Interface Structure and Charge Trapping in HfO_2-based MOSFETS

VANDERBILT UNIVERSITY

MURI - ANNUAL REVIEW, 13 and 14th May 2008

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Radiation damage in Hafnium oxide

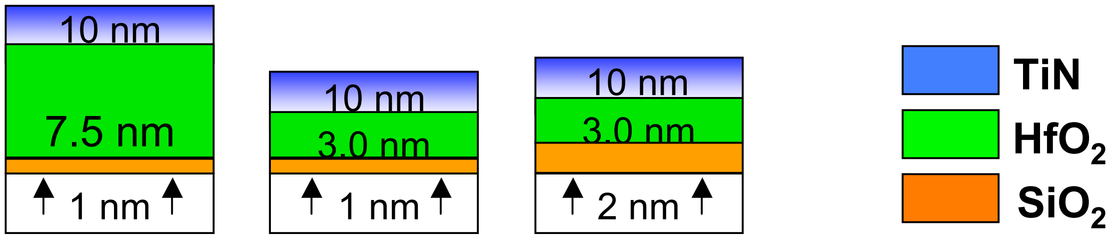
Previous radiation studies:

Most of the work on thicker oxides, mostly on capacitors

- Electron trapping reported. Kang *et al.*, APL, vol. 83, p. 3407, 2003
- Hole trapping studied. Felix *et al.*, Microelectron. Engrg., vol. 44, p. 563, 2004, Ryan *et al.*, IEEE TNS, vol. 52, p. 2272, 2005

This work:

- Radiation studies on HfO_2-based MOSFETs
- Dose response of ultrathin gate oxides
- Identify the bias stress contribution for pure rad response
- Study as a function of SiO_2 IL and bulk HfO_2 thickness



- Improved trapping efficiency calculations

Device processing & irradiation

Fabrication:

p-type Si

↓

~ 1 nm/2 nm SiO_2 IL - ozone cleaning/thermal

↓

~ 3 nm/7.5 nm Atomic Layer Deposition HfO_2

↓

~ 700 °C/60 s anneal in NH_3

↓ - - - → **Materials Analysis**

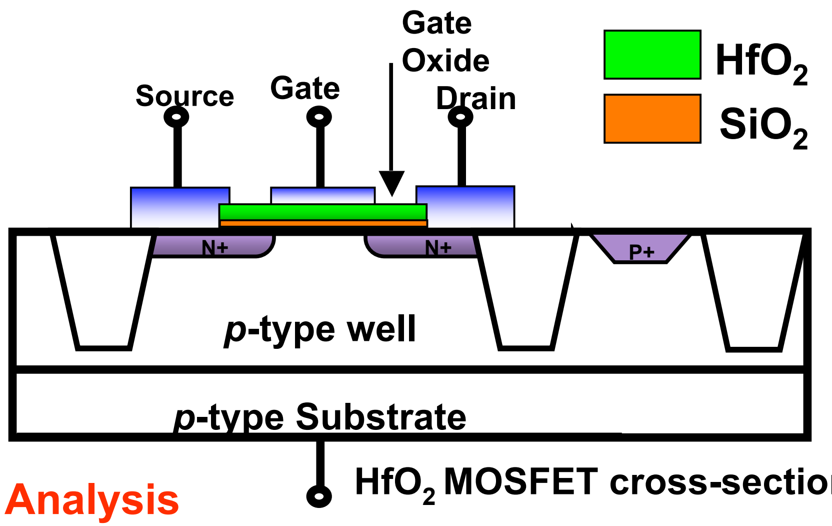
~ 10 nm TiN gate metal

↓

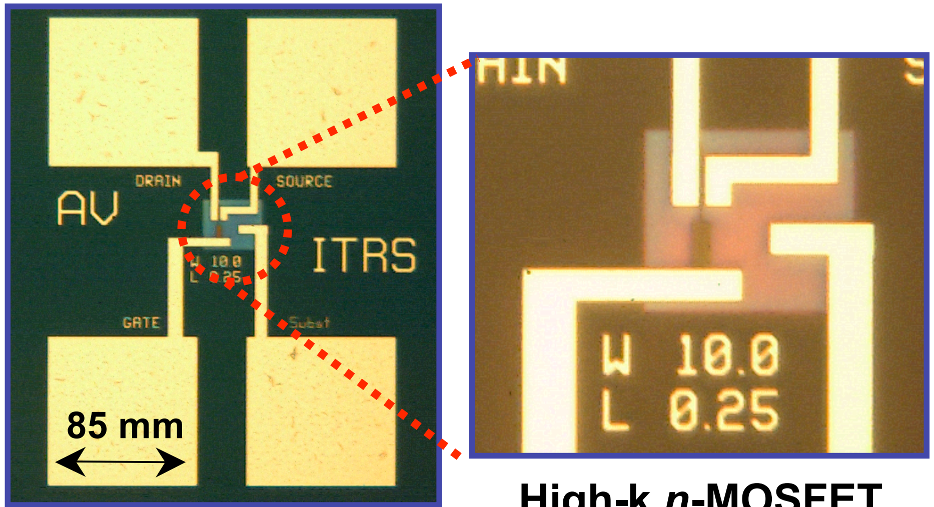
Ion implant - 1000 °C/10 s dopant activation anneal

