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Comparative Studies of CdZnTe, CdMnTe, and CdZnTeSe Materials for Room-Temperature Nuclear Detection Applications

STEPHEN U. EGARIEVWE,[1,2] STEPHAN D. SOTO,[1] SIMEON W. SYKES,[1] LESLIE J. FULLER,[1] QUENTIN J. ALSBROOKS,[1] MOHAMMAD A. ALIM,[1] UTPAL N. ROY,[2,3] EZEKIEL O. AGBALAGBA,[4] MEBOUGNA L. DRABO,[1] AND RALPH B. JAMES[3]

[1]Alabama A&M University, Huntsville, Alabama, USA
[2]Brookhaven National Laboratory, Upton, New York, USA
[3]Savannah River National Laboratory, Aiken, South Carolina, USA
[4]Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

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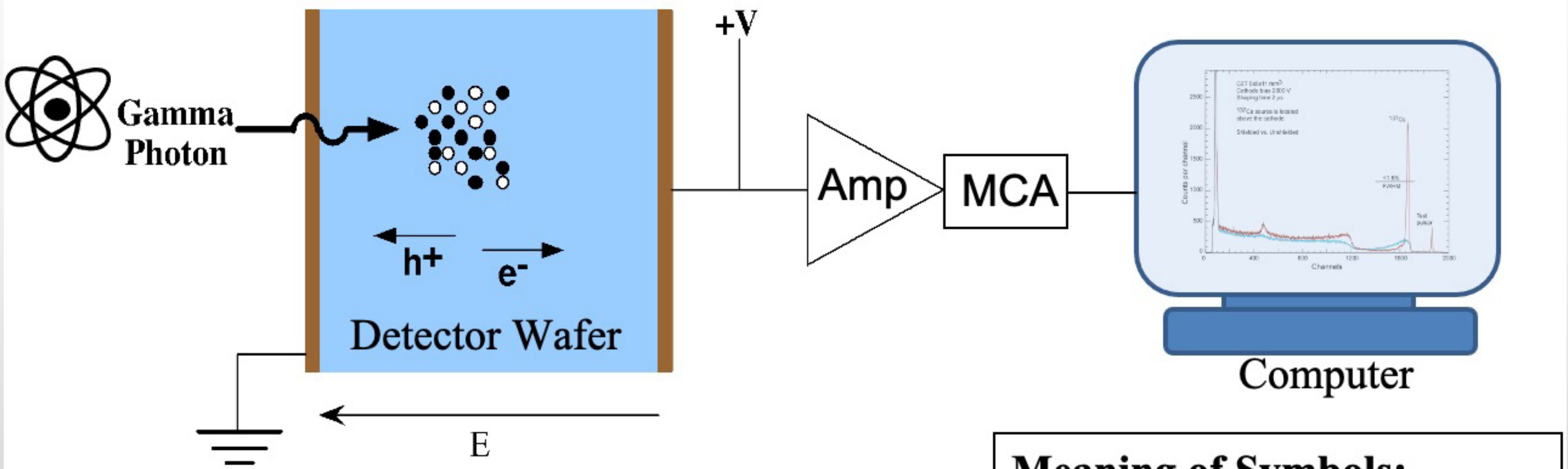
Presentation Outline

- Goals: Review of Our Recent Studies on CdTe-Based Detectors
- Operation of CdTe-Based Detectors
- Device Engineering Design Constraints
- Constant-Temperature Annealing of CdMnTe Detector
- Temperature-Gradient Annealing of CdMnTe Detector
- XPS Study of Passivated CdZnTe Surfaces
- Planar Detector Fabrication
- Electrical Instrumentation for Current-Voltage Measurement
- Surface Chemical Treatments of CdZnTe Detector
- Chemical Passivation of CZTS
- Summary

Goals

- Cadmium telluride (CdTe) and its ternary and quaternary compound have found applications in the development of X-ray and gamma-ray detectors used in medical imaging and in the detection of radiological and nuclear threats.
    - Examples: CdZnTe (CZT), CdMnTe (CMT), and CdZnTeSe (CZTS).
- These detectors can operate at room temperature without cryogenic cooling.
- The goal of this presentation is to review our recent studies of studies of CdTe-based detectors and the effects of ***chemical treatments*** on their ***electrical properties*** and ***radiation detection performances***.
- The properties to be studied include detector surface species, resistivity, and energy resolution.
- Surface treatment studies include chemo-mechanical polishing and passivation using KOH and NH_4F solutions.

Operation of CdTe-Based Detectors



Basic Operation:

- Gamma rays create electron-hole pairs.
- This creates electrical signal.
- The signal is amplified before the MCA.
- MCA displays the spectrum on the computer screen.

Meaning of Symbols:

e^-: Electron (○).
h^+: Hole (●).
V: Applied voltage.
E: Electric field direction.
Amp: Amplifier.
MCA: Multichannel analyzer.

