# High Temperature Oxygen Out-Diffusion from the Interfacial SiOx Bond Layer in Direct Silicon Bonded (DSB) Substrates

Jim Sullivan, Harry R. Kirk, Sien Kang, Philip J. Ong, and
Francois J. Henley

Silicon Genesis Corporation
San Jose, California USA

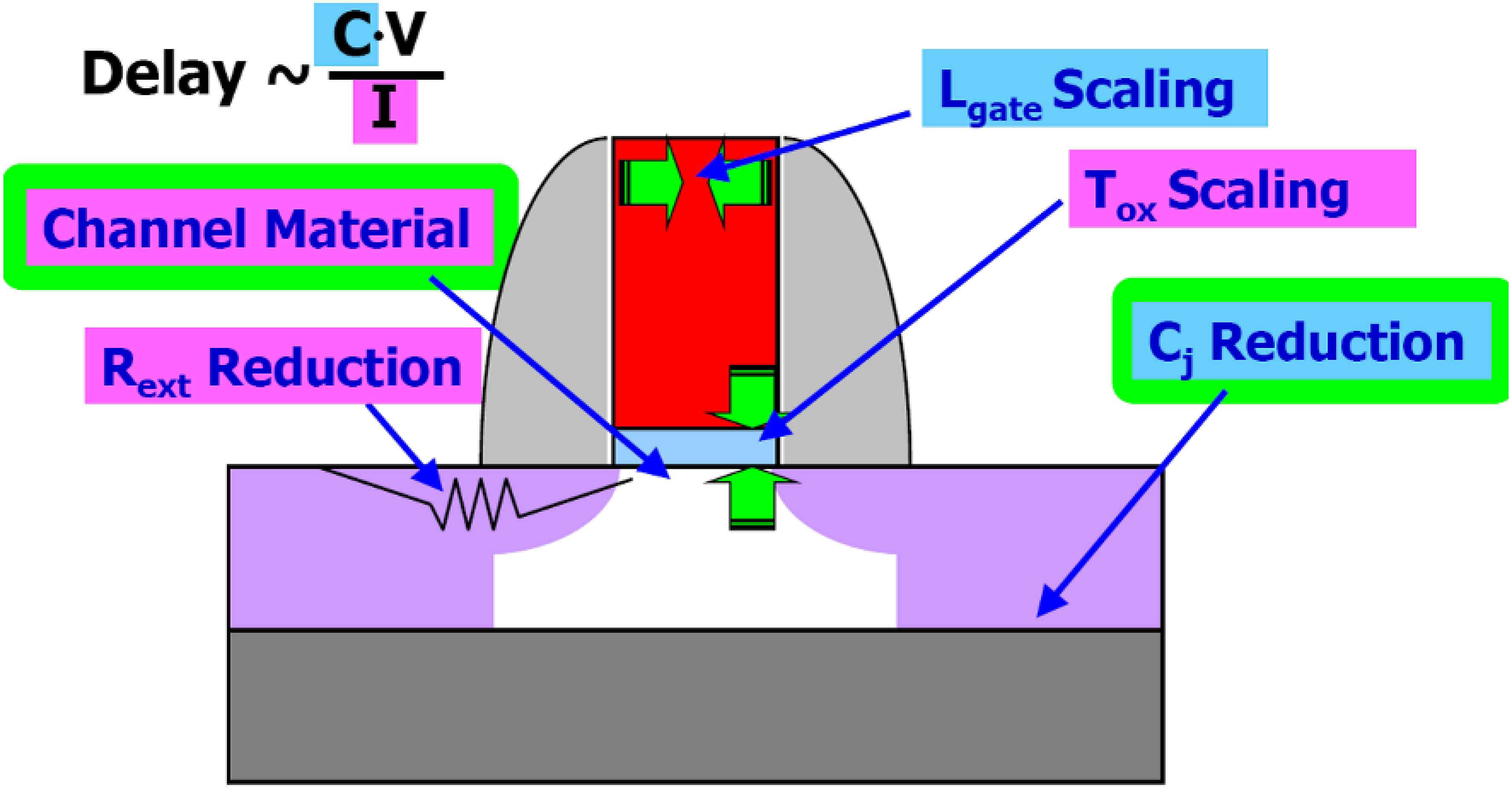
IEEE 2006 International SOI Conference

Niagara Falls, New York
2 – 5 October, 2006

# Outline

- Motivation for DSB
- Adapting an SOI Process for DSB
  - Fundamental Issues & Challenges
- Plasma Bond Process Modifications
- SiOx Metrology Considerations
- Bond Interface Oxygen Dissolution
  - Relevant Prior Work
  - Theoretical Model
  - Results
  - Special Process Considerations
- Cost-Effective Commercialization
- Conclusions

# Motivation – Better CMOS Mobility



$$\text{Delay} \sim \frac{C \cdot V}{I}$$

**Channel Material**

**$R_{ext}$ Reduction**

**$L_{gate}$ Scaling**

**$T_{ox}$ Scaling**

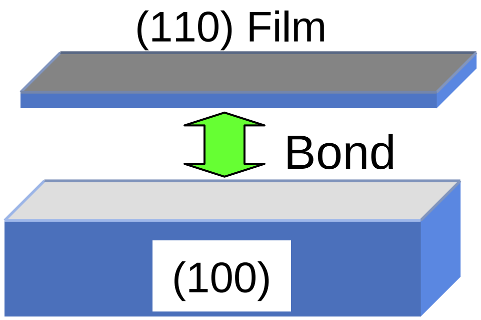
**$C_j$ Reduction**

- Finding ways to increase channel mobility is key
  - Strain and orientation are two good knobs

Welser, IEEE SVC EDS Seminar June 2005

# Hybrid Orientation - Why It Works

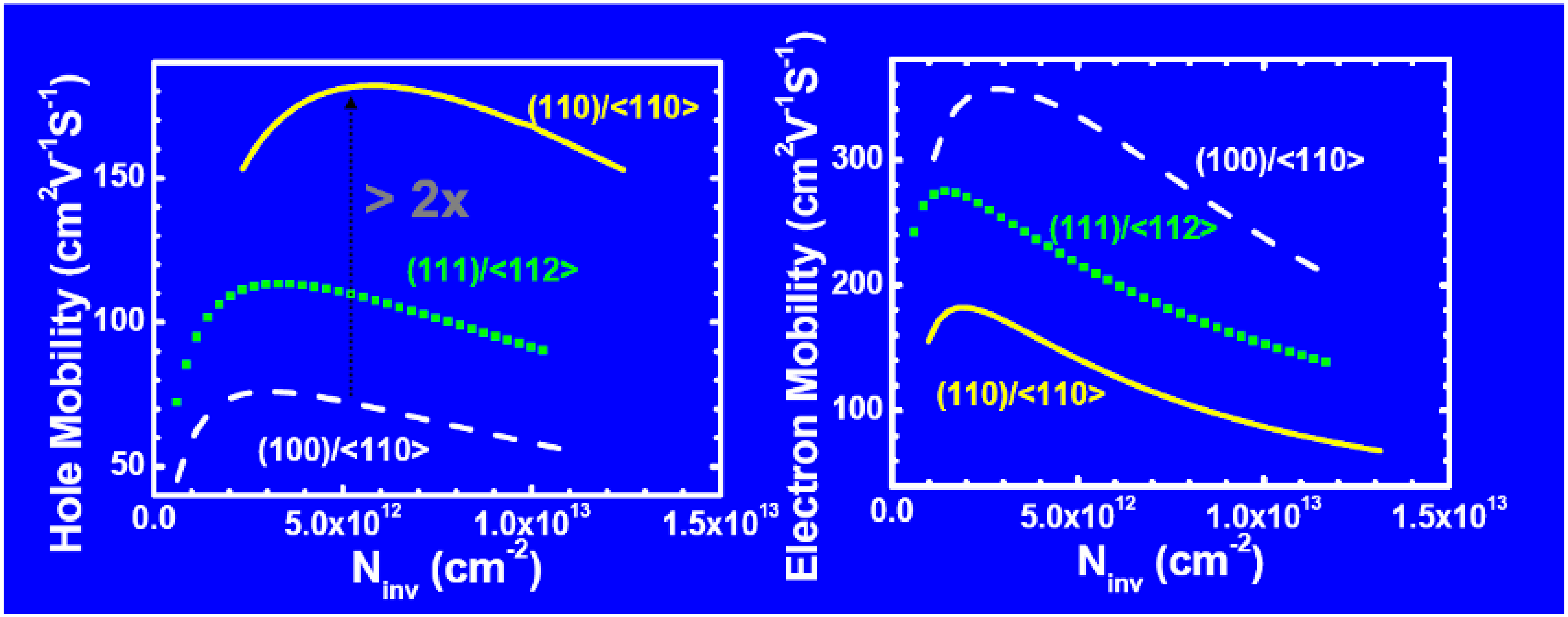
- Independently optimizes PMOS and NMOS Mobility
- Compatible with strain enhancement approaches
- DSB is a bulk-like, electrically connected version