↓

Electrical measurements



HfO_2 MOSFET cross-section



AV module

High-k *n*-MOSFET

Irradiations:

- In-situ 10 keV X-ray irradiations
- Function of bias
- Function of bulk (7.5/3 nm) & IL (1/2 nm)
- I-V characterization

Materials and Device Characterization

Before irradiation

- Thickness of SiO_2 IL and HfO_2 bulk
- Materials composition
- Amorphous/nano-crystalline

Materials Characterization

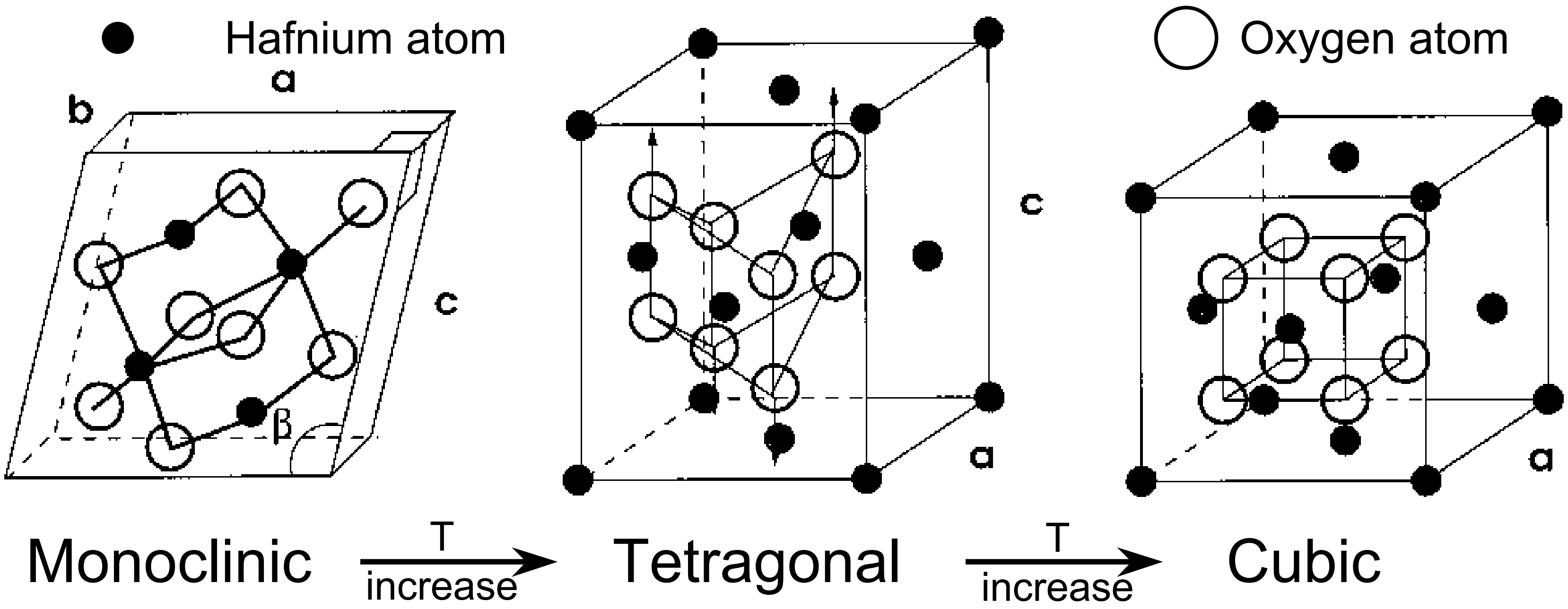
Co-relate

Electrical Characterization

After irradiation

- Charge trapping (V_T shifts)
- Trap location (SiO_2 IL or HfO_2 bulk)

