May , 2008

Radiation Effects on Emerging Electronic Materials and Devices

Radiation Effects in Emerging Materials

Overview

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And

Rutgers University

Topics of Interest

Basic radiation interaction with electronic materials-review, educational

Alternate Dielectrics and Gate Stacks-in all aspects-growth, spectroscopy, radiation effects a major emphasis on nano-scale structure--

SiGe devices and other “alternate substrates” (Ge, InGaAs, SiC)

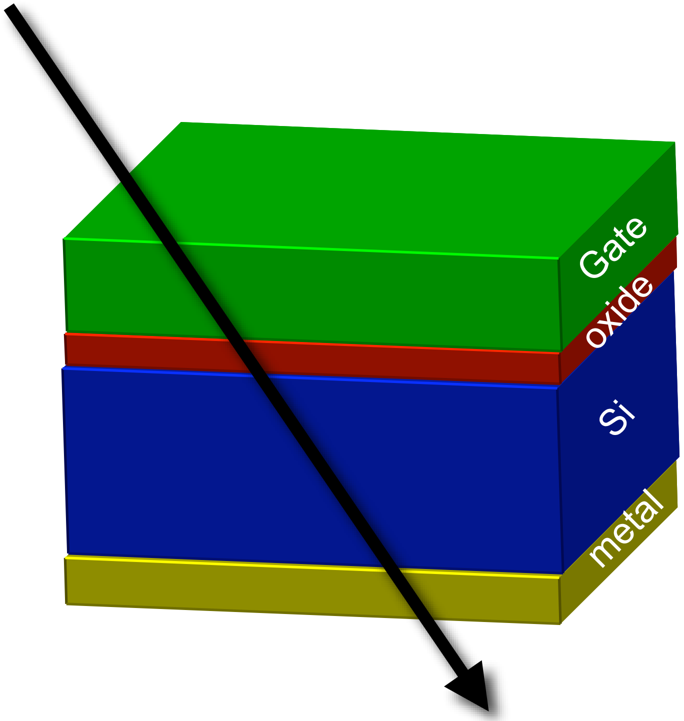
Strained silicon

Basic radiation interaction with electronic materials- modifications at the nanoscale

Nanoscale:

Basic theory of e-h pair production, particularly <u>ε</u>, the average energy required for e-h pair creation, is based on bulk concepts, including bulk density of states.

The nanoscale thicknesses, and the new understanding of nanoscale effects calls for re-examination of these concepts.