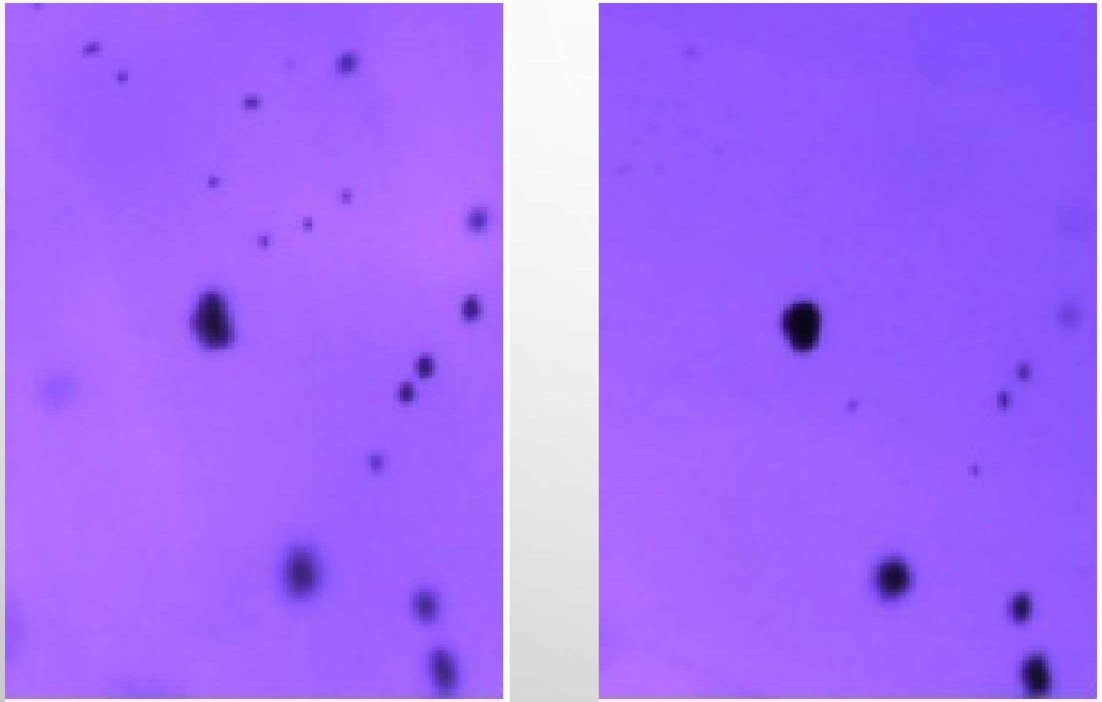
Device Engineering Design Constraints

- High resistivity > 10^8 Ω-cm.
  - Implies low current. High current could damage the pre-amplifier and amplifier.
- Low surface current (nano-amps). This is required to reduce electronic noise in the generated signal.
- Chemical passivation must result in reduced surface current.
- High charge-carrier mobility-lifetime product.
- Free of defects that affect charge collection and uniformity.
- Low production cost.

Constant-Temperature Annealing of CdMnTe Detector

- Thermal annealing is used to remove defects caused by Te inclusions in the detector wafer.
- Te inclusions and related defects limit the detector's ability to detect X-rays and gamma-rays.
- Process:
  - The detector wafer is placed together with Cd in a quartz ampoule and sealed in vacuum using a vacuum pump.
  - The ampoule is placed in the furnace region at 720°C for 12 hours.
  - Cd reacts with the excess Te to form a crystalline structure in the wafer, thus reducing the Te inclusions and related defects.

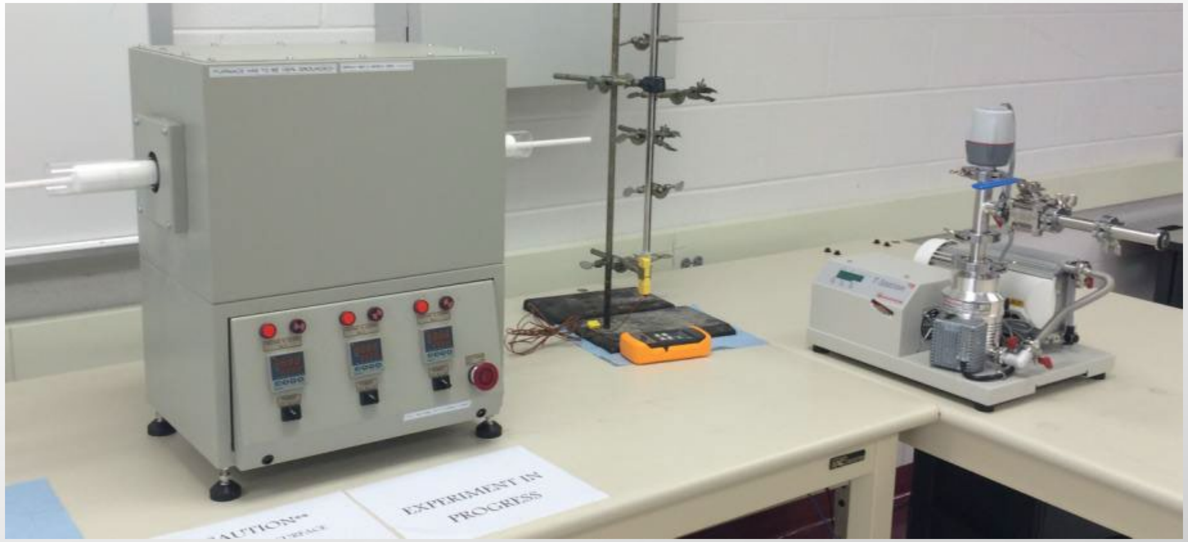
Constant-Temperature Annealing of CdMnTe Detector



