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PROBING CHARGE TRAPPING OF HIGH K DIELECTRIC STACKS UNDER IONIZING RADIATION

Devika Mehta, Christopher R. Allemang, Aldo I. Vidana, Jenny Xiong, Jeffrey A. Ivie, Shashank Misra

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PI: Shashank Misra

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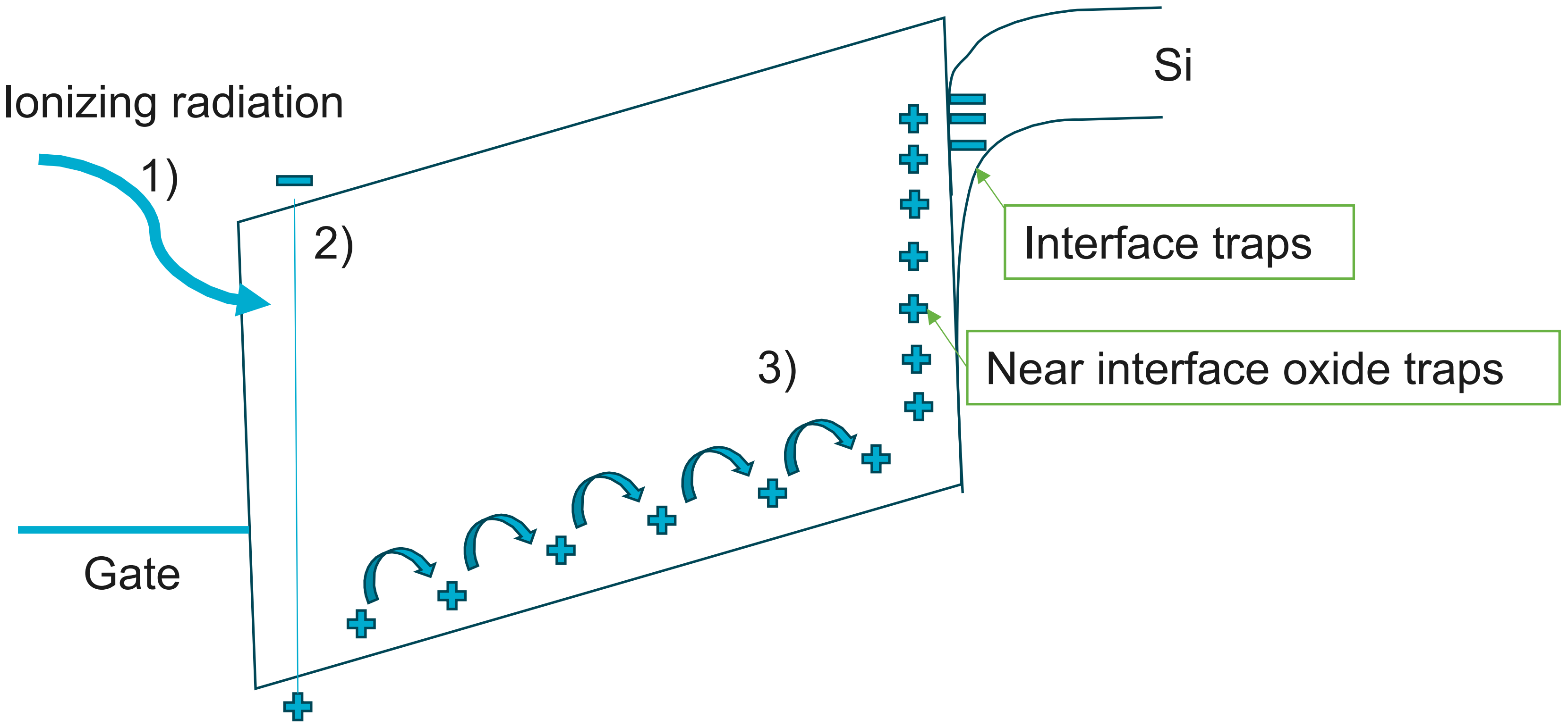
OVERVIEW

- **Motivation: Evaluate charge trapping via ionizing radiation**
- Flatband voltage as measure of trapped charge
- SiO_2 vs high k dielectrics: Al_2O_3 and HfO_2
- Single layer stacks: dosing – dielectric and thickness variation
- Stacking of multiple dielectrics
- Time-Series Measurement design and dosing strategy