Hafnium oxide - Materials perspective



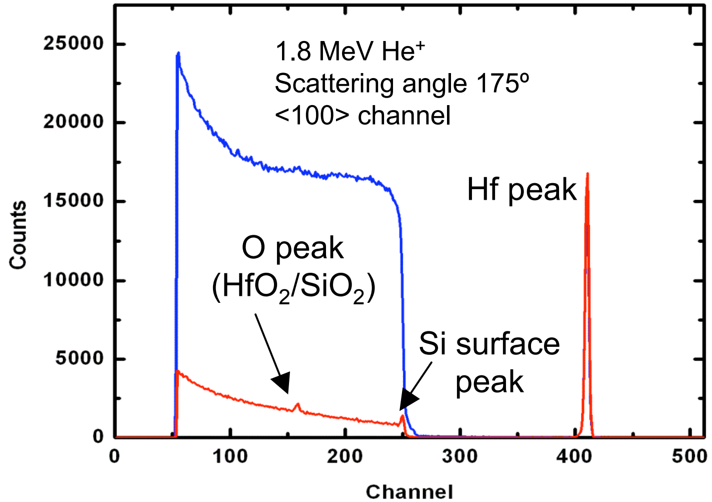
Zhao *et al.*, PRB, vol. 65, p. 233106, 2002

- Structure - Monoclinic crystallites in amorphous matrix
- Pure HfO_2 crystallizes at high temp., trapping increases with defects at GBs
- Alloying of Si increases the thermal budget, κ reduced, affects C_{ox}
- SiO_2 interlayer improves mobility, intermixing issues, amphoteric traps

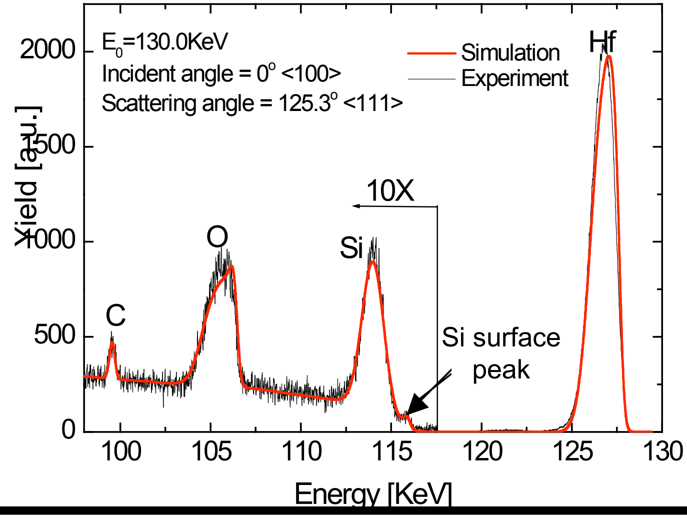
Callegari *et al.*, JAP, v.90,p. 6466, 2001