(a) Before annealing

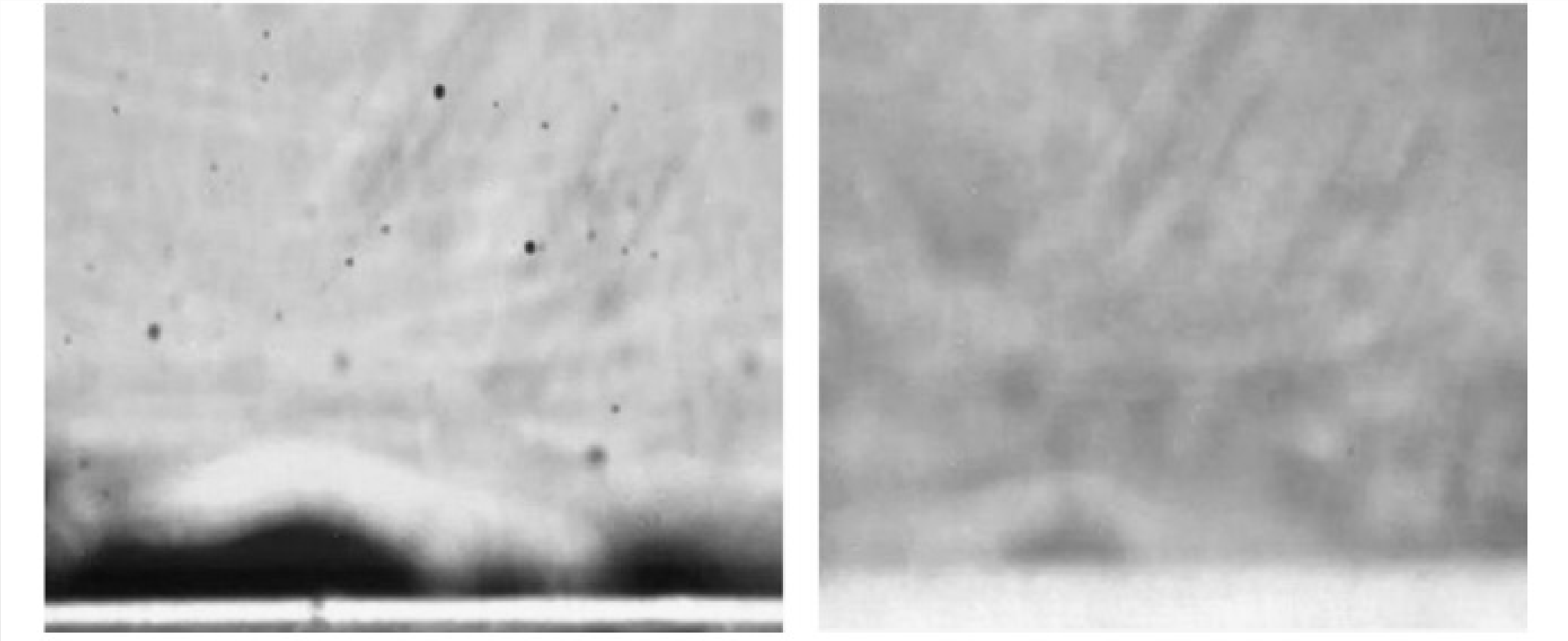
(b) After annealing

Infrared images (256 µm x 367 µm) of the same region of the CdMnTe wafer before and after annealing in Cd vapor.



Three-zone annealing furnace (shown on left-side) and vacuum pump (shown on right-side) for removing air when sealing CdMnTe wafers in ampoules.

Constant-Temperature Annealing of CdMnTe Detector



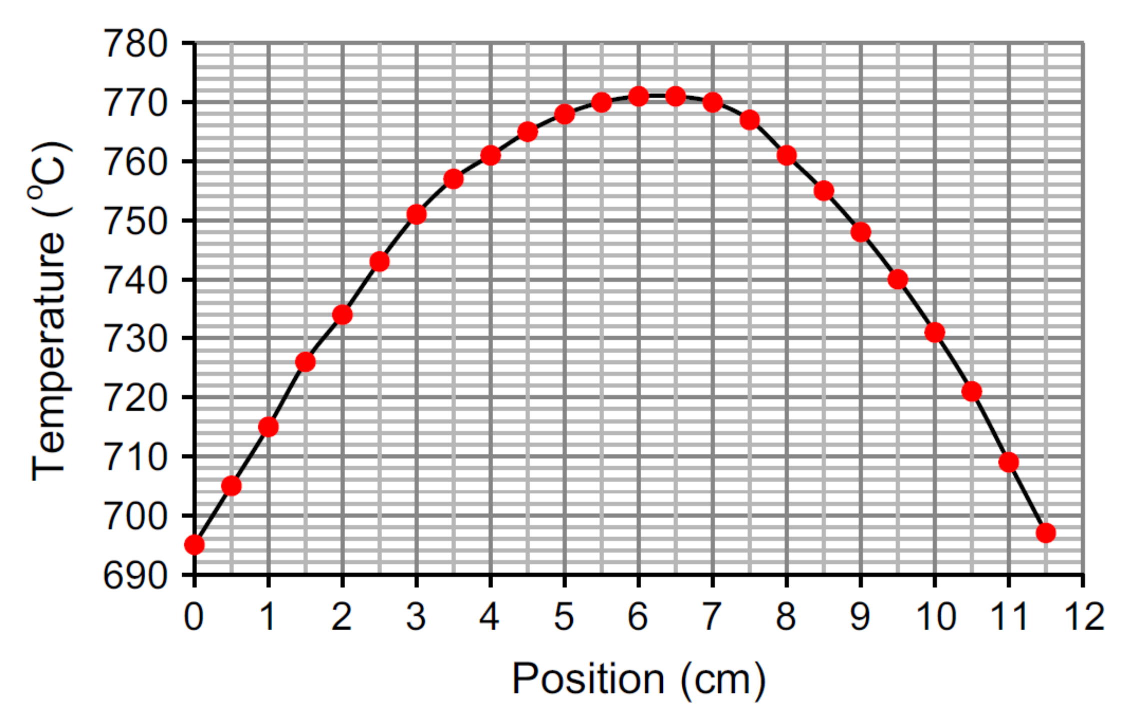
(a) Before annealing.

(b) After annealing.

Te inclusions eliminated from a CdMnTe wafer after being annealed at 570°C for 26 hours in Cd vapor.

Source: S. U. Egarievwe, G. Yang, A. A. Egarievwe, A. A., I. O. Okwechime, J. Gray, Z. M. Hales,. . . James, R. B. (2015). Post-growth annealing of Bridgman-grown CdZnTe and CdMnTe crystals for room-temperature nuclear radiation detectors. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 784, 51-55. doi: 10.1016/j.nima.2015.02.006.

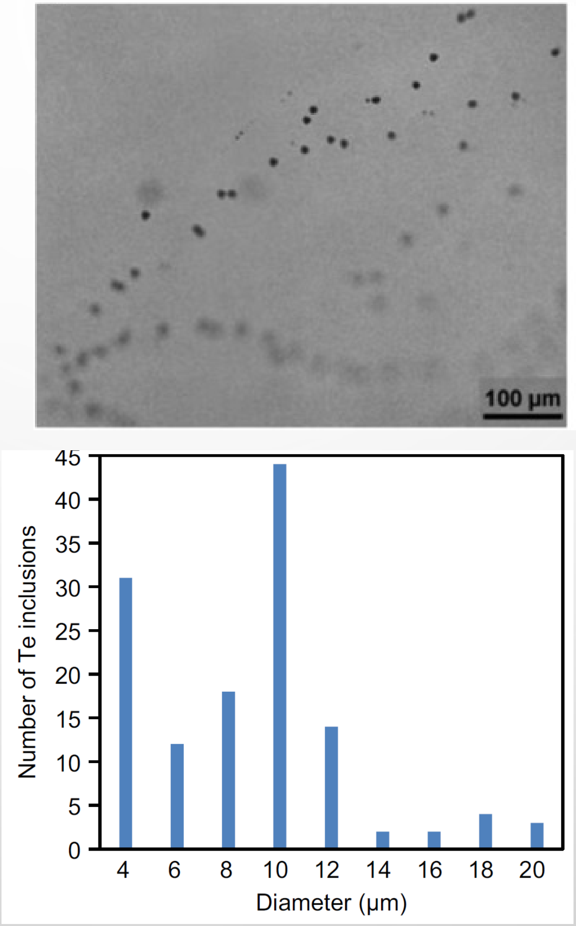
Temperature-Gradient Annealing of CdMnTe Detector