(110) Film

Bond

(100)

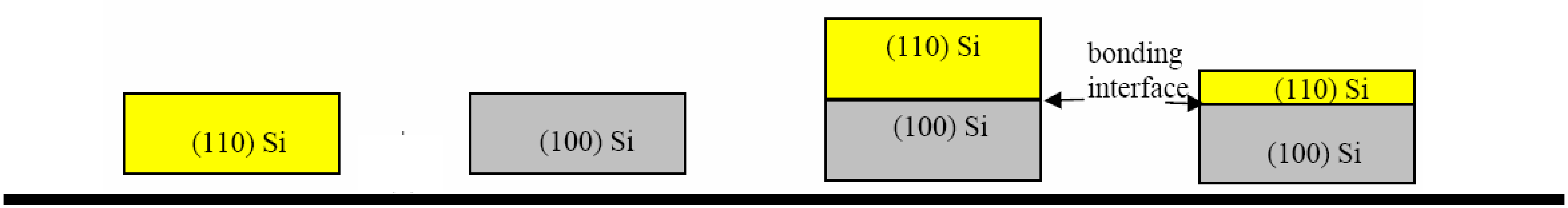
Electron mobility is highest on (100) surface
Hole mobility is highest on (110) surface

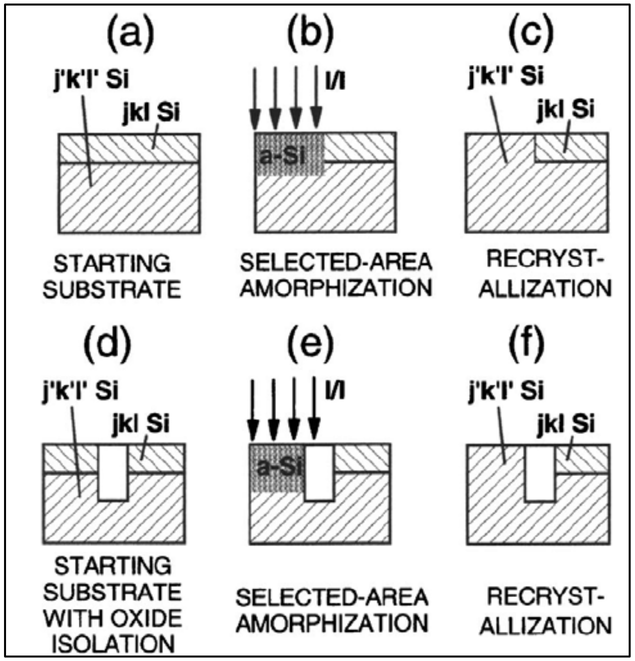


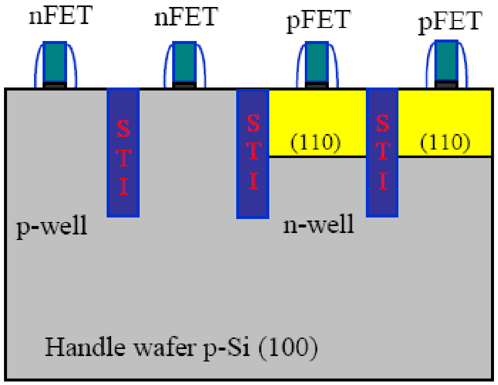
Welser, IEEE SVC EDS Seminar June 2005

# Major DSB Benefit – Bulk-Like!

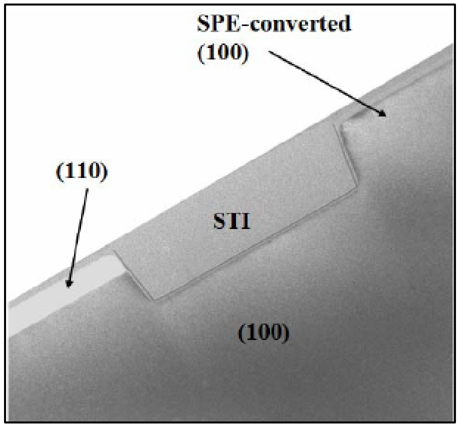
- Compatible with CMOS processes and strain enhancement approaches
- Amorphization & SPE processes to express selective orientation







CMOS Structure



TEM

Sung & al., IEDM 2005, Ref. #3 & Saenger & al, APL 87, 221911, 2005

# Adapting an SOI Process For DSB

## *Two Major Paths to Consider*

1. *Hydrophyllic Bonding*
   - Positive Points
     - Used in SOI in production
     - Highly engineered void-free bonding
     - Equipment and bond processes available
   - Negative Points
     - Generates a bond interfacial oxide
     - Electrically insulating interface

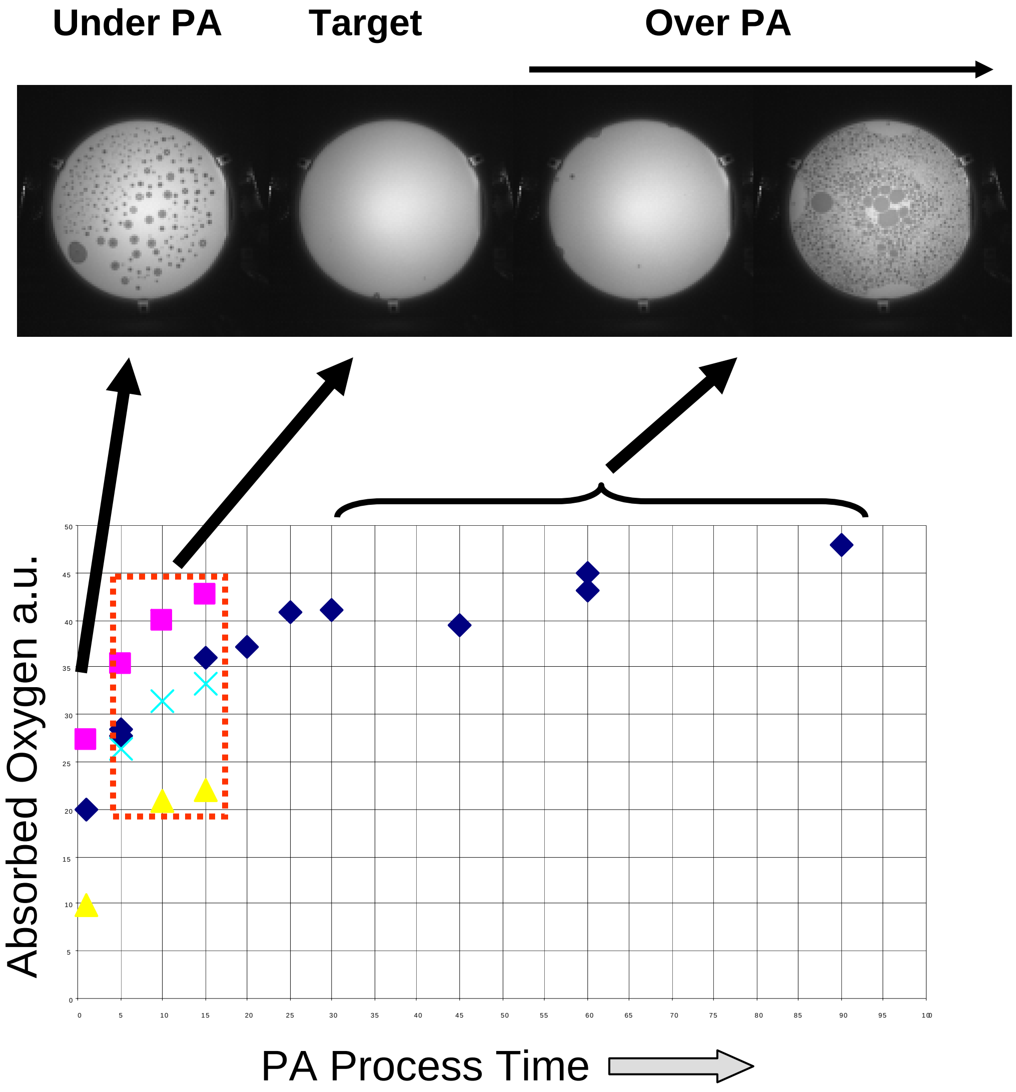
Can we eliminate the oxide?