MOTIVATION: CHARGE TRAPPING

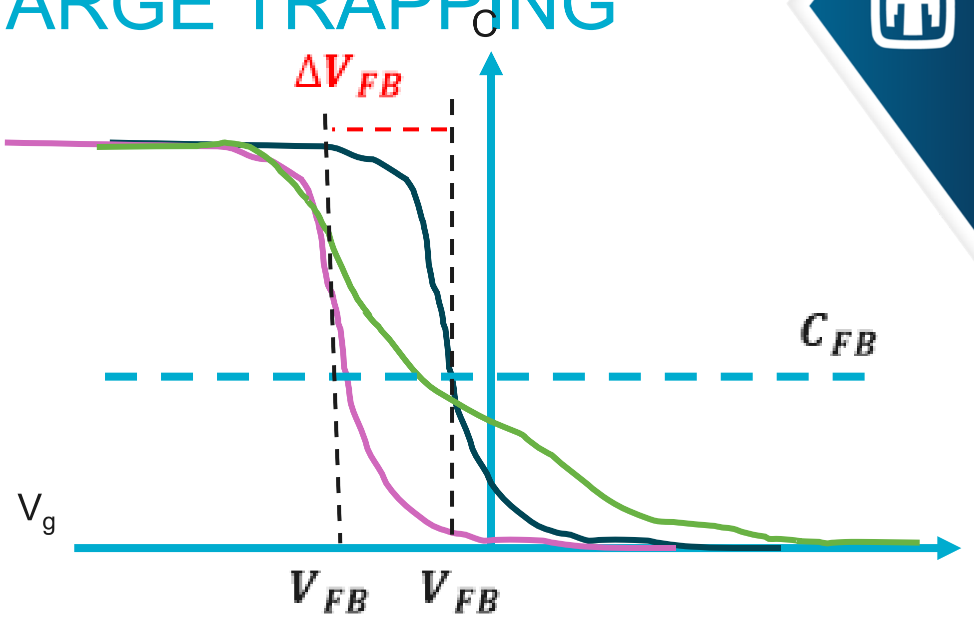
- Dielectrics: common medium for charge trapping
- Ionizing radiation to probe charge trapping via:
- 1) Generation of electron-hole pairs
- 2) With bias, electrons and holes separate in opposite directions
- 3) Lower mobility of holes → higher probability of holes being trapped in oxide traps or interface traps

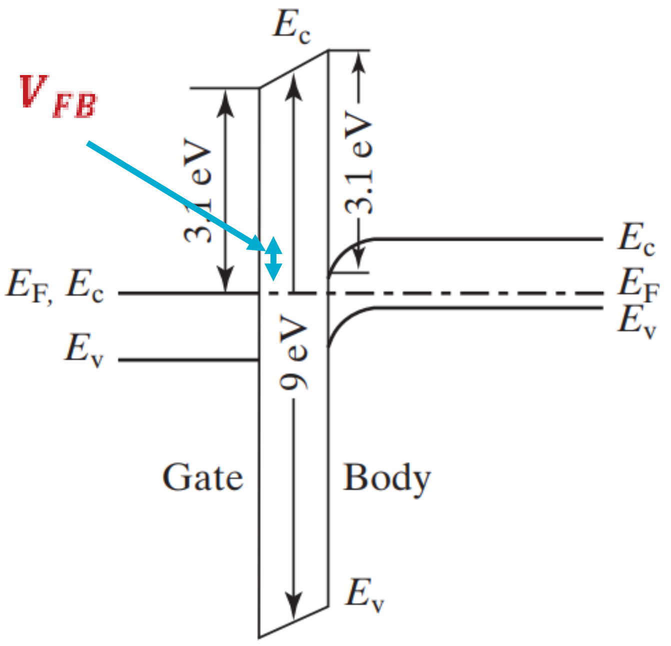


FLATBAND VOLTAGE AS MEASURE OF CHARGE TRAPPING

- Radiation induces oxide and interface traps
- Oxide trapped charge can provoke lateral shift in C-V curve
- Interface trapped charge: stretch out of C-V curve
- Buildup of trapped charge creates electric field resulting in shift in **flatband voltage (V_{FB})**:

$$V_{FB} = \phi_{ms} - \frac{Q_f - \gamma Q_m - \gamma Q_{ot} - Q_{it}(\phi_s)}{C_{ox}}$$

