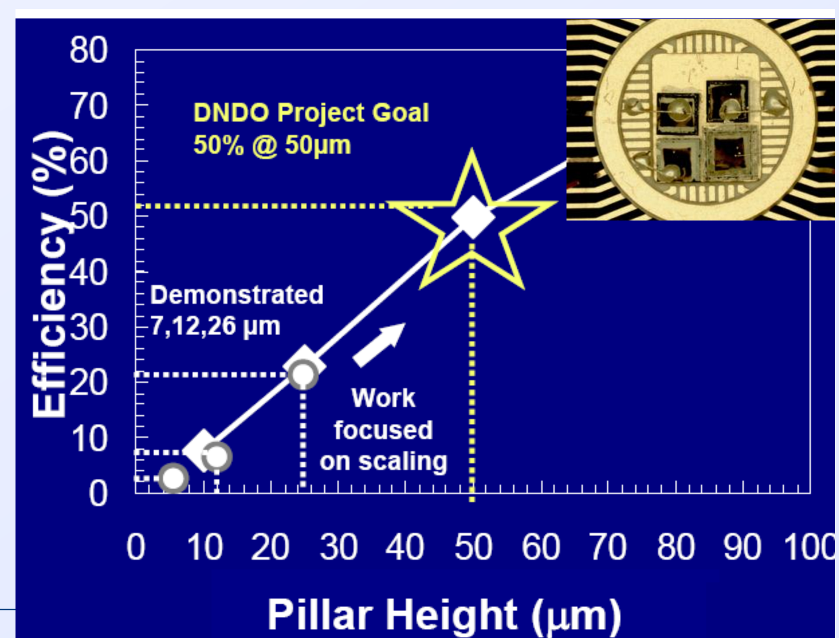
We are developing high-performance neutron detectors



50µm Pillar, > 90% fill





→20 % recent result (26 µm pillar)

→10^5 neutron/gamma discrimination

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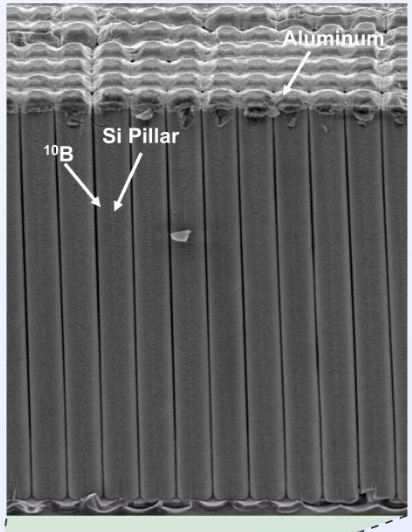
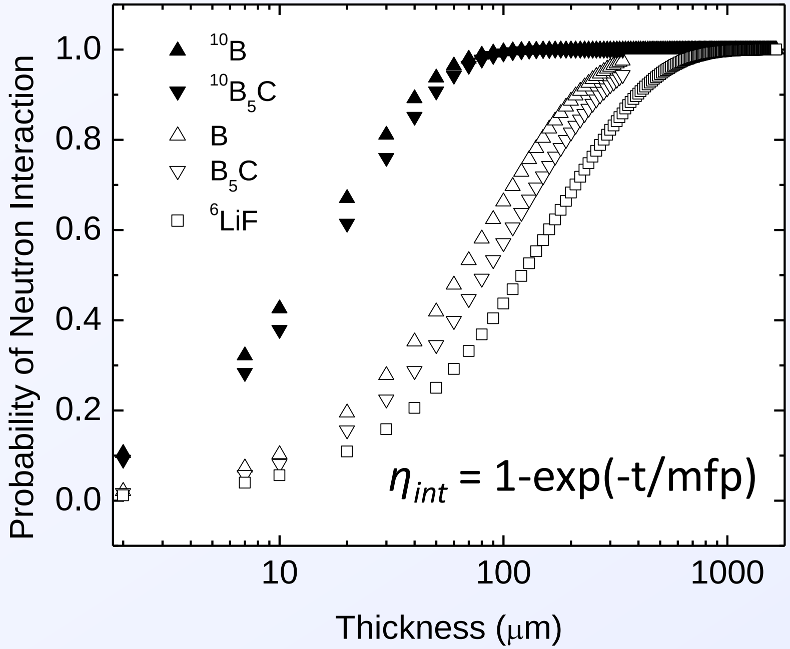
Thermal neutron detectors are needed for the detection of SNM: ^{3}He tube is current standard

- ^{10}Boron is interspersed between silicon pillars to detect thermal neutrons
- ^{10}Boron chosen for high thermal neutron cross-section 3837 barns and process compatibility



	^{3}He Tube	Pillar Detector
Efficiency	20–90%	50+%
Required voltage	1000 V	<10 V
Fieldability	Microphonics, HV, air transport	Rugged Not Commercial

Comparison: Thermal Neutron Converter Materials



Mean free path = 1/Nσ [μm]

N = number density, nuclei/volume

σ = microscopic cross-section

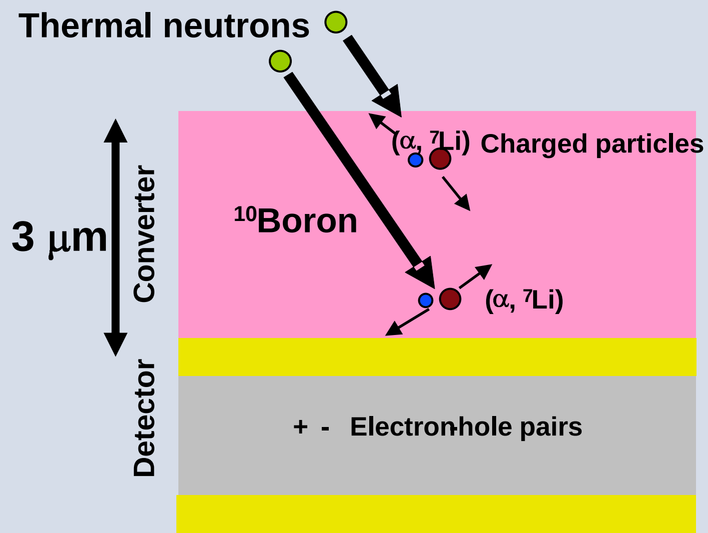
$^{10}B + n \rightarrow {}^{7}Li + \alpha$

	1st Excited State		Ground State	
Energy (MeV)	0.84 Li	1.47 α	1.02 Li	1.78 α
Distance in ^{10}B (μm)	1.85	3.6	2.0	4.4
Distance in Si (μm)	2.4	5.2	2.8	6.4

- Pillar height determined by probability of n interaction
- Pillar spacing determined by α & Li travel ranges

Pillar Detector enables high efficiency neutron detection

Standard 2D Design



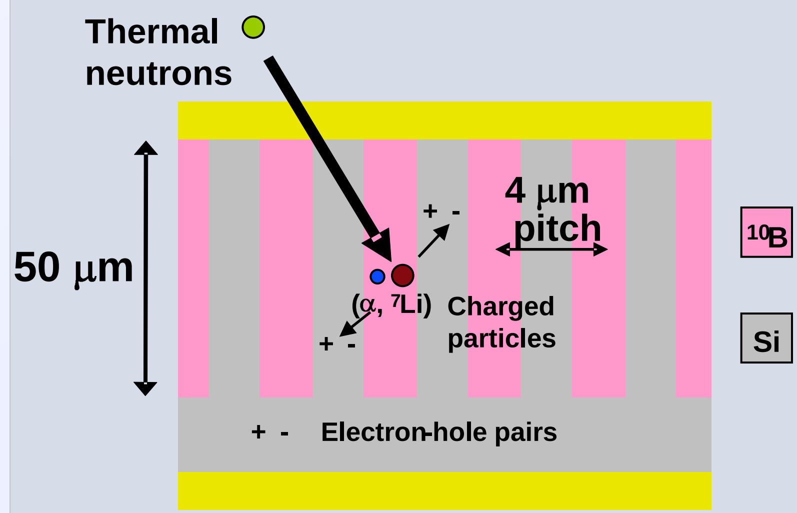
- ^{10}B efficiently produces α particles

94 % $^{10}B + n \rightarrow {}^{7}Li(0.84MeV) + \alpha(1.47MeV)$ $(Q=2.31MeV, \sigma=3571b)$

6% $^{10}B + n \rightarrow {}^{7}Li(1.01MeV) + \alpha(1.78MeV)$ $(Q=2.79MeV, \sigma=269b)$

- Most $\alpha/{}^{7}Li$ do not reach the detector
- Limited efficiency: 2-5 % (@ thermal)

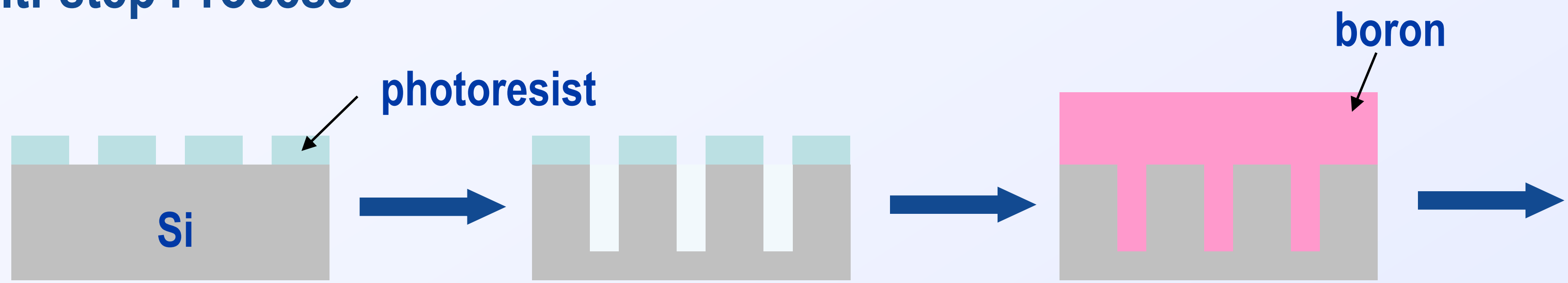
LLNL 3D Design



- Simulations show 3-D structure will increase efficiency towards 50+%
- Device geometry:
  - etch depth (50 μm) → n_o capture
  - pitch (4μm) → alpha particle range