MOS Schematic

$$\Delta V = Q/C = N_e \{(dE/dx)\, t_{ox}/\varepsilon\}\ /C$$

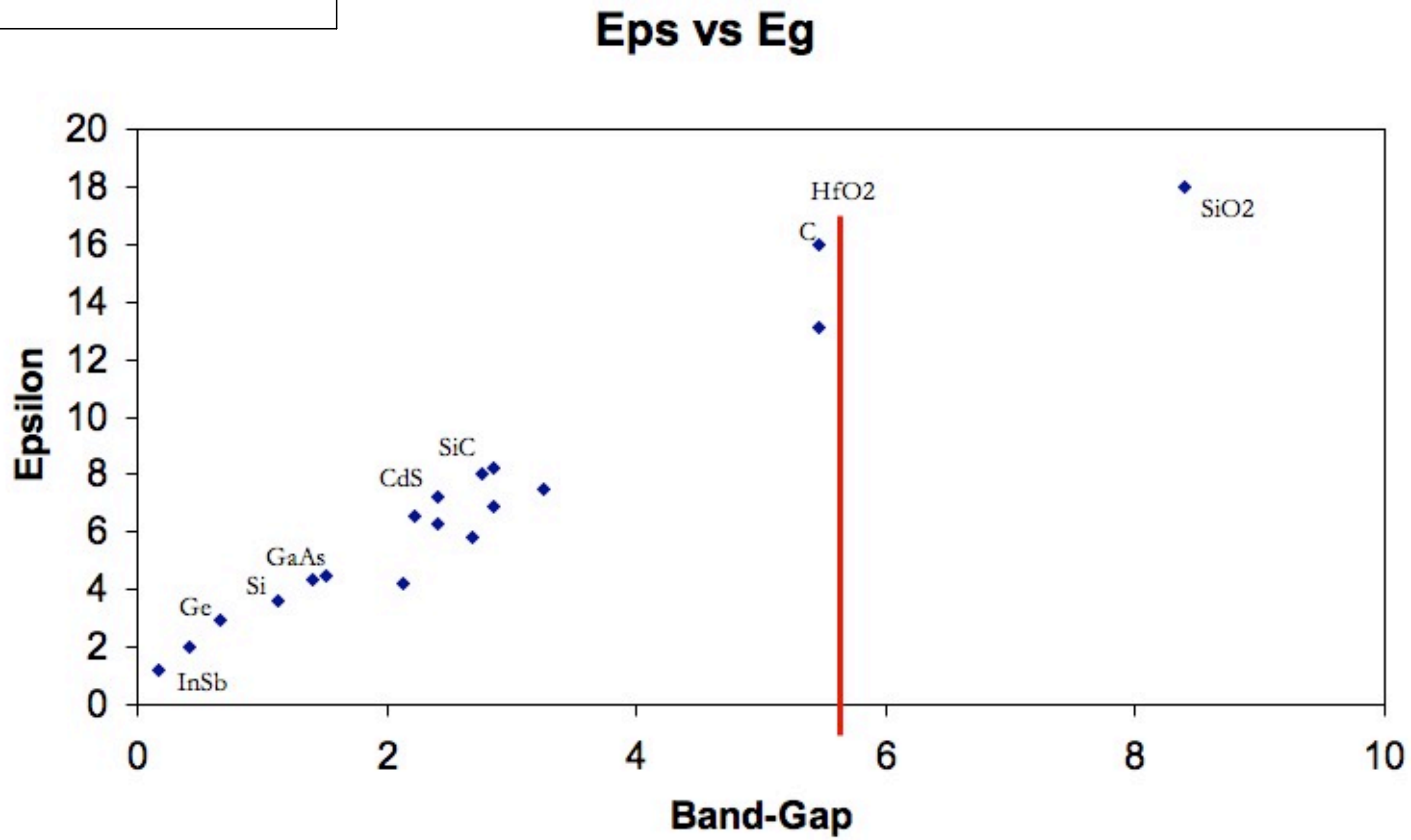
ε= average energy/e-h pair

N_e= number of electrons penetrating the dielectric

$\varepsilon = 2.6E_g + K$

Shockley-Klein

ε vs. E_g



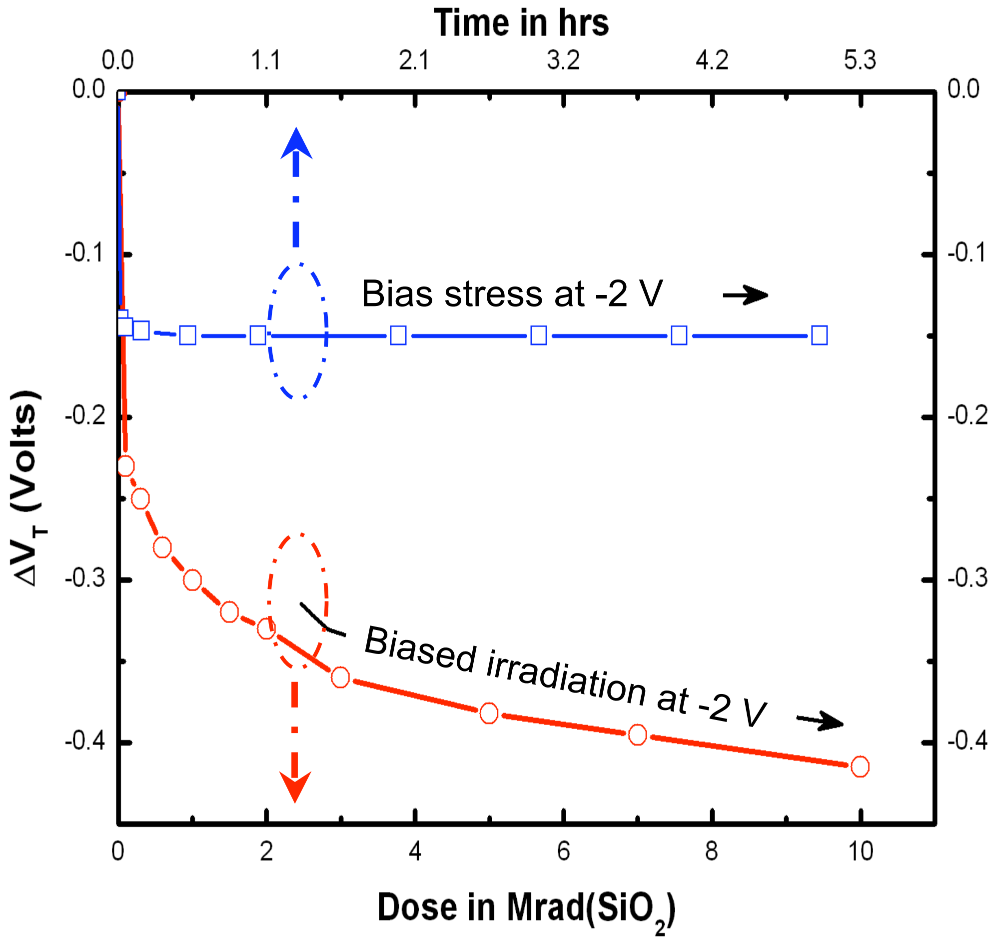
BASIC PROCESSES IN RADIATION DAMAGE STUDIES

AN UNDERSTANDING OF THE BASIC RADIATION DAMAGE PROCESSES LEADS TO CLARIFICATION OF THE EXPERIMENTS AND THEIR SIGNIFICANCE

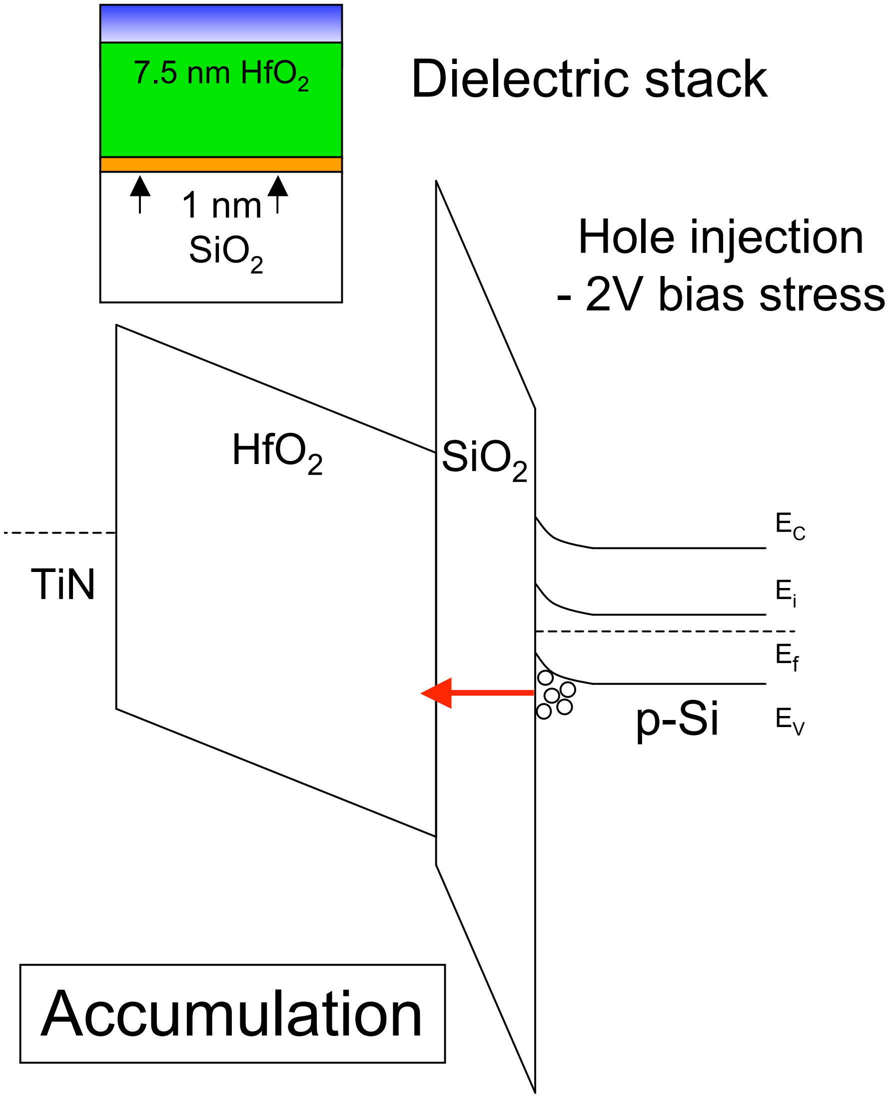
COMPARISONS OF PHOTONS AND PROTONS (IONS) PROVIDES NEW INSIGHTS

WE SHOULD ALL KNOW IT (OR BE REMINDED OF IT) IN ANY CASE.