Materials analysis - HfO_2/SiO_2 IL/Si

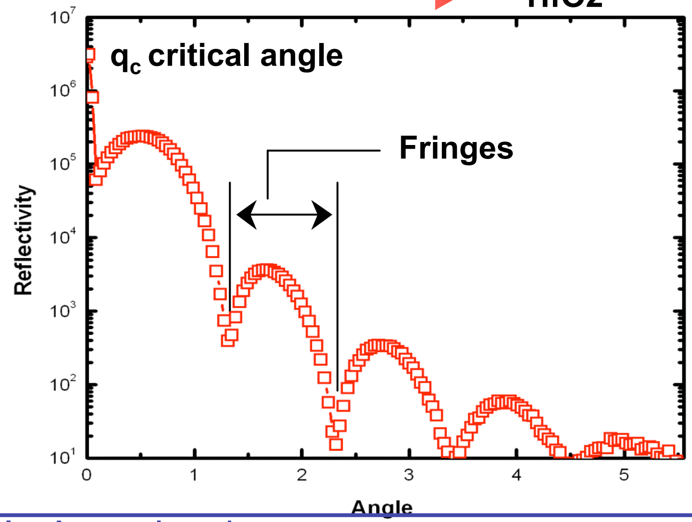
RBS/Channeling → t_{HfO2} & t_{SiO2}



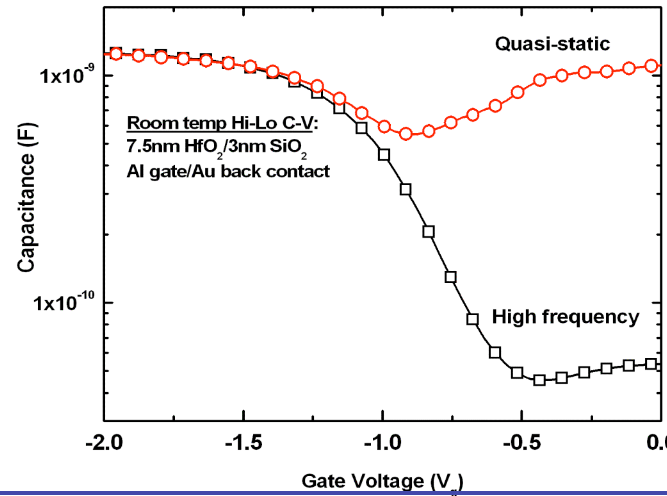
MEIS → t_{HfO2}, t_{SiO2} & Si in HfO_2



XRR → t_{HfO2}

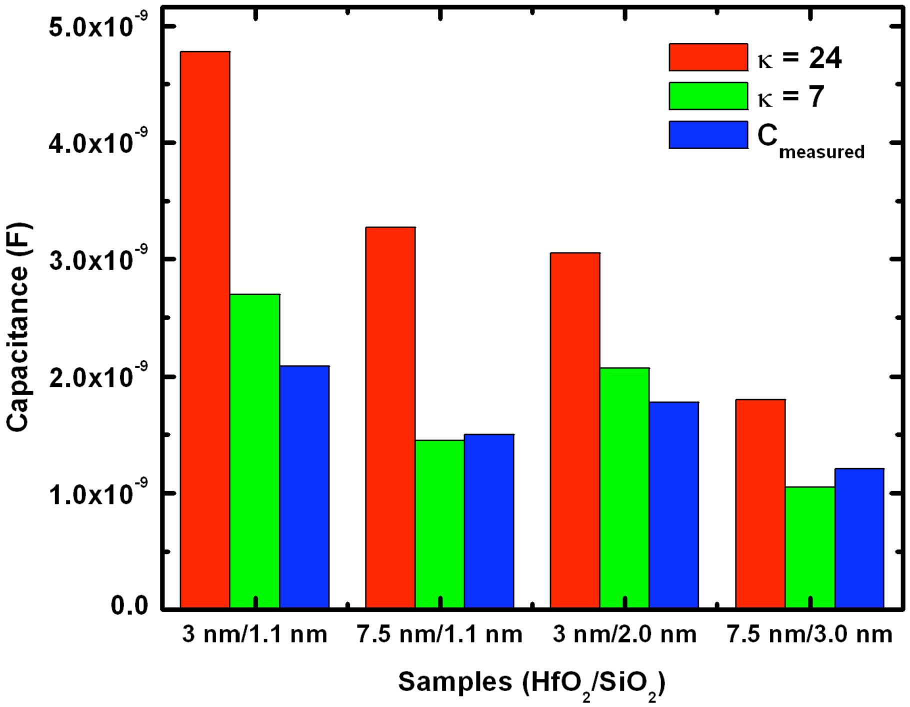


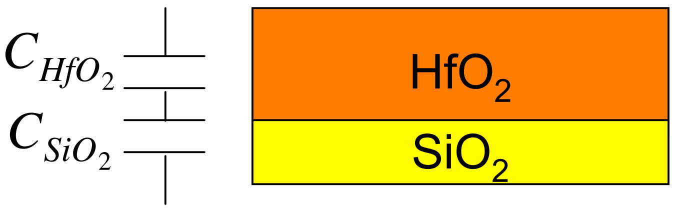
C-V → t_{HfO2}, t_{SiO2} & Si in HfO_2



Dixit *et al.*, manuscript to be submitted to JAP, 2008

C-V - Comparison (Theory & Measured)