2. *Hydrophobic Bonding*
   - Positive Points
     - No Interface oxide
   - Negative Points
     - Void-free bonding is difficult
     - No production low-temperature bond experience
     - Production equipment and processes unavailable

# Plasma Activation (PA) for DSB – SiOx Control

- Low temperature cleaving possible
- Void-Free Production Bonding
- Control of SiOx at interface

*SiGen plasma-activation chamber (open chamber in background) integrated into an EV850 bond tool*

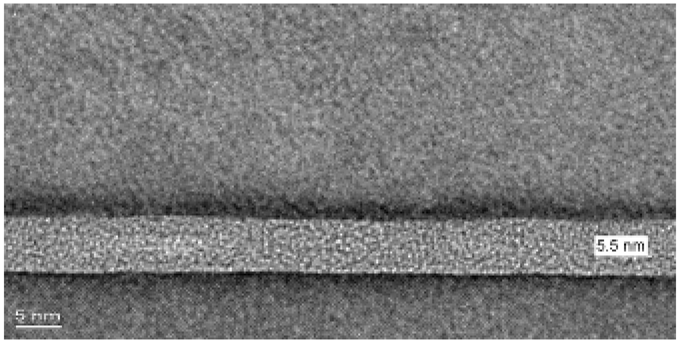


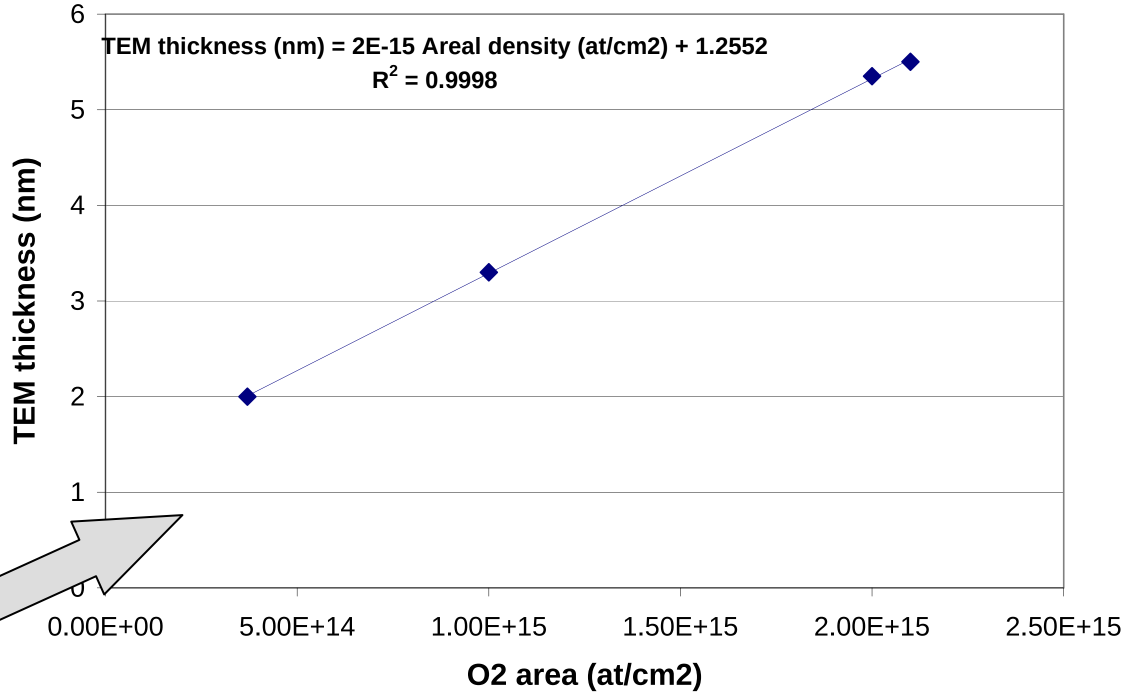
**Under PA** **Target** **Over PA**

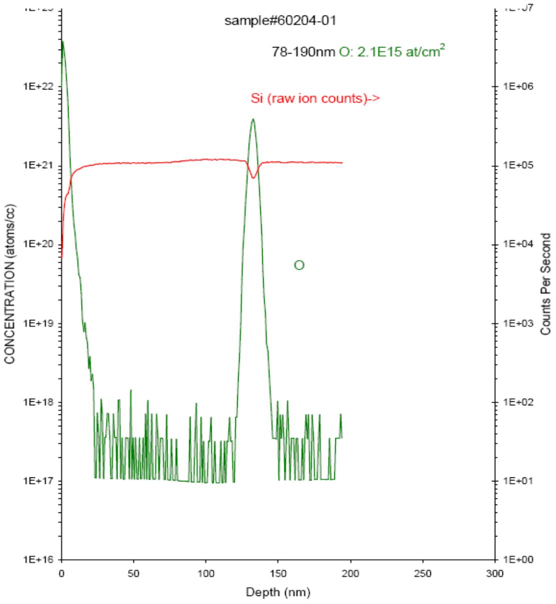
# SiOx Metrology Considerations

- SiOx elimination requires good metrology
- SiOx stochiometry used TEM and SIMS
    - First measurements gave x=4 !
    - SIMS technique had to be refined:
        - Detected CsO+ secondary ions with Cs+ primary beam)
        - This approach minimize the typical matrix effects in SIMS analysis and allows accurate quantification in presence of interfaces
- SiGen/CEA successfully developed an effective characterization method based on “Calibrated SIMS”
- Method Development:
    - Measured samples with TEMs and SIMS Cs+
    - Generated an effective correlation of total oxygen dose versus TEM thickness
    - Dissolution results in good agreement with absolute oxygen numbers