CVS and irradiation - 7.5 nm/1 nm



At 10 Mrad(SiO_2), $\Delta N_t = \sim 3.8 \times 10^{12}$ cm^{-2}



Accumulation

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

Rutgers CMOS Materials Analysis

Use high resolution characterization methods to:

- Determine composition, structure and electronic properties gate stacks that use new (post-Si) materials
- Help determine physical and chemical nature of radiation induced defects

Surface/interface analysis:

- Ion scattering: RBS, MEIS, NRA, ERD – composition, crystallinity, depth profiles, H/D
- Direct, inverse and internal photoemission – electronic structure, band alignment, defects
- Scanning probe microscopy – topography, surface damage, electrical defects

Motivation: Help develop a fundamental understanding and control of radiation induced defects in future CMOS materials.

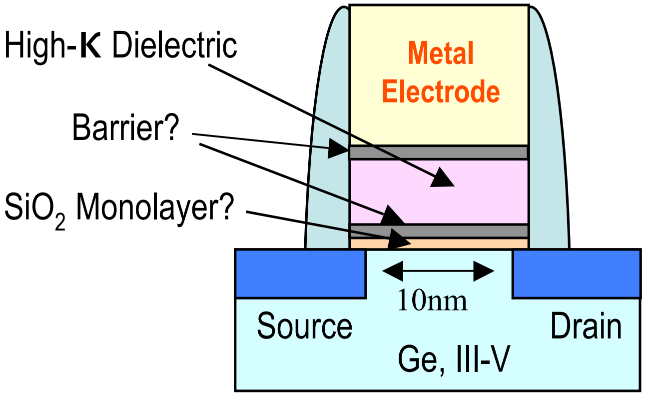
Rutgers team uses high resolution characterization tools to:

- Determine composition, structure and electronic properties of gate stacks that use new (post-Si) materials
- Help determine physical and chemical nature of pre-existing and radiation induced defects

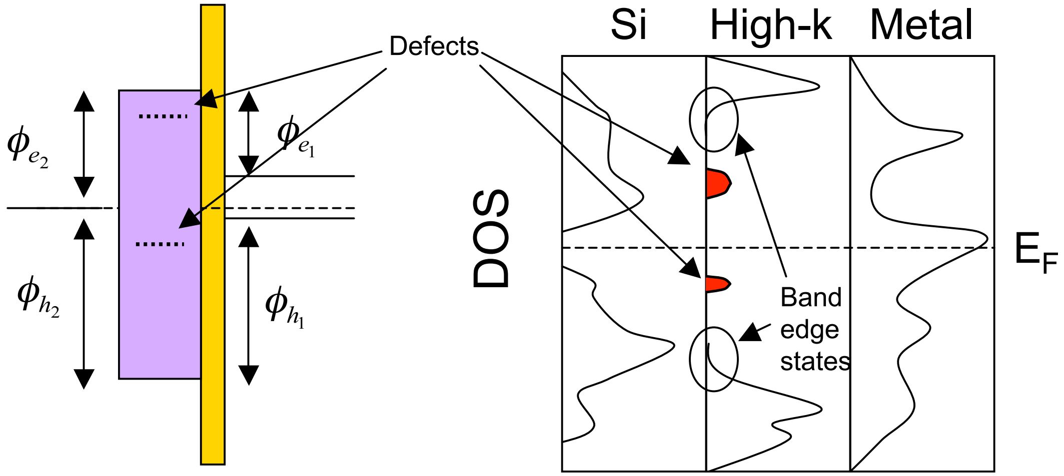
Experimental studies of High-k on Ge and III-V substrates:

- Composition and depth profiling – MEIS, XPS, RBS…
- electronic structure – PES, IPE, optical and electrical methods…

Materials stability, band alignment and defects in CMOS nanoelectronics



CMOS gate ~2010?



L. Goncharova, S. Rangan, O. Celik, C.L. Hsueh, R.A. Bartynski, T. Gustafsson and E. Garfunkel

Departments of Chemistry and Physics, and

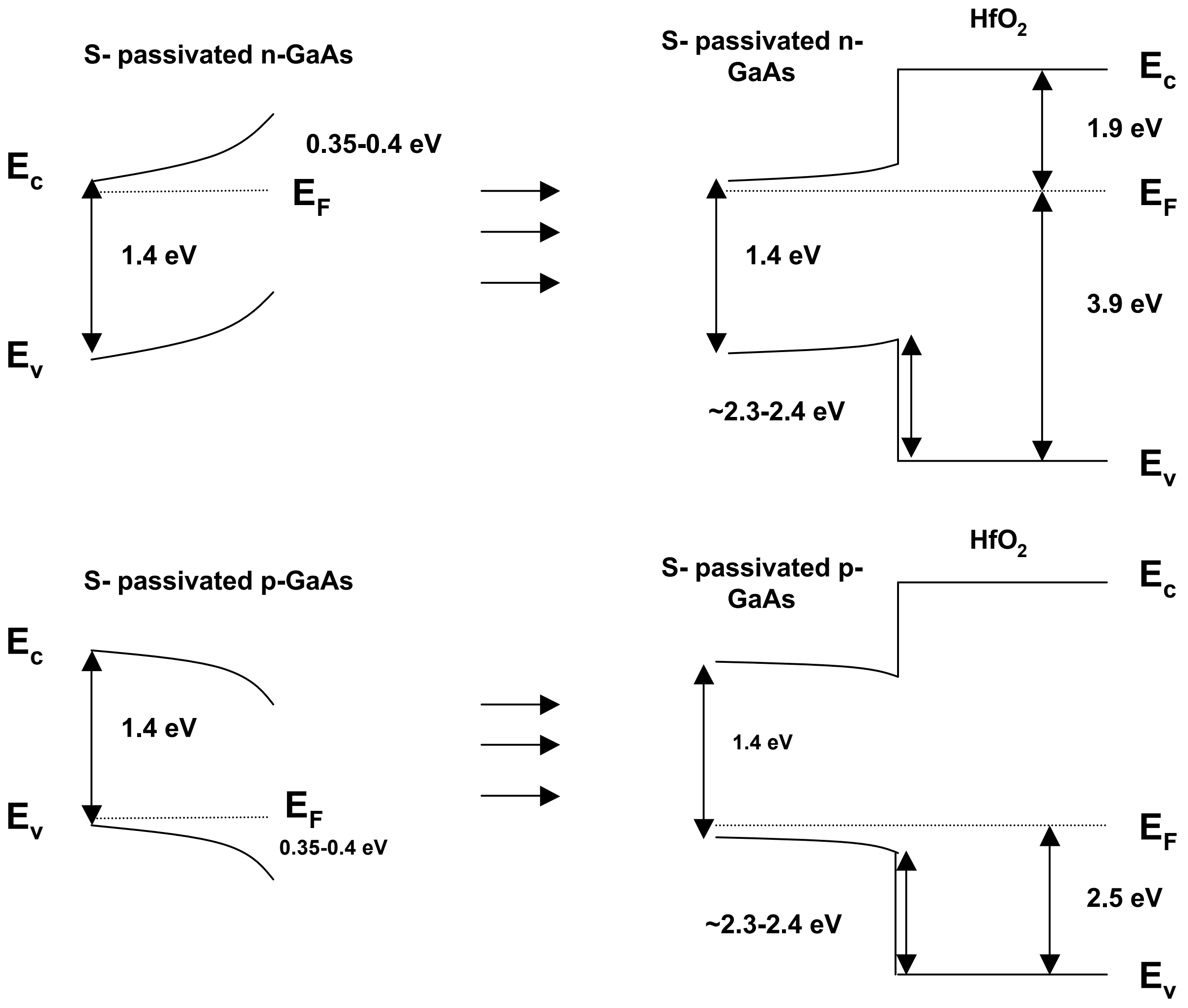
Institute for Advanced Materials, Devices and Nanoelectronics