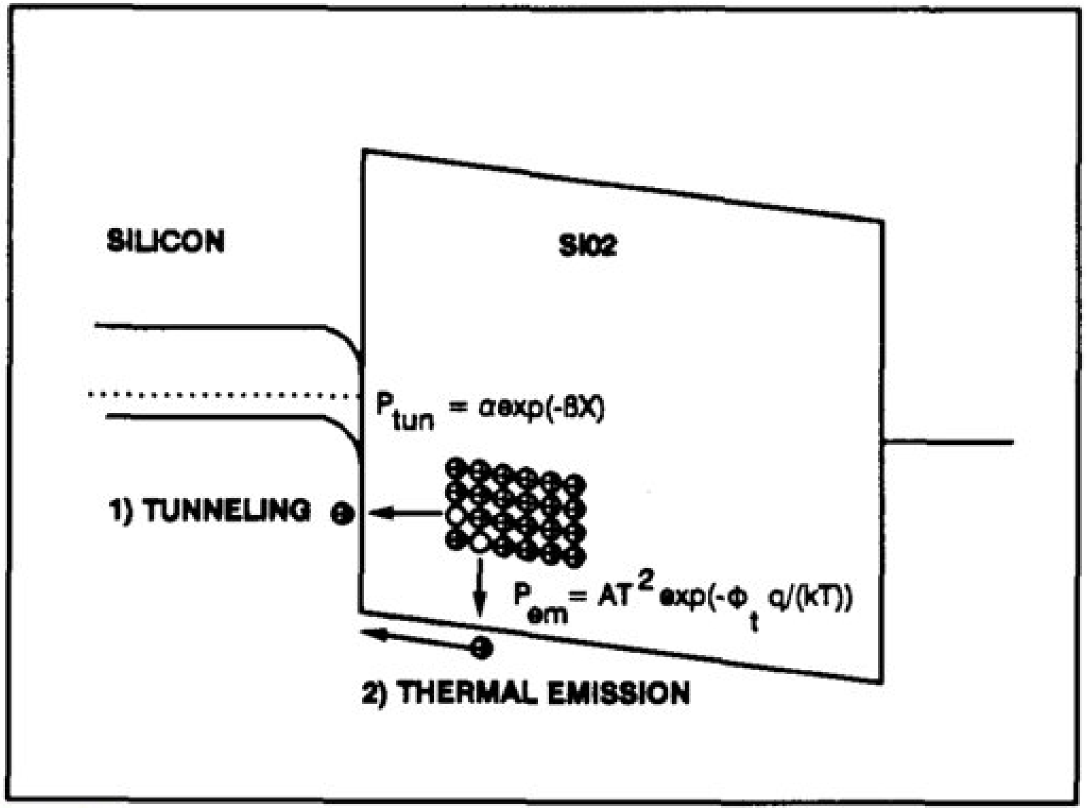




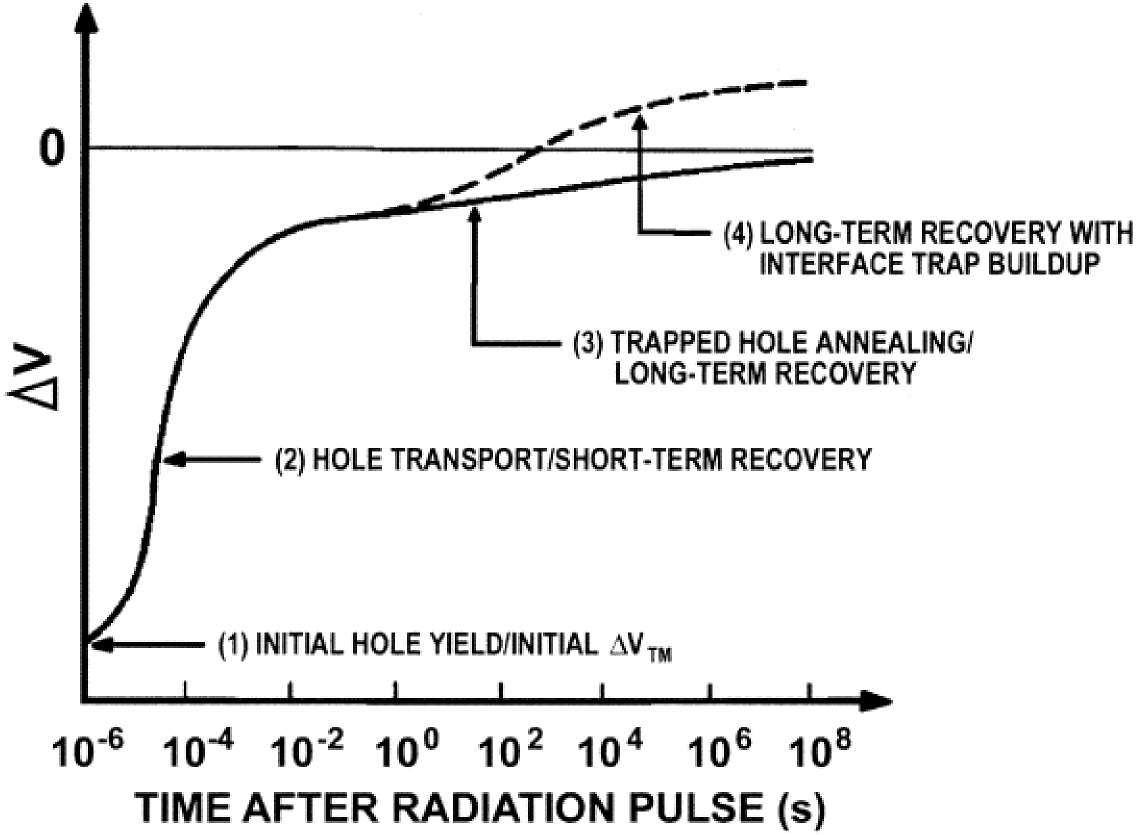
Pierret, R. F. *Semiconductor Device Fundamentals.*

FLATBAND VOLTAGE AS MEASURE OF CHARGE TRAPPING

Neutralization of oxide charge: tunneling or thermal emission



P. J. McWhorter, S. L. Miller and W. M. Miller, *IEEE Transactions on Nuclear Science*, vol. 37, no. 6, pp. 1682-1689, (1990)



T. R. Oldham and F. B. McLean, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, vol. 50, no. 3, pp. 483,, (2003)

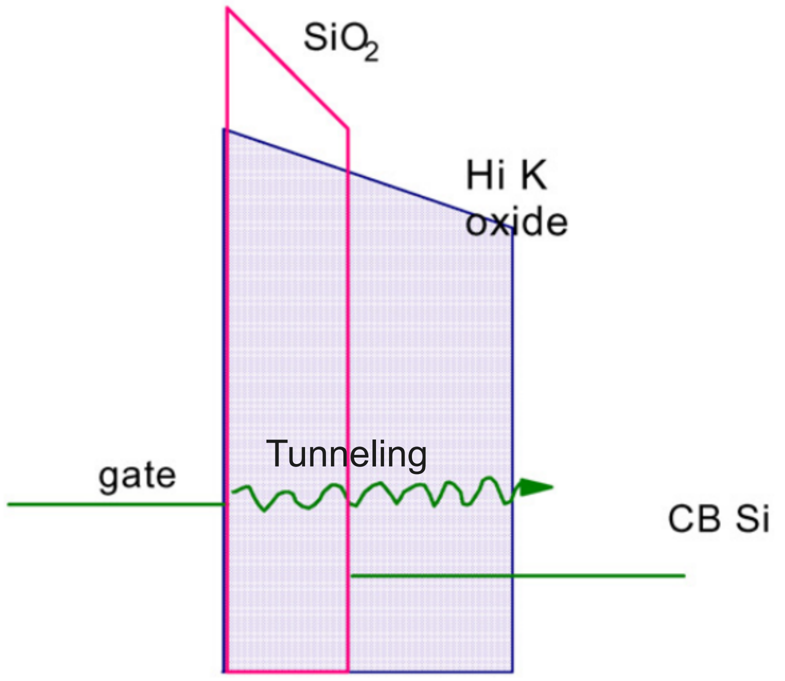
SIO_2 VS HIGH K DIELECTRICS

- Concern of leakage currents in using thin SiO_2 as gate dielectric
- High dielectric constant (k) materials allow for thinner films with equivalent capacitances = **E**quivalent **O**xide **T**hickness

