CHARACTERIZATION OF THE OXIDE-SEMICONDUCTOR INTERFACE IN NO, P, AND N-PLASMA PASSIVATED *4H*-SiC/SiO_2 STRUCTURES USING TEM

Joshua Taillon,[1] Joon Hyuk Yang,[1†] Claude Ahyi,[2] John Rozen,[3‡] John Williams,[2] Sarit Dhar,[2] Leonard Feldman,[4] Tsvetanka Zheleva,[5] Aivars Lelis,[5] and **Lourdes Salamanca-Riba**[1]

55th Electronic Materials Conference
Wednesday, June 26, 2013 – 10:20AM D2

*Supported by ARL under contract no. W911NF-11-2-0044 and W911NF-07-2-0046.

[1] Materials Science and Engineering, University of Maryland College Park
[2] Physics, Auburn University
[3] Physics and Astronomy, Vanderbilt University
[4] Institute for Advanced Materials, Rutgers University
[5] U.S. Army Research Laboratory

Present addresses:
[†] LG Innotek, Korea
[‡] IBM T.J. Watson Research Center, NY

Motivation and background

- SiC: Very promising for high temperature, high power, and high radiation environments
  - MOSFET devices limited by poor channel carrier mobility and reliability
  - Best device μ_{FE}: SiC ~ 125 $\frac{\mathrm{cm}^2}{\mathrm{V{\cdot}s}}$ (a-face P passivation)[◊]; Si ~ 600 $\frac{\mathrm{cm}^2}{\mathrm{V{\cdot}s}}$ (uniaxial <100> strain)[ϕ]
  - Electrically active defects at the SiC/SiO_2 interface inhibit devices during channel inversion
- How to passivate these defects and improve mobility?
  - Incorporation of N at interface
    - NO anneal – improves μ, but can introduce additional defects[†]
    - N-plasma anneal – incorporates N without additional oxidation[⊖]
  - Incorporation of P at interface
    - Anneal in P_2O_5 – P dopants have lower activation energy than N[⊗]
  - N and P passivate dangling bonds/modify interface

[◊] G. Liu *et al.*, IEEE Electron. Dev. Lett. **34,** 181–183 (2013).
[ϕ] K. Uchida *et al.*, IEDM Tech. Dig. 229-232 (2004).
[†] J. Rozen, in *Physics and Technology of Silicon Carbide Devices* (InTech, 2012), pp. 251–278.
[⊖] X. Zhu *et al.*, Solid-State Electron. **57,** 76–79 (2011).
[⊗] Y. Sharma *et al.*, Solid-State Electron. **68,** 103–107 (2012).

Central questions

How do the structure and chemistry of the 4H-SiC/SiO_2 interface change under various processing conditions?

What do these changes tell us about the effect of these passivation processes?

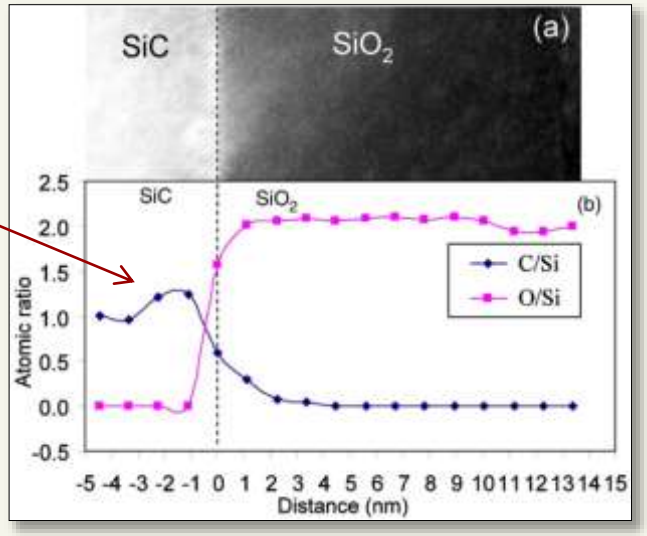
Outline

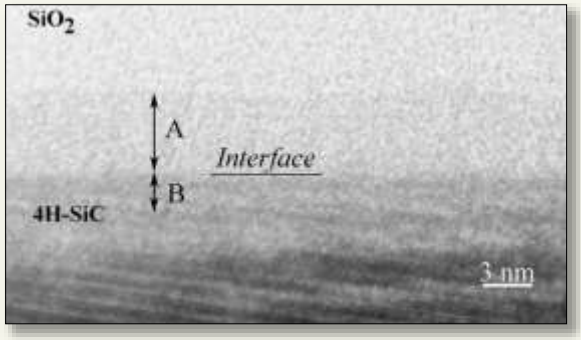
- Characterization of transition layer in NO-annealed *4H*-SiC MOSFETs
  - J. Taillon *et al.*, *J. Appl. Phys.* 113, 044517 (2013).
  - Experimental Methods
    - TEM with HAADF-STEM and EELS Spectrum Imaging
  - Transition layer width results
    - Traditional measurements
    - Chemical shift measurement
  - Correlation with electronic properties

