FEMTOMETRIX®

Assuring Quality Interfaces

Rapid Non-destructive Characterization of Trap Densities and Layer Thicknesses in HfO_2 Gate Materials Using Optical Second Harmonic Generation

Prepared For: Semicon Korea

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Company Profile

Semiconductor Quality Assurance Tool Provider

Company Headquarters

FemtoMetrix, Inc.

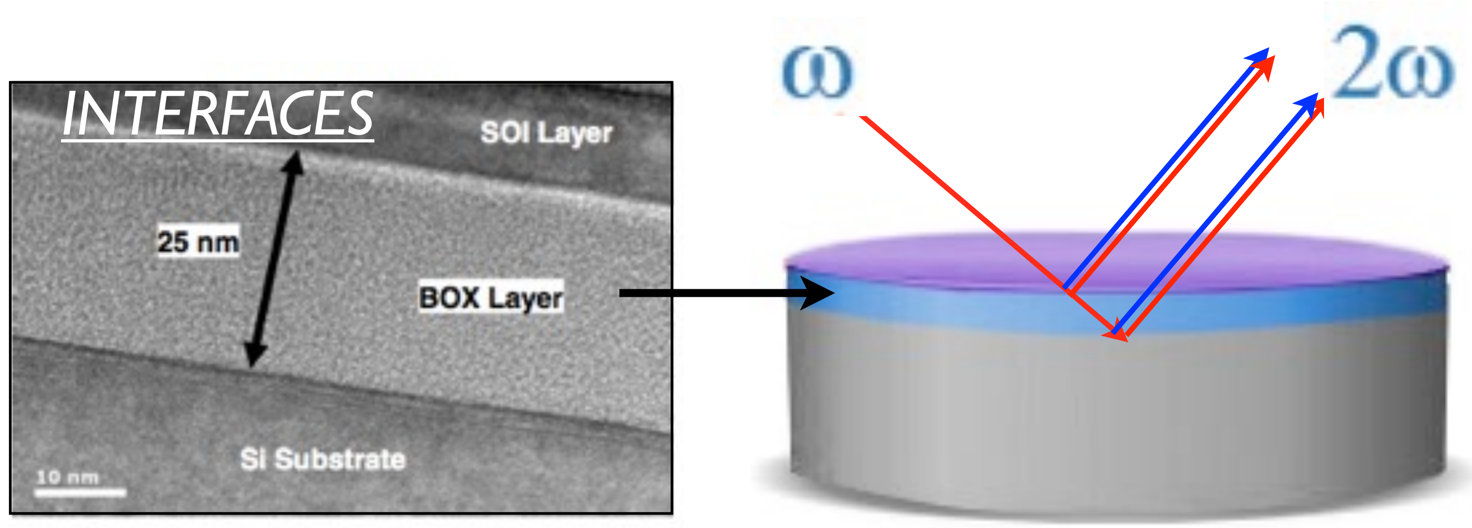
- Founded 2011
- Headquarters in California, USA
- Demo site at LETI
- Korean Distributor: Ahtech LTS

Technology Overview

Harmonic F1x®: Second Harmonic Generation (SHG)

SHG Technique

- The second harmonic signal is sensitive to electric fields at interfaces of materials.
- SHG is forbidden in materials with inversion symmetry (this includes Si + SiO_2).
- At interfaces symmetry is broken + SHG is allowed.
- This makes SHG highly interface/surface specific.



SOI Wafer Example

SHG Capabilities

Key Benefits to Device Fabs:

- Non-destructive optical subsurface analysis
- High in-line throughput (20-30 WPH+)
- Enhanced defect + contaminant detection
- Enables Go/NoGo in-line: inspection survey

Tool Results Correlate To:

- Metal Contamination at Interfaces
- Trapped Charges
- Interface Roughness
- Layer Thickness
- Doping
- Structural Defects
- Strain

Production Tool

Harmonic F1x®

- Sensitive surface and subsurface analysis
- Layer thickness measurements
- SMIF or FOUP loading configurable
- High in-line throughput (20-30+ WPH)
- Minimal facilities requirement - only power, vacuum, ESD + seismic
- ISO Class 1 cleanroom mini-environment
- Bay + Chase / Ballroom compatible
- 200mm or 300mm configurable

Support + Maintenance

- 1 year full coverage warranty
- No sample prep, consumables or reagents
- Modular design with offerings from reputed brands like Brooks, Owens, Peer and Aerotech
- No bindings / exclusivity on parts
- 24/7 support with dedicated engineer assigned
- Easy to use and interpret technology

"...(SHG is) needed, techniques that allow to characterize and monitor various aspects of the epitaxial structures without damaging the wafers in processing, and to evaluate how these aspects evolve during subsequent processing."