$$EOT = \frac{t_{high-k}(k_{SiO_2})}{k_{high-k}}$$

- Al_2O_3 : k = 7.8 and amorphous HfO_2 : k =20
- Charge trapping centers in high k dielectrics
  - Oxygen vacancies in bulk
  - Defect states
  - Interface traps

Step 1: Evaluate single dielectric layers to understand trapping possibilities of Al_2O_3, HfO_2



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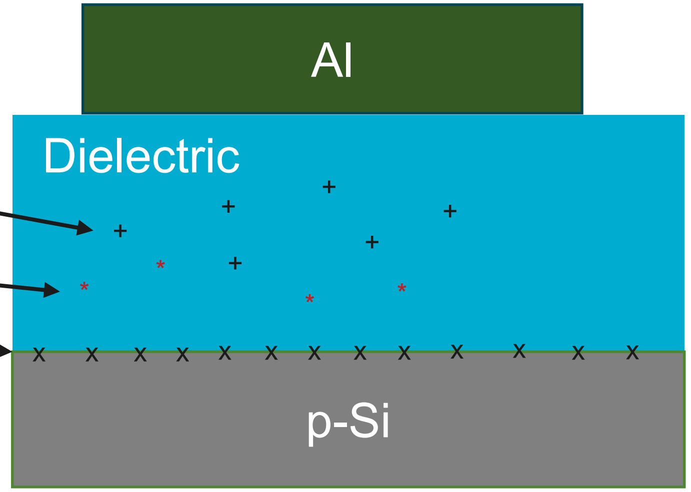
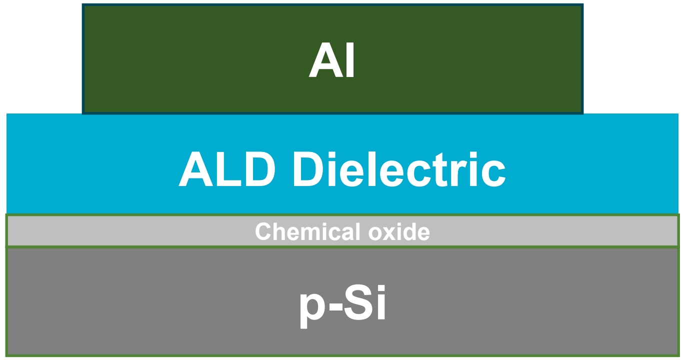