Pillar Detector Fabrication

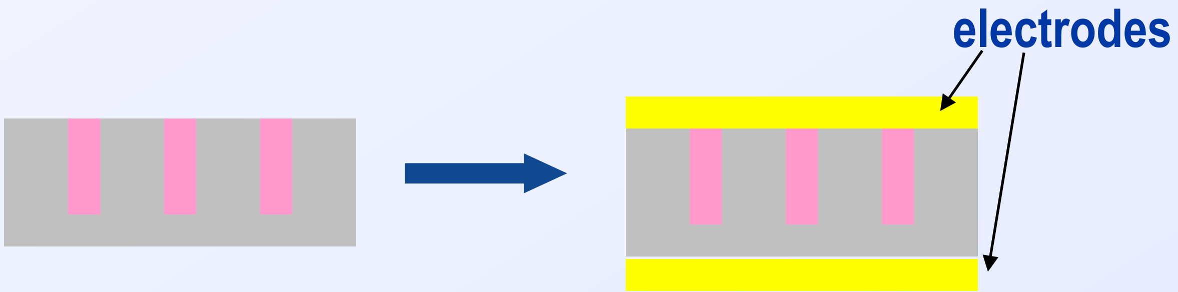
Multi-step Process



1. Pattern pr mask

2. Deep RIE etching

3. Conformal Boron Deposition

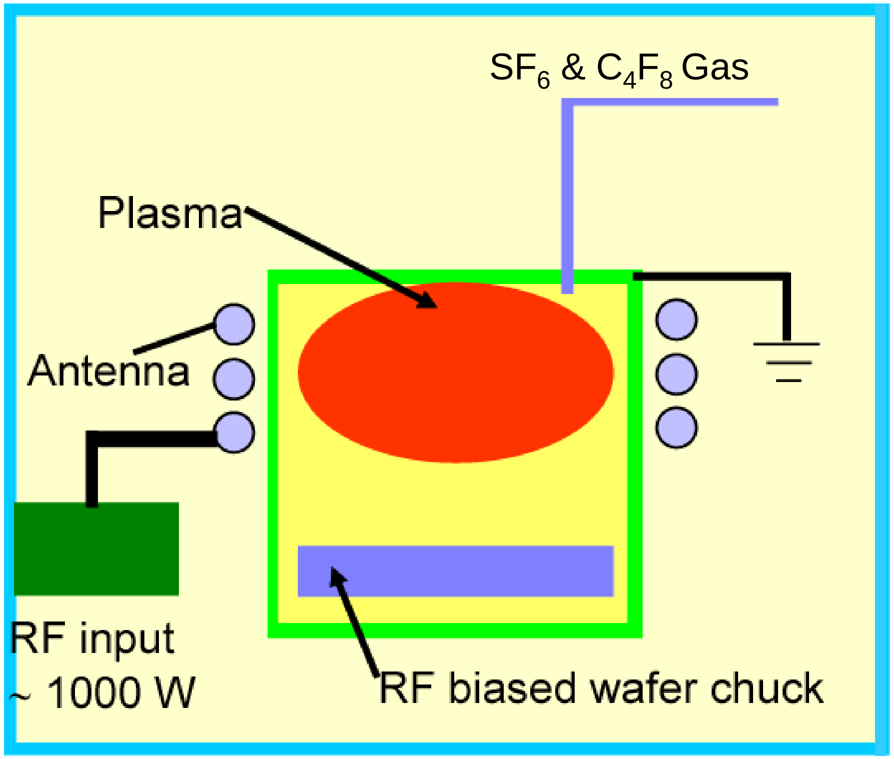


4. Plasma etching of boron

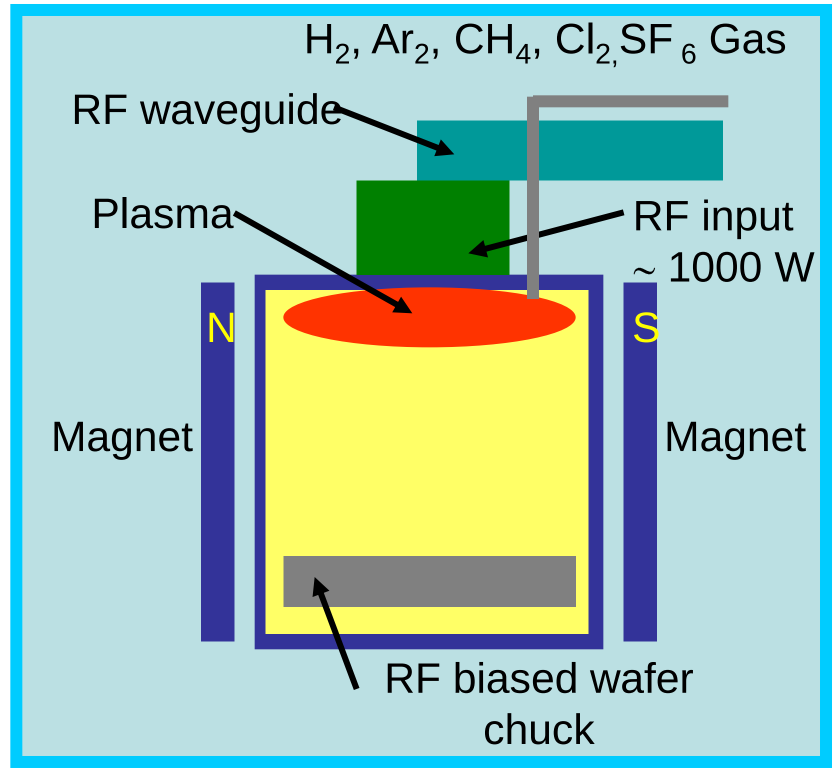
5. Deposit contacts

High-density plasma processing for high aspect ratio structures

Inductive-Coupled Plasma (ICP)



Electron Cyclotron Resonance (ECR)



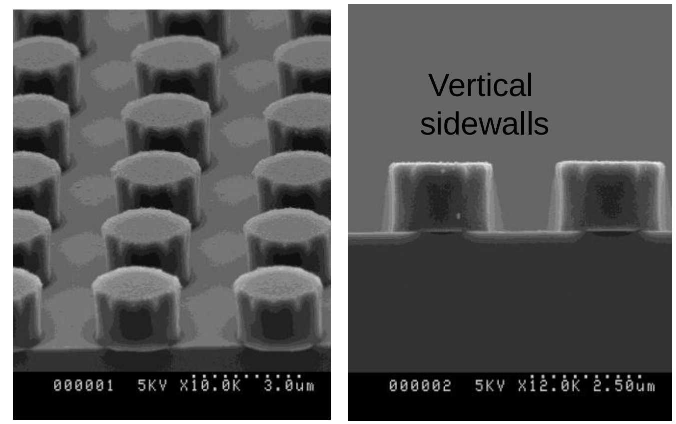
Control ion density and RF power independently
⇒ 1. Less damages to etched materials; 2. Flexibility in mask materials;
3. High etch rate; 4. Low substrate temperature

“Pillar” Chips for ^{10}B R&D and Detector Fabrication

Pillar Litho well-developed

- ❖ Large area pillar litho developed
- ❖ Developing negative pr process for large area

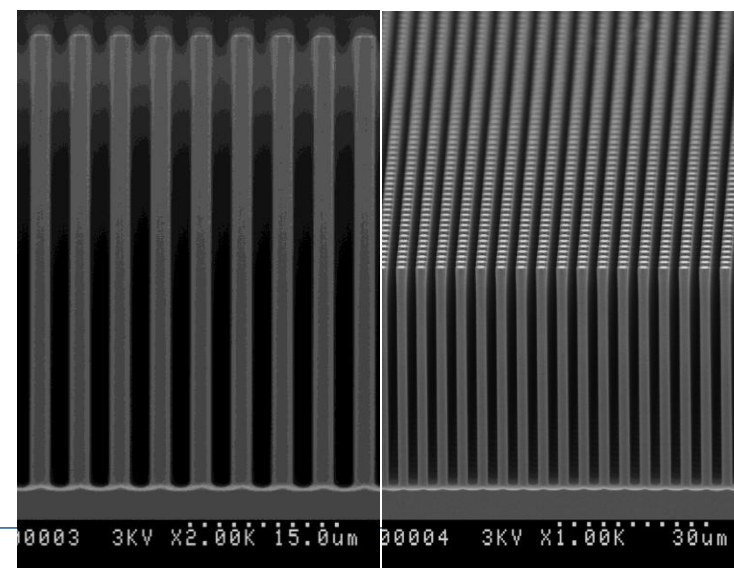
nLOF 2020



ICP Etch

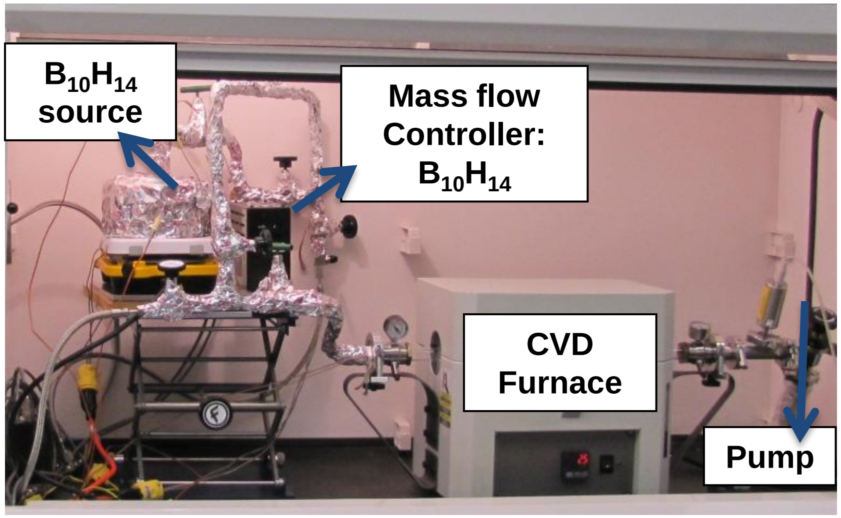
- ❖ 50 µm pillar process developed
- ❖ Compatible with 2” and 4” wafers