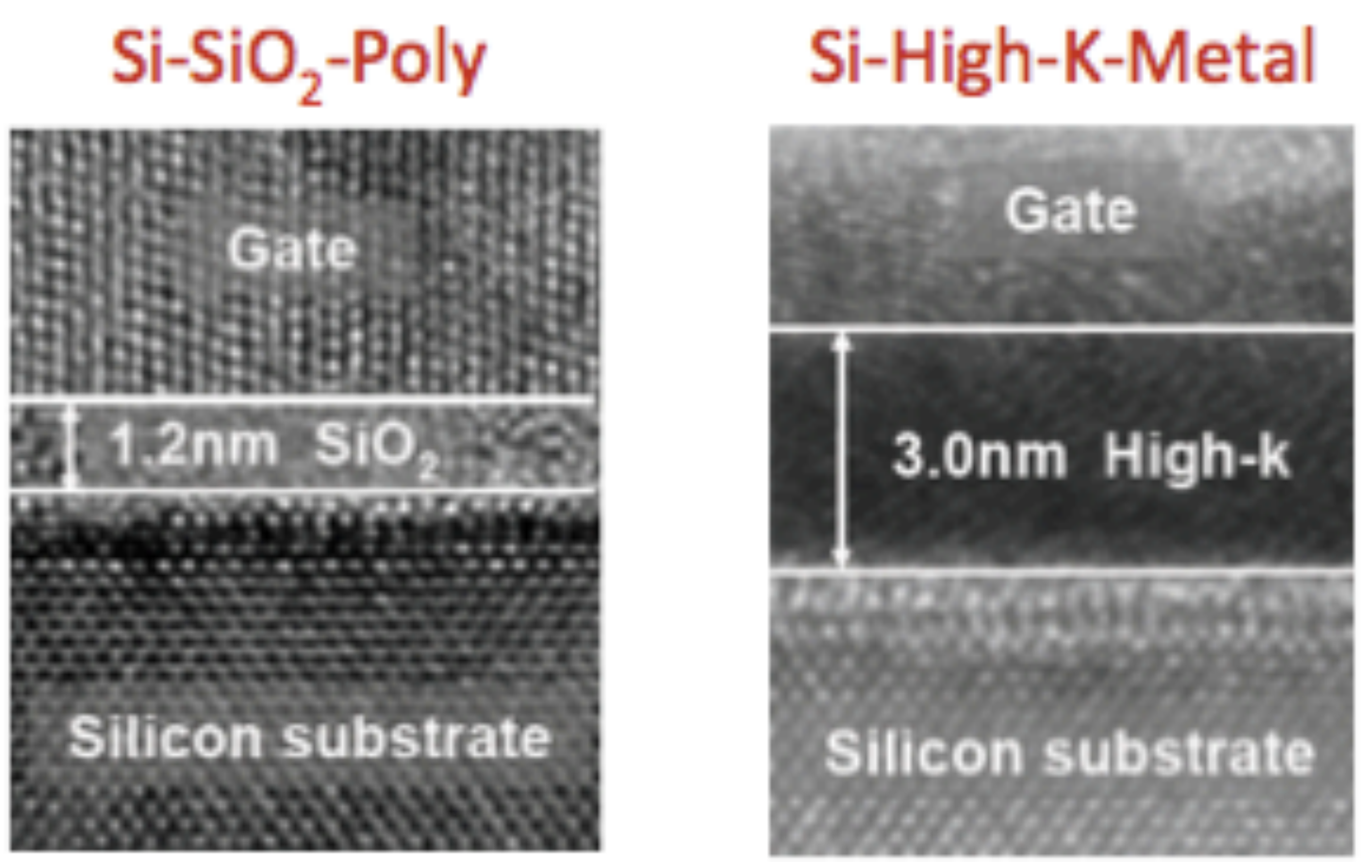
-Dr. Matty Caymax
Chief Scientist, Imec

imec

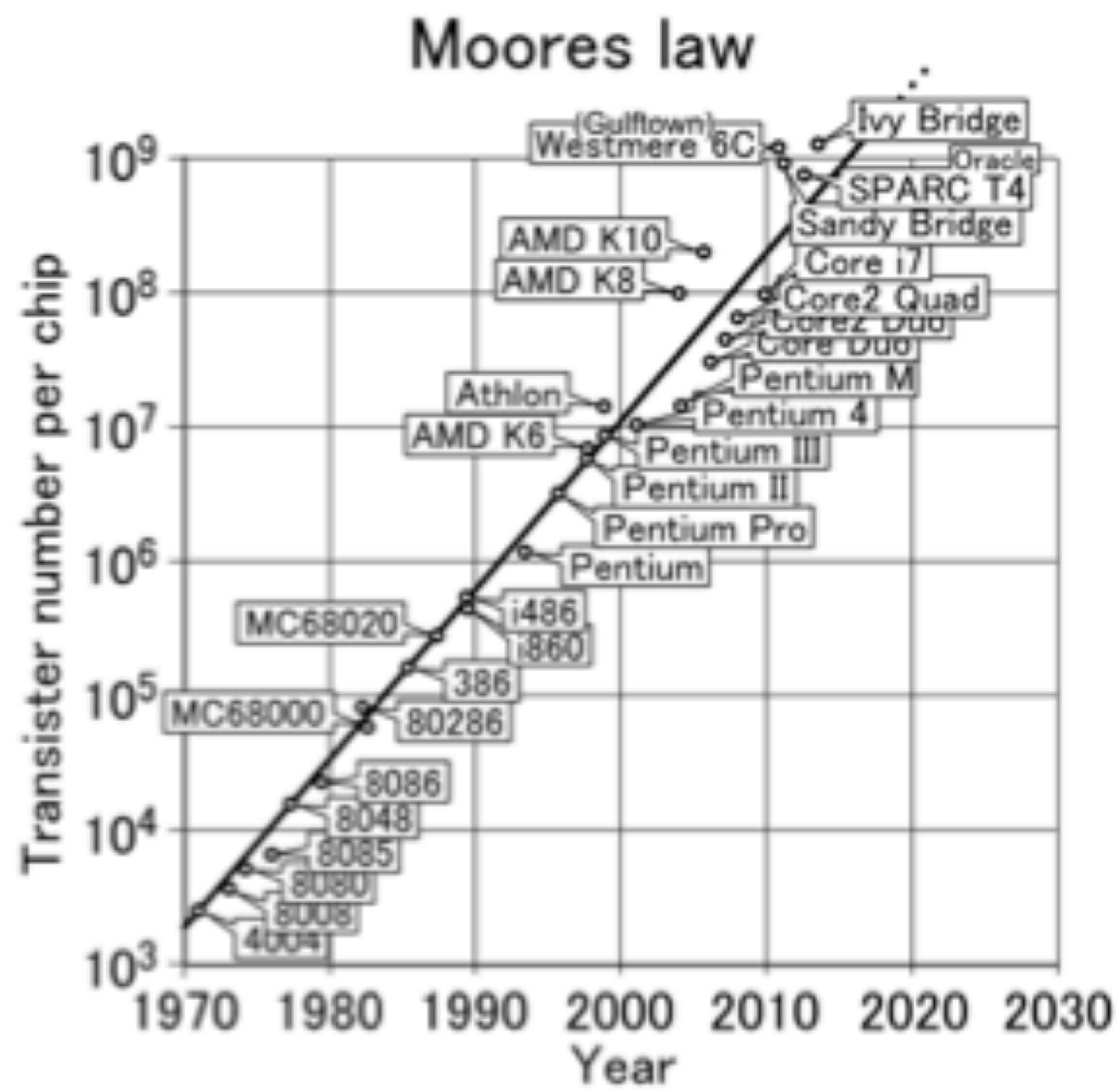
Applications Overview

Material	Information	Comments
Bulk Si / TSV	Dielectric traps, interfacial roughness, contamination @ interface, minority carrier lifetime, Dit, stress/strain, doping	Can assist AFM, TXRF, VPD-ICPMS, SIMS, TEM, IPE + others
High-K / HfO_2	**O_2 Vacancy, Layer thicknesses, Barrier Energy @ Heterointerface**	**Can assist XPS, CV/IV, Ellipsometry + others**
FD-SOI	Bulk + buried interfaces / BOX	All values for bulk + optical pseudo-MOS + buried interfaces
SiGe	Stress/strain, dopant concentrations	Can assist AFM, VPD-ICPMS, SIMS, Haze + others
III-V (GaAs)	Anti-phase boundaries, lattice defects	Can assist TEM

Why High-K Dielectrics?



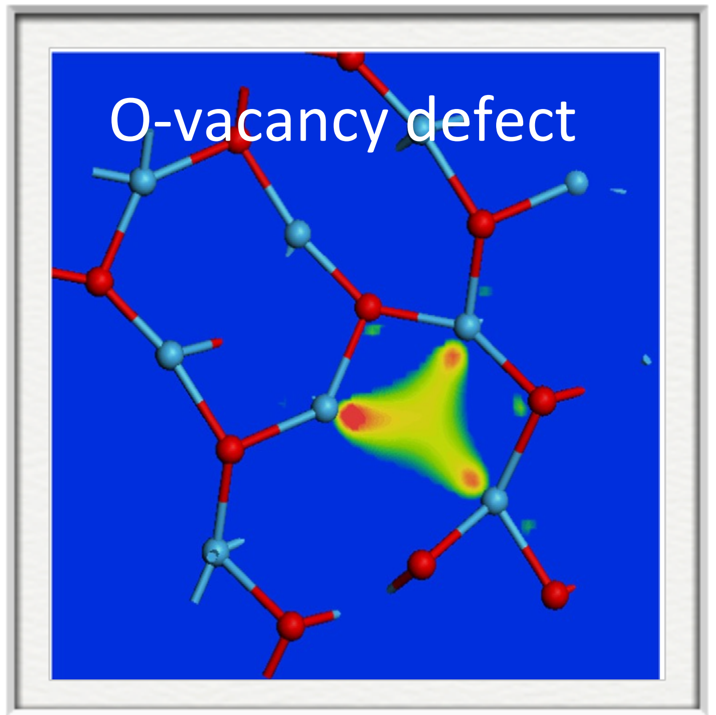
	High-k vs. SiO_2	Benefit
Capacitance	60% greater	*Much faster transistors*
Gate dielectric leakage	> 100x reduction	*Far cooler*



Dielectric insulator is a key component of electronics (CPU, Memories ….)
With scaling, SiO_2 layers have only few atomic layers
High gate leakage current is a concern => a solution is High-K dielectrics

High-K Dielectric Issues

- **Typical High-K dielectrics are**
  - HfO_2 as gate dielectric in CPUs
  - ZrO_2 as capacitor dielectric in DRAMs
  - Al_2O_3 as the blocking oxide in charge traps memories



- **Introducing High-K materials into fab processes leads to many reliability challenges due to structural defects**
  - Asymmetric gate band structure induce polarity effects
  - Threshold voltage instability
  - Challenge to achieve lifetime equal or better than SiO_2 transistors
  - Hysteresis phenomena

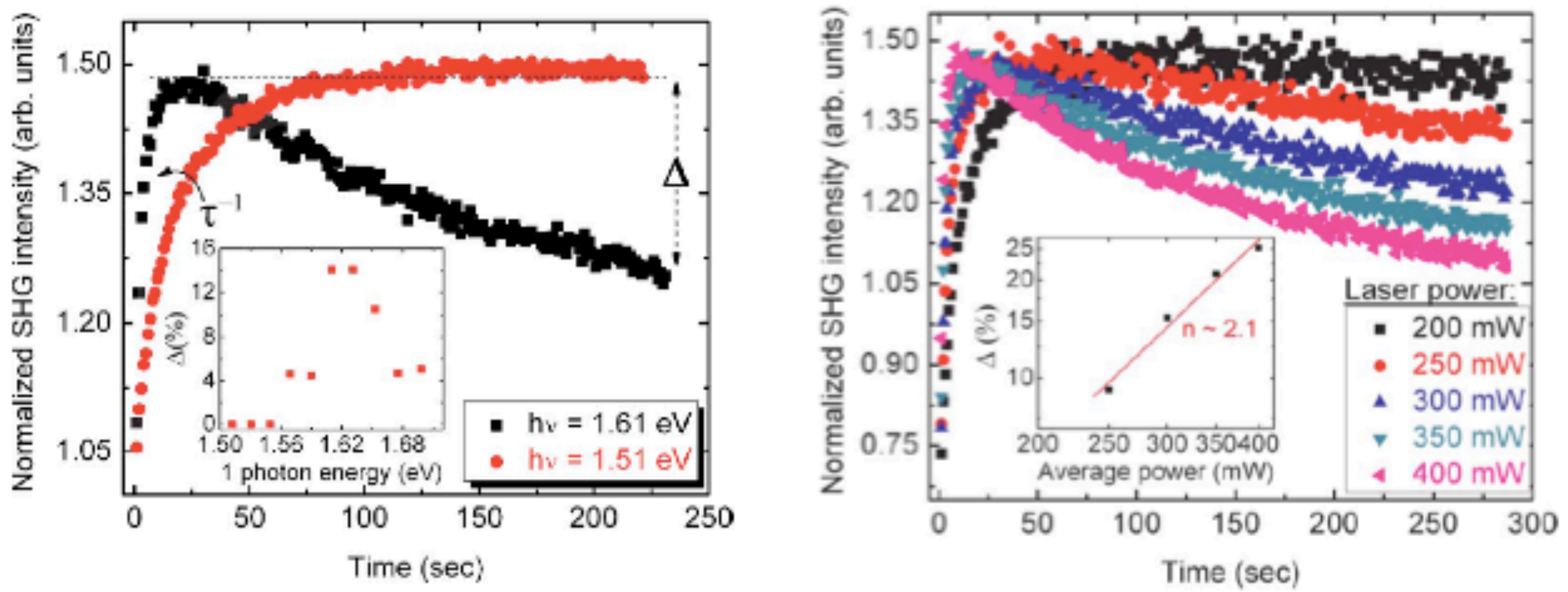
Finding innovative ways to characterize and model these defects will help develop high quality advanced commercial product that are highly reliable

Technique Comparisons

Tool => Uses	CV/IV	XPS	Ellipsometry	2nd Harmonic Generation: Harmonic F1x®
In-line	✗	✓	✓	✓
Non-Destructive	✗	✓	✓	✓
Chemical Analysis	✗	✓	✗	✓*
Electrical Properties	✓	✗	✗	✓
Structural Properties	✗	✗*	✓	✓
No Sample Preparation	✗	✓	✓	✓