# SiOx Metrology Considerations





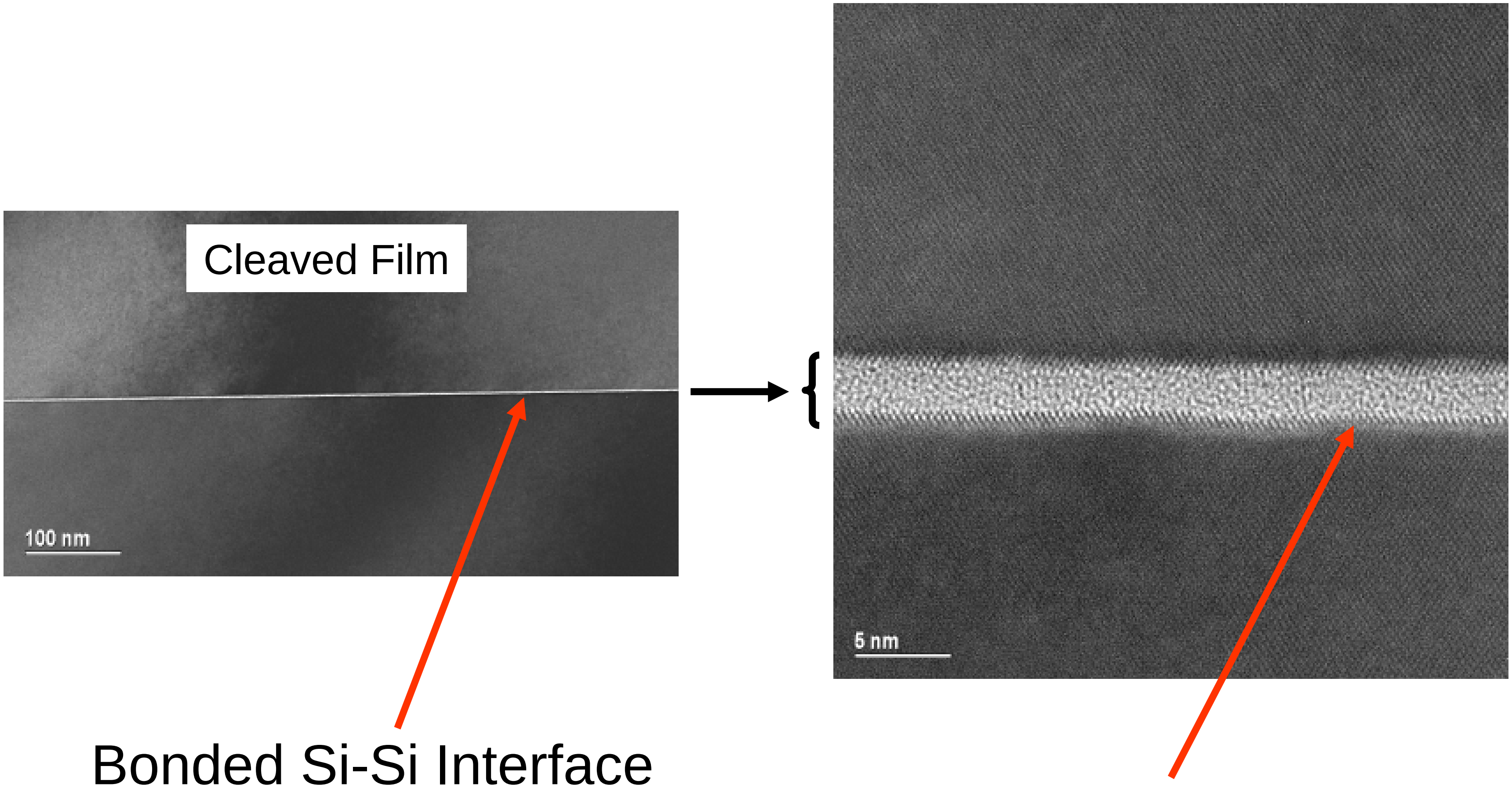


- A linear relationship between TEM thickness and SIMS oxygen content was found

  => Quantification was accurate

# Cross-section TEM (As-Cleaved DSB)

## Pre-Dissolution



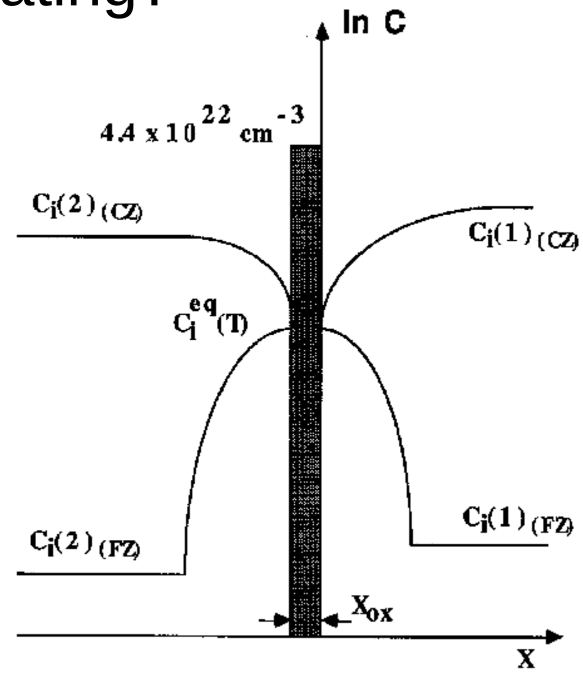
Bonded Si-Si Interface

Interfacial layer = ~30Å-60Å

# Bond Interface Oxygen Dissolution

- Fundamental Approach
  - Use a high-temperature anneal to dissolve oxygen through the upper interface
- Production worthy? Defect Generating?
- Relevant Prior Work
  - Ahn & al, Appl. Phys. A 50, 85-94 (1990)

- Used bonded wafers with thin oxide interface
- No layer-transfer, “infinite” silicon thickness on each side
- FZ, CZ substrates studied
  - FZ: Dissolution possible
  - CZ: Net oxide growth occurs

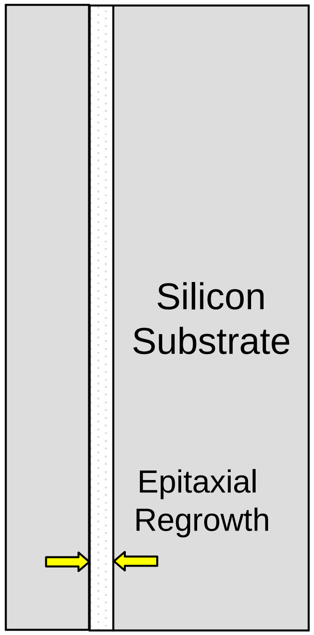


$$\Delta X_{ox} = \frac{2[C_i(1)+C_i(2)-2C_i^{eq}(T)]}{n_{ox}}\sqrt{\frac{D_i(T)t}{\pi}}$$

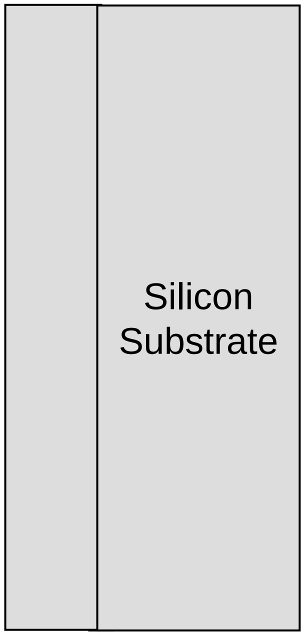
# Bond Interface Oxygen Dissolution

## Post-Cleave Treatment Anneal for elimination of SiOx interface layer

- High-T anneal after surface treatment in inert or reducing atmosphere (ex. Argon, Hydrogen )
- Allows Oxygen to diffuse and escape from surface
- Requires clean surface & free from getter sites
- Single-crystal silicon grows by solid-phase epitaxy to close the interface as the oxygen and other interfacial elements are diffused out

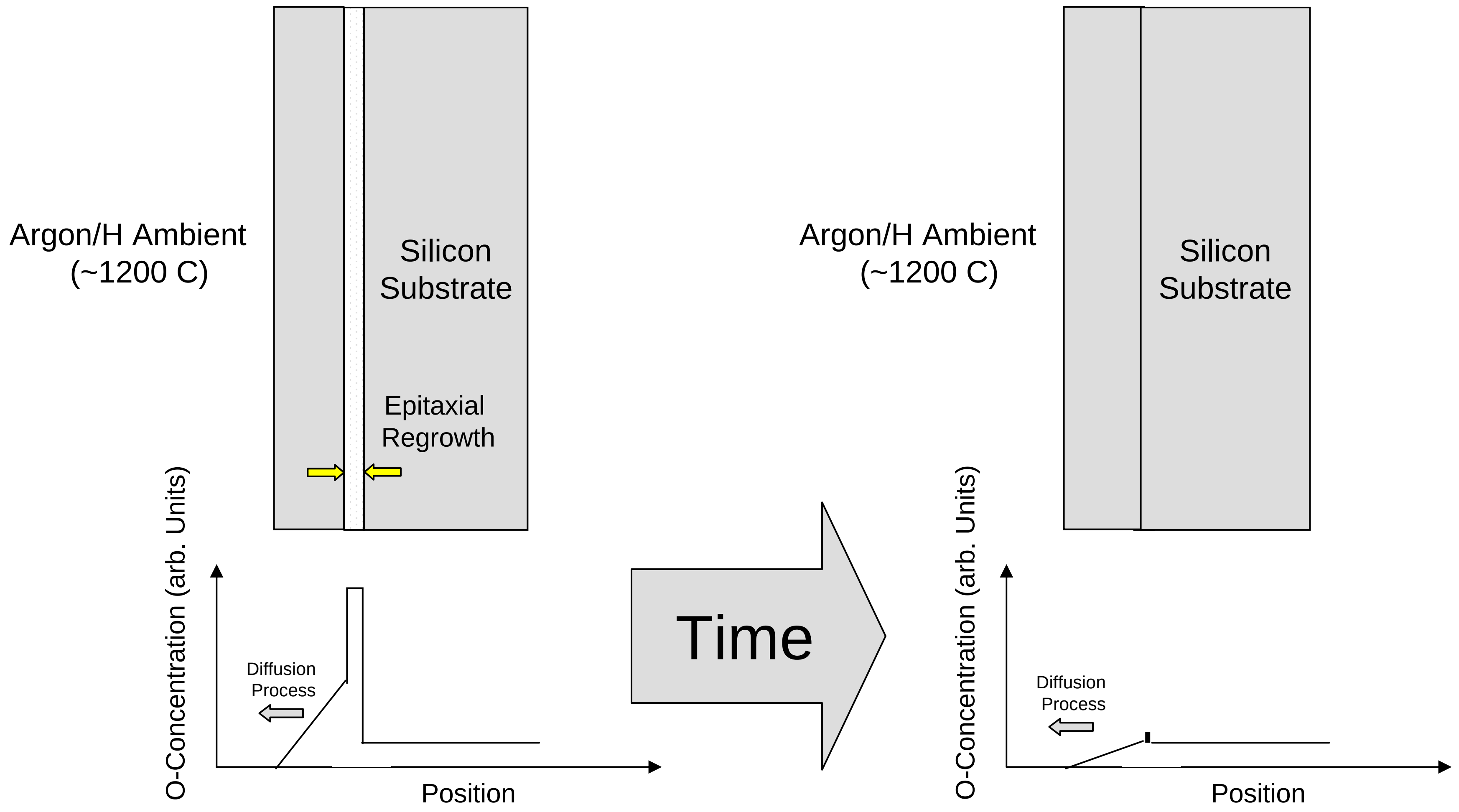


Argon/H Ambient
(~1200 C)



Argon/H Ambient
(~1200 C)