Rutgers University, Piscataway, NJ

Collaboration: **Vanderbilt, Sematech, NIST, IMEC, IBM, Intel, Bell Labs, NCSU, Penn State, Stanford, UT-Dallas, UT-Austin, Albany.…**

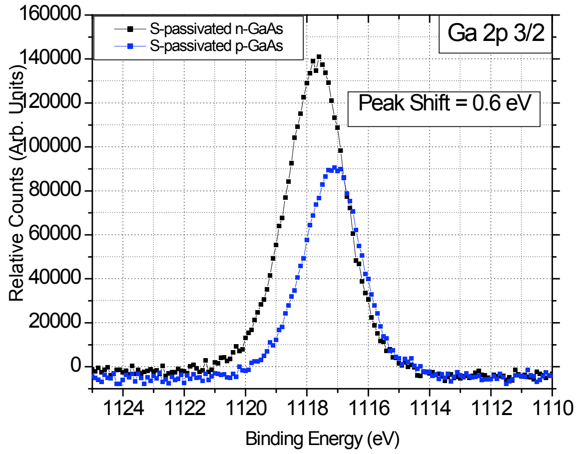
S-passivated film Fermi levels partially pinned; after HfO2 growth, little pinning.

Conduction and valance band offsets measured; agree with literature.

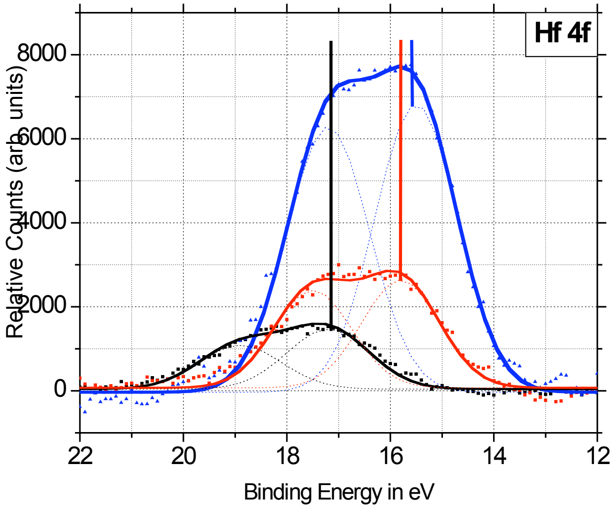


GaAs surface passivation and gate stack growth:

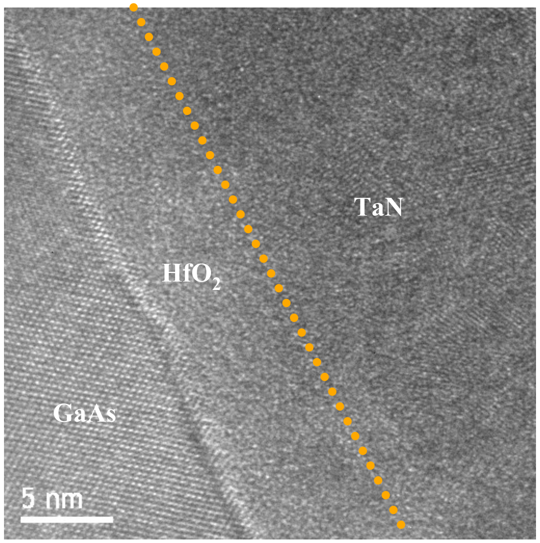
GaAs with S-passivation XPS band alignment (highly doped n and p-type)



- **Shift in photoemission peaks between n-type and p-type samples ~1.2-1.4 eV means *the GaAs Fermi level is <u>not</u> strongly pinned by HfO_2.***



GaAs/HfO_2/TaN Gate Stack

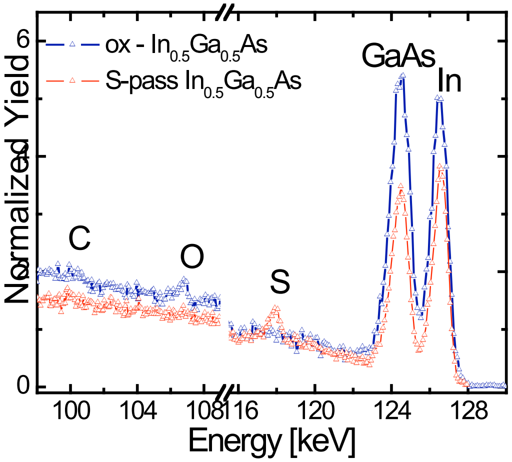


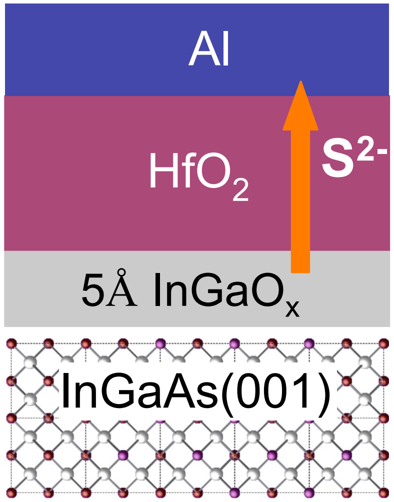
A TEM image of a GaAs sample with following process: native oxide etched, sulfur passivated, HfO2 grown by ALD, TaN metal grown by PVD.