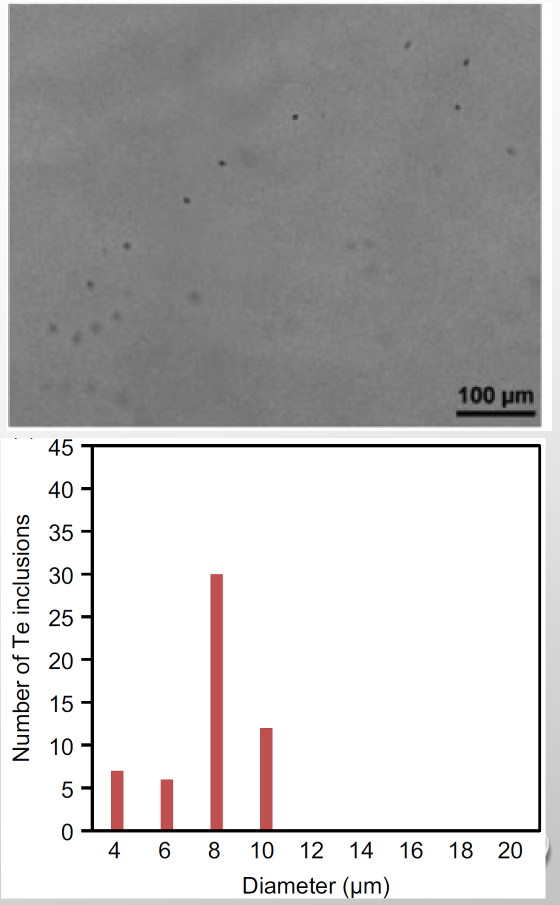
Furnace temperature profile for temperature-gradient annealing.

Temperature-Gradient Annealing of CdMnTe Detector

Size reduction and elimination of Te inclusions in CdMnTe wafer after it was annealed at 730° C for 18 hours at 18°C/cm temperature gradient.



(a) Before annealing.



(b) After annealing.

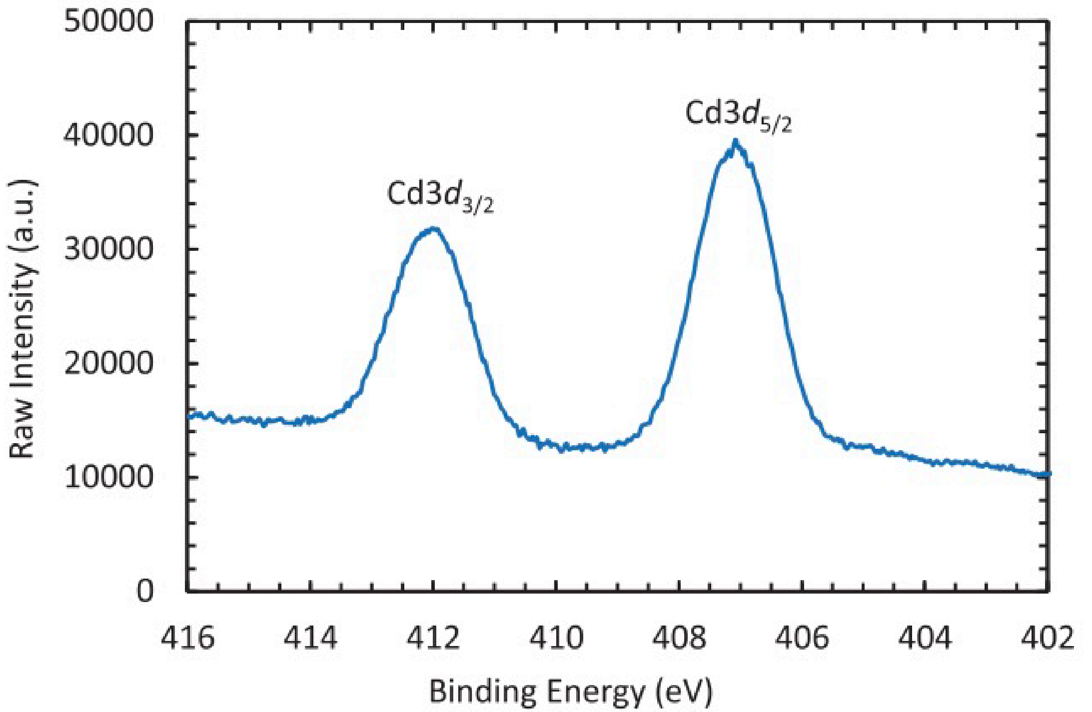
Source: S. U. Egarievwe, G. Yang, A. A. Egarievwe, A. A., I. O. Okwechime, J. Gray, Z. M. Hales,. . . James, R. B. (2015). Post-growth annealing of Bridgman-grown CdZnTe and CdMnTe crystals for room-temperature nuclear radiation detectors. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 784, 51-55. doi: 10.1016/j.nima.2015.02.006.

XPS Study of Passivated CdZnTe Surfaces

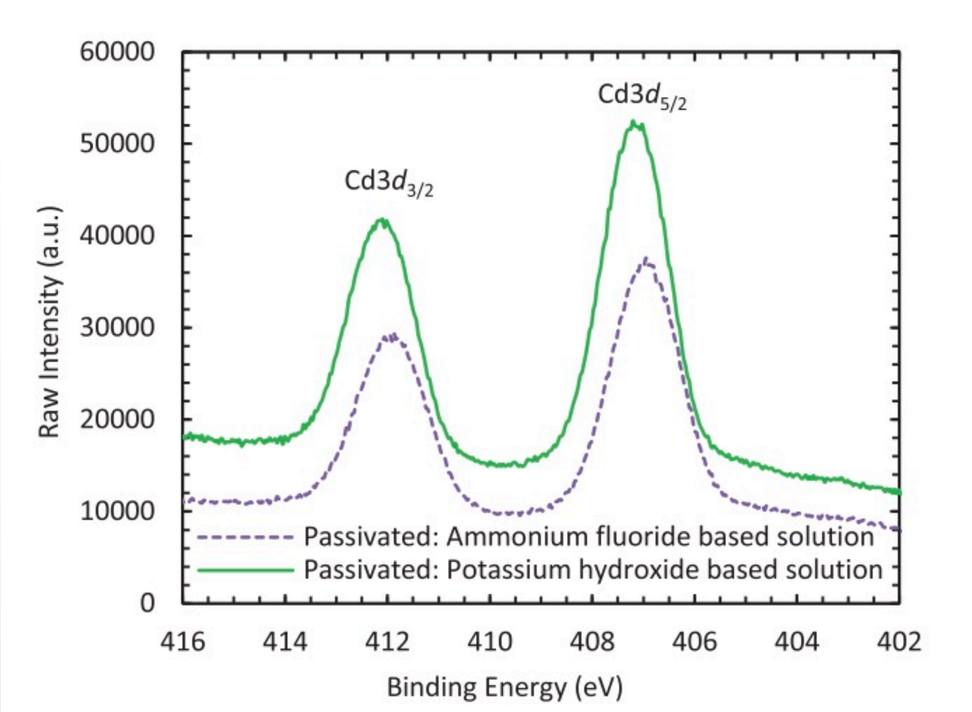
- Passivation helps to reduce the surface current and improve shelf-life of the device.
- Process: The detector wafer is dipped in the passivation solution and dried with compressed air.
- Chemicals used in Our Studies:
  - A mixture of 0.1-g potassium hydroxide (KOH) and 10-ml 30% hydrogen peroxide (H_2O_2) aqueous solution.
  - A mixture of ammonium fluoride and 10% hydrogen peroxide in distilled water ($NH_4F + H_2O_2 + H_2O$).