50µm Pillar Chips, 2µm Width



Vertical vs. Horizontal CVD System for ^{10}B Deposition

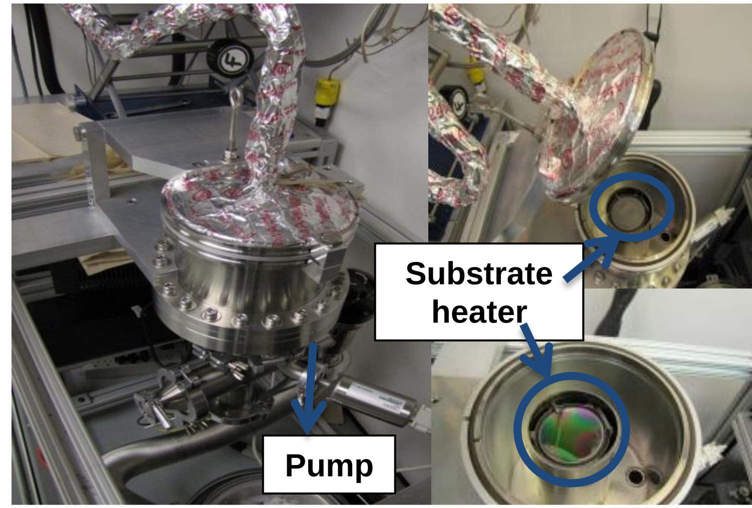
Horizontal CVD System



Features

- Inexpensive set up
- Easy cleaning of quartz tube chamber
- Limited control of precursor and heating profiles for samples
- Long sample loading time
- Potential for chemical exposure

Vertical CVD System



Features

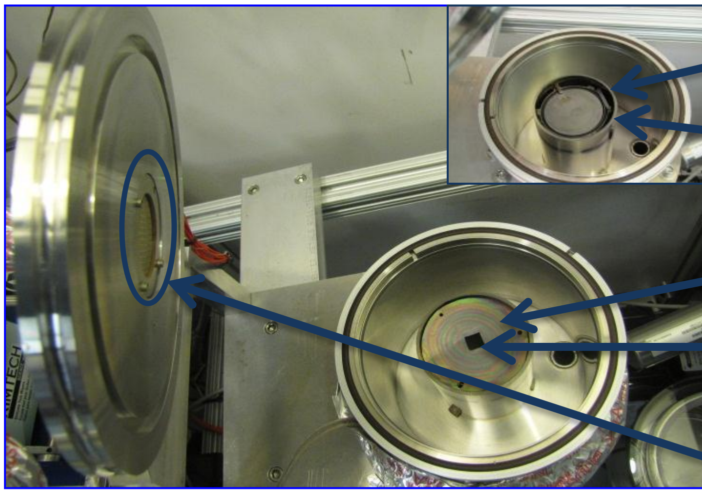
- Better control of precursor and sample heating
- Quick sample loading
- Large conductance → Effective pump rate & lower operation pressure
- Tailor for scale up with larger wafers
- Low chemical exposure

Vertical CVD system provides improved film reproducibility and safety.

Activating New Vertical CVD System

Heat shielding improves heat profile and boron filling.

Vertical CVD system



Substrate heater

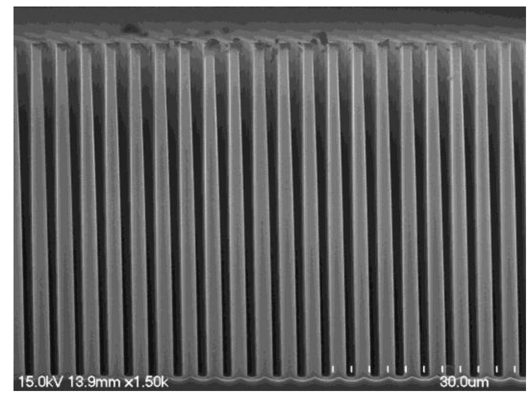
Side wall shielding

Top side shielding

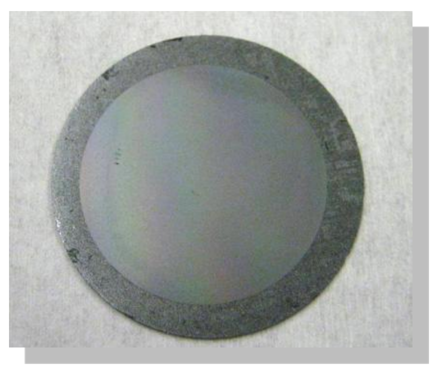
Sample location

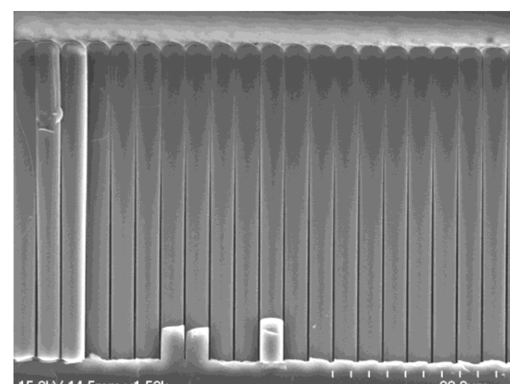
Shower head

50-μm silicon pillar samples before boron coating



High fill factor achieved

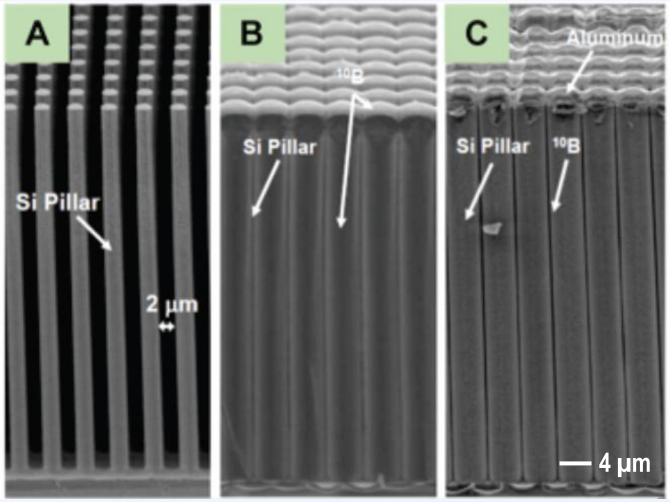




- First device runs had low efficiency
- Optimizing vertical process in parallel with 1'' CVD tube

We have developed specialized processing and characterization tools for ^{10}B

Boron CVD and Etch Back



A) Pillar Platform 1:25 aspect ratio

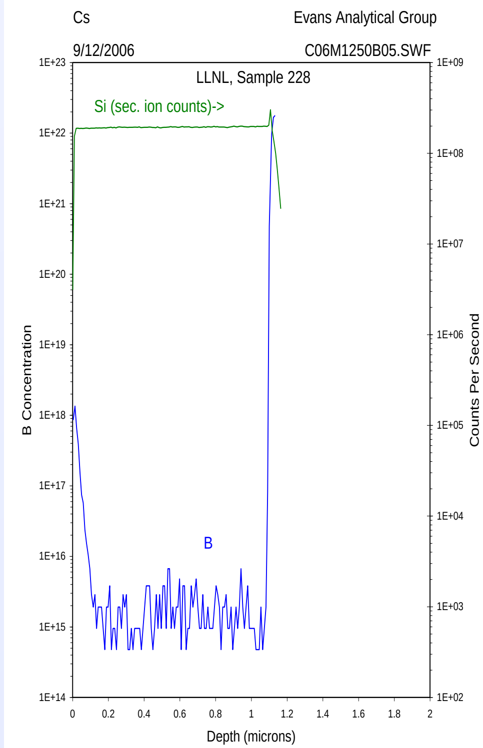
B) Conformal boron filling

C) Rapid removal of boron with high B:Si selectivity

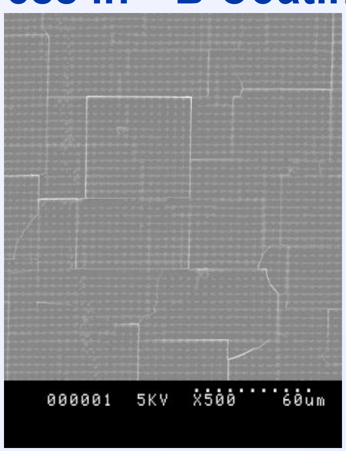
SIMS:

No B diffusion Si/B interface

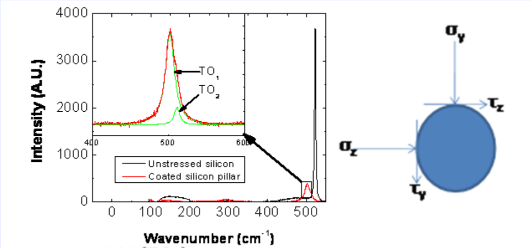
Boron CVD 600 °C – 900 °C



Stress in ^{10}B Coating



Raman Spectroscopy

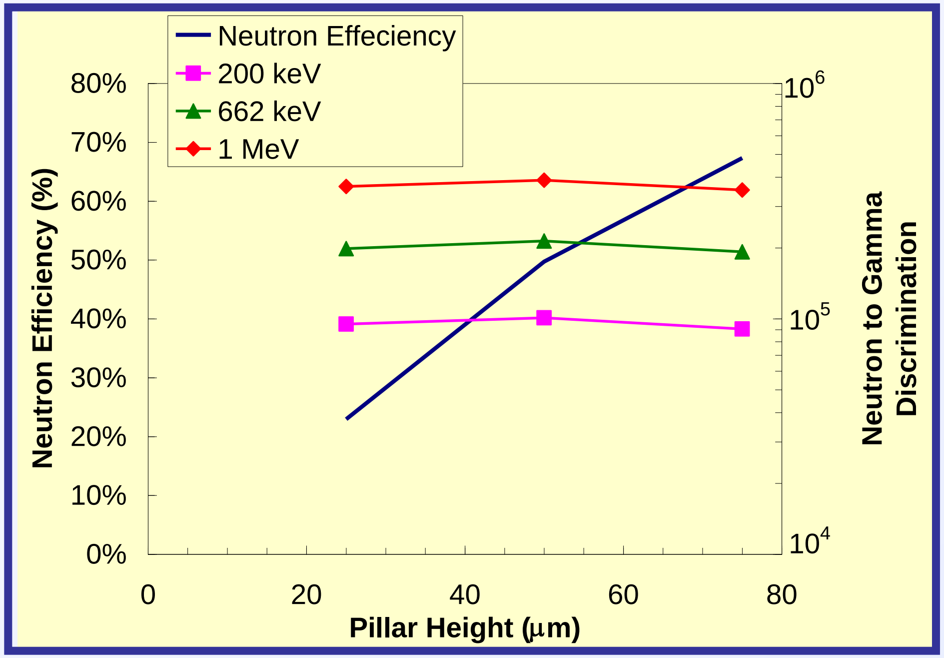


$$\sigma = \begin{pmatrix} -141(TO_1) \\ -251(TO_2) \\ -2910(LO_1) \end{pmatrix} x\,\Delta\,\omega\ (\mathrm{MPa}) \rightarrow \sim 2.7\ GPa$$

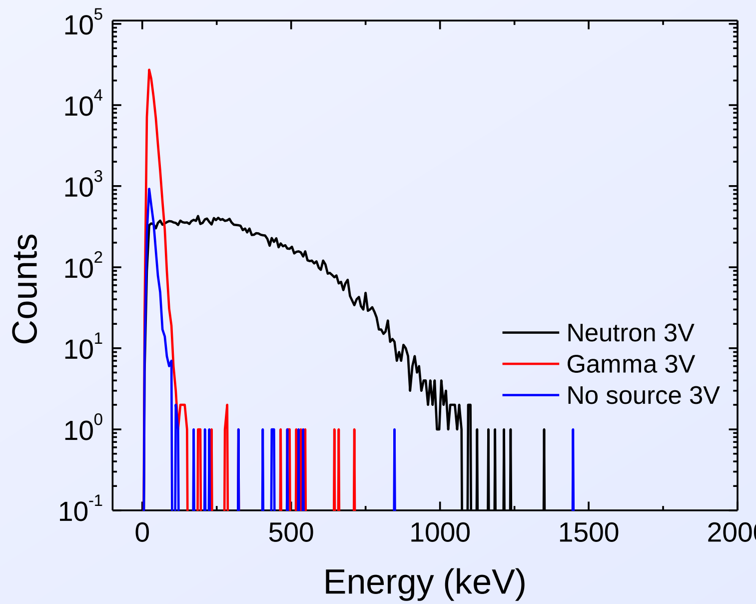
Stress induced on silicon pillars calculated from Raman shift

Efficiency by simulations and measurement

Simulations



Measurements



Simulation Tool-box
- MCNP → Neutron history
- TRIM → alpha, lithium trajectory
- Silvaco → semiconductor device physics

→20 % recent result (26 μm pillar)

→10^5 neutron/gamma discrimination

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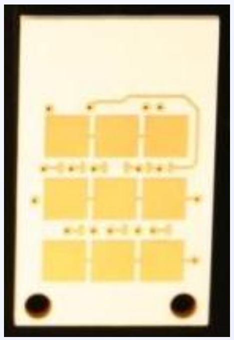
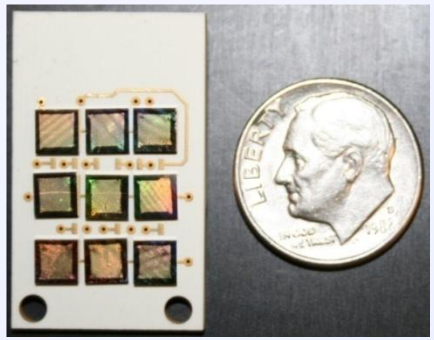
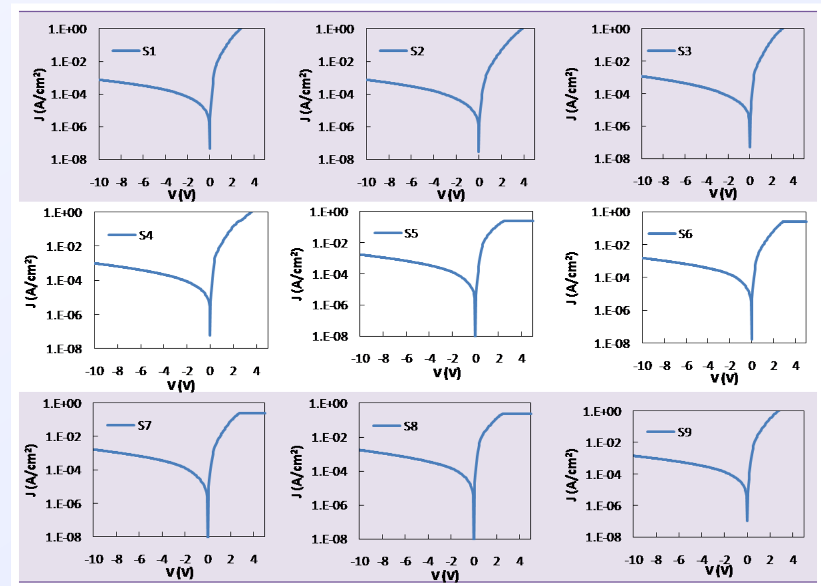
We are increasing detector area and channel number

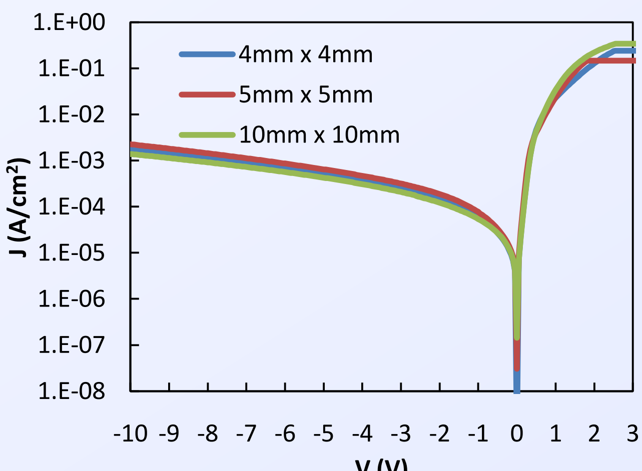
Interposer board 4 mm x 4 mm detectors







Scaling to Larger Area



Excellent uniformity across 9, 4 mm x 4 mm detectors

J_{leak}: 10^{-3} A/cm^2

Thermal neutron detection efficiencies measured at LLNL

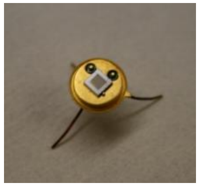
Process for measuring thermal neutron efficiency:

- MCNP of source and lab for # of incident thermal neutrons
- Eff = Measured counts / simulated incident counts
- Measure "calibration" detector using poly moderated ^{252}Cf source
- Other detectors:
  - Compare to calibration detector to determine relative efficiency
- All detectors from "EPI-26" family 1'' CVD system

Part #	Efficiency
EPI 26-1-1*	**22**
EPI 26-1-4	23
EPI 26-7-1	~20
EPI 26-6-3	16.4
EPI 26-7-2	16.1
EPI 26-7-3	19.2
EPI 26-7-4	17.8
EPI 26-1-2	~20
EPI 26-2-3	~20
EPI 26-2-4	~20