SINGLE LAYER STACKS – DOSING – DIELECTRIC AND THICKNESS VARIATION

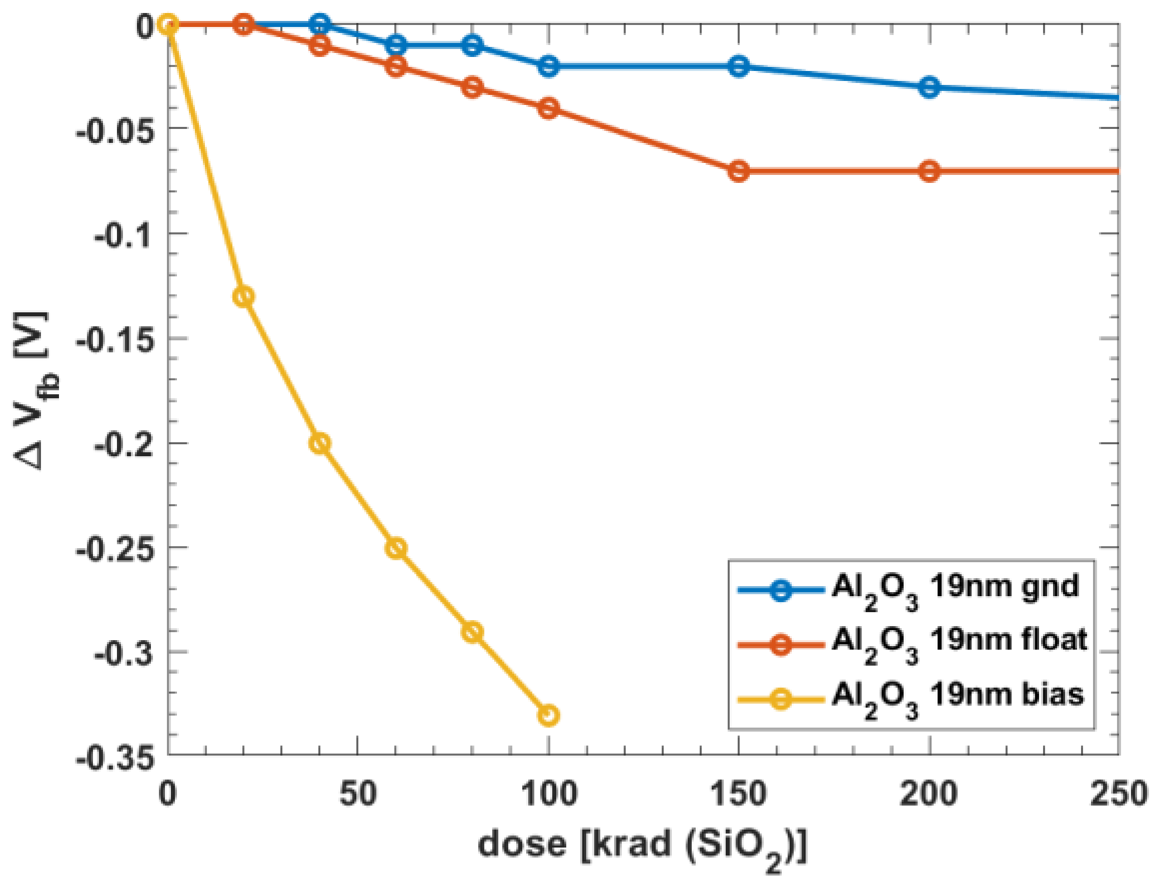


Extracted from multifrequency C-V pre-irradiation

ALD Dielectric	Thickness [nm]	D_{it} (cm^{-2} eV^{-1})
HfO_2	15.5	**4.16e11**
Al_2O_3	18.9	**2.33e12**
Al_2O_3	28.2	**3.01e12**

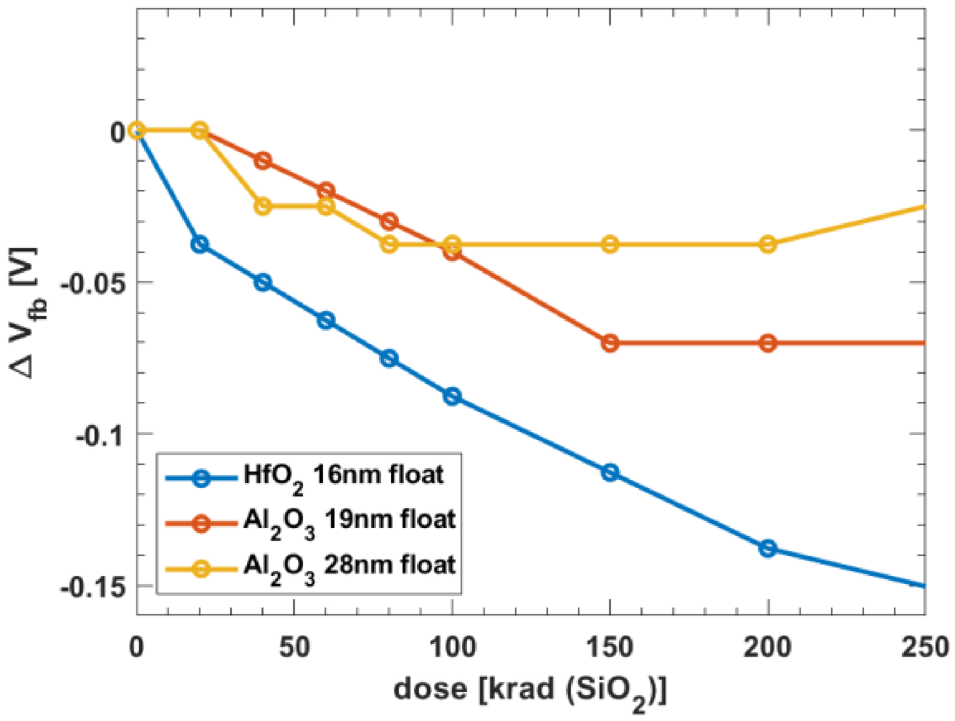
SINGLE LAYER STACKS DOSING – BIAS CONDITIONS

- **Bias during irradiation** separates electrons and holes, preventing recombination, maintaining built-in potential and shift in flatband voltage

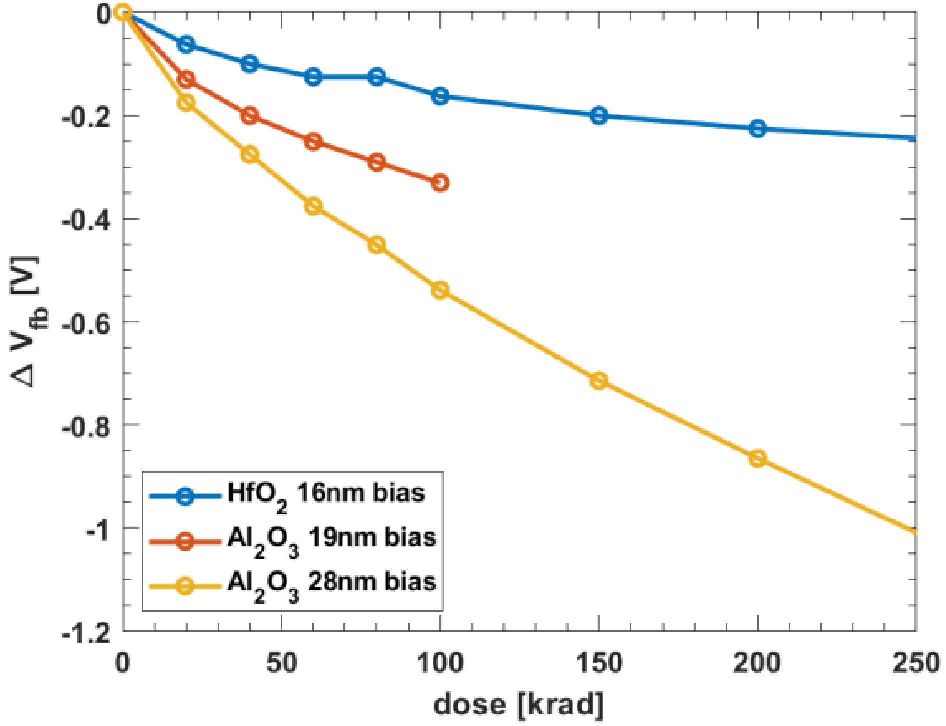


SINGLE LAYER STACKS – DOSING – DIELECTRIC AND THICKNESS VARIATION

Dosing under 3 bias conditions: V_{fb} calculated from 1MHz C-V sweeps between doses