High-performance XPS Surface Analysis System by Thermo Fisher

XPS Spectra of CdZnTe Surfaces: Cadmium (Cd) Peaks

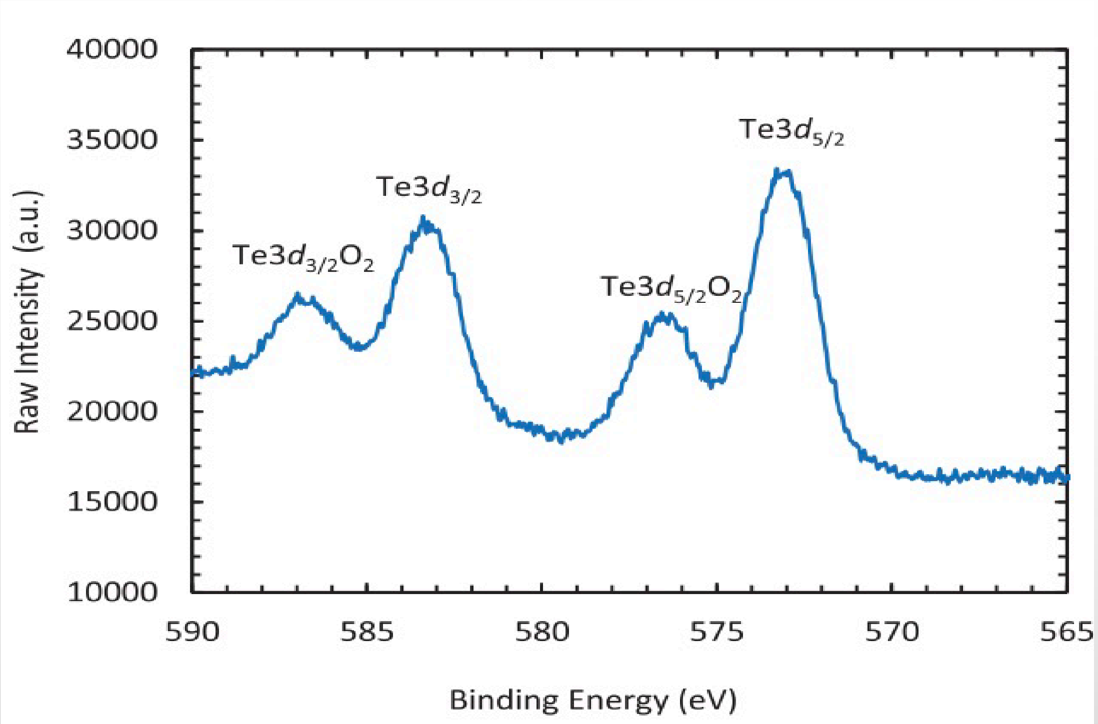


(a) Before passivation.

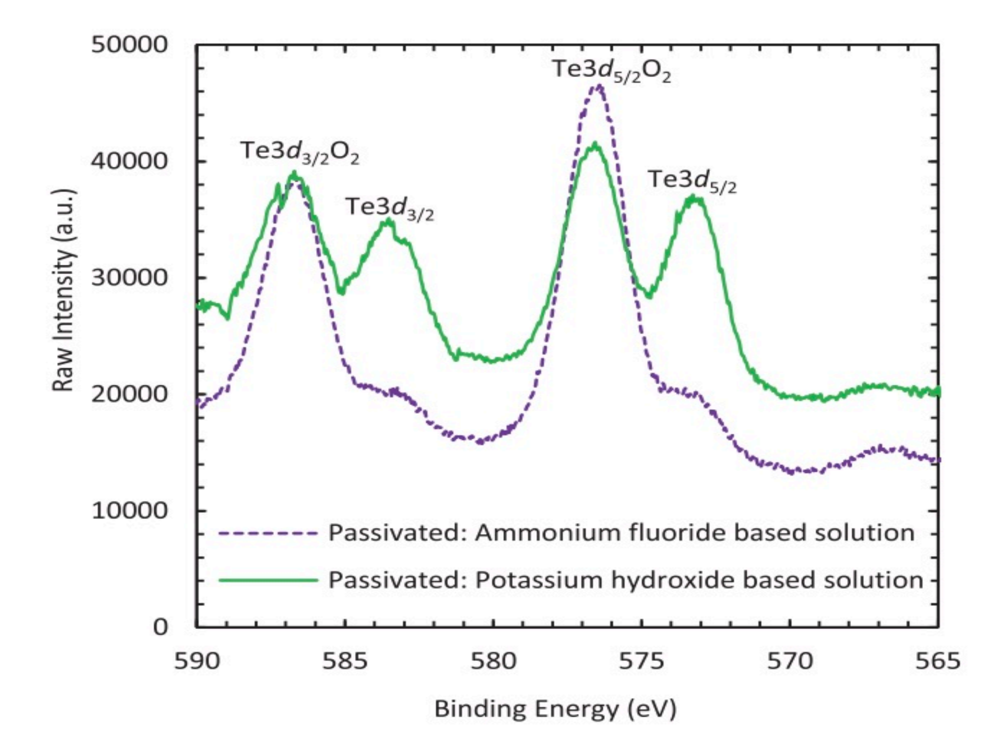


(b) After passivation in KOH, and NH_4F.