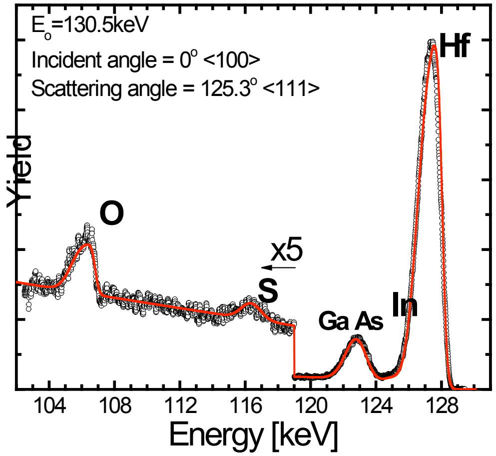
From TEM images (and microscopic elemental analysis, AFM, etc.), we find that the interface roughens after this specific chemical oxidation and passivation

Defects in the post-Si era: Al/HfO_2/$In_xGa_{1-x}As$

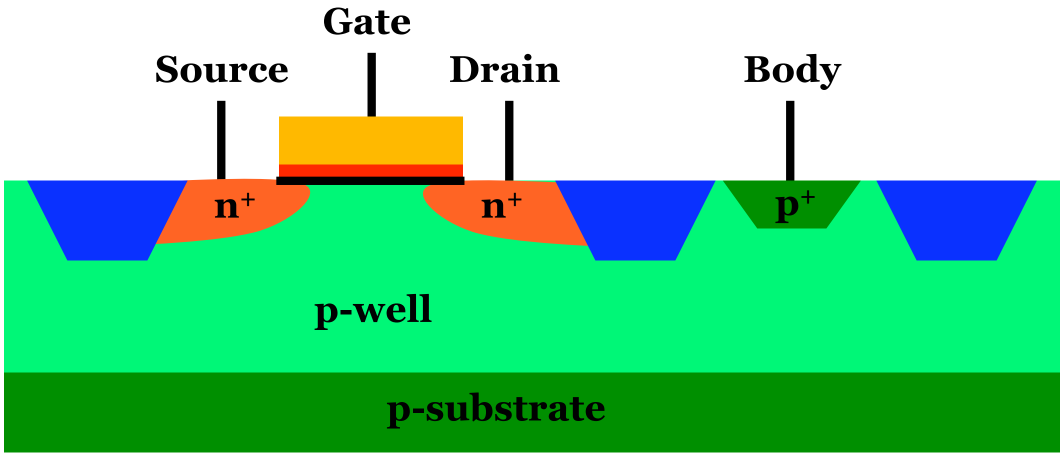
- Surface passivation and composition of interfacial layer
- High-K deposition
- Post-deposition annealing
- Metal gate effects
- “Normal” and radiation induced defects – nature and evolution







HfO_2 sample details



HfO_2 based nMOSFET

Samples

- State-of-the-art samples, SEMATECH, Inc.
- 65 nm technology node
- nMOSFETs with W/L = 10μm/0.2μm
- t_{phys} = 7.5 nm and 3.0 nm (EOT = 1.2 nm and 0.5 nm)
- SiO_2 interlayer (~ 8Å)

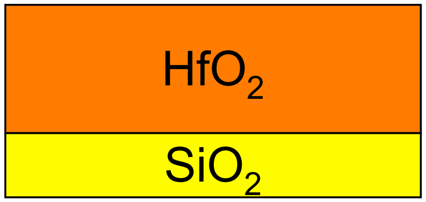
Experimental

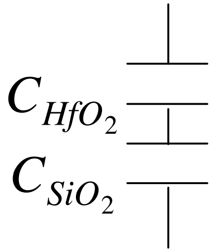
- 10 keV X-rays, RT irradiation
- Function of dose
- Function of bias
- Characterization done using I-V measurements

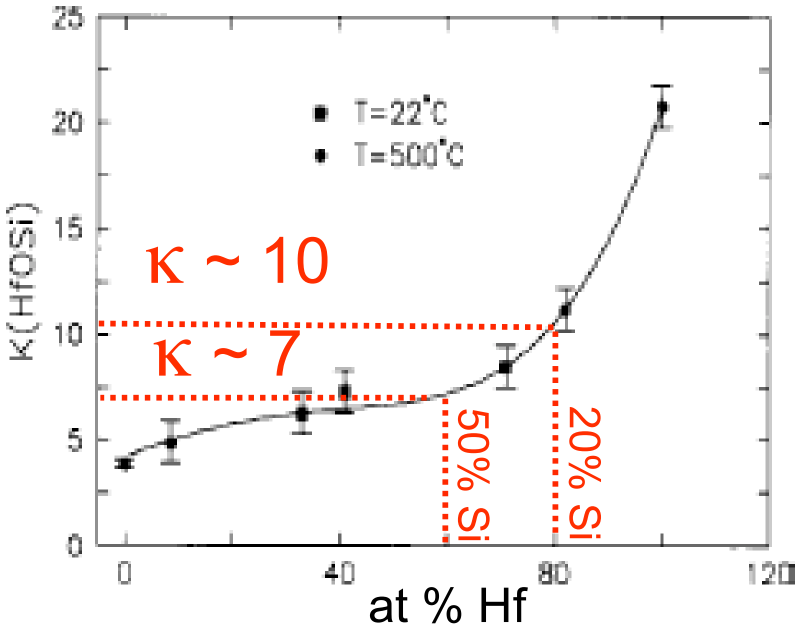
C-V - Comparison (Theory & Measured)