# Bond Interface Oxygen Dissolution



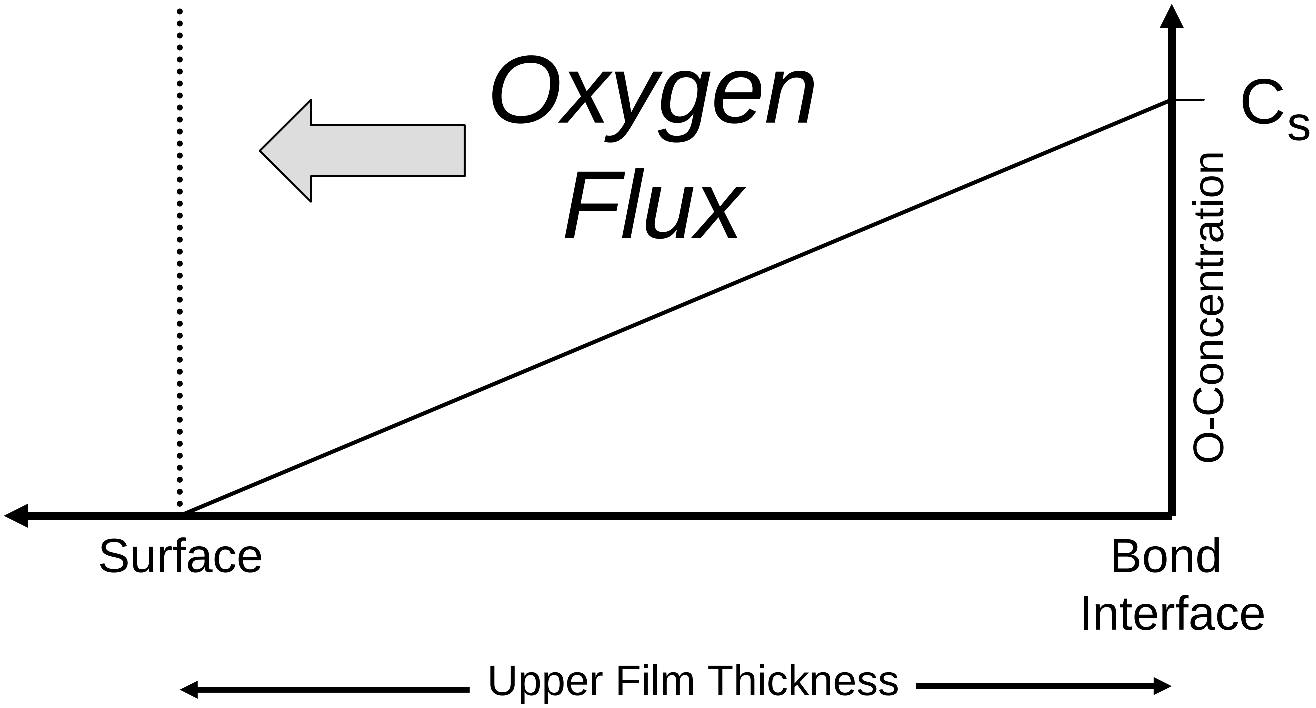
# Theoretical Model

$$Flux = -D(dC/dx) \approx \frac{D(Cs-0)}{t(film)}$$

Fick's Law

$$D = 0.14\exp(-2.53eV/kT)\frac{cm^2}{\sec^2}$$

$$Cs = 9.1E22\exp(-1.57eV/kT)cm^{-3}$$



# Diffusion Calculation (Example)

- Parameters
  - Silicon Layer thickness ($t_{Si}$): 200 nm
  - Argon Ambient, 1200 °C treatment
  - 50 Å interface layer, $SiO_{0.5}$ stochiometry

- Diffusion Law (oxygen in silicon)

$$\text{Flux (atoms/cm}^2 - \text{sec)} = D_o(T) * [ (C_S(T) - 0)/ t_{Si}]$$

- At 1200 C, $C_S(T) \sim 4.6\ E{+}17\ cm^{-3}$, $D_o(T) \sim 3.15\ E{-}10\ cm^2/sec$
  - Flux = 7.24 E+12 O-atoms/$cm^2$-sec

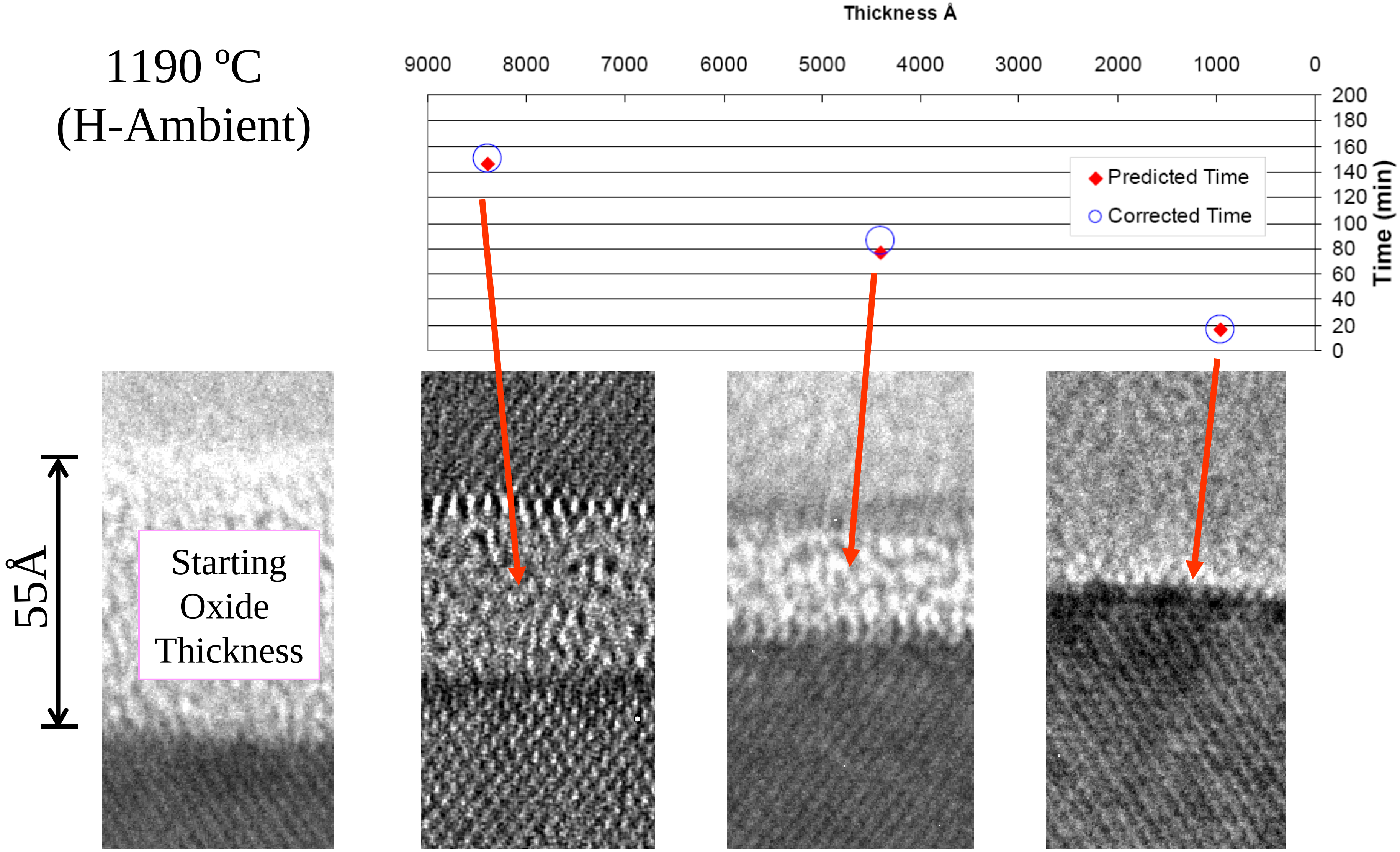
- Total O-Dose = [4.4 E+22 $cm^{-3}$ /4] * 5nm = 5.5 E+15 atoms/$cm^2$

Time = Total O-dose/Flux = 5.5 E+15 atoms/$cm^2$ / 7.24 E+12 O-atoms/$cm^2$-sec

**Time to dissolution = 760 seconds**

# Oxide Dissolution Kinetics – Experimental Verification

1190 ºC
(H-Ambient)