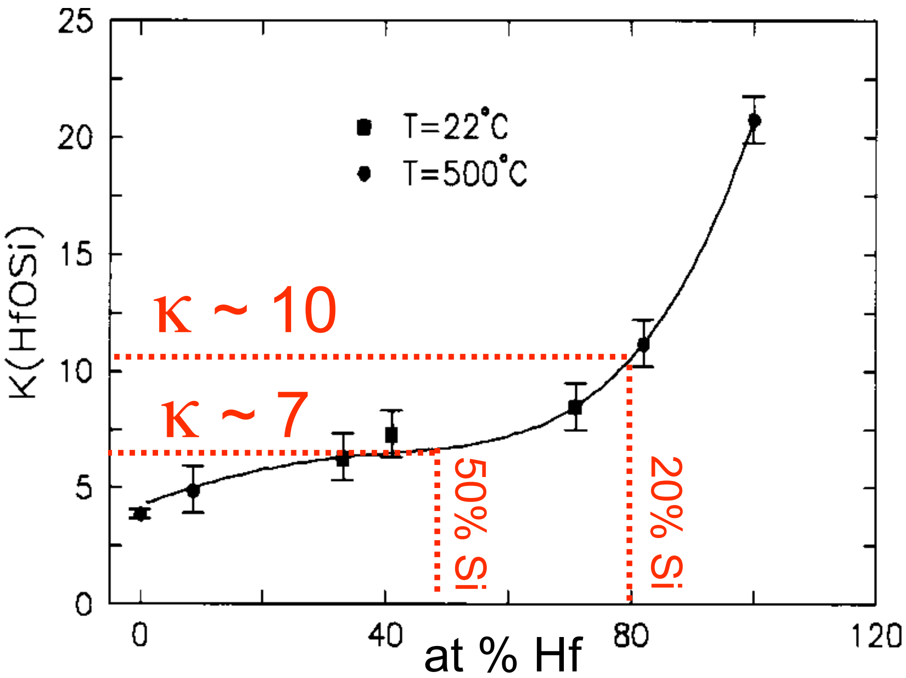




$$\frac{1}{C_{eff}} = \frac{1}{C_{HfO_2}} + \frac{1}{C_{SiO_2}}$$

κ_{eff} not well-understood for silicates

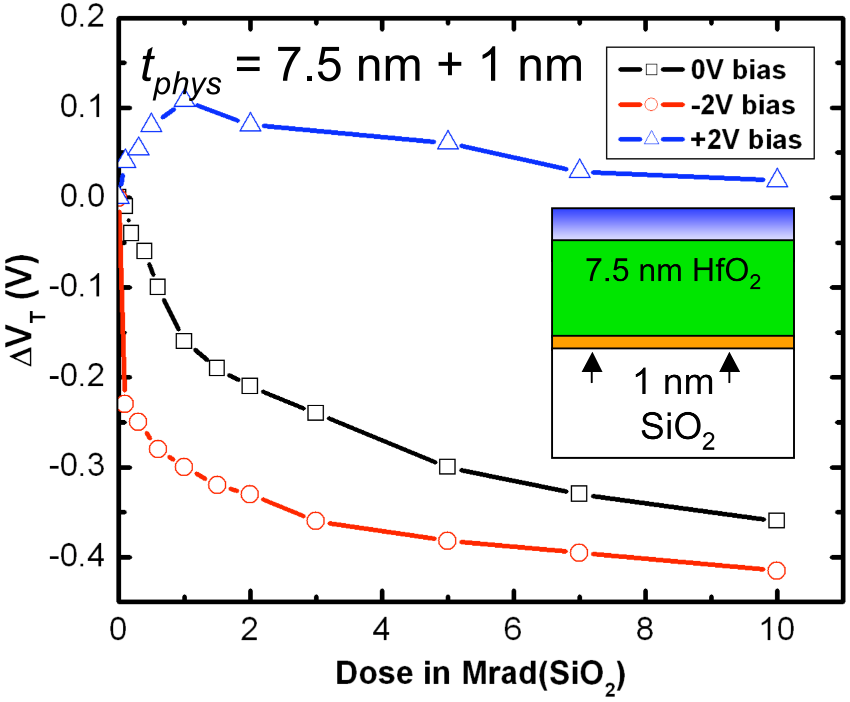
- HfO_2 deposition + PDA at 700 °C
- Intermixing issues
- Interlayer sub-stoichiometric
- κ_{eff} reduces