Prior SHG / HfO_2 Work

TD-SHG on Si/SiO2/HfO2 stacks



After Price et al. Appl. Phys. Lett. ***95****, 052906 2009*

- **TD-SHG signature depends on many factors**
  - Laser power, photon incident energy, SiO_2 and HfO_2 thicknesses and post-deposition anneal (PDA) and alloying HfO_2 with silicate

Our experimental observations are in line with prior work
We do not see decay due to SiO_2 thickness (~2nm)

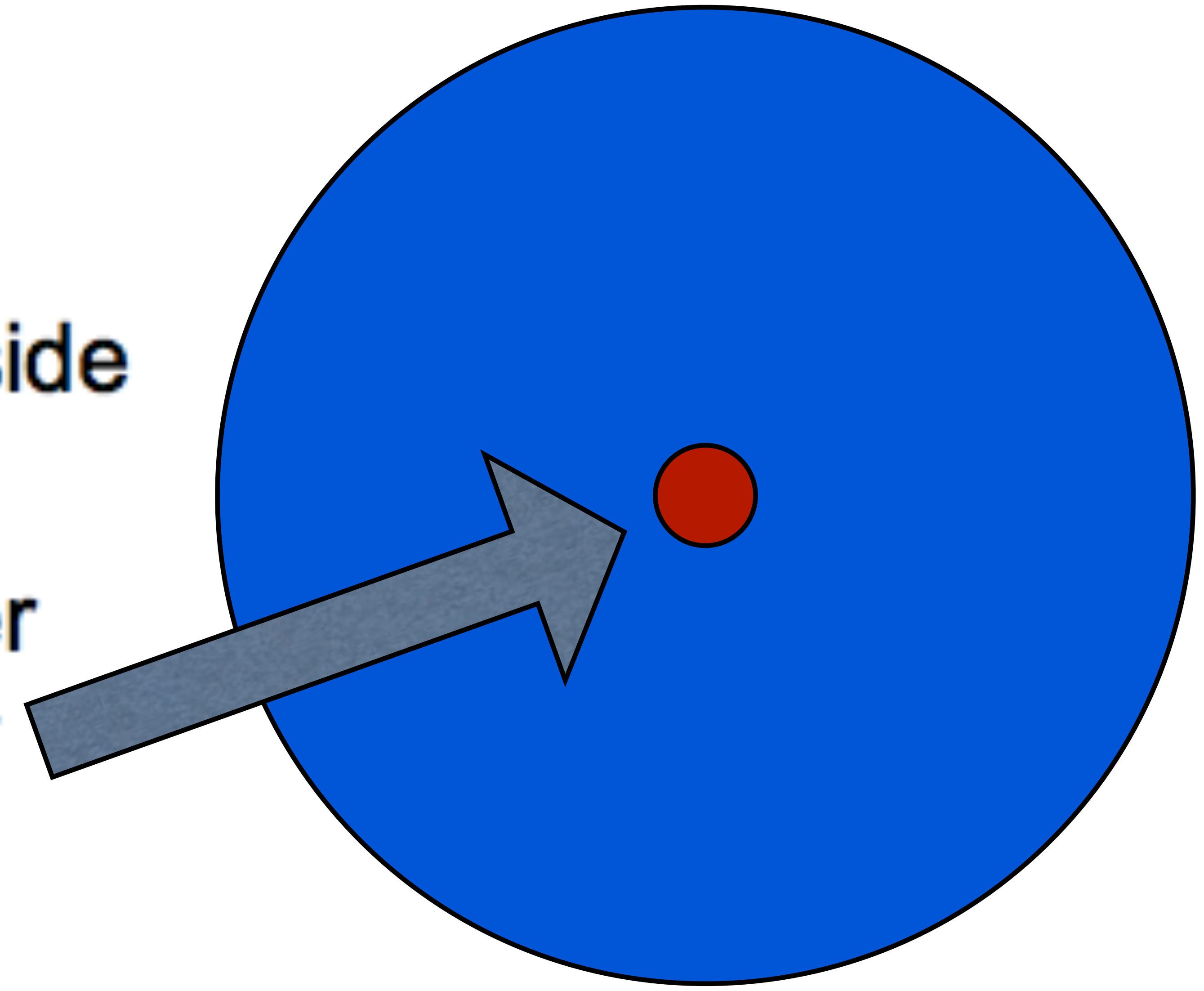
HfO_2 Sample Creation

- Eight (8) 100mm Si wafers
  - Orientation: <1-0-0>
  - Resistivity: 1-5 ohm-cm
- Variables:
  - HfO_2 Thickness
  - H_2O Vapor Pulse
  - Annealing
- H_2O Vapor Pulse affects O-vacancy ratio
- Anneal: 30min @ 1000°C in N_2 ambient
- Thickness measured by Ellipsometry

Sample Number	ALD Cycles	Water Vapor Pulse	PDA	HfO2 Film Thickness (Å)
6	10	0.015	As deposited	22.31
7	25	0.015	As deposited	34.66
8	40	0.015	As deposited	45.37
9	25	0.060	As deposited	33.22
10	10	0.015	Annealed	52.13
11	25	0.015	Annealed	58.11
12	40	0.015	Annealed	70.66
13	25	0.060	Annealed	57.53

CV Measurements

- **Capacitance-Voltage (CV) measurements taken of all wafers**
  - Hg probe as contact on wafer front side
- **Measurement conditions**
  - Measured from front-to-back of wafer
    - 926um Hg probe on wafer center 100kHz frequency
  - -1.0 to 1.0 V range