*Calibration detector

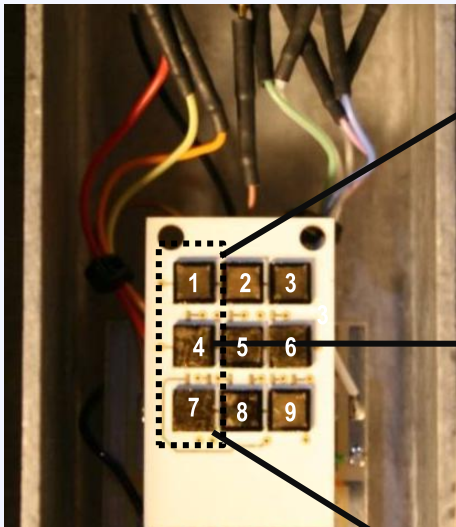
Packaged LLNL Pillar Detector



TO can
2 mm x 2 mm detectors

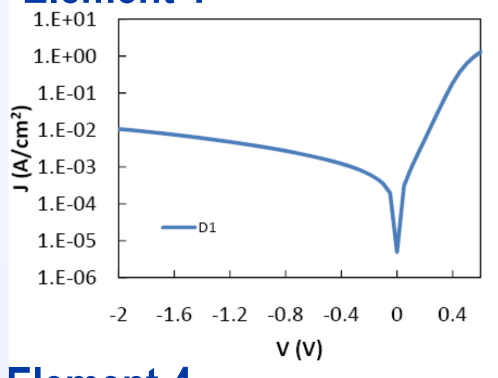
Characterization of 9 Element Detector Array

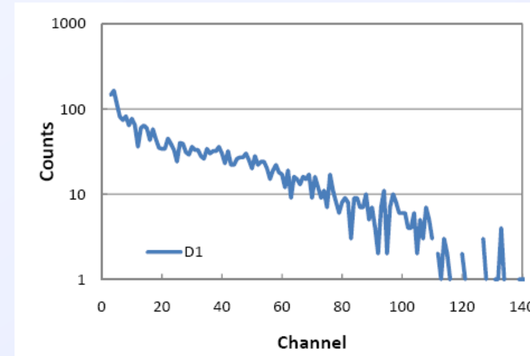
Measurements with rack-mount electronics



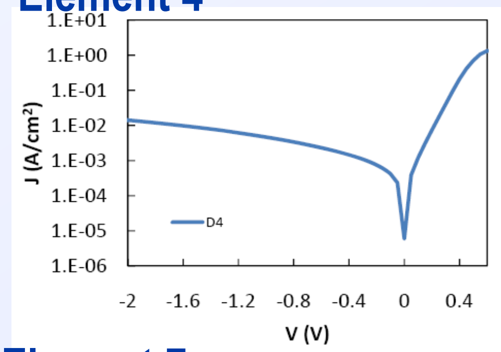
- Detector size 2 mm x 2 mm
- Moderated ^{252}Cf sources
- 1.5 m distance
- Detector unbiased
- Measurement time 3000 sec.
- Total counts Channels Σ 1-9 = 16k
- 14 counts/sec/cm^2

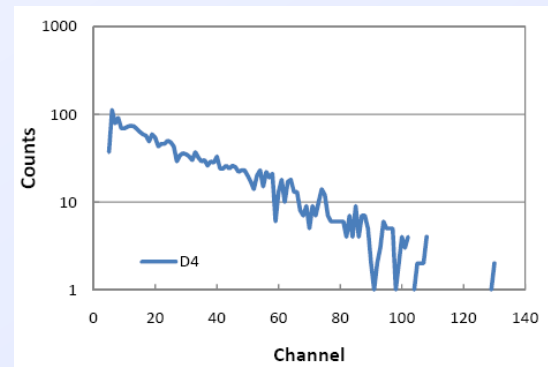
Element 1



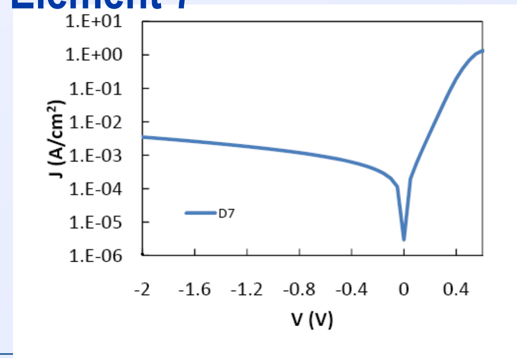


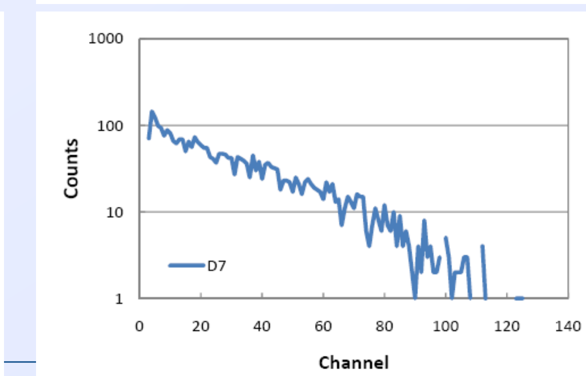
Element 4





Element 7

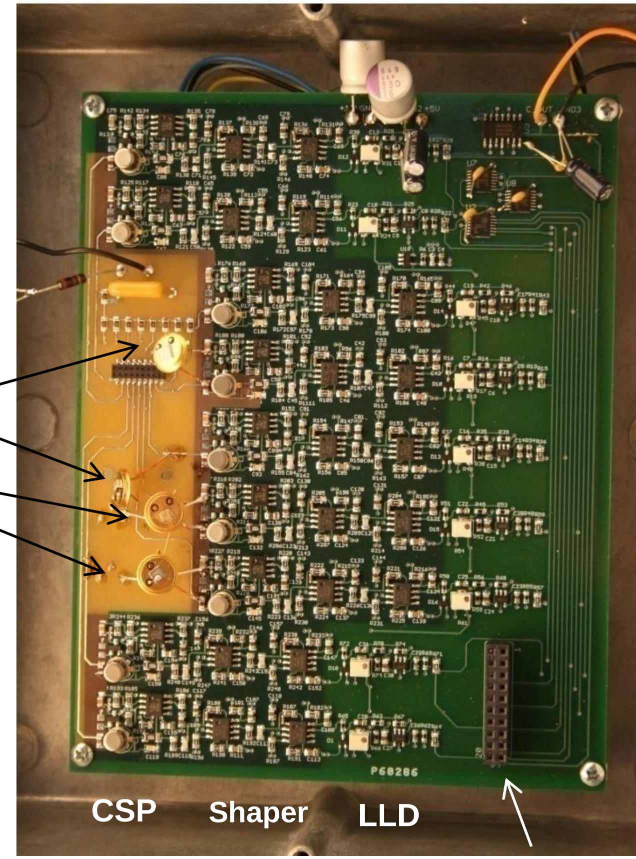




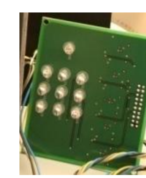
9 channel custom circuit with discrete components

- Custom design and layout with discrete COTS components
- Integrates 9 detectors with individual readout chain
  - Packaged individually
  - Or, on interposer board
- Readout chain includes:
  - Charge sensitive preamp
  - Shaping amplifier, 250 ns shaping time
  - Low level discriminator
  - Driver circuit for TTL output
  - LED display and driver circuits
  - Can readout either electron or hole signal