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

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



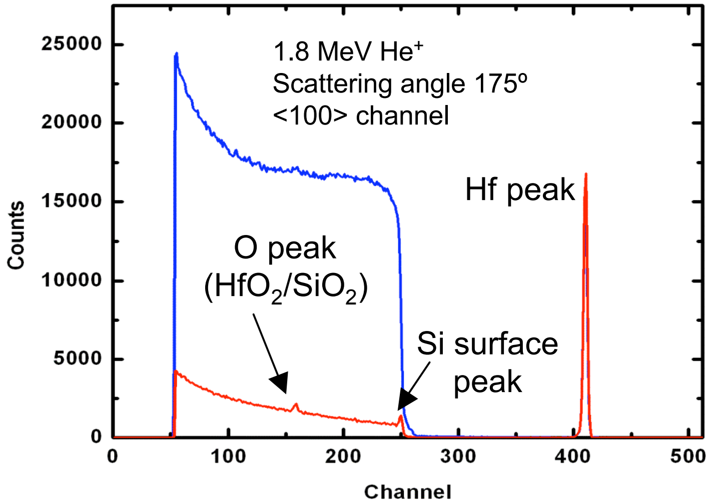




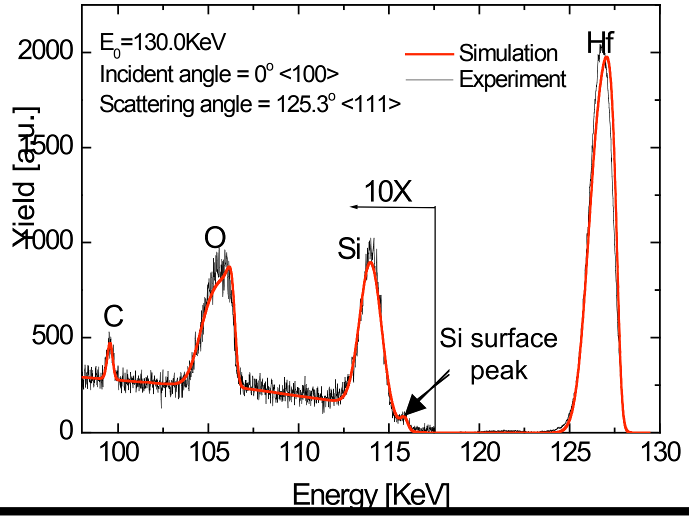
Callegari *et al.*, JAP, v.90,p. 6466, 2001

Materials analysis - HfO_2/SiO_2 IL/Si

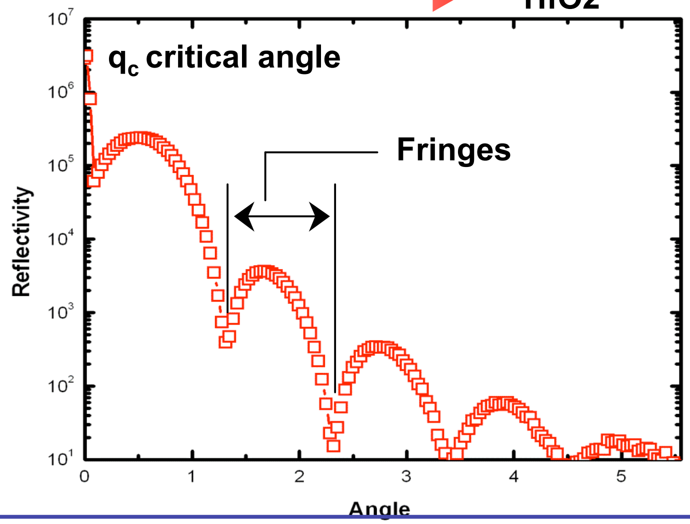
RBS/Channeling → t_{HfO2} & t_{SiO2}



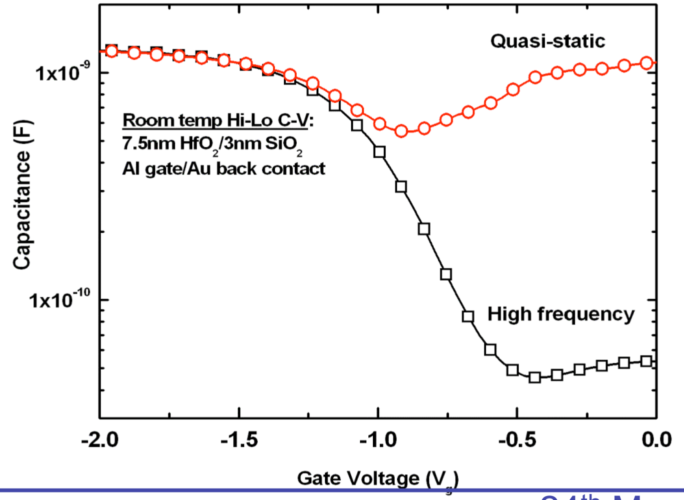
MEIS → t_{HfO2}, t_{SiO2} & Si in HfO_2



XRR → t_{HfO2}

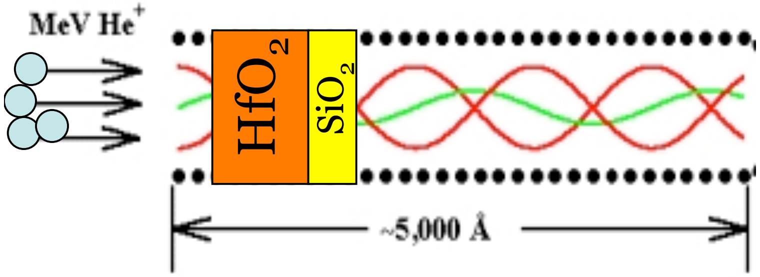


C-V → t_{HfO2}, t_{SiO2} & Si in HfO_2

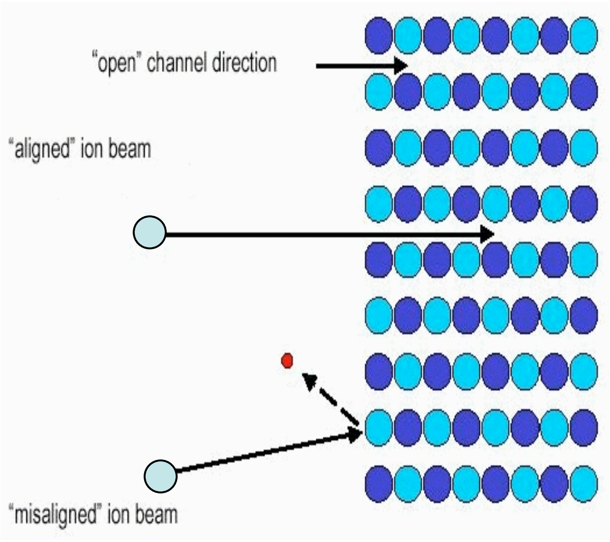


Dixit *et al.*, manuscript to be submitted to JAP, 2008

RBS/MEIS - HfO_2/SiO_2 IL/Si



% <100> χ_{min} for Si ~ 4 %



Feldman *et al.*, Material analysis by ion-channeling: Submicron crystallography, Academic Press, NY, 1982