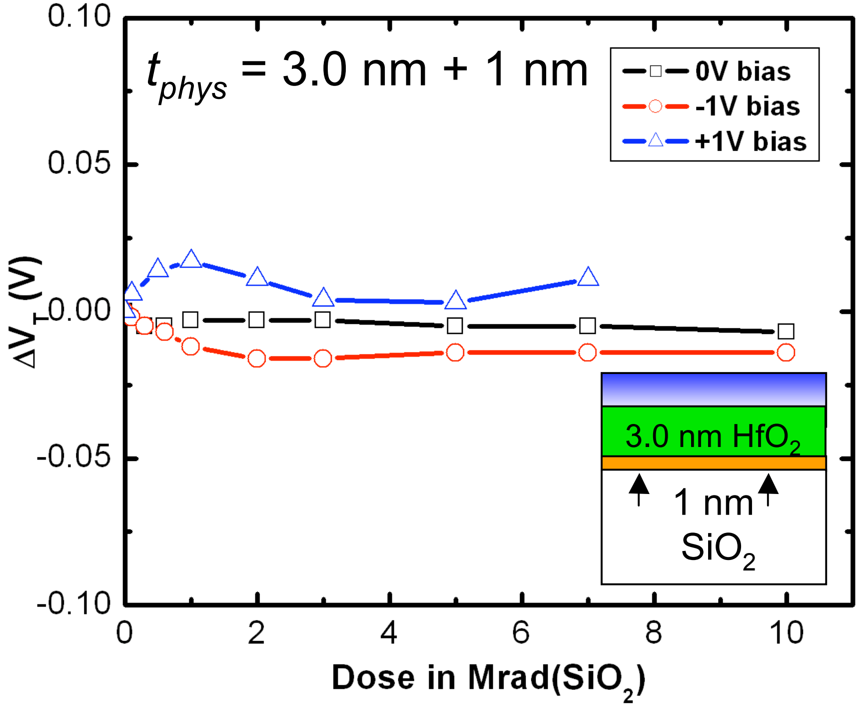


Callegari *et al.*, JAP, v.90,p. 6466, 2001

Comparison 7.5 nm and 3 nm HfO_2 samples

Threshold voltage shifts at -2 MV/cm and +3 MV/cm gate bias





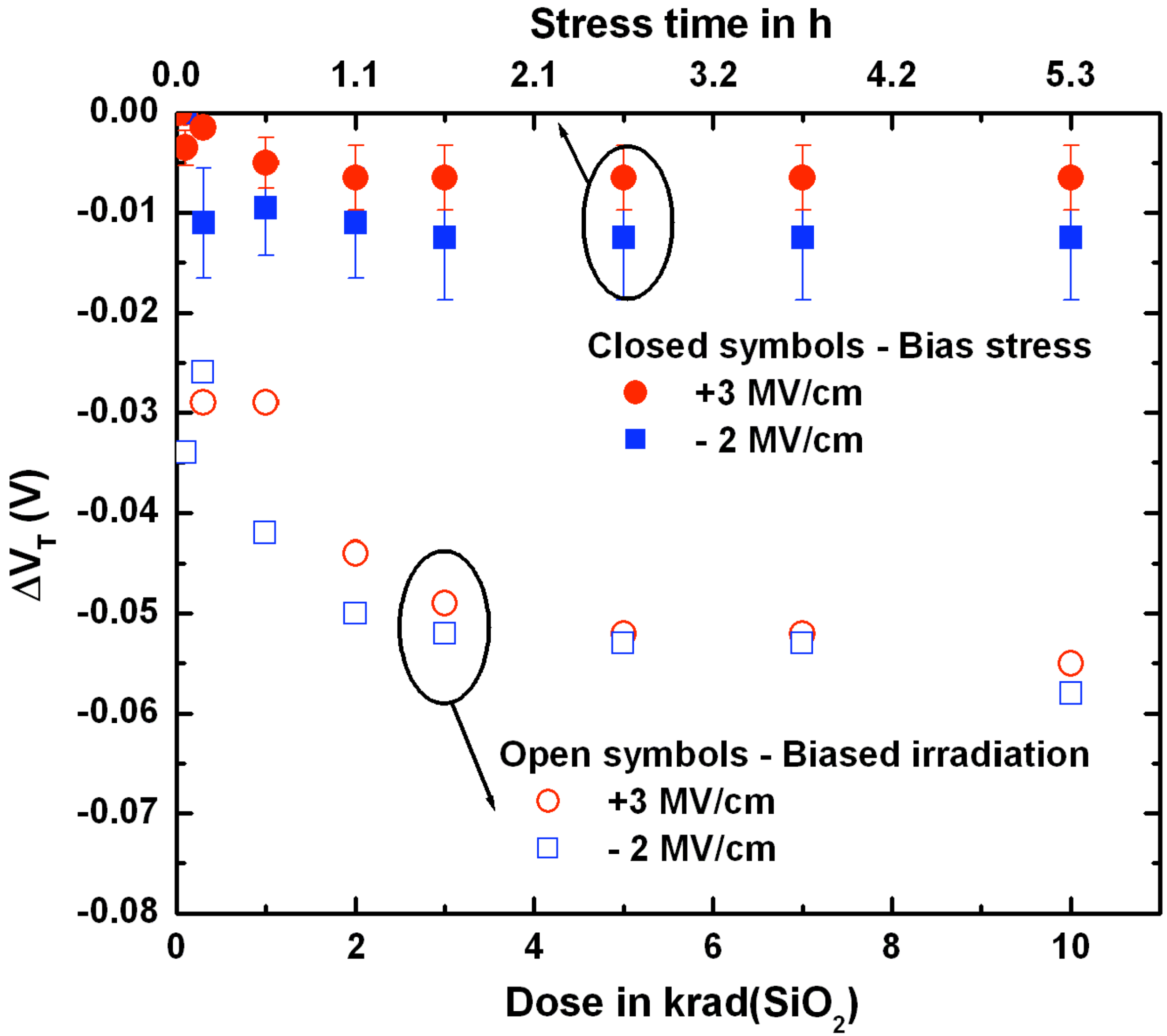
- **Net hole trapping - radiation**
- **ΔN_t = ~ 3.8 x 10^{12} cm^{-2} at max.dose**
- **Significant SiO_2 IL trapping**