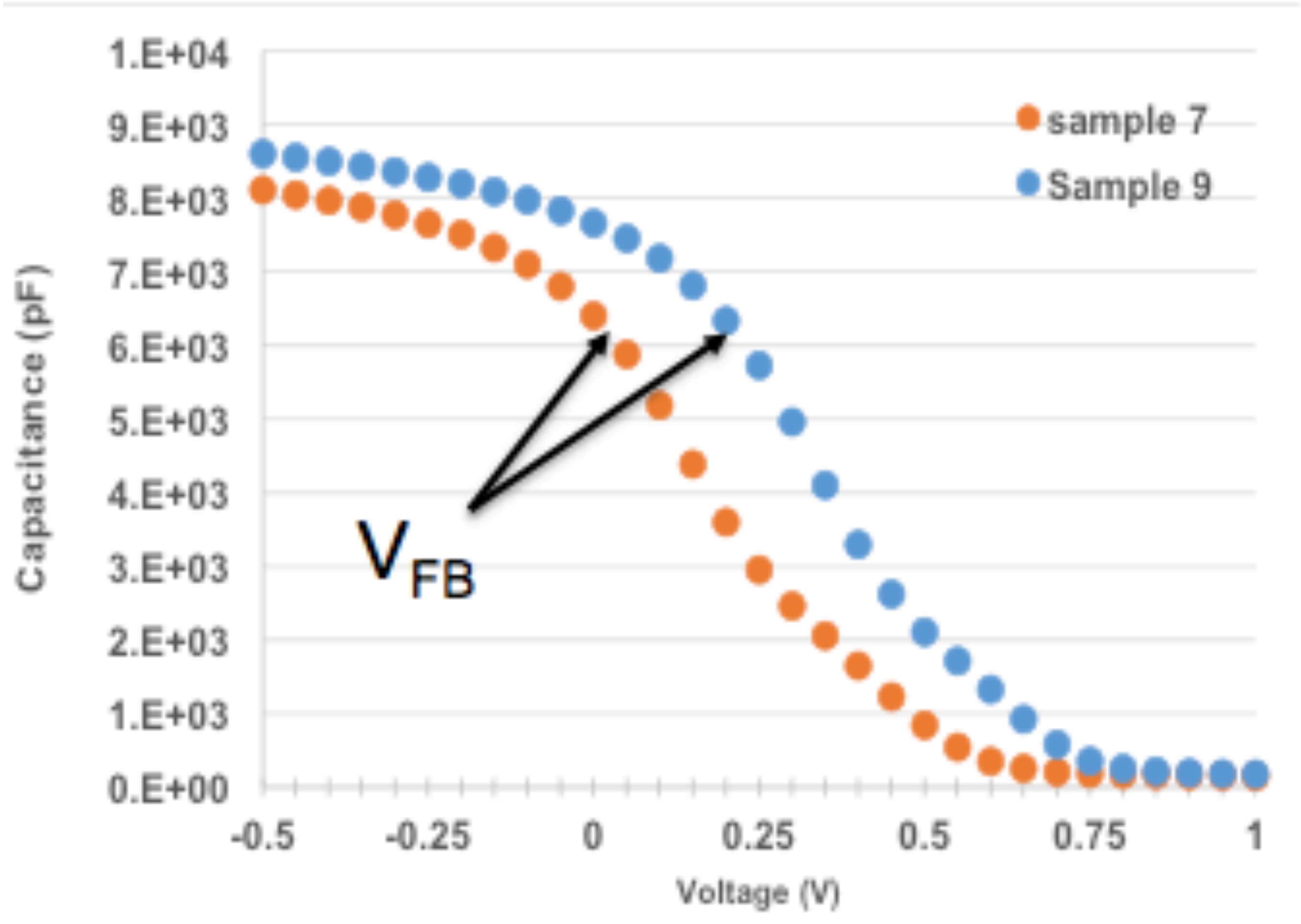


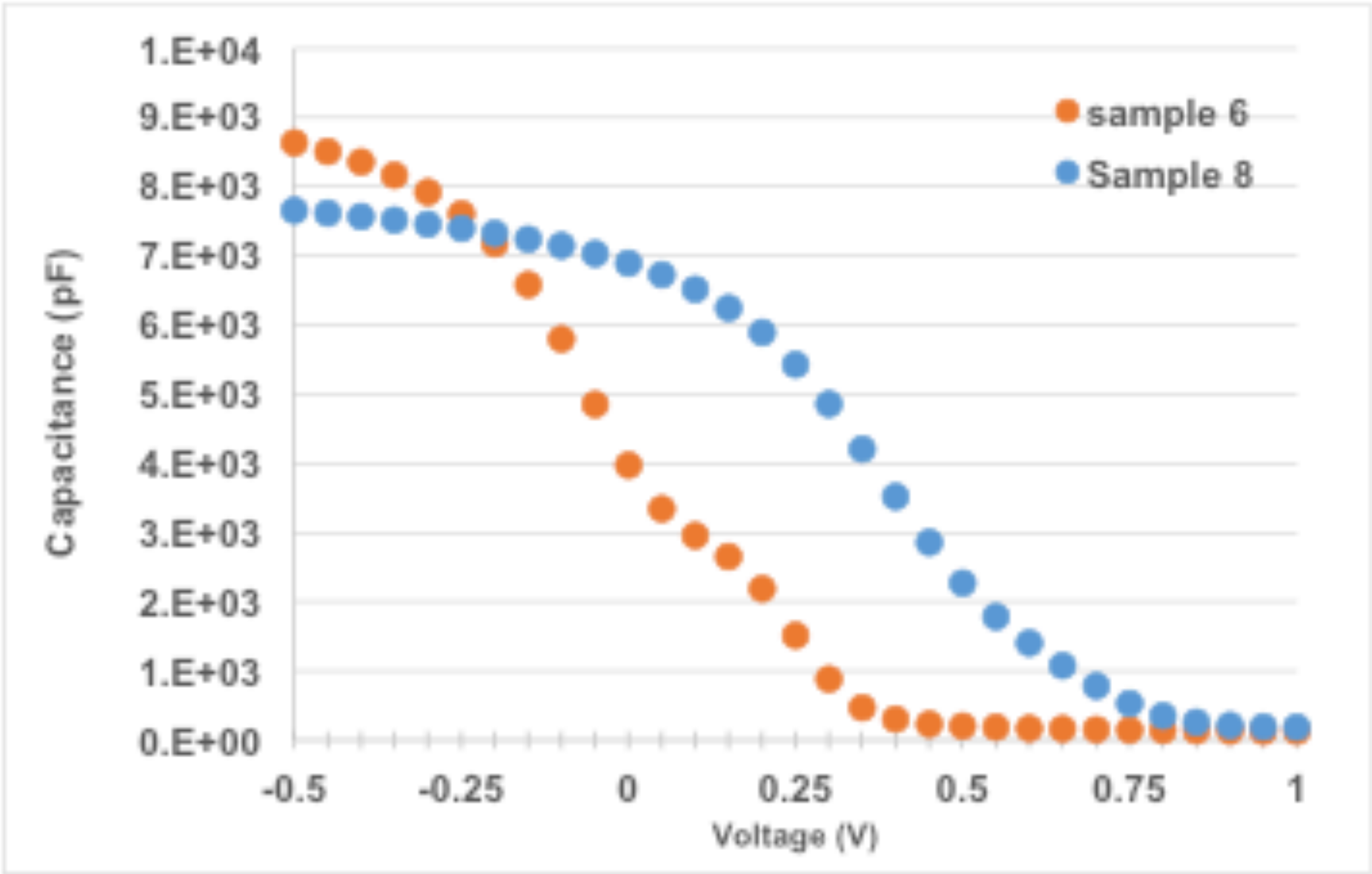
V_{FB} α Dd (Defect densities)

Goal was to detect variations in V_{FB} voltage in the CV characteristics which is an indication of variation in defect densities for a fixed thickness

CV Results: As Deposited

Unannealed samples





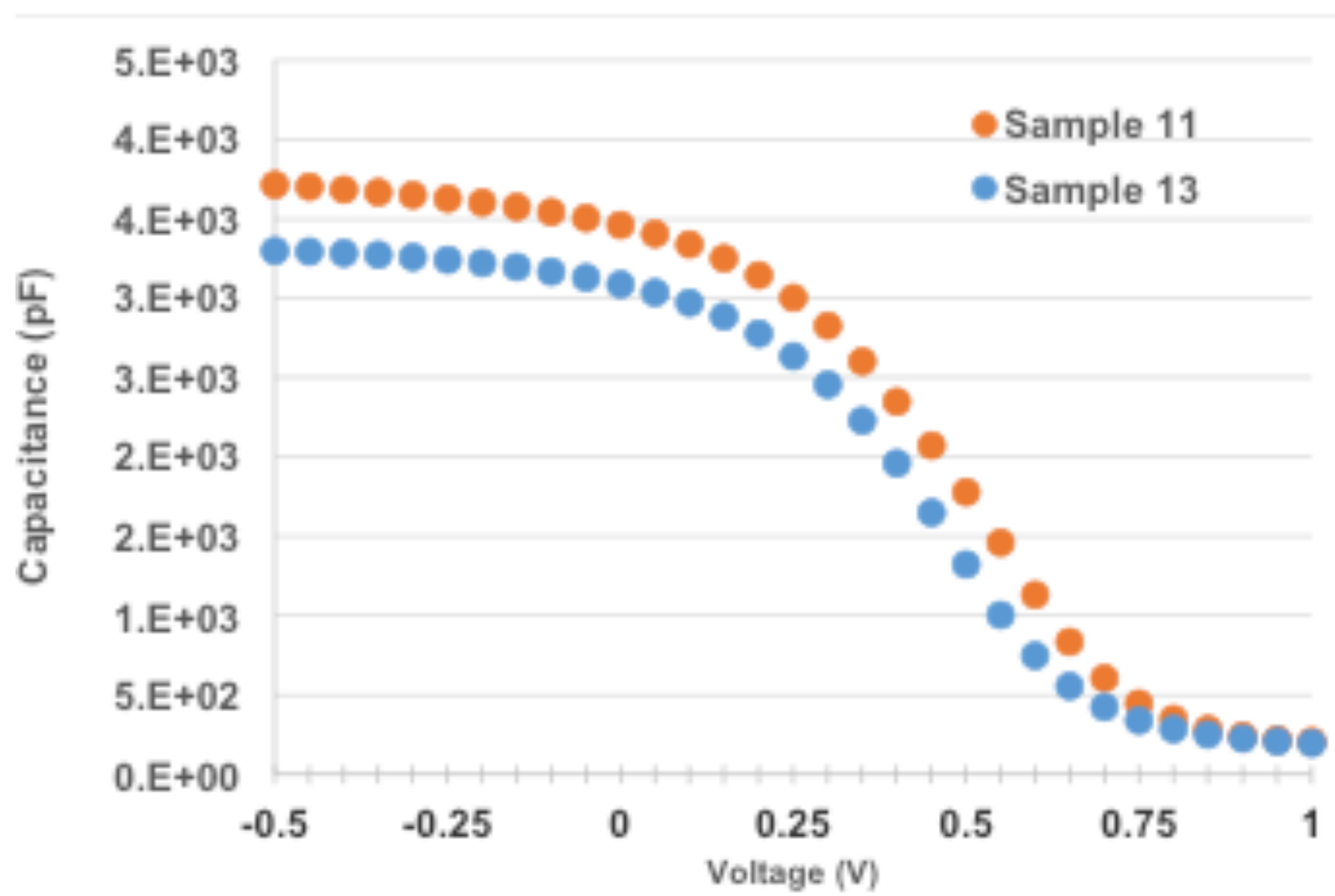
V_{FB} (7) < V_{FB} (9) => variation in defect densities
S7 and S9 have equal HfO2 thicknesses