Float or ground during irradiation: HfO_2 largest shift



Biased during irradiation: Al_2O_3 largest shift

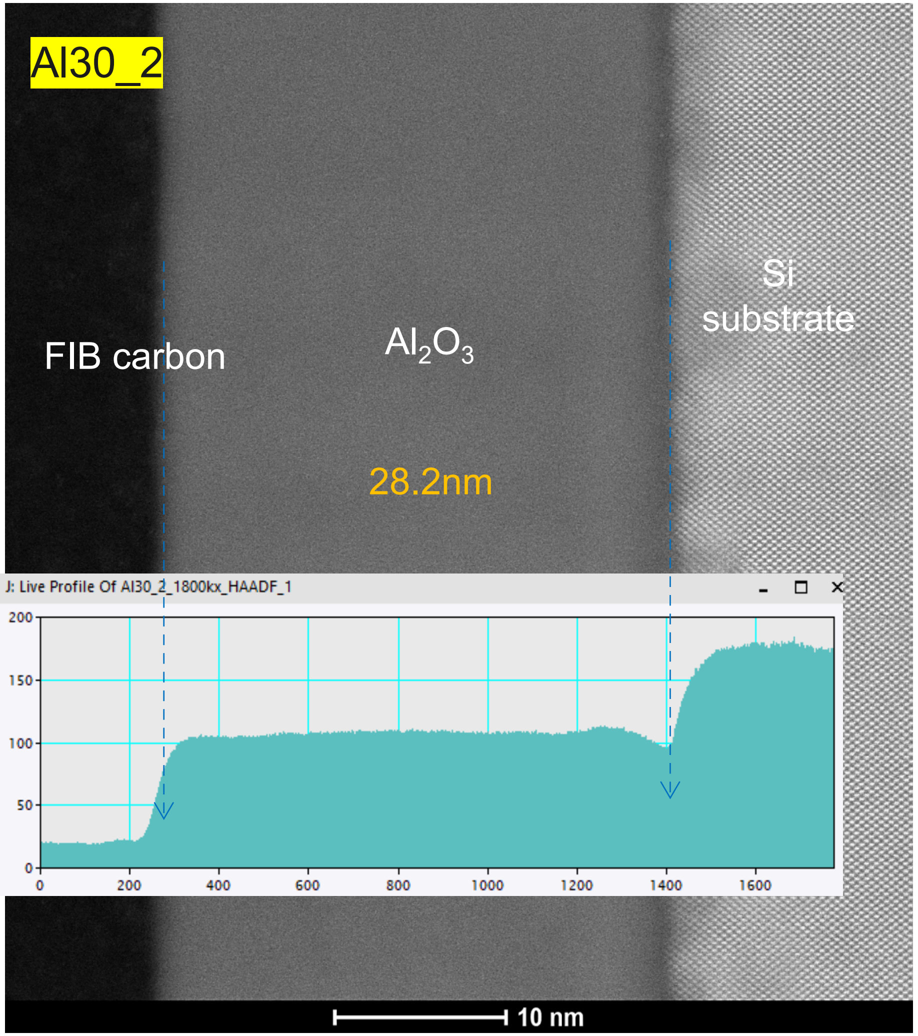
Preliminary takeaways from initial dosing and C-V measurements of single layer stacks:

- Origin of radiation-induced trapped charge (oxide vs interface states, etc.) needs to be confirmed
- Requires more examination (bias stress measurements, etc.)