- **Radiation tolerant**
- **J_g ~ 10 A/cm^2 leakage**
- **No significant V_T shifts**

Dixit *et al.*, IEEE TNS, vol. 54, p. 1883, 2007

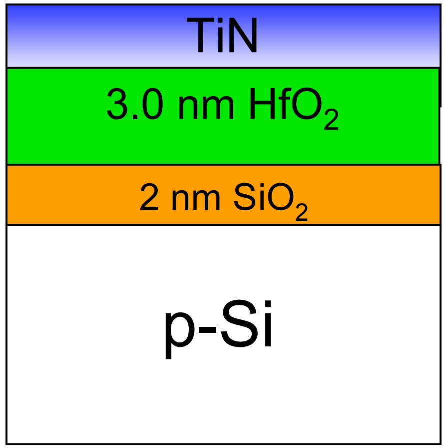
Sample with minimal injection desired - pure radiation response

CVS and irradiation - 3 nm/2 nm



Dixit *et al.*, manuscript to be submitted to APL, 2008

Dielectric stack



- Minimal shifts under bias stress
- Maximum V_T shift under irradiations was ~ 50 mV

CVS and irradiation - 3 nm/2 nm

Key findings - 3 nm HfO_2/2 nm SiO_2

- IL better blocking electrode (no charge injection)
- Pure radiation response of ~ 50 mV (predominant hole trapping)
- Lowest J_g ~ 8 x 10^{-4} A/cm^2 (minimal neutralization of trapped charge)

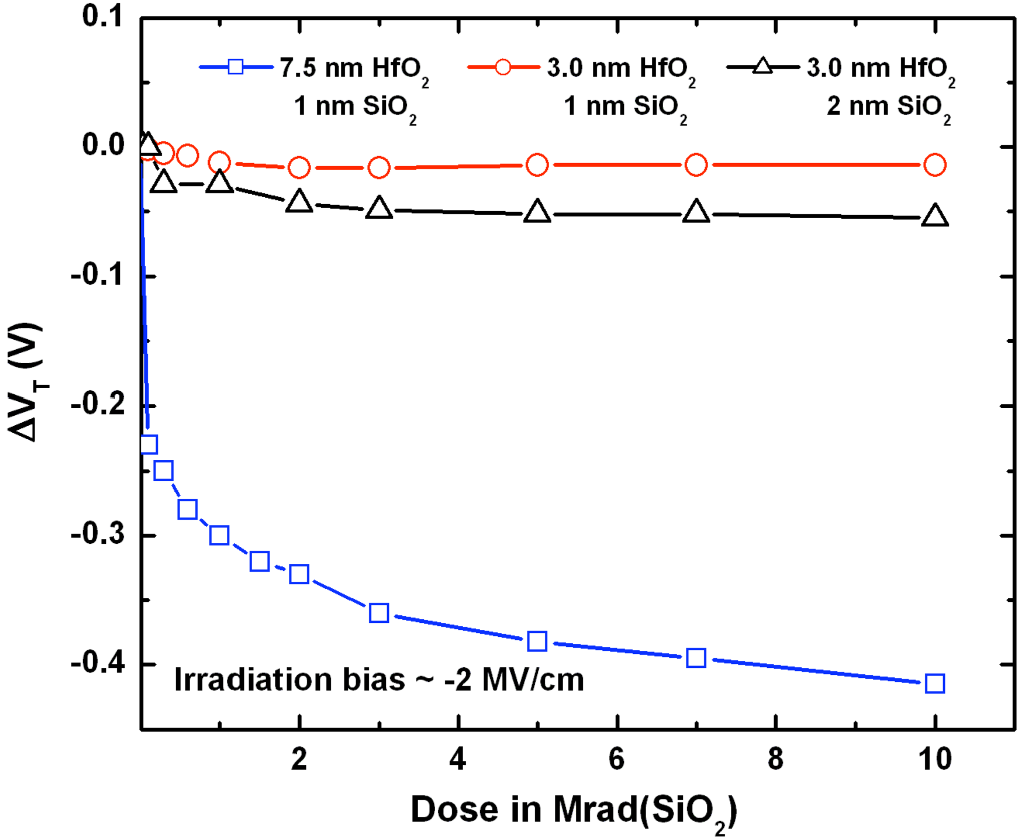
Thinner HfO_2, less bulk traps
Felix *et al.*, Ryan *et al.*, & Foster *et al.*