Individually packaged detectors



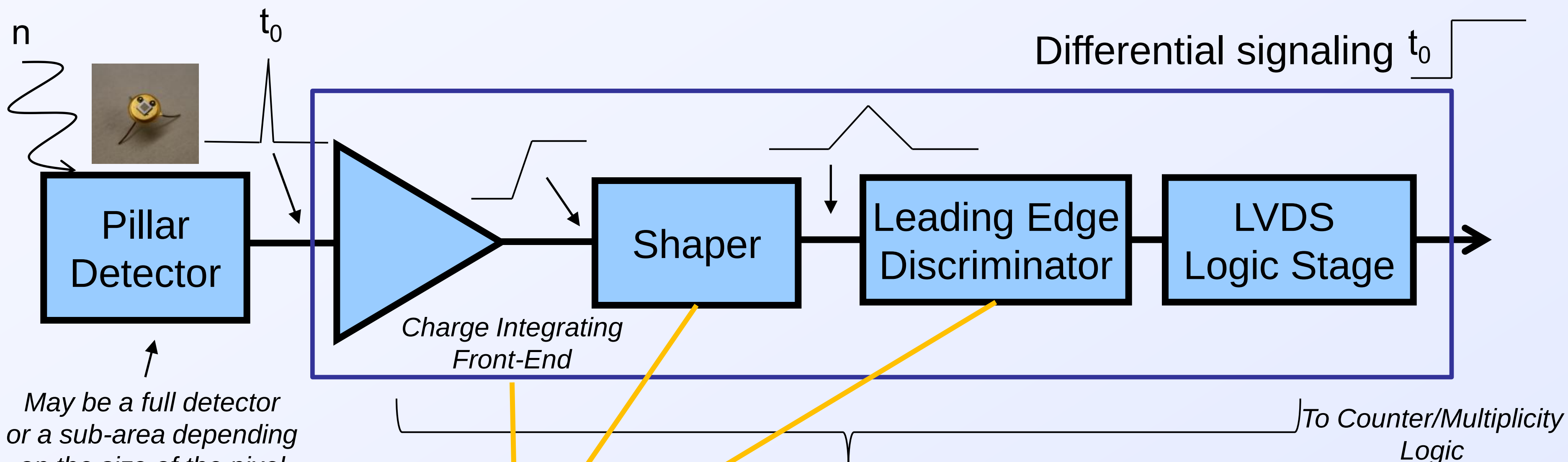
Output to LED display



Video: 3 detector channels detector size 2 mm x 2 mm

Read Out Design: ASIC

- Example for single channel, 8 channel was implemented



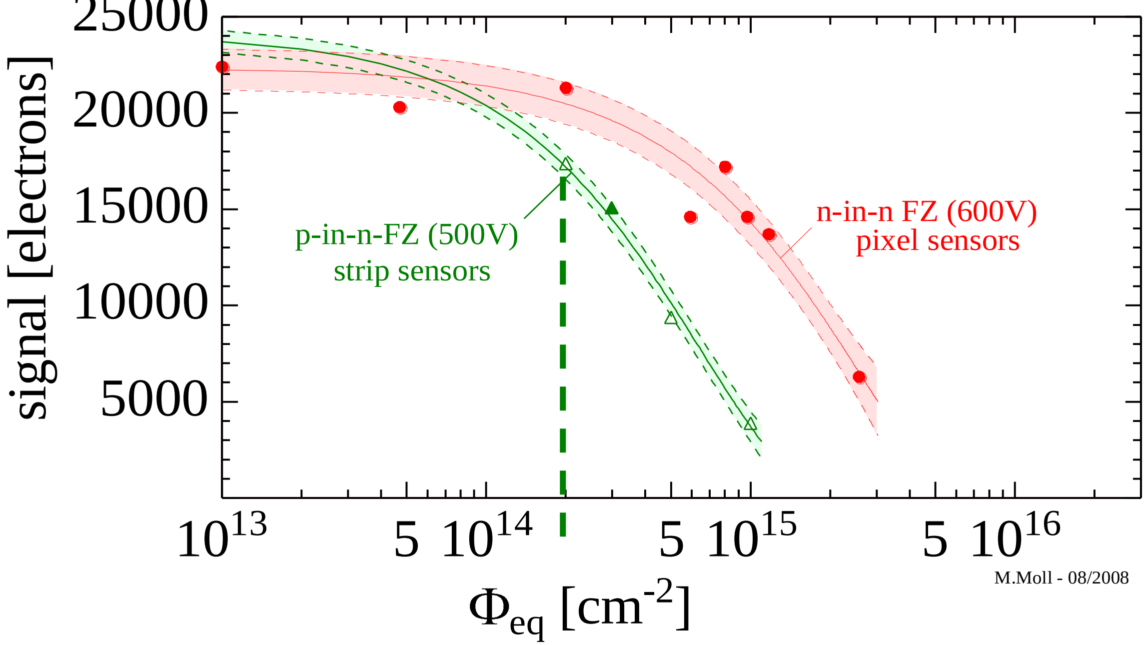
Single ASIC Channel

ASIC
2.8 mm x 4.0 mm
8 Channels per ASIC
Mosis Foundry

20 ASICs received Dec. 2010

Silicon Detector for HLC: High radiation tolerance possible

***Silicon FZ Strip Detectors for High Luminosity Colliders**



NIEL - nonionizing energy loss

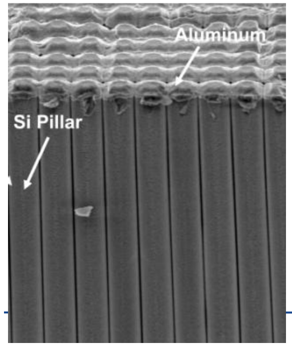
IEL – ionizing energy loss

Radiation Damage to Sensors:

- **Bulk damage** due to **NIEL**
  - Change of <u>effective doping concentration</u>
  - Increase of <u>leakage current</u>
  - Increase of <u>charge carrier trapping</u>
- **Surface damage** due to **IEL**

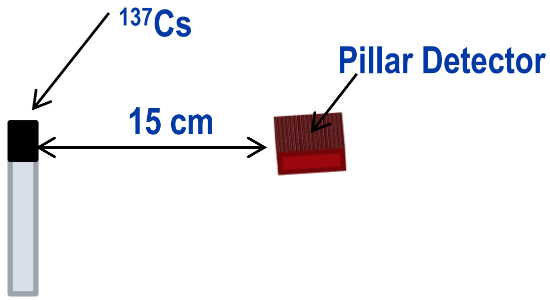
  (accumulation of positive charge in oxide & interface charges)

- **Determine if Pillar Detector has elevated damage due to:**
  - **large surface area**
  - **composite material structure**

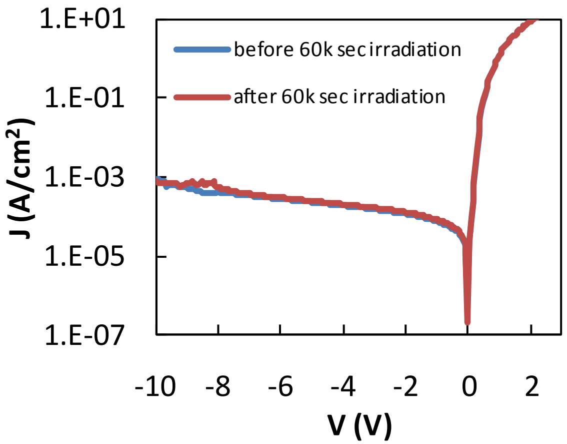


High fluence measurements: gamma

Test setup



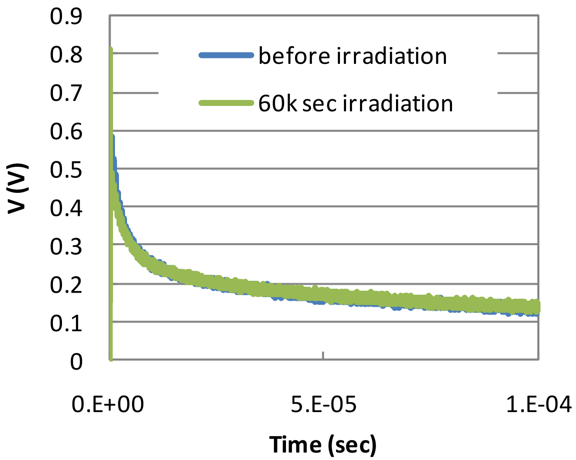
- Electrical measurements done before and after irradiation
- Time, 60ksec (16 hours)
- Gamma flux: 2.64×10^9 photons/($cm^2 \cdot$sec)
- Total gamma fluence delivered: 2.0×10^{14} photons/cm^2
- Electrical properties of I-V, C-V and transient voltage decay remain same:



I-V remains the same

→ No trapping centers introduced

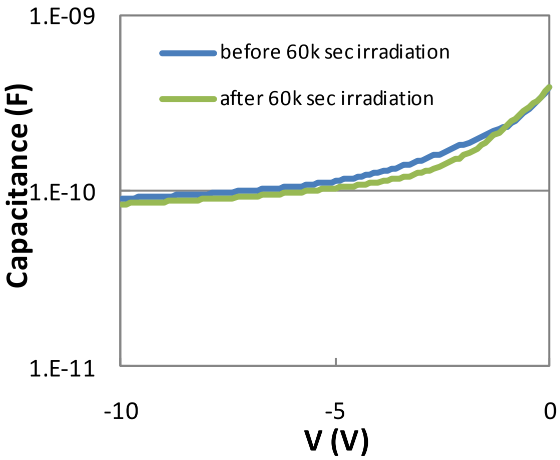
→ No damage in the depletion region



Transient voltage decay remains the same

→ No change in effect lifetime: ~ 1.0 μs

→ No damage in bulk or pillar sidewalls



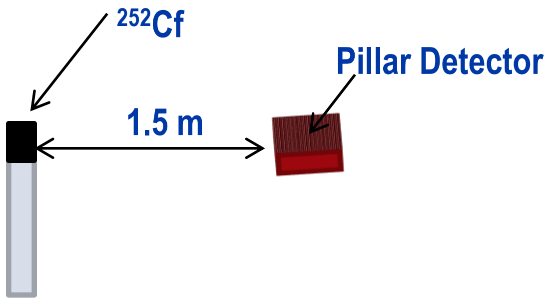
C-V remains the same

→ No change in voltage pulse for a certain amount of induced charges

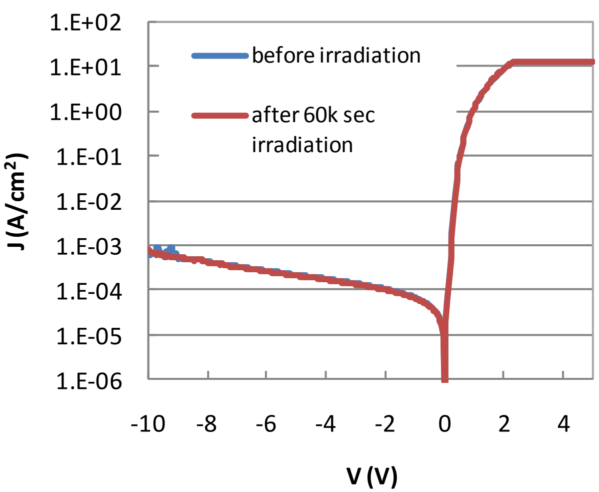
→ Neutron detection performance not degraded