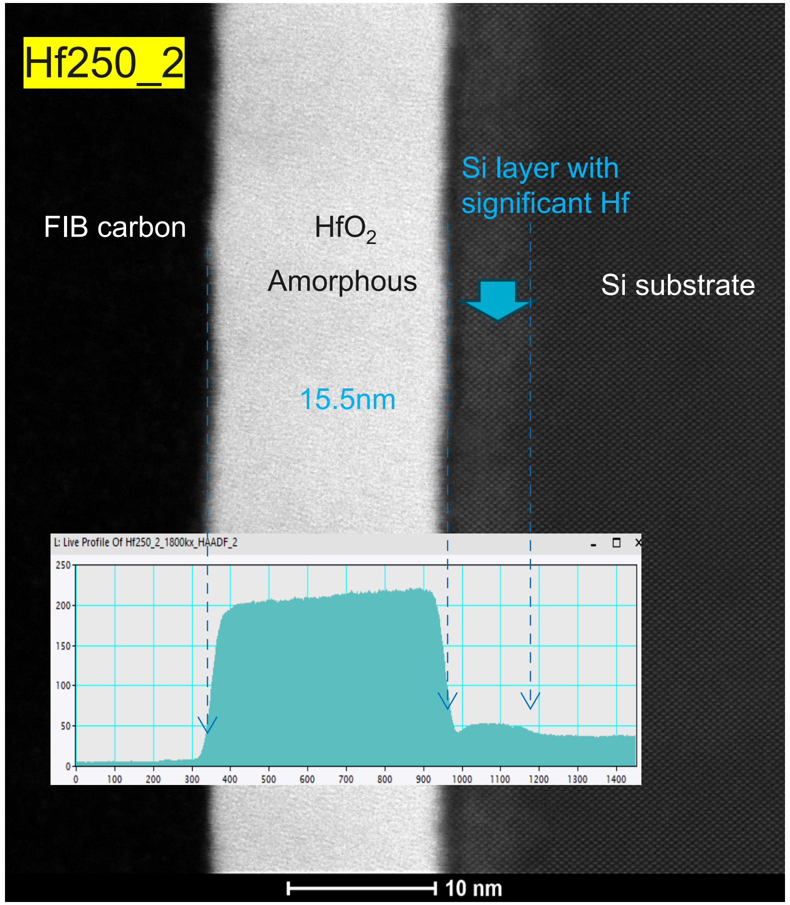
TEM: SINGLE LAYER DIELECTRIC ON SILICON

What is the effect of interface quality?

Sharp interface at Al_2O_3/Si

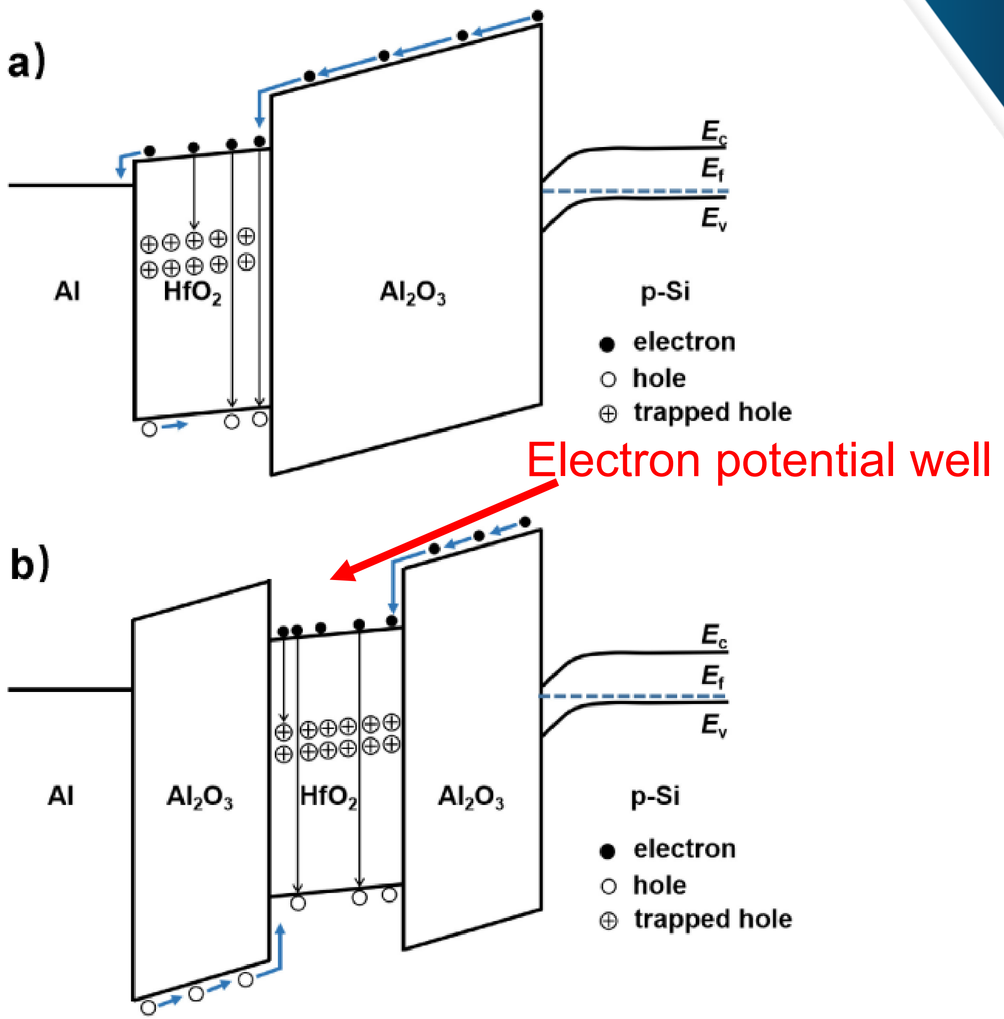


Hf-Si intermixing transition layer



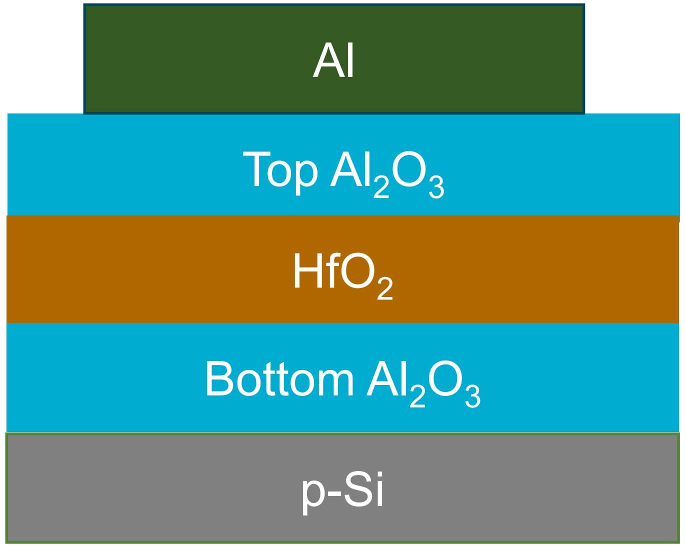
STACKING OF MULTIPLE DIELECTRICS

- **Enhance charge trapping ability by leveraging multiple layers, varying stacking order and thicknesses**
- Interface quality at Al_2O_3/Si in comparison to HfO_2/Si
- Band offsets → energy barriers and potential wells
- Trade-off: charge generation vs trapped charge recombination
- **Step 2: Configuration of layers to optimize charge trapping**