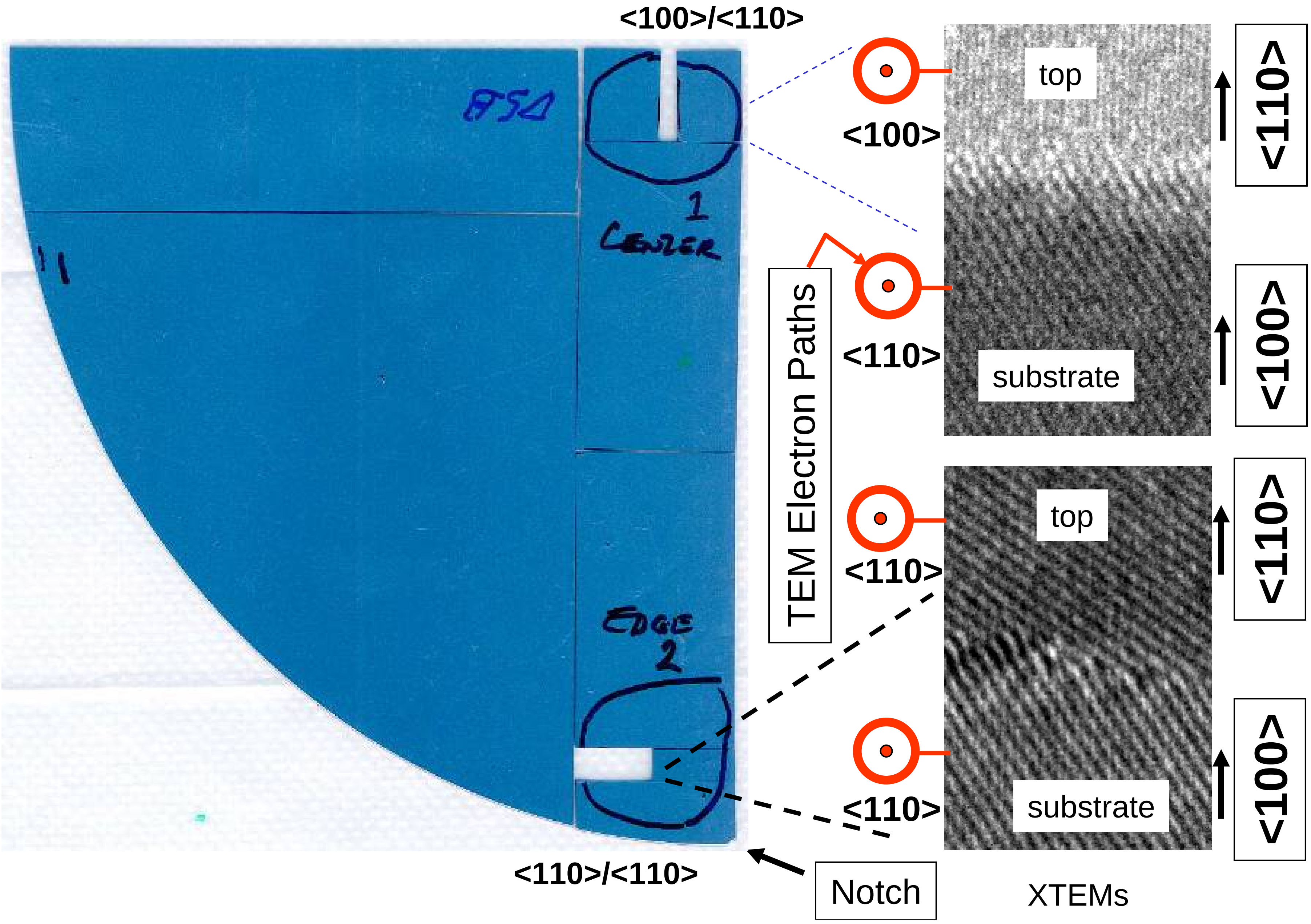
0% dissolved

40% dissolved

70% dissolved

100% dissolved

# (110) Silicon DSB on (100) Silicon Test Sample



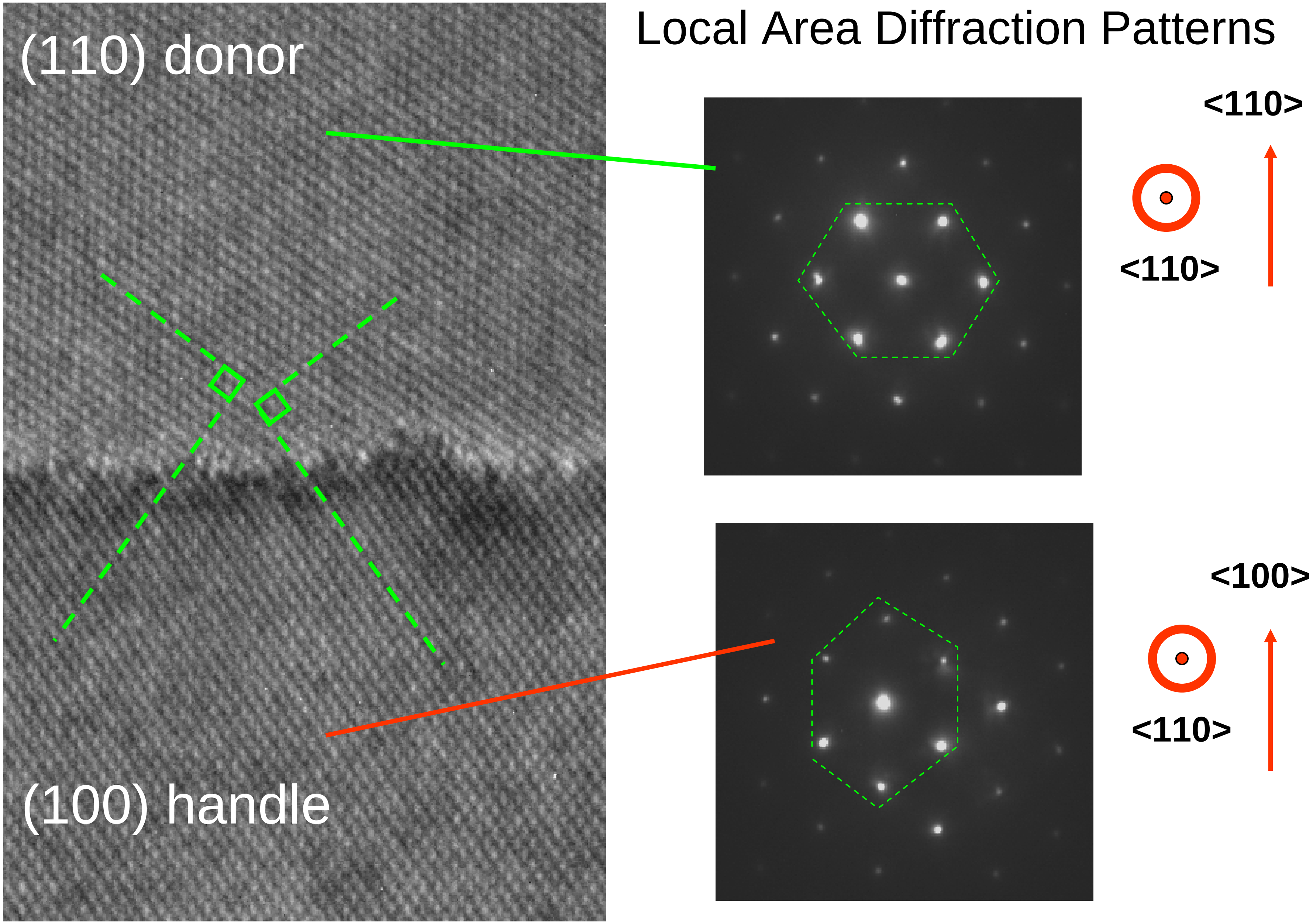
TEM Electron Paths

Notch

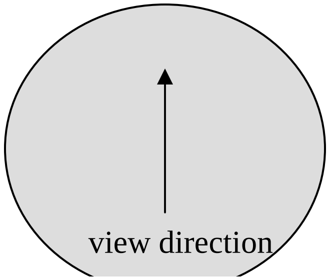
XTEMs

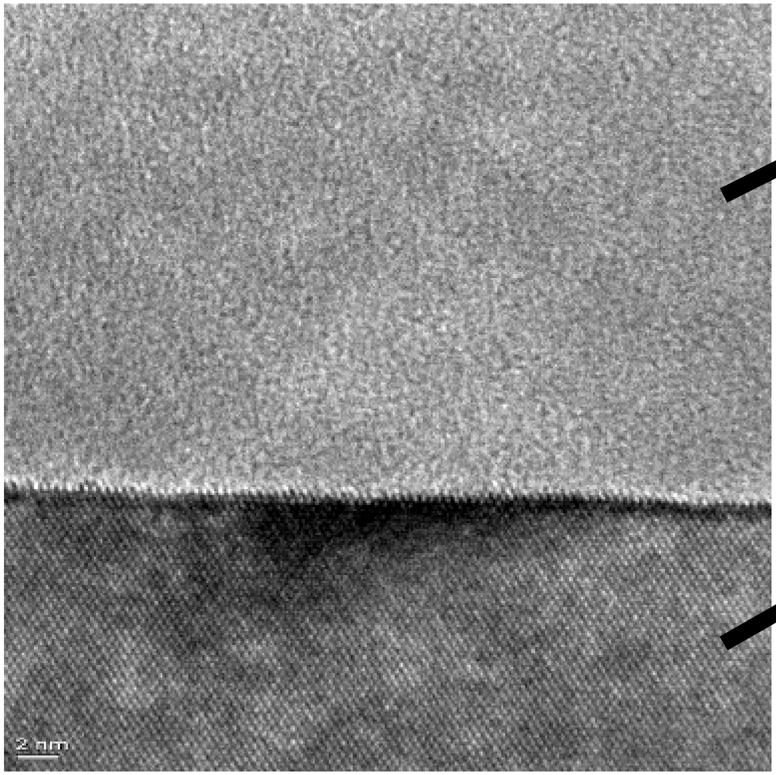
# Edge Top and Bottom Diffraction

Local Area Diffraction Patterns

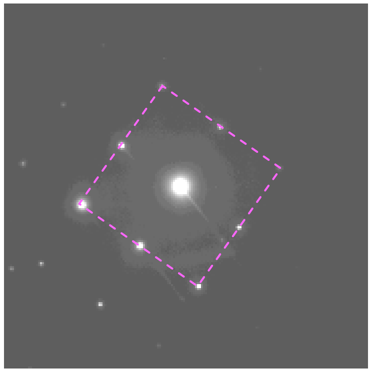


# TEM: Pre/Post H-Anneal Tests

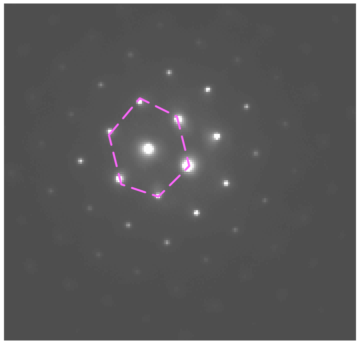




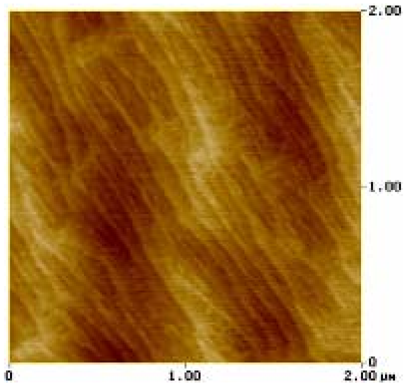
<110> direction (across and along view)