‘Hf’ concentration

Samples	‘Hf’ expected (10^{15} at/cm^2)	‘Hf’ RBS (10^{15} at/cm^2)	‘Hf’ MEIS (10^{15} at/cm^2)
3nm/1nm	8.24	8.29 ± 0.03	8.32
7.5nm/1nm	20.6	20.2 ± 0.005	19.95
3nm/2nm	8.24	8.10 ± 0.03	7.9
7.5nm/3nm	20.6	20.7 ± 0.005	19.51

RBS/MEIS - HfO_2/SiO_2 IL/Si

‘O’ concentration

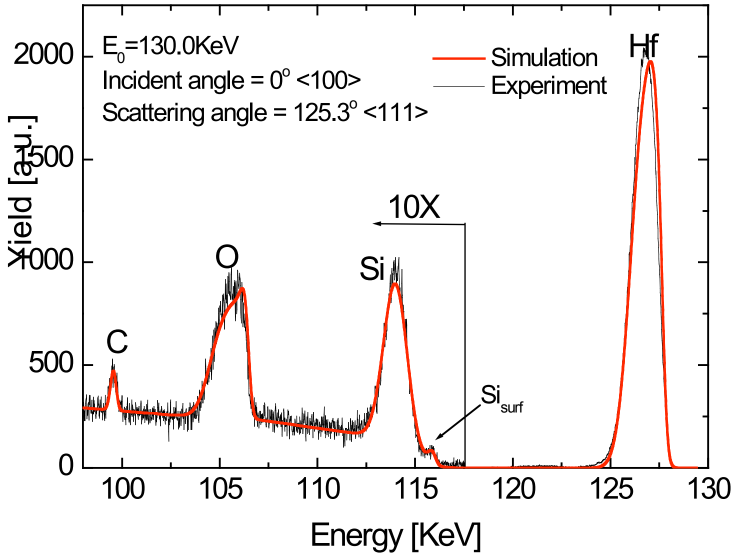
Samples	‘O’ expected (10^{15} at/cm^2)	‘O’ RBS (10^{15} at/cm^2)	‘O’ MEIS (10^{15} at/cm^2)
3nm/1nm	21.28	21.9 ± 0.2	22.37
7.5nm/1nm	46.0	45.5 ± 0.2	36.82
3nm/2nm	25.28	24.2 ± 0.2	20.16
7.5nm/3nm	54.4	55.1 ± 0.3	55.81

Interlayer ‘O’ concentration

Samples	IL ‘O’ expected (10^{15} at/cm^2)	IL ‘O’ RBS (10^{15} at/cm^2)
3nm/1nm	4.84	5.32 ± 2.01
7.5nm/1nm	4.84	5.10 ± 2.42
3nm/2nm	8.80	8.02 ± 2.32
7.5nm/3nm	13.2	13.6 ± 2.92

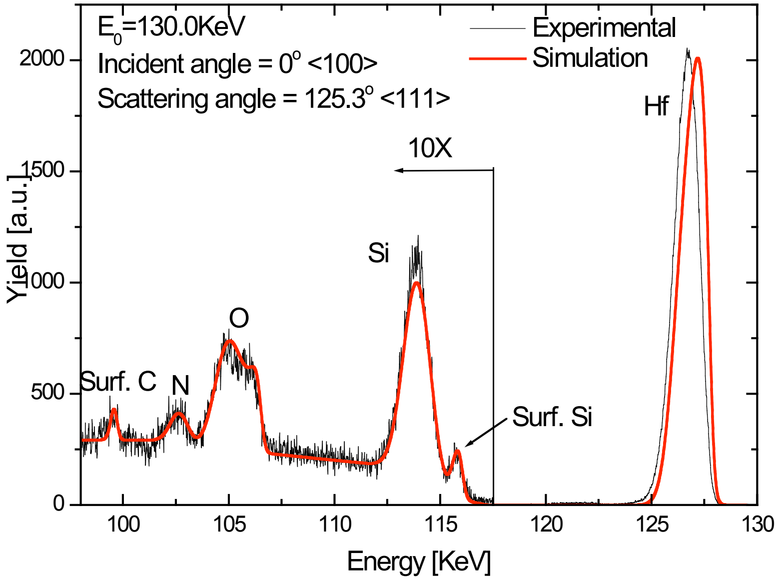
MEIS - HfO_2/SiO_2 IL - 3nm/1 nm

No Anneal



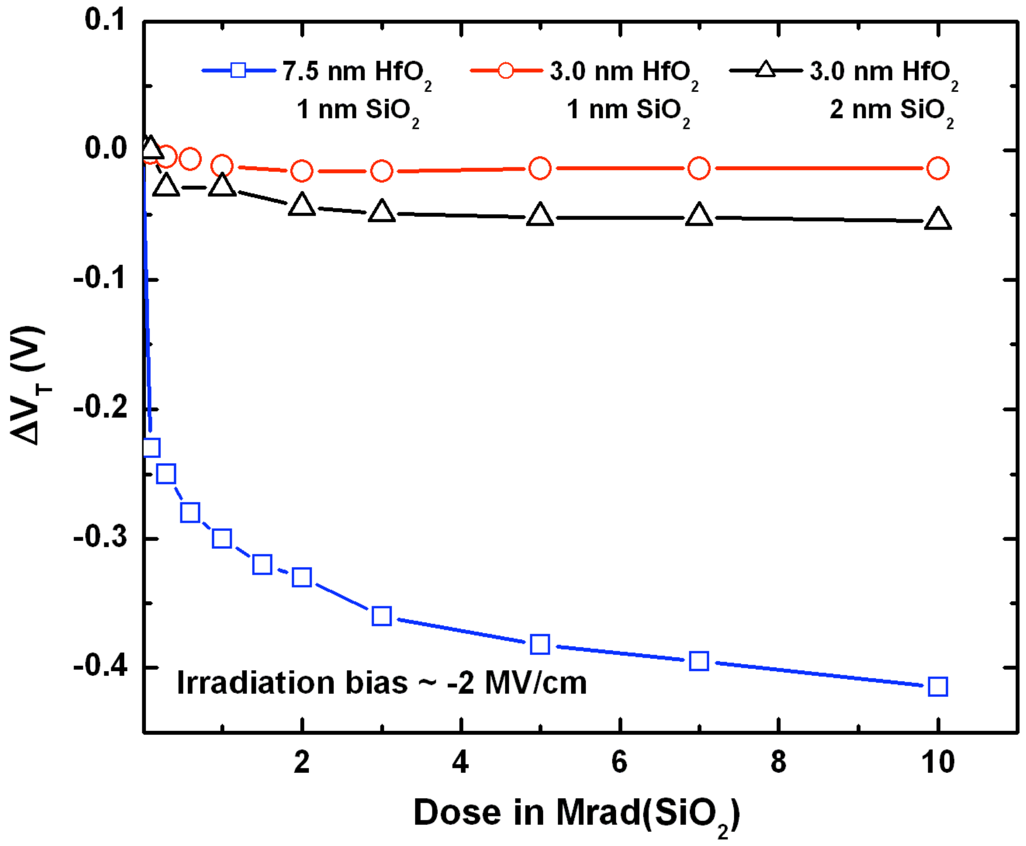
Element	Concentration ×10^{15}[atoms/cm^2]
Hf	8.32
Si	3.87
O	22.37