H. Zhao, et. al. *IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY*, 23, 1, (2023)

MULTILAYER STACKS - DESIGN



Develop series of stacks to discretely investigate following effects on charge trapping and ΔV_{FB}

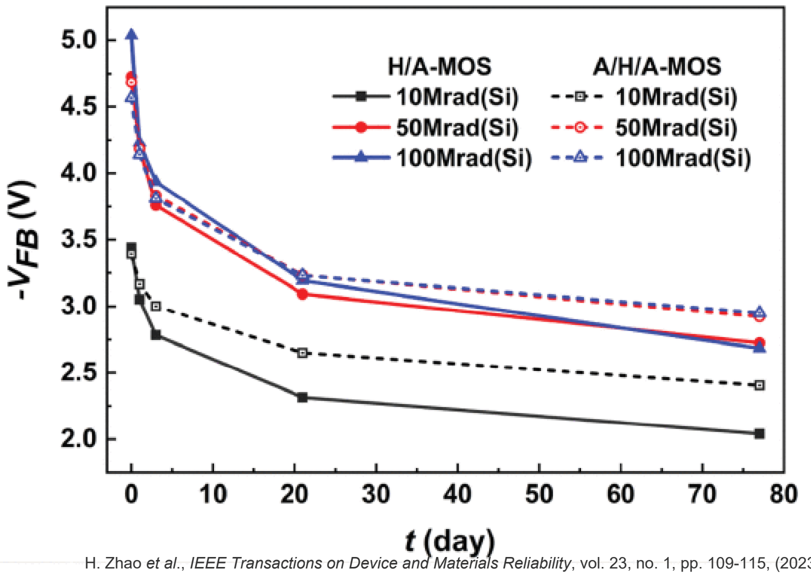
- Tunneling from Si by decreasing thickness of bottom Al_2O_3
- Charge generation by increasing thickness of top Al_2O_3
- Impact of electron well (trapping) versus charge generation by removing top Al_2O_3
- Impact of thickness of HfO_2 on charge generation by increasing its thickness

Goal: Distinguish role of layer stacking and thickness in long-term charge trapping

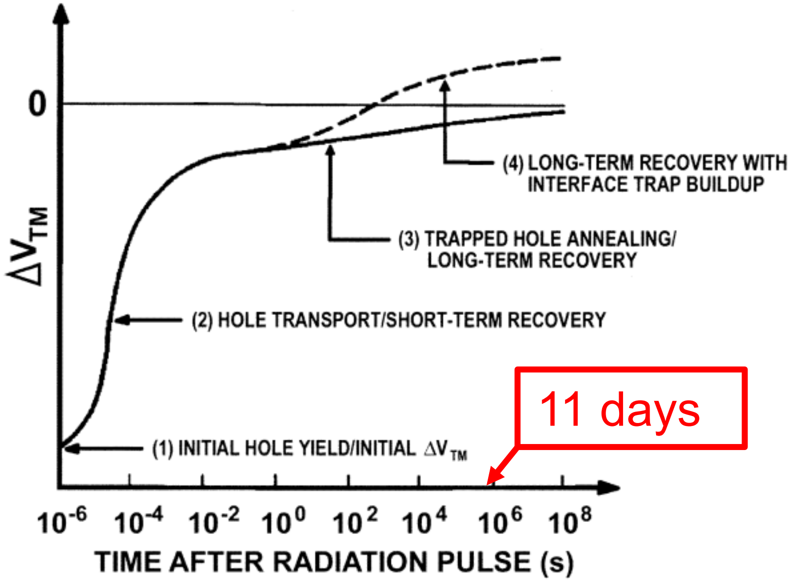
TIME-SERIES MEASUREMENT DESIGN AND DOSING STRATEGY

- Plan of dosing work on multilayer stacks:
  - Dose with 1MHz C-V sweep between doses to observe ΔV_{fb} vs dose under different biasing conditions
  - Time-series measurement: 1MHz C-V sweep up to 20 days

Long-term annealing trends manifesting in 10-20 days



H. Zhao *et al.*, *IEEE Transactions on Device and Materials Reliability*, vol. 23, no. 1, pp. 109-115, (2023)



T. R. Oldham and F. B. McLean, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, vol. 50, no. 3, pp. 483,, (2003)

SUMMARY AND IMPLICATIONS

Developing and understanding the use of high k dielectrics in a material stack for charge trapping purposes

  - Ionizing radiation as probe
  - Understand radiation response of high k dielectric and origin of trap states
  - Understanding effect of biasing conditions on charge trapping and neutralization
  - Observe charge neutralization over time

- **Implications for charge trapping materials to be incorporated into wide range of devices**

ACKNOWLEDGEMENTS

- Thank you!

Team Members	Role
Devika Mehta	Electrical measurement
Chris Allemang	Fabrication and Electrical Measurement
Aldo Ivana and Jenny Xiong	Dosing and electrical measurement
Jeff Ivie	APAM devices
Shashank Misra	Principal Investigator

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