High fluence measurements: fast neutron

Test setup



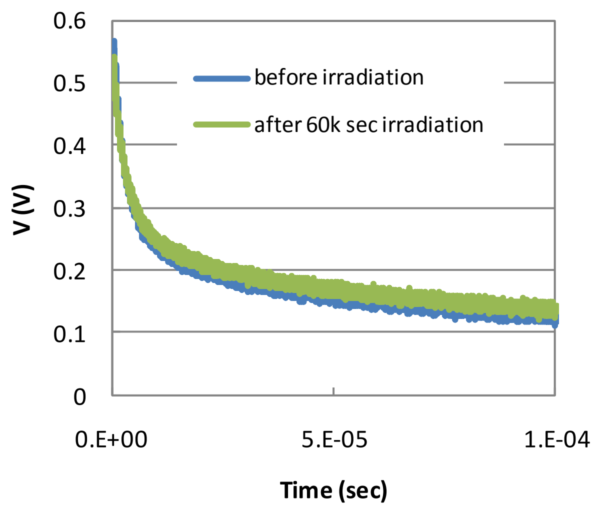
- Electrical measurements done before and after irradiation
- Time, 60ksec (16 hours)
- Neutron flux: 3.2×10^3 n/(cm^2·sec)
- Total neutron fluence delivered: 1.9×10^8 n/cm^2
- Electrical properties of I-V, C-V and transient voltage decay remain same



<u>I-V remains the same</u>

→ No trapping centers introduced

→ No damage in the depletion region



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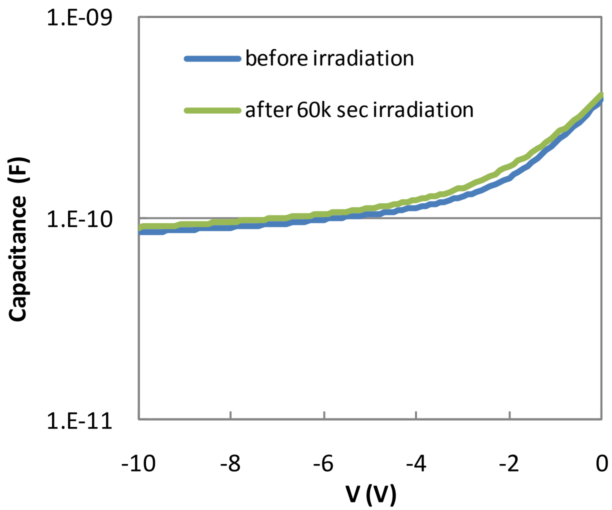


<u>C-V remains the same</u>

→ No change in voltage pulse for a certain amount of induced charges

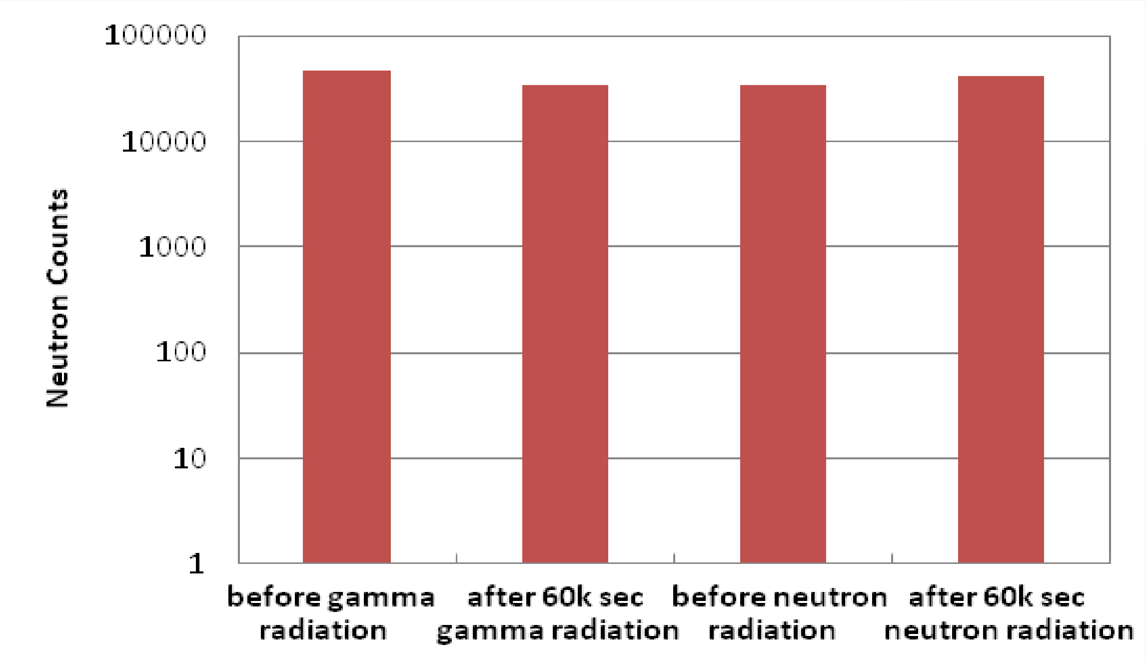
→ Neutron detection performance not degraded

High fluence measurements summary

Thermal neutron counts monitored before & after irradiation testing

Thermal Neutron Counts Set-up

- Moderated ^{252}Cf source $4x10^8$ n/sec
  - 30 cm diameter D_2O covered with 1 mm Cd
- Time 60k sec (16 hours)
- 0.5 micro-sec shaping time
- Detector bias = 0V



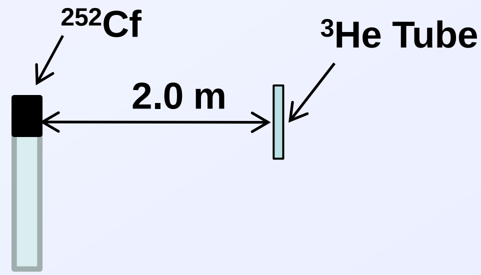
Gamma and Neutron Radiation

Gamma (#/cm²s)
10^9
Neutron (#/cm²s)
10^3

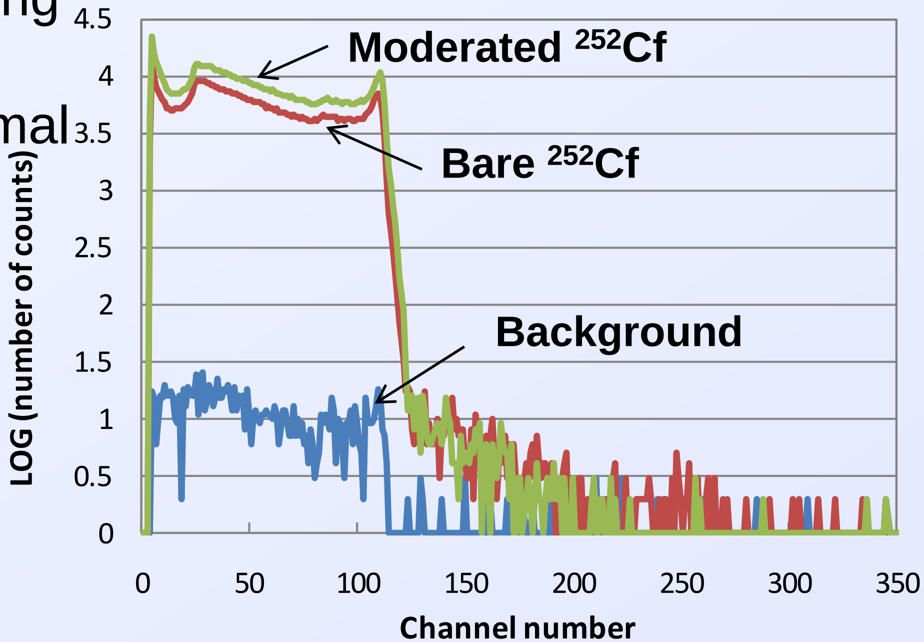
No reduction in n counts

Measurement of He-3 detector for comparison with Pillars

- ^{3}He detector can be used for efficiency calibration
- He-3 detector used:
  - Cylindrical ^{3}He from LND, Inc.
  - Active volume
    - 1.55 cm diameter, 2.39 cm long
  - 4 Atm ^{3}He, 850V
  - Data sheet efficiency ~30% thermal neutrons
- Initial measurements performed
- Efficiency calculations underway