XPS Spectra of CdZnTe Surfaces: Te and TeO_2 Peaks



(a) Before passivation.



(b) After passivation in KOH, and NH_4F.

Source: S. U. Egarievwe, A. Hossain, I. Okwechime, A. Egarievwe, D. Jones, Dominique U. Roy, and R. B. James, (2016). Effects of Chemical Treatments on CdZnTe X-Ray and Gamma-Ray Detectors. IEEE Transactions on Nuclear Science. 63. 1091-1098. 10.1109/TNS.2016.2527779.

XPS Spectra of CdZnTe Surfaces: Te and TeO_2 Peaks

Process	$Te3d_{3/2}O_2/Te3d_{3/2}$	$Te3d_{5/2}O_2/Te3d_{5/2}$
Before Passivation	0.49	0.46
After passivation in KOH.	1.25	1.19
After passivation in NH_4F.	4.90	5.34

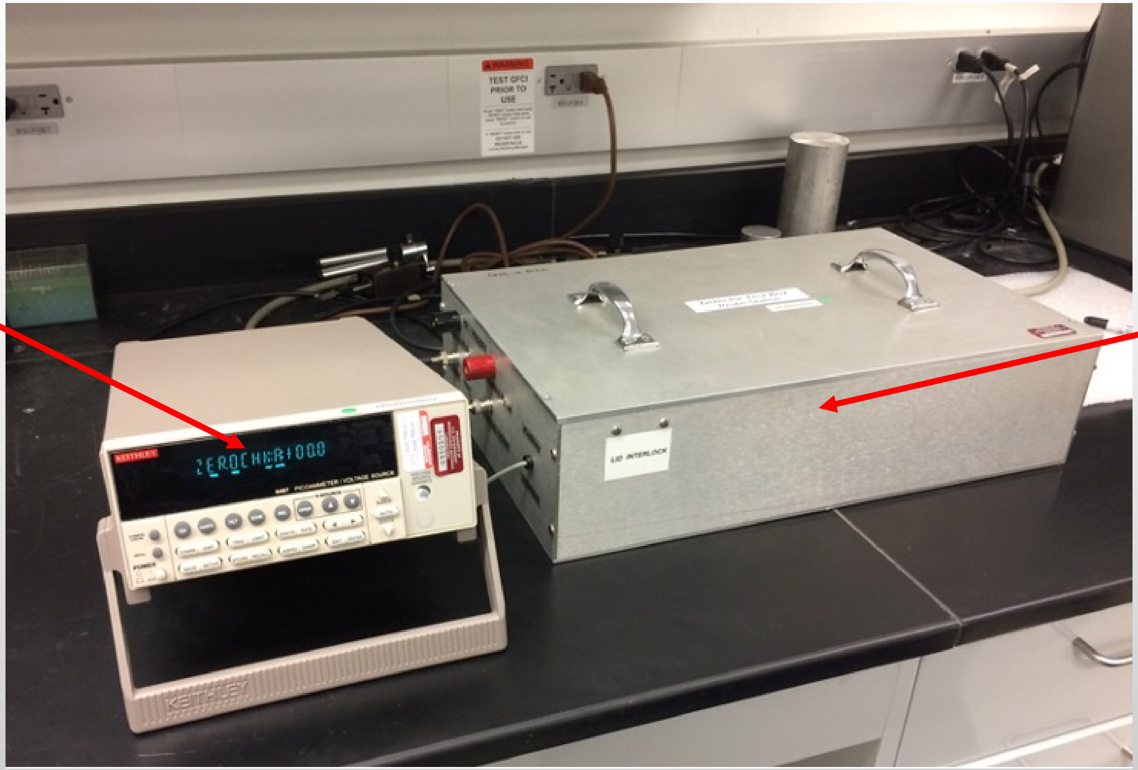
- TeO_2 peaks increased after passivation. This shows the formation more TeO_2.
- Passivation in NH4F produces more than passivation in KOH.
- Thus, NH_4F is better passivation chemical than KOH.

Planar Detector Fabrication

- Involves four major steps.
  - Wafer Cutting:
    - Cuts detector wafer to desired dimensions using a special cutting machine.
  - Mechanical Polishing:
    - Remove surface defects and residue using silicon-carbide abrasive papers.
  - Chemical Etching and Drying:
    - Used to remove any fine residual damage caused by mechanical polishing.
  - Deposition of Electrical Contacts:
    - Use electroless contact deposition method to deposit electrical contact on two opposite planner surface of the wafer.