- Comparison with P and N-plasma passivated *4H*-SiC devices
  - Preliminary results from *a*-face and Si/C-face devices

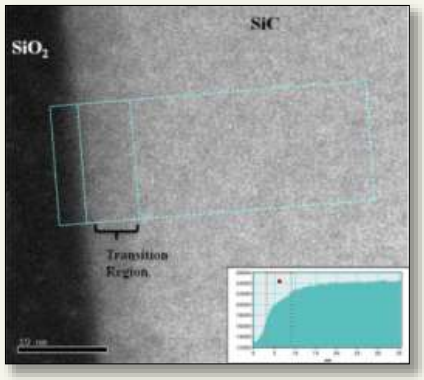
Previous work

- Transition layer at SiC/SiO_2 interface
  - EELS evidence of enhanced C concentration in SiC at interface
    - T. Zheleva, *et al*. Appl. Phys. Lett. **93,** 022108 (2008).





  - Transition layer width (w_{TL}) lowered by NO post-anneal
    - Measured with HAADF-STEM intensity profiles
    - Inverse linear correlation between w_{TL} and mobility
    - T. Biggerstaff, *et al*. Appl. Phys. Lett. **95,** 032108 (2009).

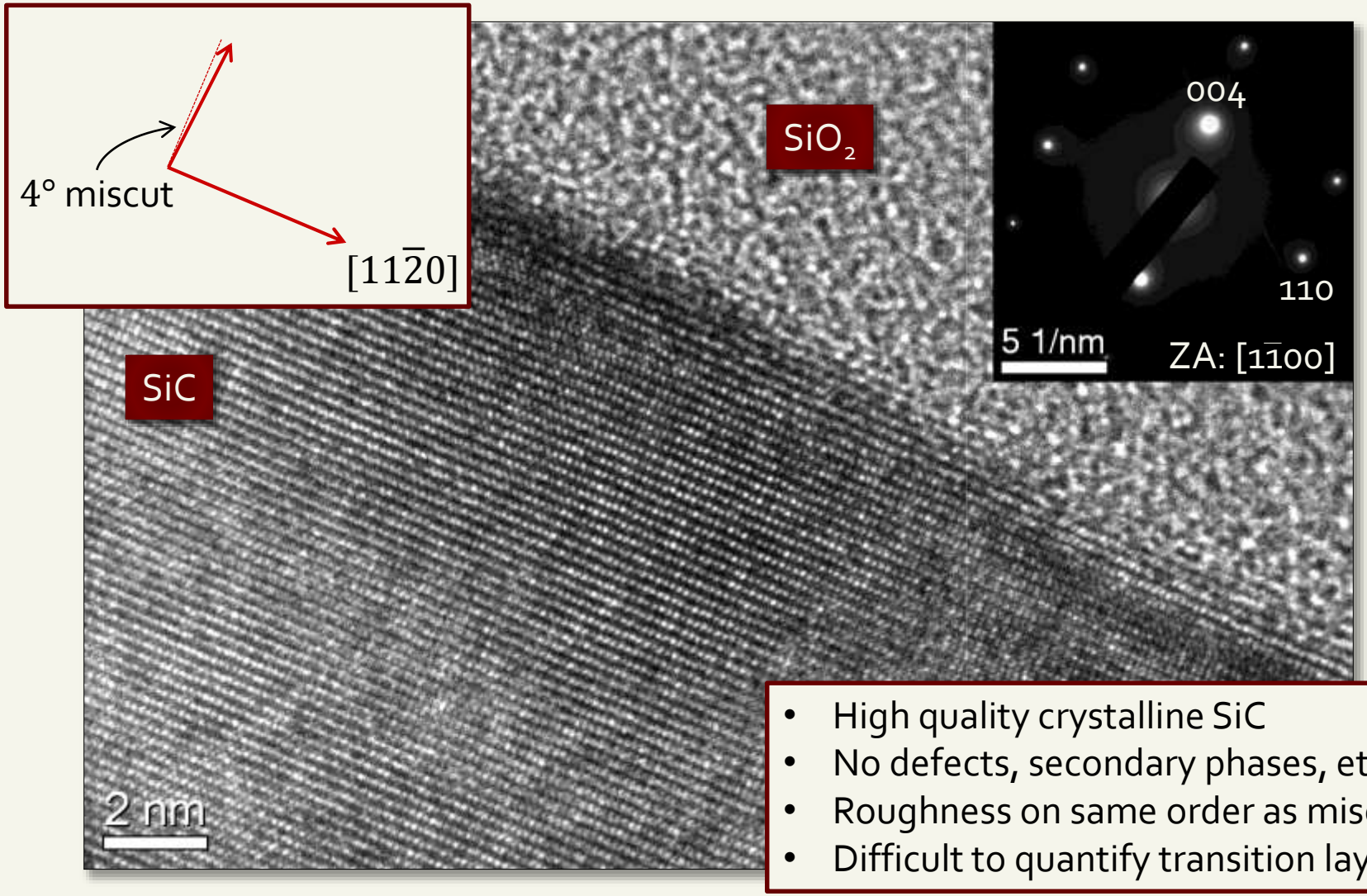


NO-anneal samples

- Six SiC/SiO_2 samples: 0-240 minutes of NO-anneal

  - 150 μm *n*-channel MOSFET devices