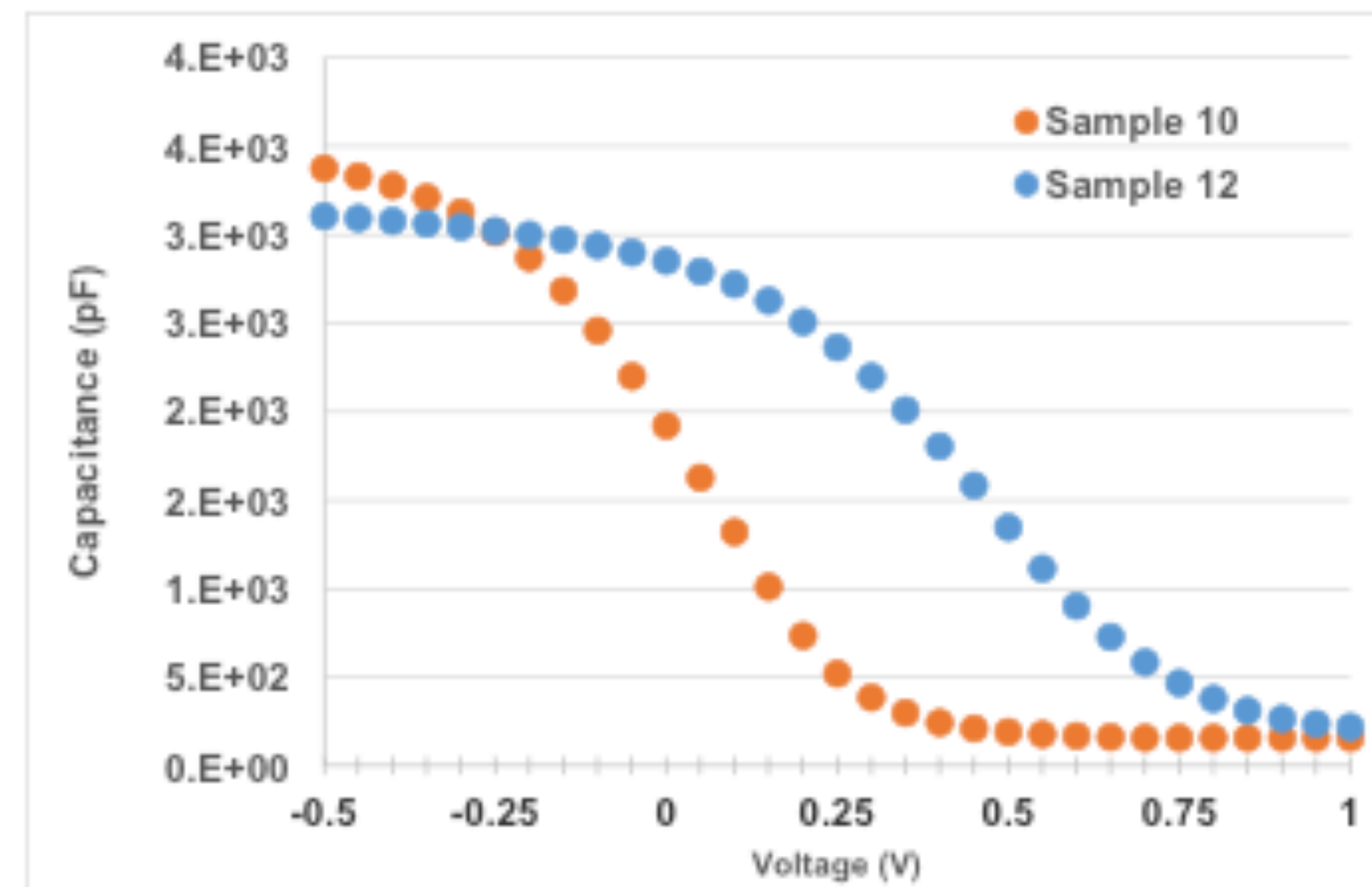
V_{FB} (6) < V_{FB} (8) => variation in defect densities
S6 and S8 have different HfO2 thicknesses

In first order, we see differences in CV responses between samples
VFB variation is an indication of defect density variation

CV Results: Annealed

Annealed samples





V_{FB} (13) < V_{FB} (11) => variation in Dd
S11 and S13 have equal HfO2 thicknesses

V_{FB} (10) < V_{FB} (12) => variation in Dd
S10 and S12 have different HfO2 thicknesses

In first order, we see differences in CV responses between samples
VFB variation is an indication of defect densities variation

XPS Calibration

X-Ray Photoelectron Spectroscopy (XPS)

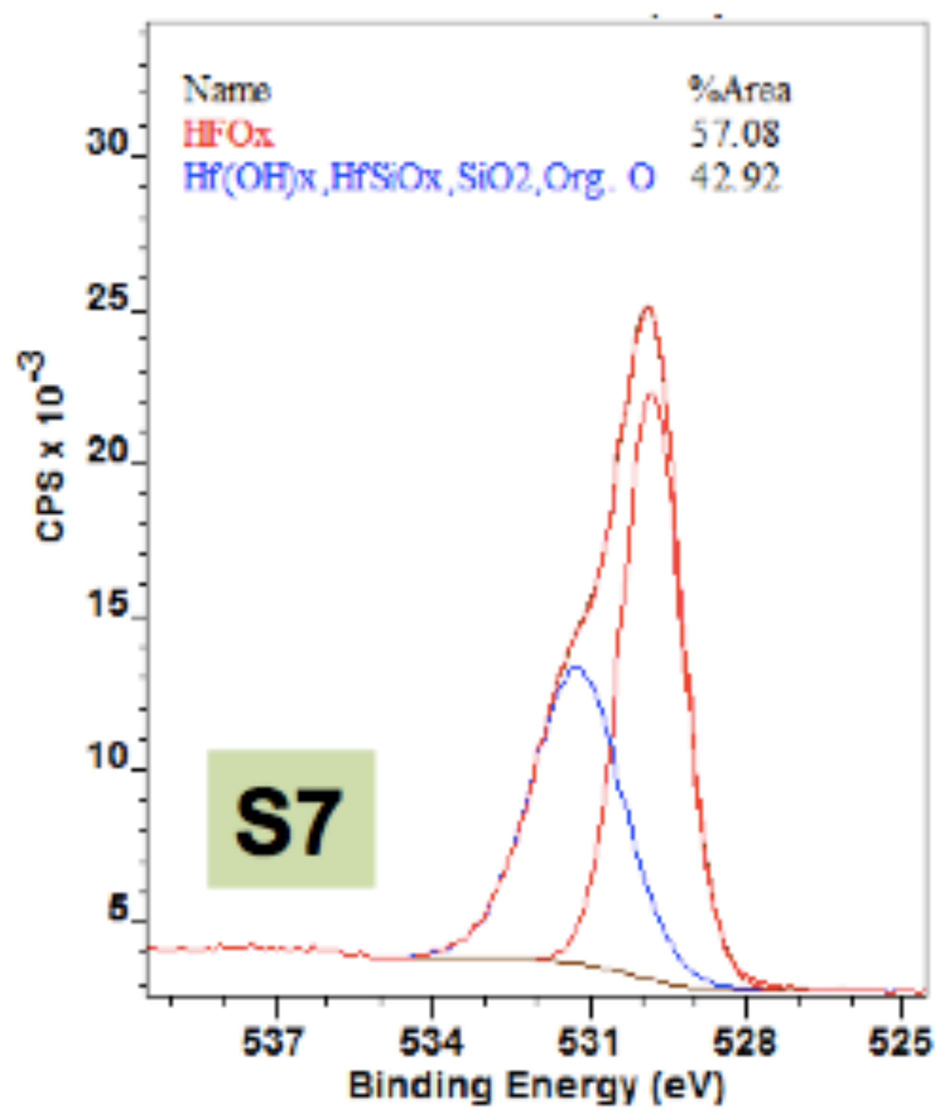
Instrument	PHI Quantum 2000
X-ray source	Monochromated Alk$_\alpha$ 1486.6eV
Acceptance Angle	±23°
Take-off angle	45°
Analysis area	1400μm x 300μm
Charge Correction	C1s 284.8 eV

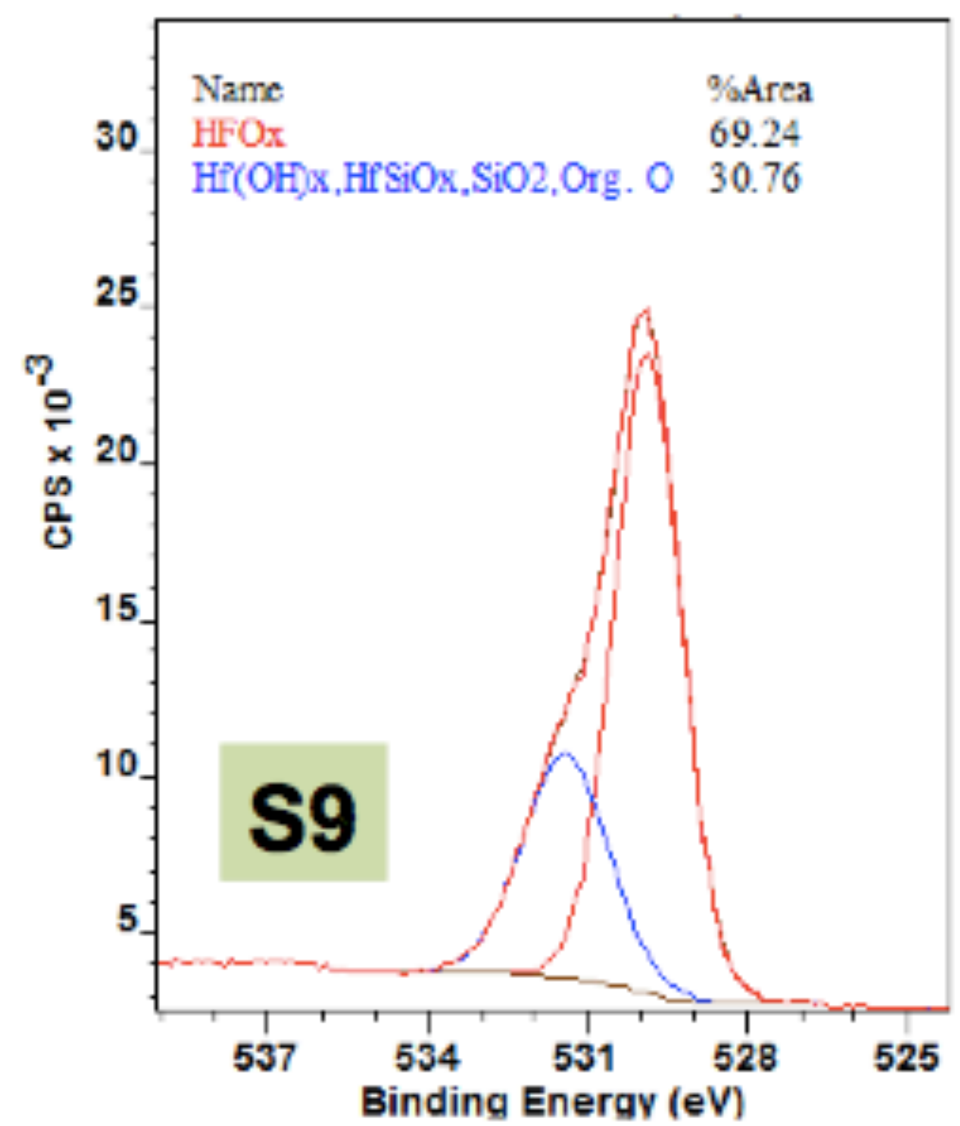
- Measure elemental composition of top ~5-10nm
- Sensitivity: 1.0 to 0.05 atomic %

Goal is to determine the composition and chemistry of wafer samples and compare the O-content within the HfO_x films.