Electrical Instrumentation for Current-Voltage Measurement

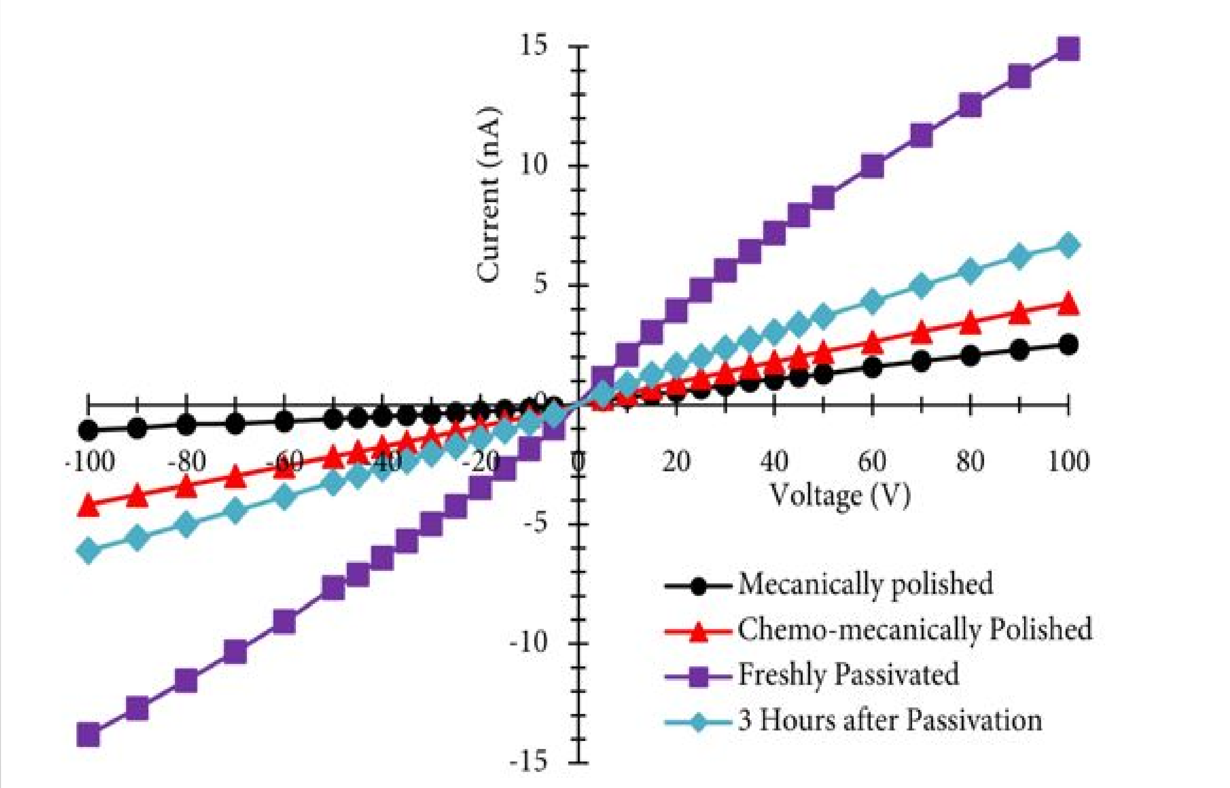
Keithley Picoammeter/Voltage Source



Aluminum box where sample is mounted

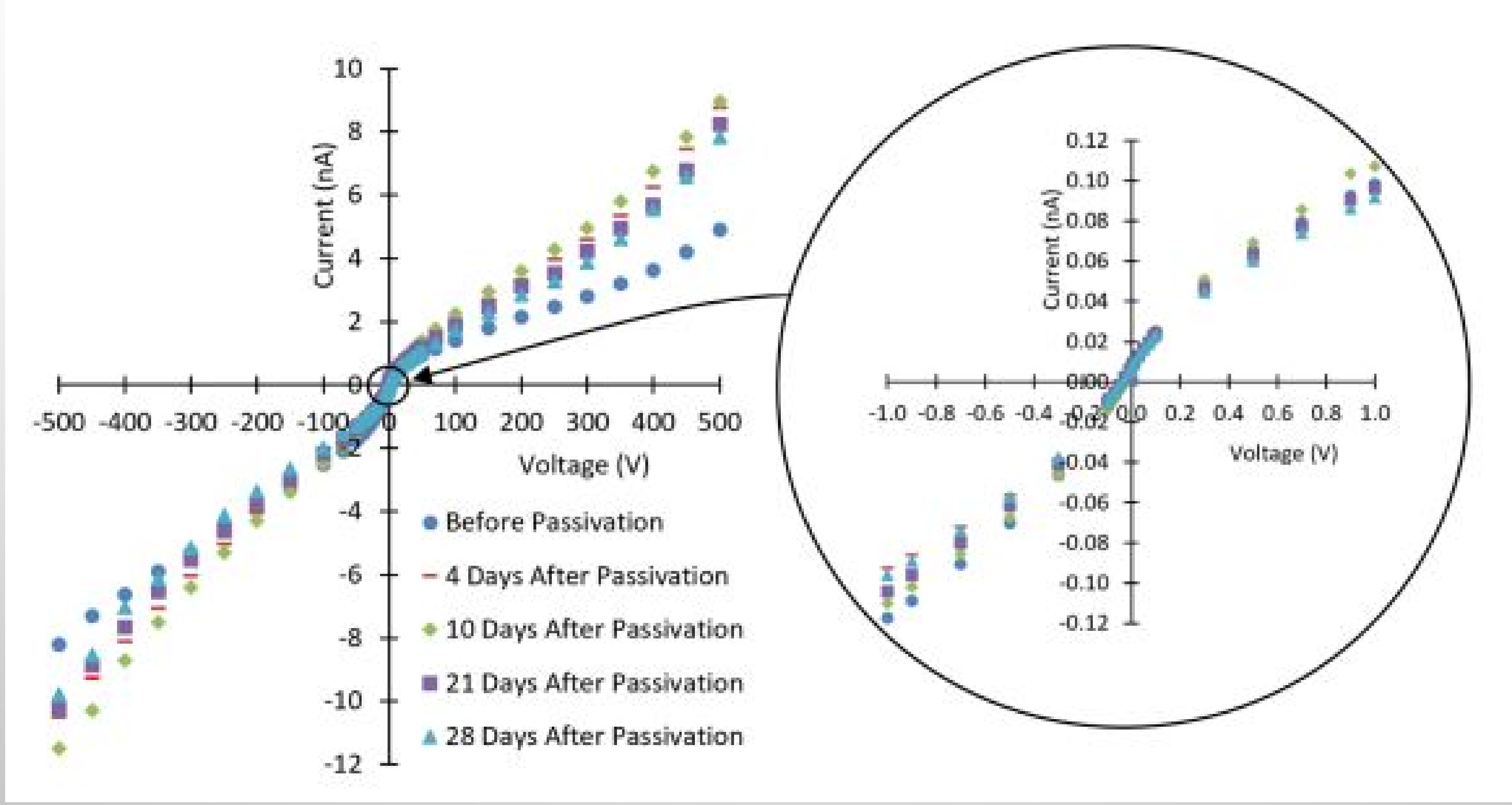
Current-Voltage measurement system at Brookhaven National Laboratory.

Surface Chemical Treatments of CdZnTe Detector



Current-voltage plots for different surface chemical treatments of CdZnTe.