  - deposited epitaxial layer ($N \approx 5 \times 10^{15}\ cm^{-3}$)
  - (0001) 4° miscut wafers from Cree, Inc.
  - Cross-sections from gate region of devices

HRTEM of transition layer



- High quality crystalline SiC
- No defects, secondary phases, etc.
- Roughness on same order as miscut
- Difficult to quantify transition layer

Transition layer width measures

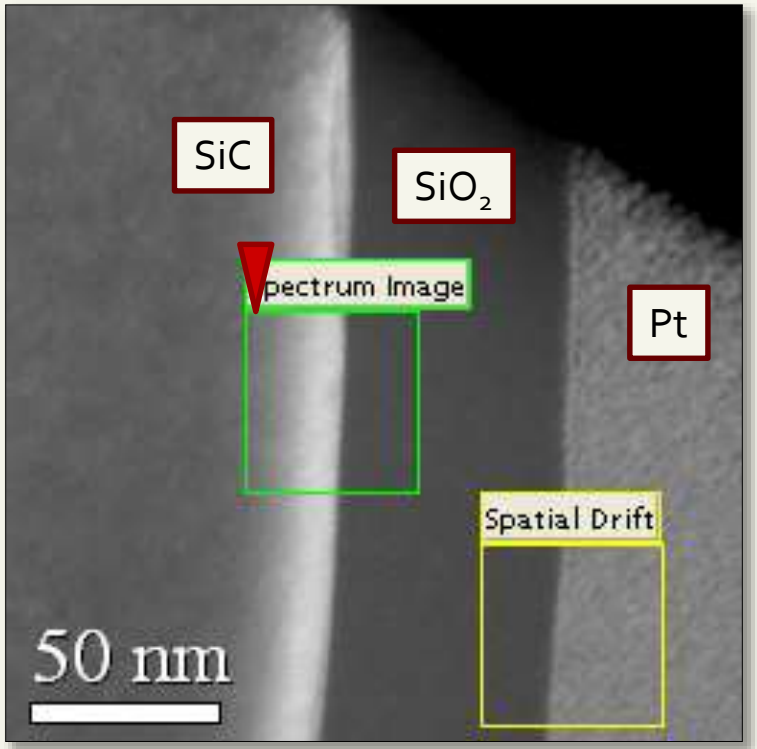
- Electron energy-loss spectroscopy (EELS)

- Chemical shift of Si-$L_{2,3}$ EELS edge
  - Well-documented shift in edge onset energy (SiC: 100 eV; SiO_2: 104 eV)
    - G. Auchterlonie, *et al.* Ultramicroscopy, **31**, 217 (1989).
  - Reveals information about local Si bonding, less sensitive to noise
  - Has not been used in this system previously