<100> Reciprocal



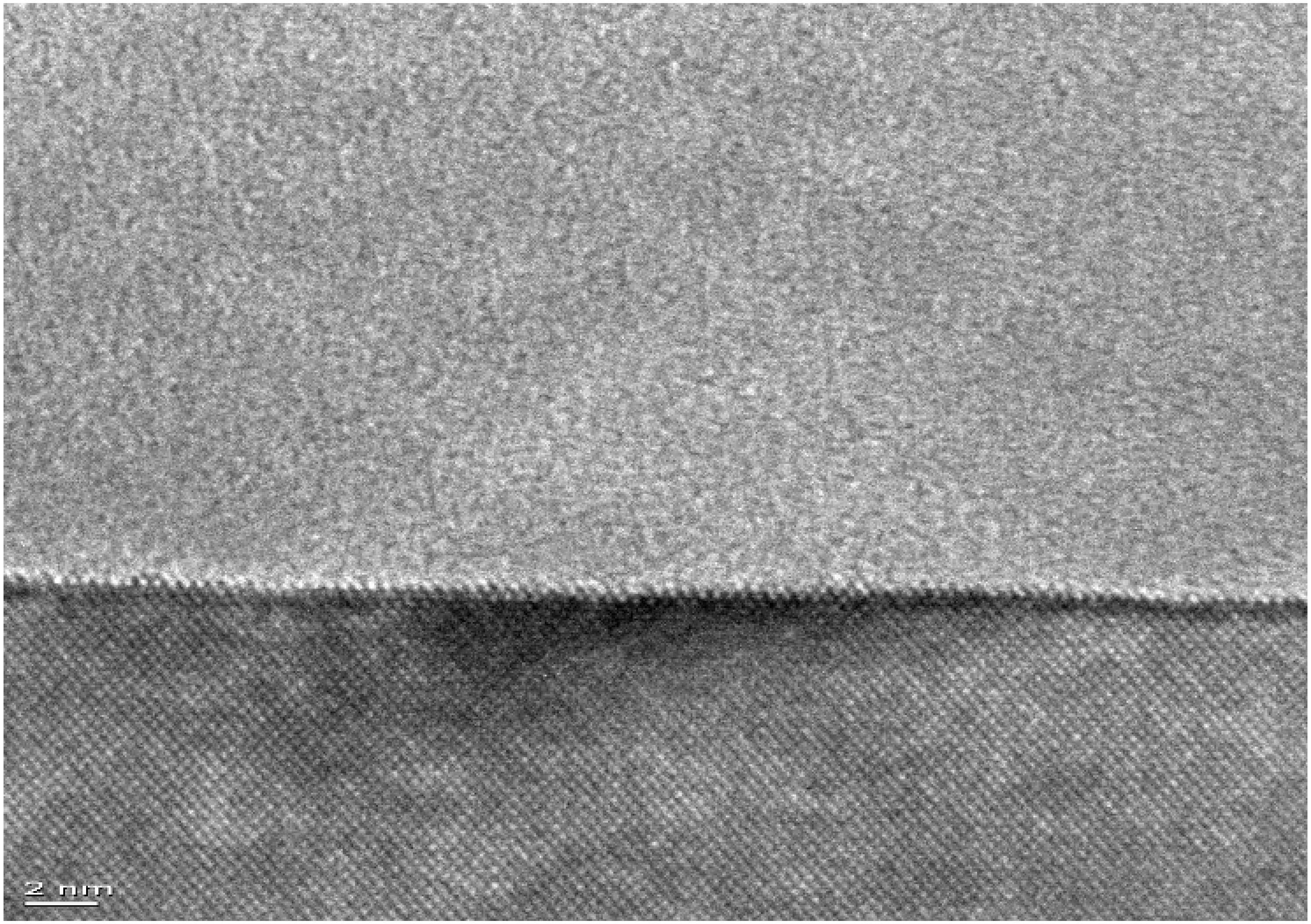
<110> Reciprocal



Surface AFM (2um x 2um)
1.43 Å RMS, 9 Å Range

***Interfacial Layer Reduced to 1-2 monolayers***

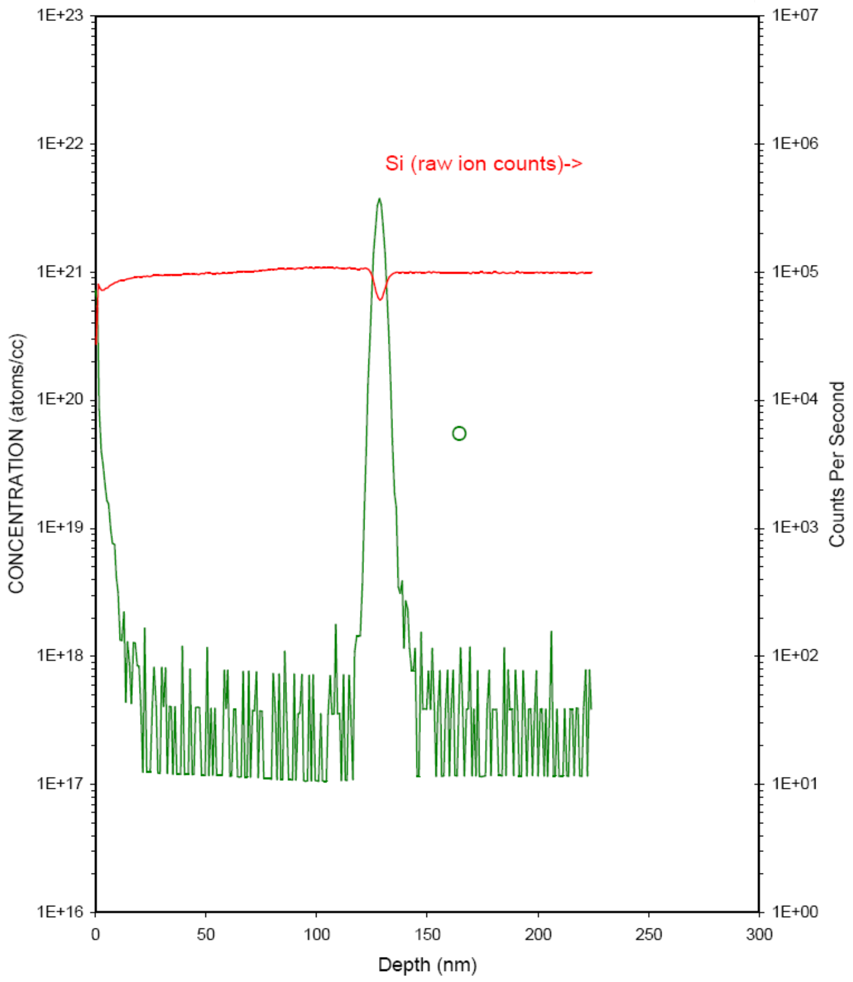
# Oxide free hybrid interface



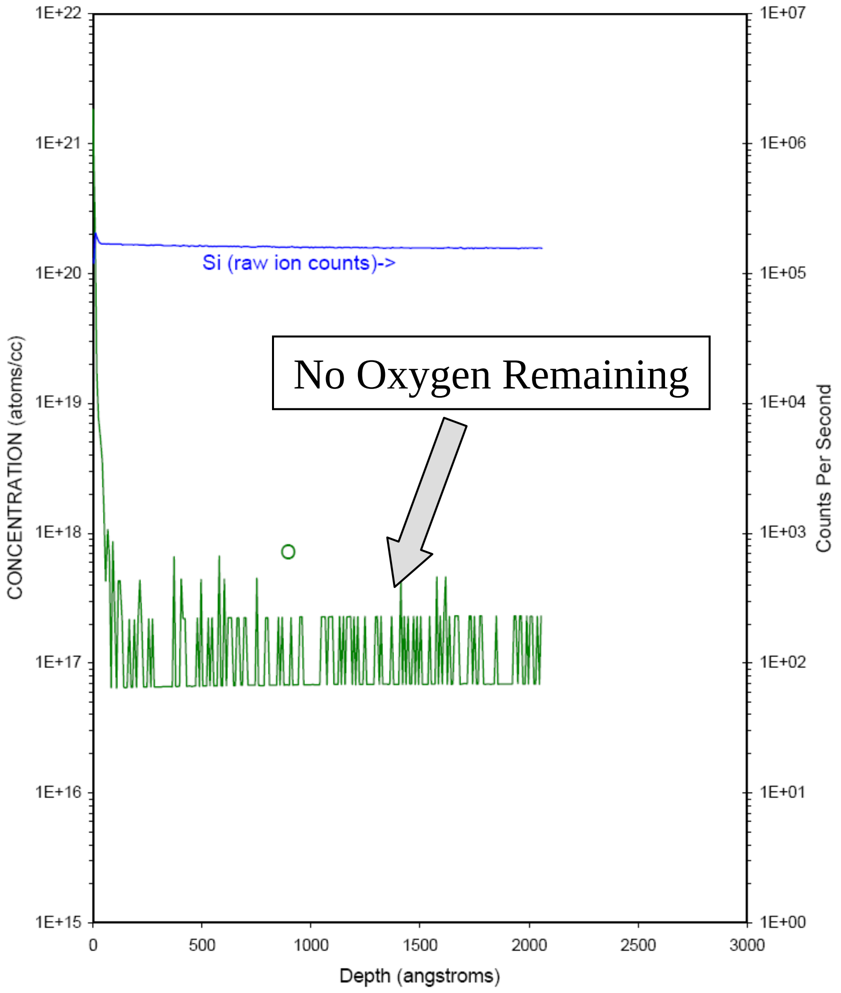
<110>

<100>

# SIMS – SiOx Layer Dissolution Confirmed



As-Cleaved

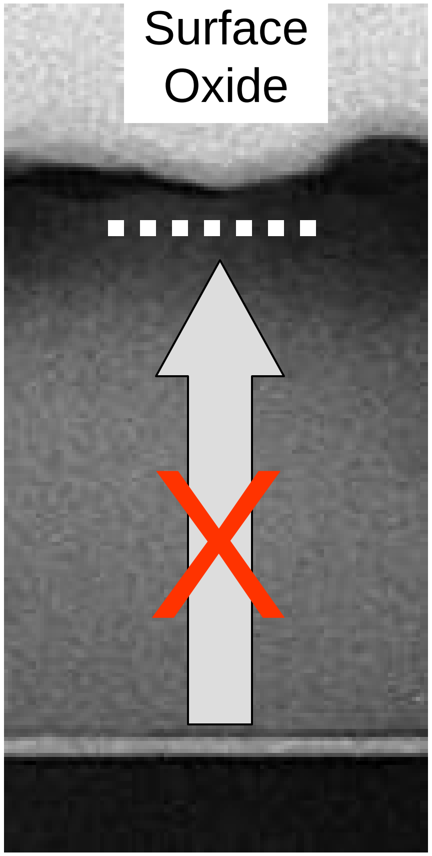


No Oxygen Remaining

Post Anneal

# Special Process Considerations

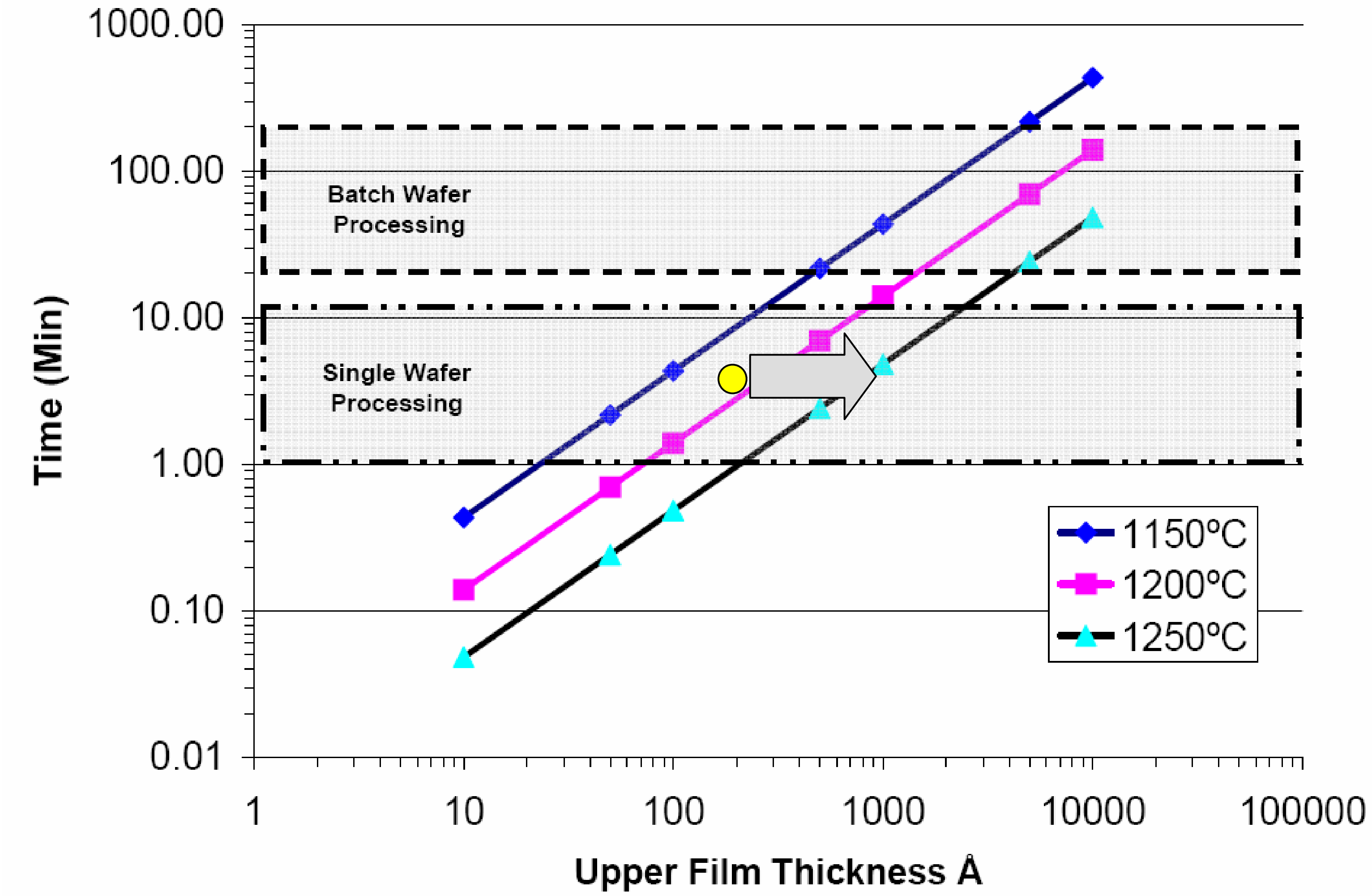
- Solid phase epitaxial re-growth of crystalline silicon during out-diffusion
- Avoidance of oxygen clustering (Ref # 6)
- Metrology of oxygen in SiOx
- Choice of Handle Material
  - Little difference between CZ & FZ
- Surface oxide and ambient
  - ➢ No Surface Oxides!



No Dissolution

Anneal ambient must be oxygen free
…..trace amounts will prevent oxygen out-diffusion

# Cost-Effective Commercialization



- ***High Throughput Options***
  - Select thinner upper silicon thickness speed out-diffusion
  - Re-grow silicon to desired thickness epitaxially

# Conclusions

- Plasma-activated bond and cleave effective at controlling defects and interfacial oxide for as-cleaved DSB materials
- Oxygen out-diffusion may be employed to reduce the interfacial oxide to zero or desired target levels

DSB can be commercialized cost-effectively using a SOI layer-transfer process variant for next-generation CMOS process nodes