XPS Results A

Results: Un-annealed Wafers (S7, S9)





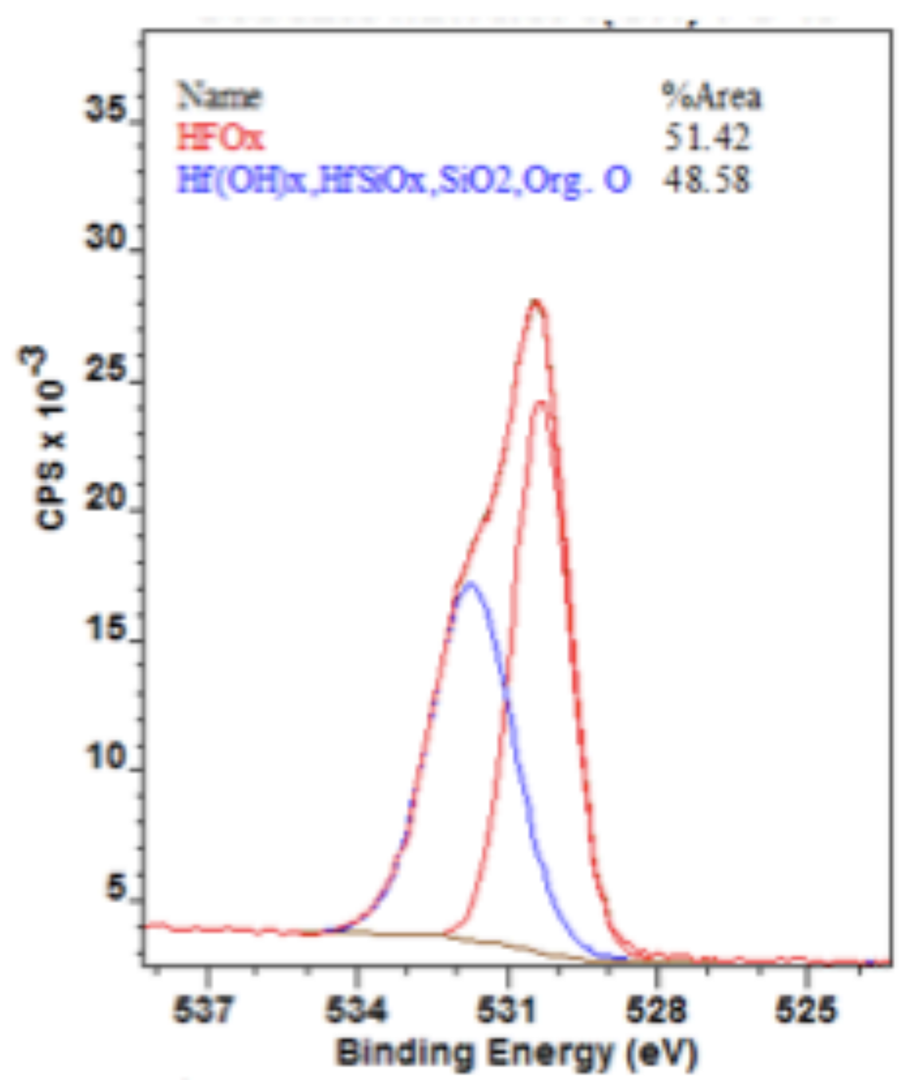
Sample	C	O	F	Si	Hf	Hf/ O^{total}	Hf/ O^{Hf-O}
S7	23.9	47.2	0.2	11.3	17.4	0.368	0.486
S9	20.7	49.0	0.3	10.9	19.1	0.390	0.495

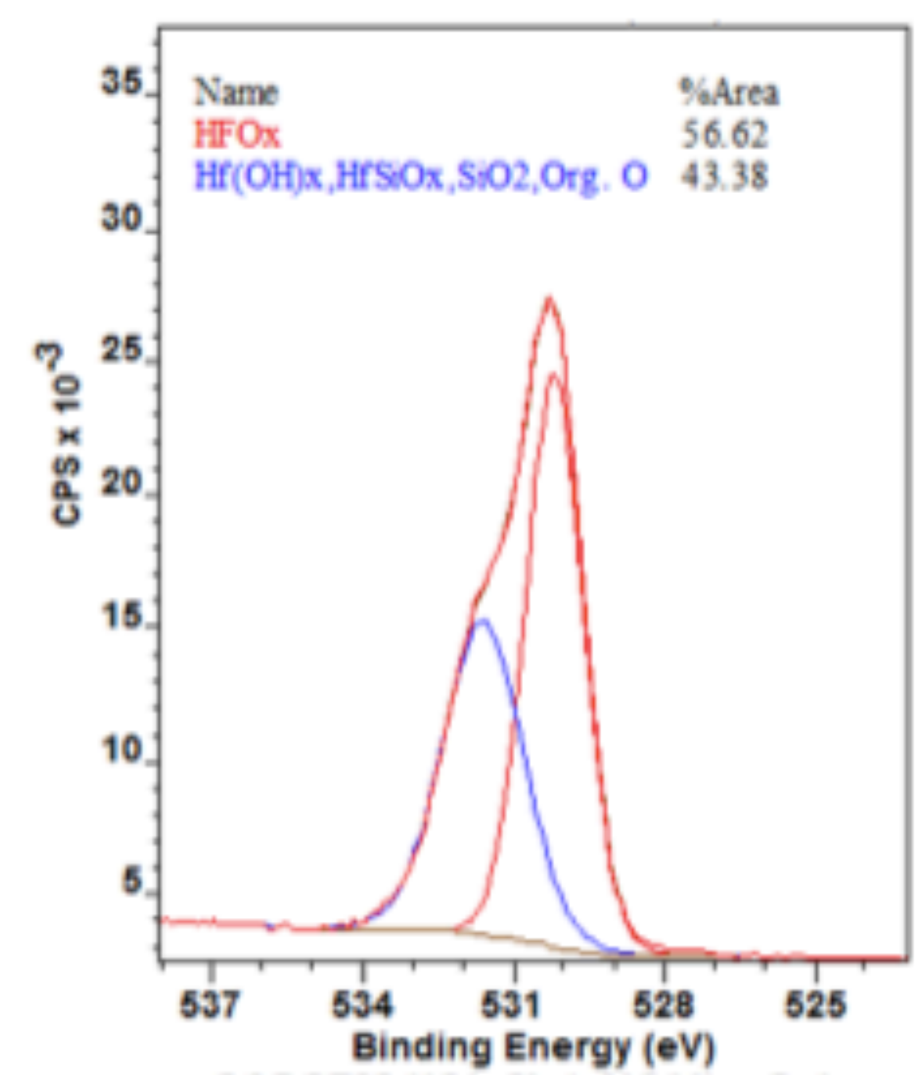
(S7) 2.8% oxygen sites in HfO_2 are vacant

(S9) 1.0% oxygen sites in HfO_2 are vacant

XPS Results B

Results: Annealed Wafers(S11, S13)





Sample	C	O	F	Si	Hf	Hf/ O_{total}	Hf/ O^{Hf-O}
S11	19.4	52.9	-	11.8	15.8	0.300	0.544
S13	20.5	52.1	<0.1	10.7	16.6	0.318	0.552

Both samples have hafnium-oxygen ratios in excess of stoichiometric

– (0.5, or 1 Hf per 2O)