700 C NH_3 Anneal



Element	Concentration × 10^{15}[atoms/cm^2]
Hf	7.90
O	20.16
N	3.68
Si (surface)	0.97

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])

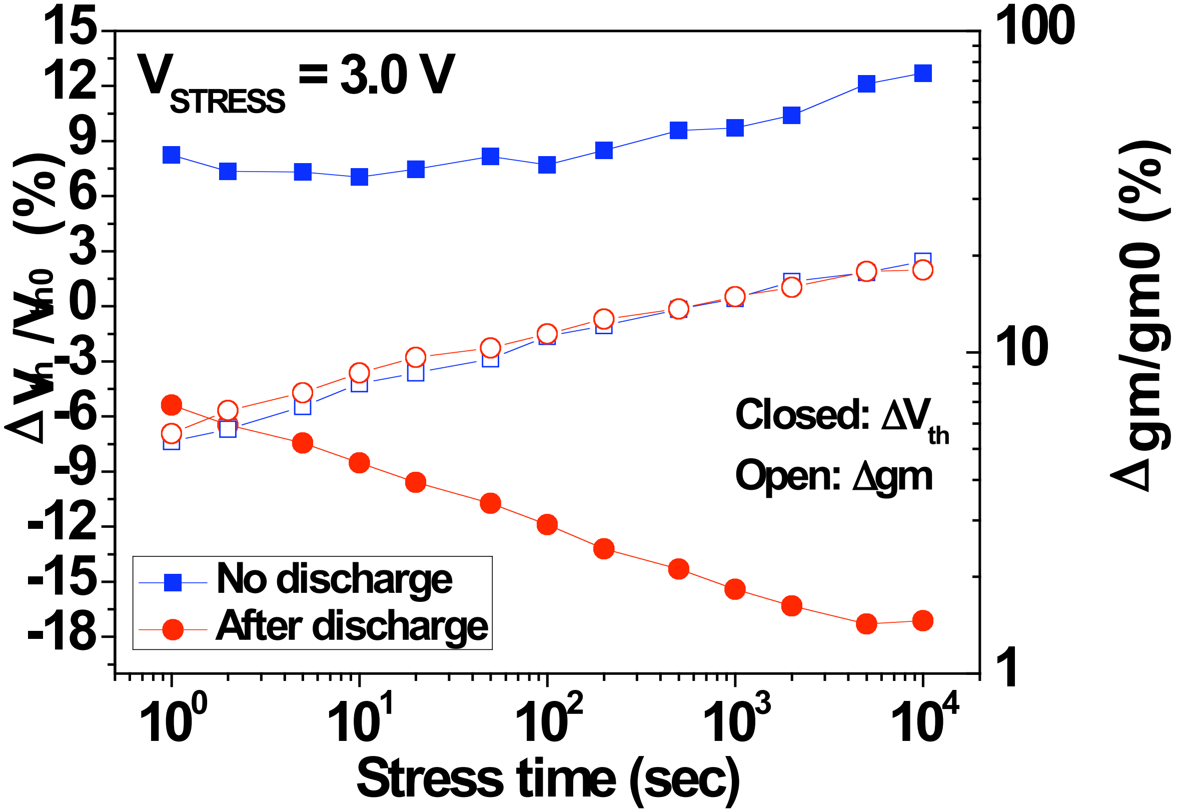
- I-V sweeps modify the charge (~ 50%)
(border traps in the SiO_2 IL[c])

- 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

A New Dielectric Degradation Phenomenon in High-k Devices

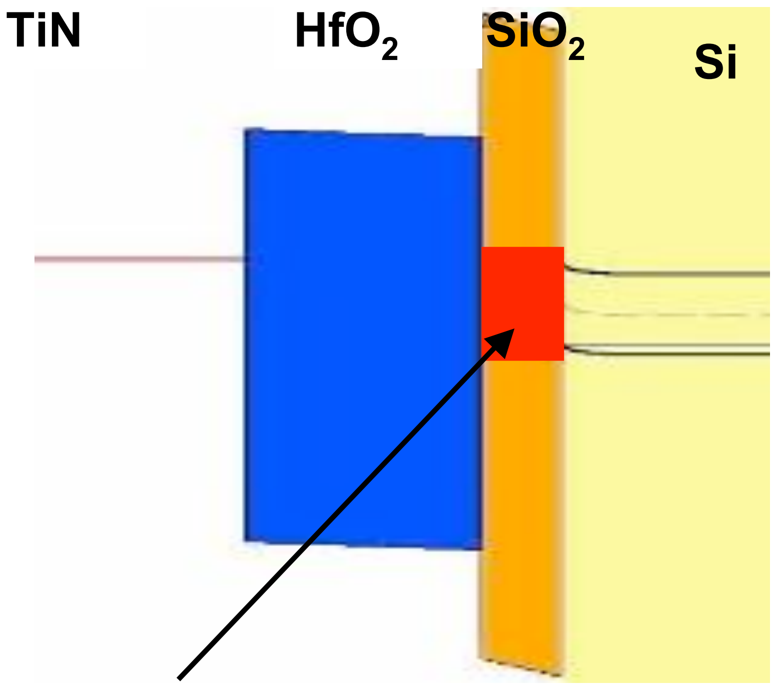


Positive charge buildup caused by electron injection stress

Gennadi Bersuker, SEMATECH

- Hole traps are generated in the interfacial layer of nMOS high-k devices during inversion stress; tentatively attributed to N species in high-k stack

→ may affect evaluation of radiation-induced degradation mechanism



Hole trap location