Thinner HfO_2, better SiO_2 IL
Bersuker *et al.* & Ryan *et al.*,

Felix *et al.*, Microelectron. Engrg., vol. 44, p. 563, 2004
Ryan *et al.*, IEEE TNS, vol. 52, p. 2272, 2005
Foster *et al.*, PRB, vol. 65, p. 174117, 2002.

Bersuker *et al.*, JAP, vol. 100, p. 094108, 2006,
Ryan *et al.*, APL, vol. 90, p. 173513, 2007

Total dose results comparison



Irradiation Bias ~ -2 MV/cm

Key results 3 nm HfO_2/2 nm SiO_2

- IL O leaching ↑ 7.5 nm HfO_2
(exposure t ↑ at higher temp. growth[a,b])

- I-V sweeps modify the charge (~ 50%)
(border traps in the SiO_2 IL[c])

- Residual V_T after stabilization
(traps in HfO_2 and/or away from interface)

[a]Bersuker *et al.*, JAP, vol. 100, p. 094108, 2006,
[b]Ryan *et al.*, APL, vol. 90, p. 173513, 2007,
[c]Fleetwood *et al.*, *IEEE TNS,* vol. 39, p. 269, 1992.

Dixit *et al.,* manuscript to be submitted to APL, 2008

Conclusions - HfO_2 based MOSFETs

- 3 nm/1 nm devices radiation tolerant and resistant to constant-voltage stress

- Total dose comparison between 7.5 nm/1 nm and 3 nm/2 nm MOSFETs suggest substantial hole trapping in the SiO_2 IL

- Residual V_T shift suggest the presence of some of the holes trapped charge away from the interface, probably in the HfO_2 bulk

Acknowledgements

Vanderbilt

- Dr. Leonard C. Feldman (advisor)
- Dr. Sokrates T. Pantelides
- Dr. Ronald D. Schrimpf
- Dr. Daniel M. Fleetwood

SEMATECH, Inc.

- Dr. Gennadi Bersuker
- Dr. Chadwin Young
- Dr. Rino Choi

Rutgers

- Dr. Eric Garfunkel
- Dr. Torgny Gustafsson
- Dr. Lyudmila Goncharova
- Mr.Tiang Feng (Ph.D. candidate)

Group Members

- Dr. S. V. S Nageswara Rao
- Dr. Sarit Dhar
- Dr. John Rozen
- Dr. Anthony B. Hmelo

Special thanks to INTERNATIONAL SEMATECH, Inc. for their collaboration in this research effort.

This work was supported in part by the Air Force Office of Scientific Research (AFOSR) through the MURI program

Publications

Published work

1) **S. K. Dixit**, X. J. Zhou, R. D. Schrimpf, D. M. Fleetwood, S. T. Pantelides, R. Choi, G. Bersuker and L. C. Feldman, "Radiation induced charge trapping in ultrathin HfO_2-based MOSFETs," *IEEE Trans. Nucl. Sci.*, vol. 54, pp. 1883-1890, 2007.

Manuscripts in preparation

2) **S. K. Dixit**, E. Garfunkel, C. D. Young, G. Bersuker, and L C. Feldman, "Physical and electrical characterization for bulk HfO_2 and SiO_2 interlayer (IL) thickness verification in advanced gate stacks," manuscript to be submitted to *J. Appl. Phys.*

3) **S. K. Dixit**, X. J. Zhou, R. D. Schrimpf, D. M. Fleetwood, C. D. Young, G. Bersuker and L. C. Feldman, "Hole trapping in HfO_2-based MOSFETs studied as a function of varying HfO_2 bulk and SiO_2 interlayer (IL) thicknesses," manuscript to be submitted to *Appl. Phys. Lett.*