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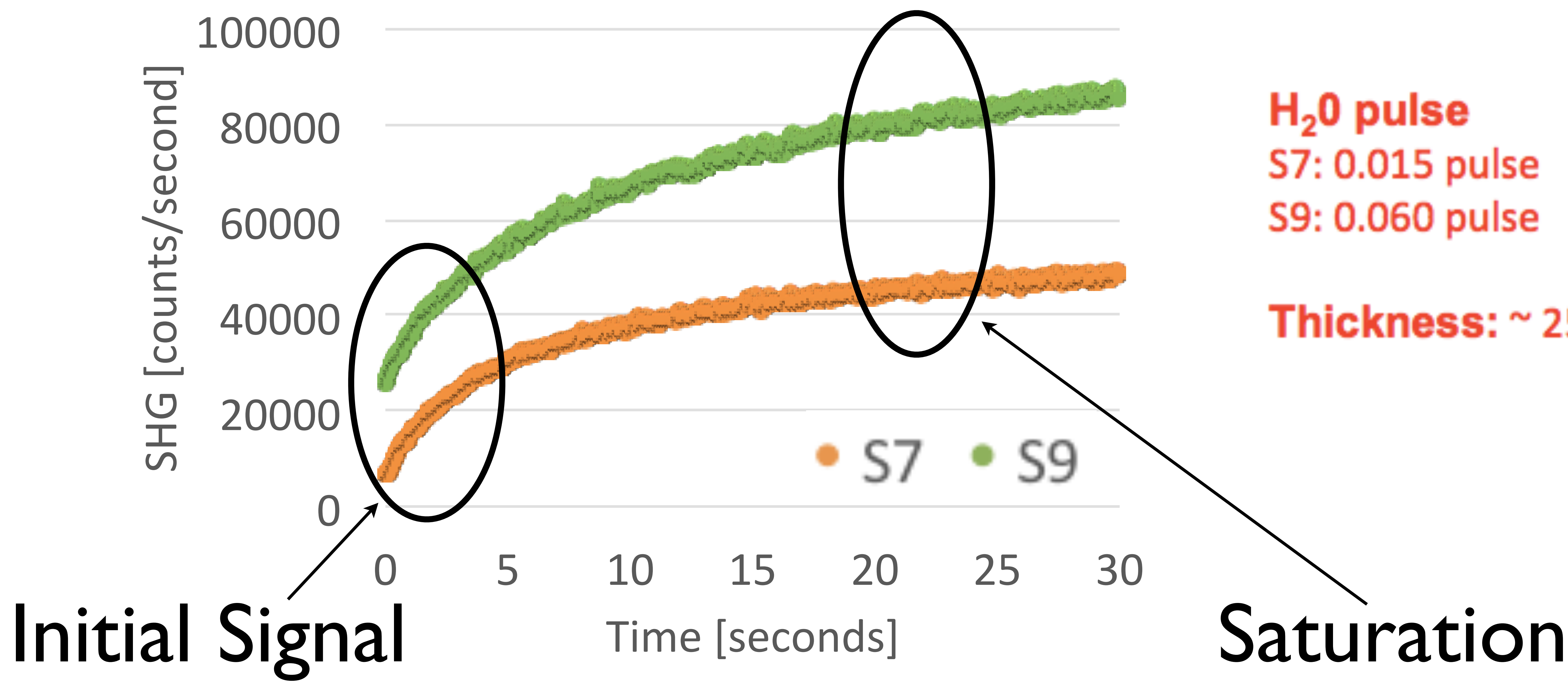
SHG Tool Configuration

PARAMETER	SETTING
Laser Average Power	300 mW
Laser Photon Energy	1.5895 eV
Incident Beam Polarization	P
Output Collection Polarization	P
SHG Photon Energy	3.179 eV
Incident Angle	45°

TD-SHG Results A

Results: Un-annealed Wafers (S7, S9)



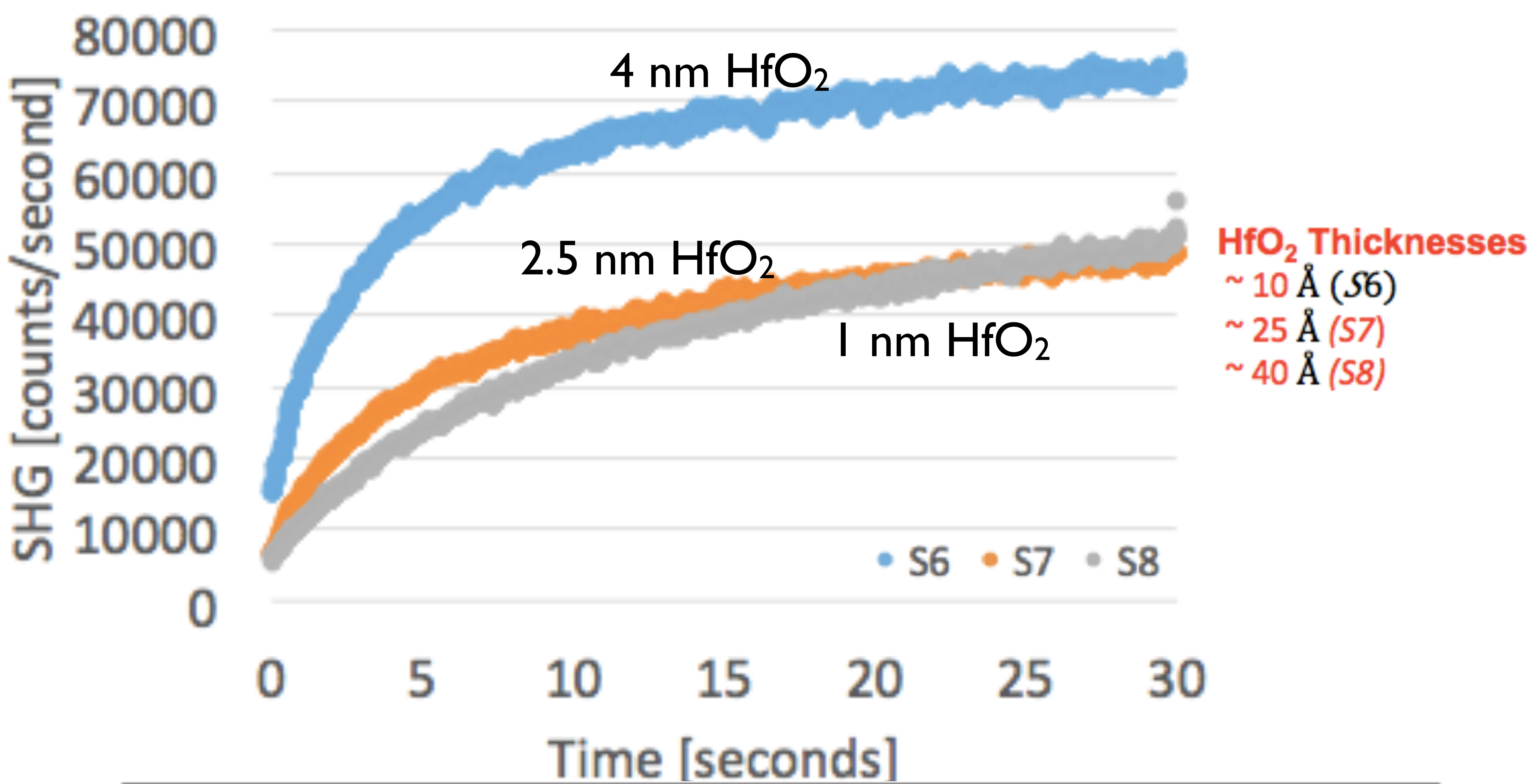
$H_2$0 pulse
S7: 0.015 pulse
S9: 0.060 pulse

Thickness: ~ 25 Å

Longer H2O pulse results in higher initial and overall signal
Un-annealed samples show strong time dependence

TD-SHG Results B

Results: Un-annealed Wafers (6,7,8)



Initial signal rise time is slower with increasing thickness
Initial signal value decreases with increasing thickness

Trap Quantification: HfO_2

Modeling Tool

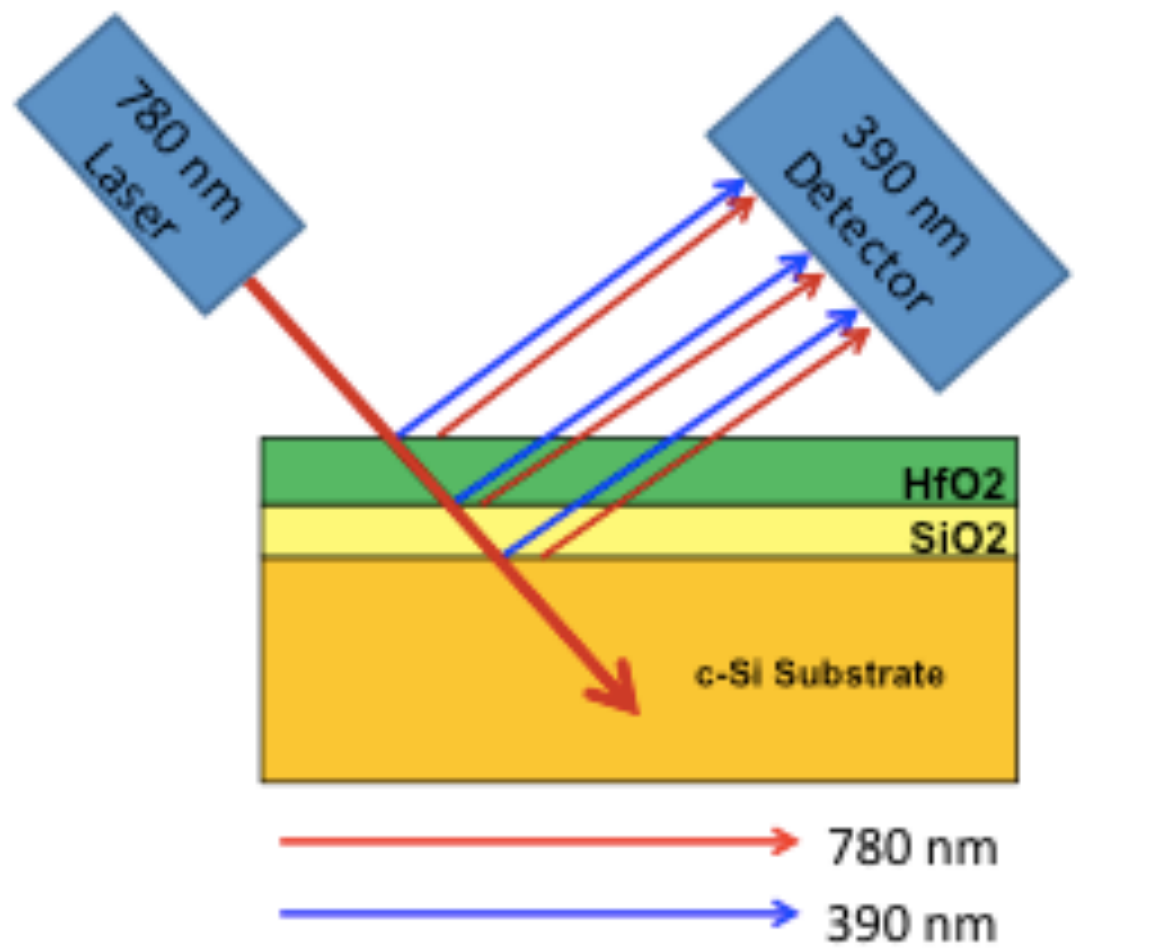
Thin dielectric quantified trapping/ de-trapping model

$$\frac{\partial n_t(x,t)}{\partial t} = \frac{[N_t - n_t(x,t)]}{\tau_t} - \frac{n_t(x,t)}{\tau_{dt}}$$