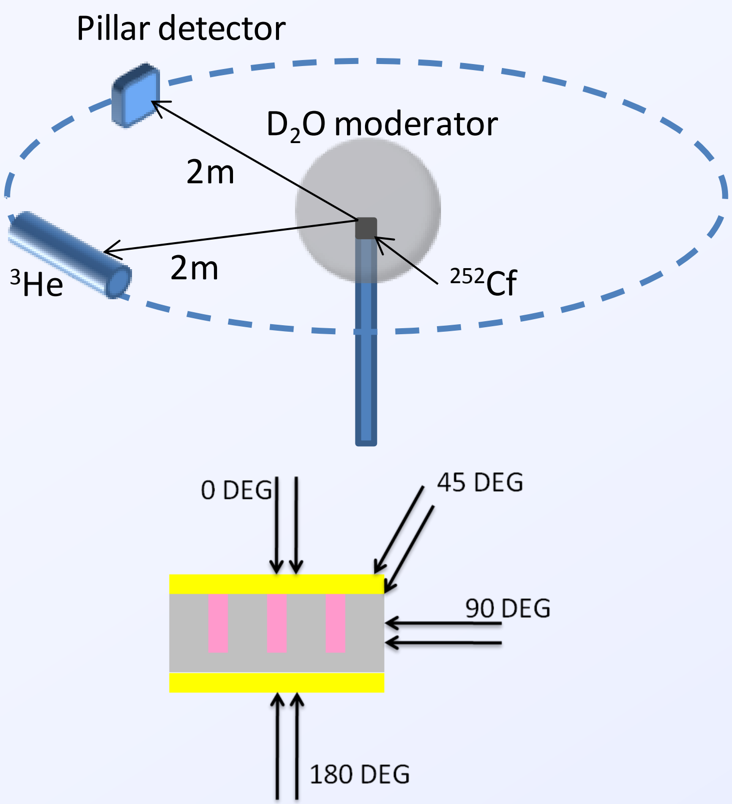


Conditions	Counts
No Source	1393
Bare ^{252}Cf	622413
Moderated* ^{252}Cf	887504



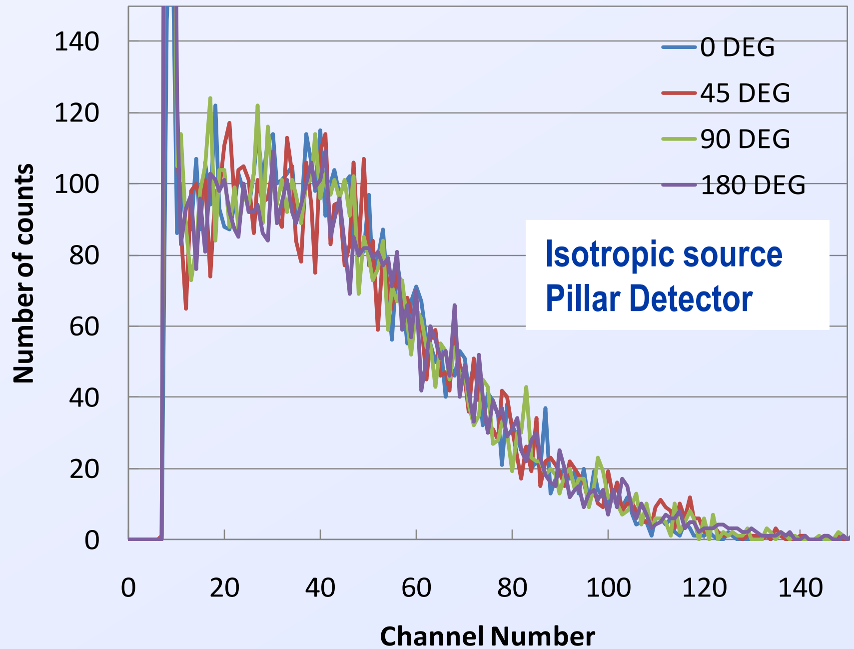
*15cm D2O sphere

^{3}He vs Pillar Detector



Detector	^{3}He tube* (LND-25177)	Pillar detector (EPI26-1-1)
Active dimensions (cm)	Diameter:1.55 Length:2.39	0.2 x 0.2
Operation voltage (V)	850	0
Total counts (1 hour)	886,111	3067
CPS/area (#/cm^2·s)	66.44	21.30

*Gas pressure: 3040 torr

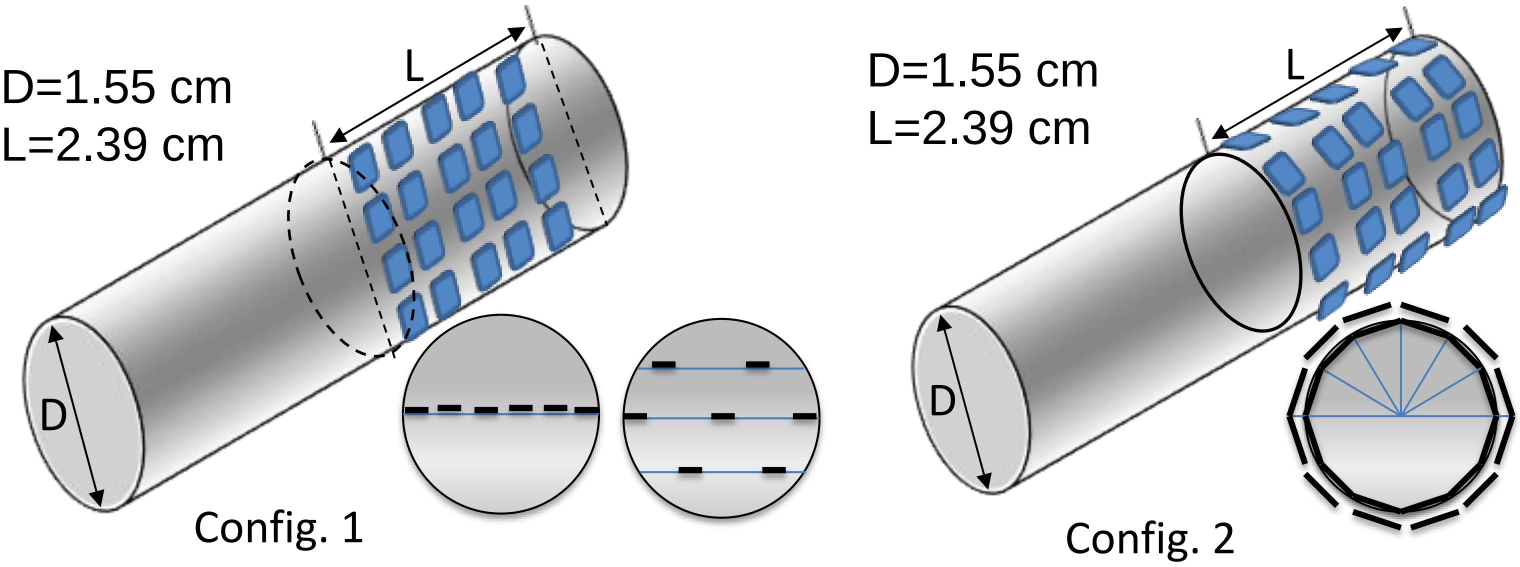


Isotropic source
No angular dependence (as shown in measurements)

Non-Isotropic source
Little streaming 4.6 ° solid angle to deflect out Si

OUO

Mapping Pillar Detector Over ^{3}He Tube Form: Efficiency Comparison



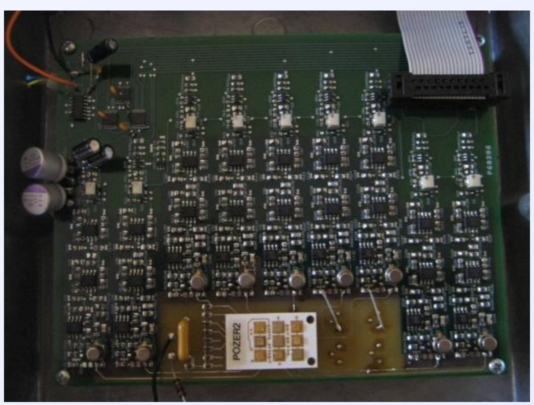
Comparison of ^{3}He and pillar detector(**246.14 cps for ^{3}He**)

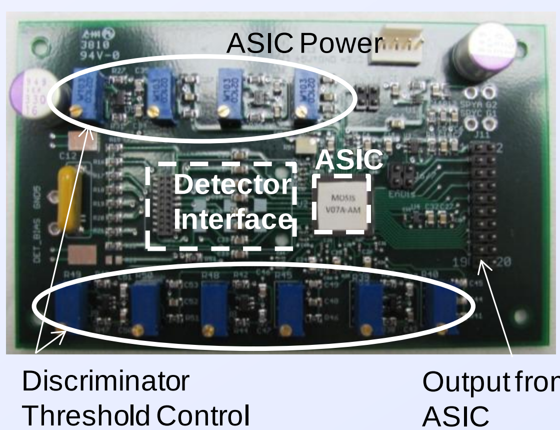
Configurations		Pillar Efficiency	Number of detectors	Total counts per second	Sensitivity normalized to ^{3}He
1	Single side	22 %	7 x 11 (77)	65.45	0.27
	Single side	44 %	7 x 11 (77)	130.9	0.53
2	Single side	22 %	12 x 11 x 2 (264)	224.4	0.91
	Single side	44 %	12 x 11 x 2 (264)	449	1.82

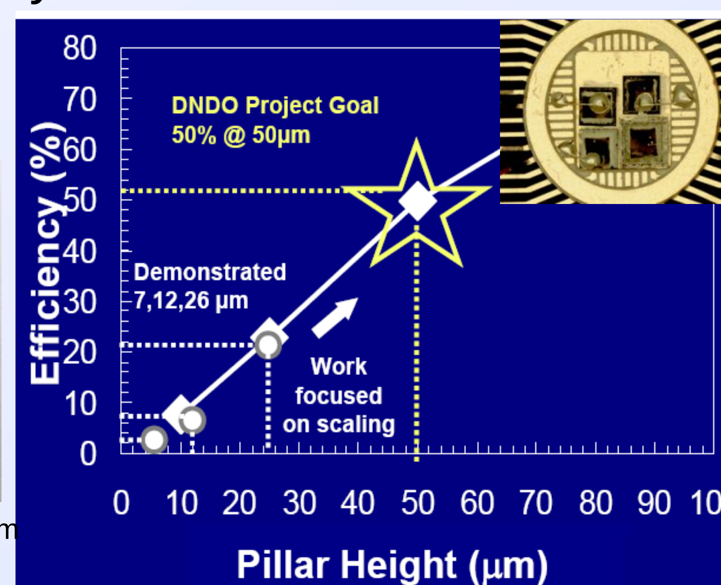
Pillar efficiency can increase by lining multiple layers within the form factor

Summary

- Pillar based neutron detectors can be a ^{3}He replacement (small form factor applications)
- Ideal material system is Si (electron/hole collection) and ^{10}B (neutron conversion)
- High aspect ratio structures of 2 μm x 2 μm pillars, with a 4 μm pitch and scaled to ~ 50 μm can achieve 50 % thermal neutron detection efficiency, currently at 20 %
- 8-channel ASIC read-out integration underway
- Scaling for efficiency and area







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