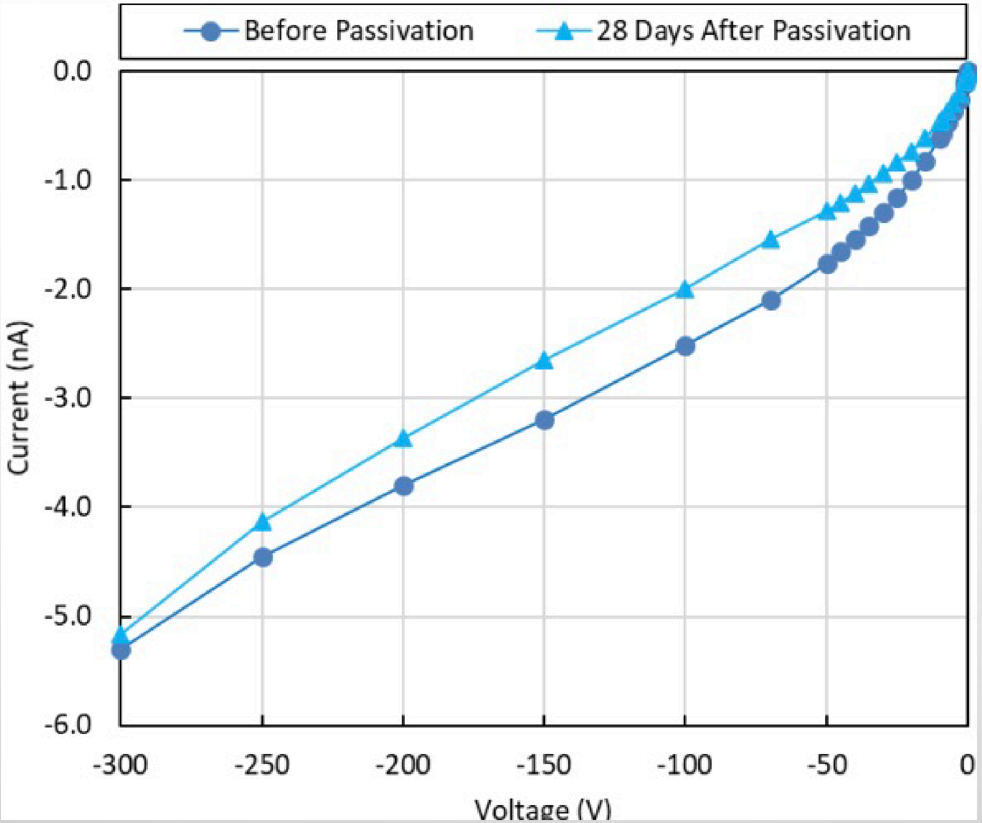
Chemical Passivation of CZTS



Current-Voltage plots that show passivation results after different days.

Source: S. U. Egarievwe, U. N. Roy, C. A. Goree, B. A. Harrison, J. Jones, and R. B. James, (2019). Ammonium fluoride passivation of CdZnTeSe sensors for applications in nuclear detection and medical imaging. Sensors, 19(15), 3271.

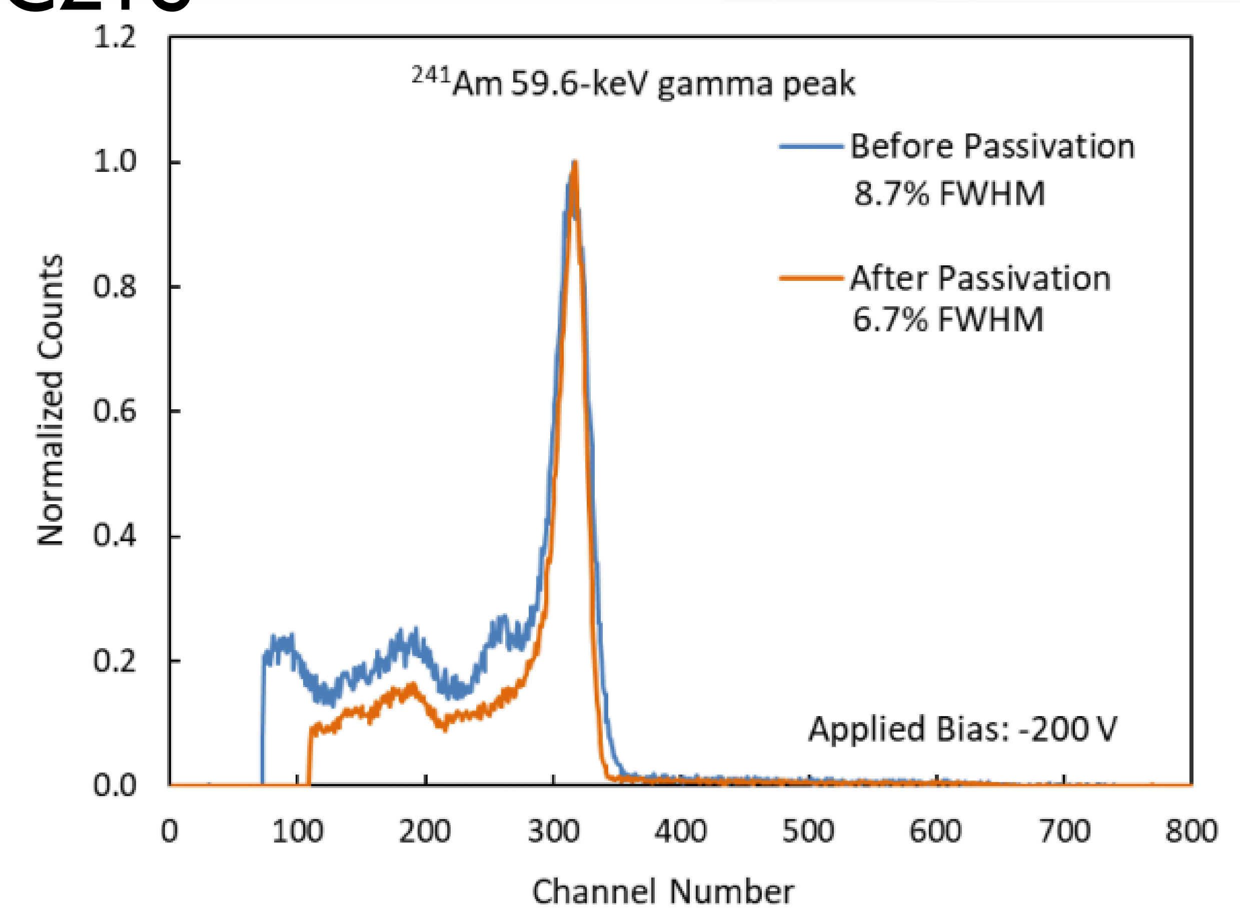
Chemical Passivation of CZTS



Voltage regions with reduced current 28 days after passivation.

Chemical Passivation of CZTS

CZTS detector response from a ^{241}Am source at -200V before passivation and 28 days after passivation.



Summary

- Thermal annealing reduces the sizes and concentrations of Te inclusions.
- XPS studies of passivated samples showed that:
  - TeO_2 formation increased after passivation.
  - NH_4F is better passivation chemical agent than KOH.
- Passivation in NH_4F improves energy resolution.

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Thank You