N_t is the trap concentration

- Theoretical model that describes the physical mechanisms of defects in SiO_2 systems
- Use finite-difference methodology to perform numerical calculations of defects densities
- Applicable to HfO_2/SiO_2 systems

Measurement technique

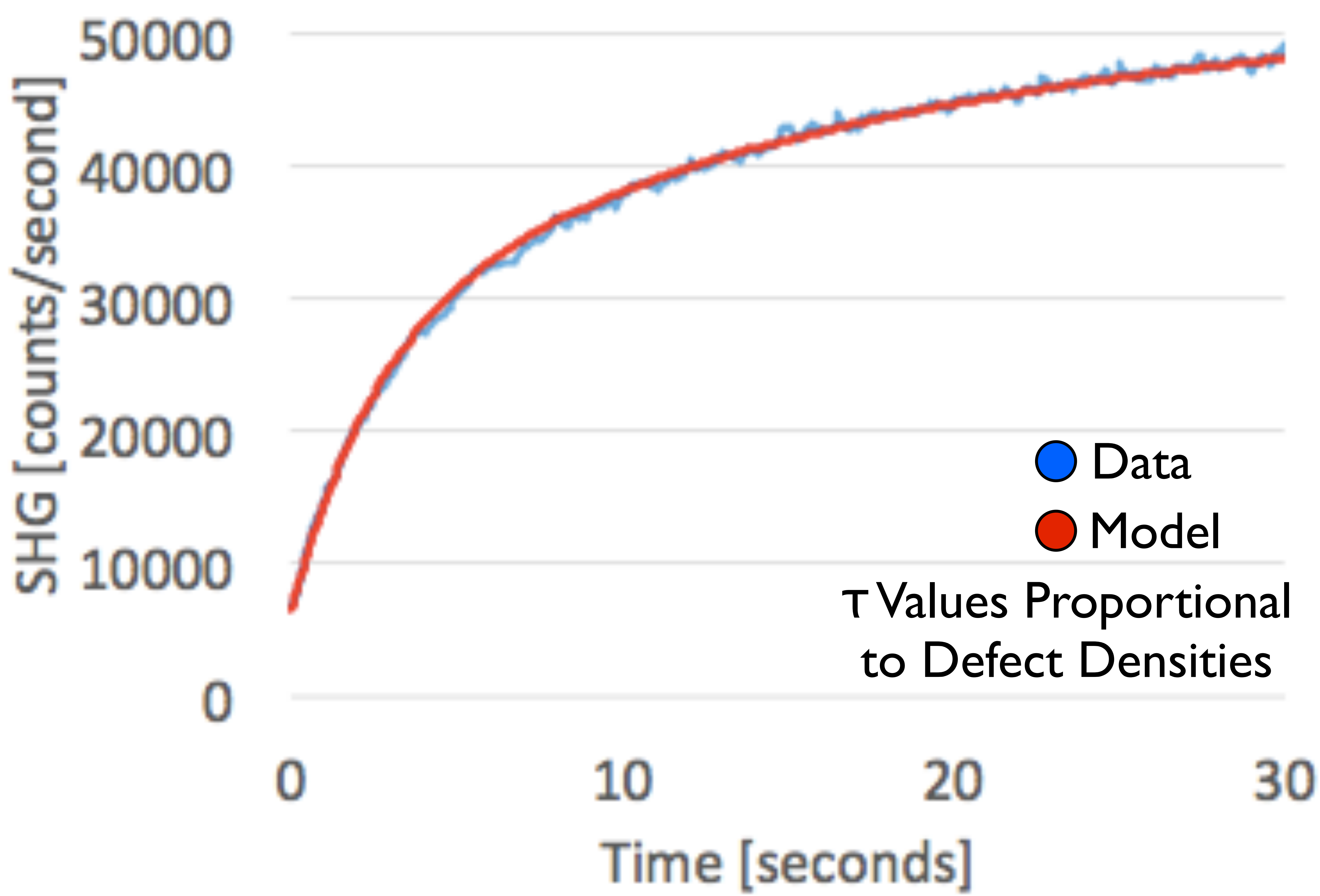


$$I^{2\omega}(t) \propto \left|\chi^{(2)} + \chi^{(3)} E(t)\right|^2 (I^{\varpi})^2$$

- SHG is sensitive to electric fields across interfaces, with E-field induced second-harmonic signal from a Si/SiO_2 interface
- Applicable to HfO_2/SiO_2 systems

Model is needed to understand experimental data from SHG measurements

Applied Tau Model



Tau-1	Tau-2	I01	I02	I00	R2 (0-1sec)	R2 (1-30 sec)
2.6	17	21000	25000	6500	0.833685689	0.912572317

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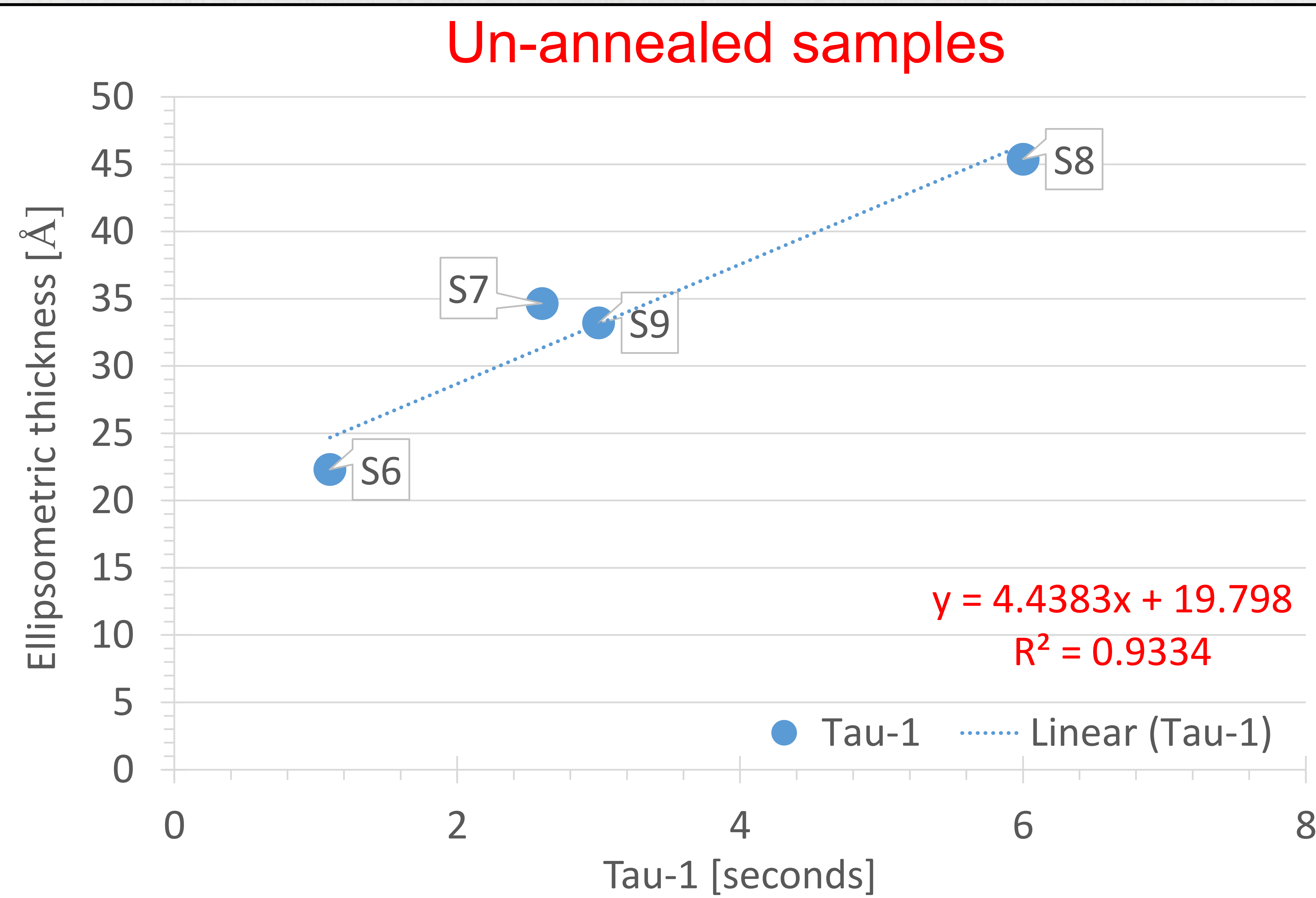
Layer Thickness Correlation



Reasonable correlation between Tau-1 and reported ellipsometry data
Attractive to extrapolate thicknesses for a same process

Results Summary

- Eight $Si/SiO_2/HfO_2$ wafers were created for characterization of the gate stacks
- Ellipsometry, CV, XPS + SHG data were taken on the center point of each wafer
- SHG has been correlated with ellipsometry + results are consistent with prior work
- SHG observes differences in trap density confirmed by XPS + CV characterizations
- Layer thickness + trap densities have been parsed from the raw SHG signal
- Next steps are derivation of quantified values: layer thickness, O-vacancy densities

Questions?