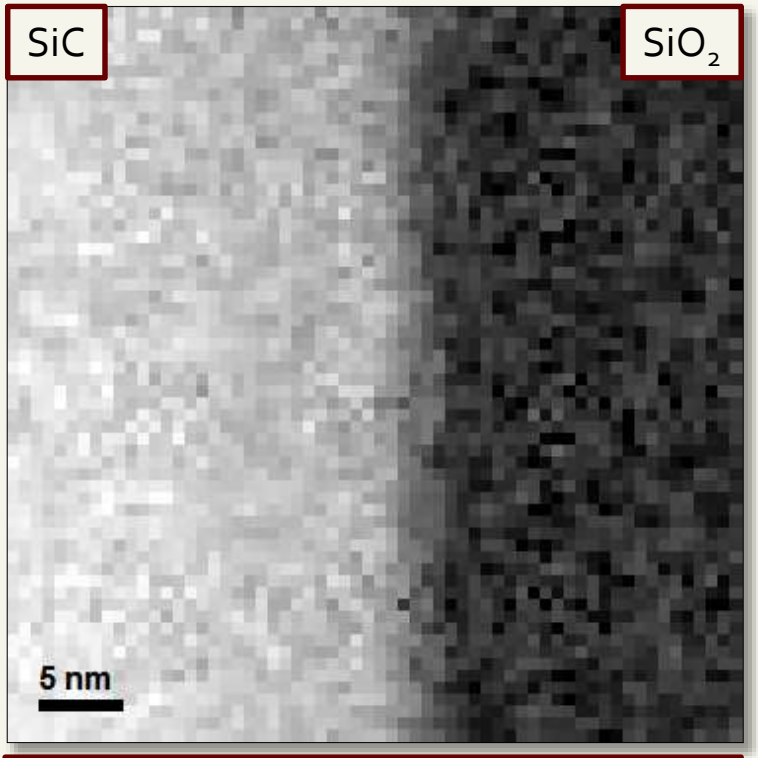
- Relative composition ratios from EELS ($^{C}/_{Si}$ and $^{O}/_{Si}$)
  - Eliminates many sources of systematic error[1]
  - Still sensitive to spectral noise and errors from calculated scattering cross-sections

[1] R. Brydson and R.M.S. (UK), *Electron Energy Loss Spectroscopy*, Microscopy Handbooks (Bios, 2001).

Spectrum Imaging

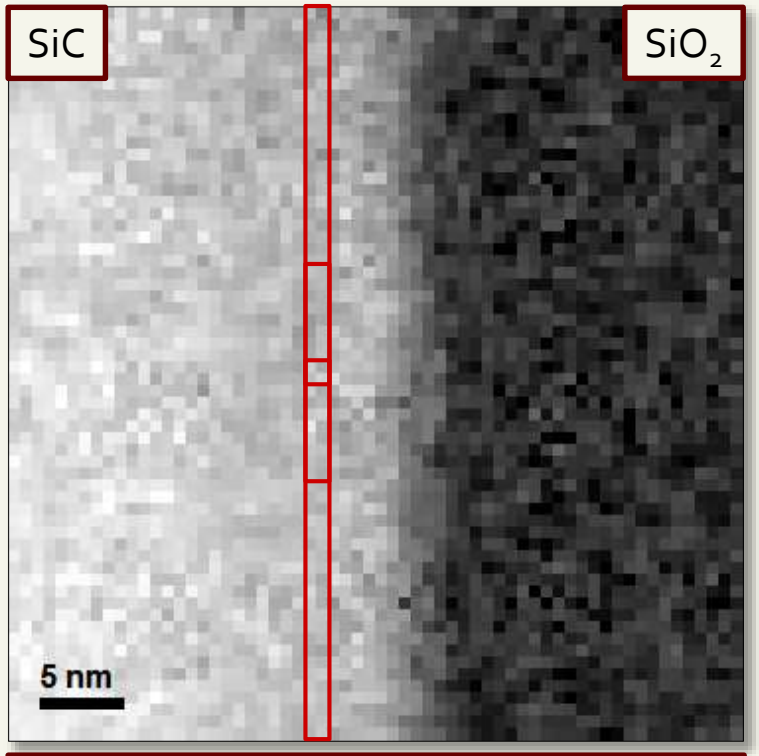


HAADF Image
(60 minute anneal)

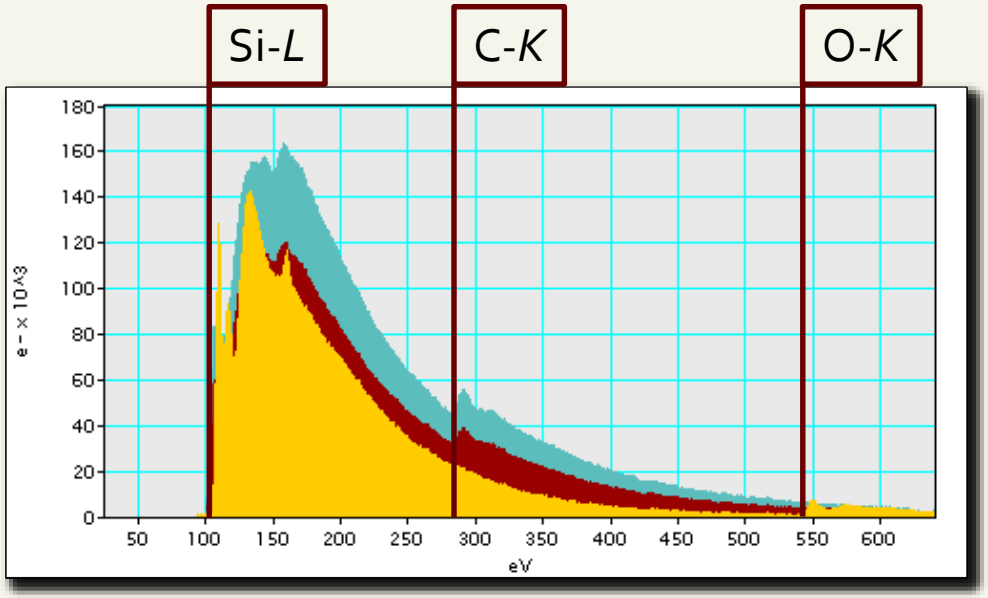


Spectrum Image
(60 minute anneal)

Spectrum imaging

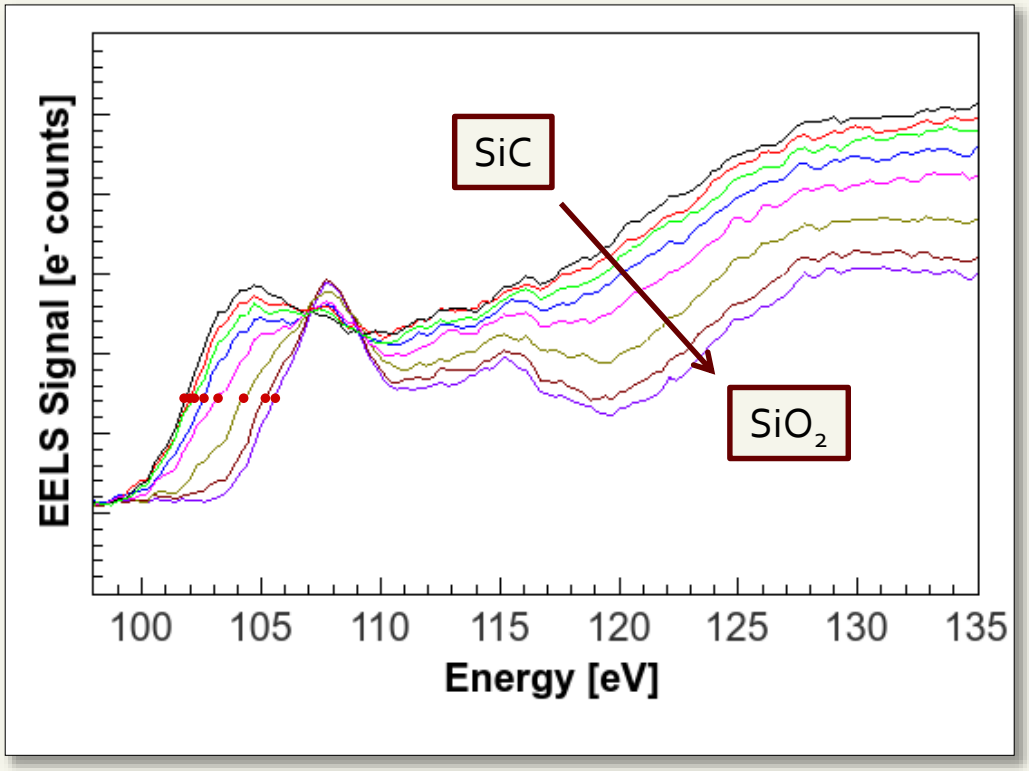


Spectrum Image
(60 minute anneal)



Background-subtracted spectrum
(60 minute anneal)

Si-$L_{2,3}$ chemical shift

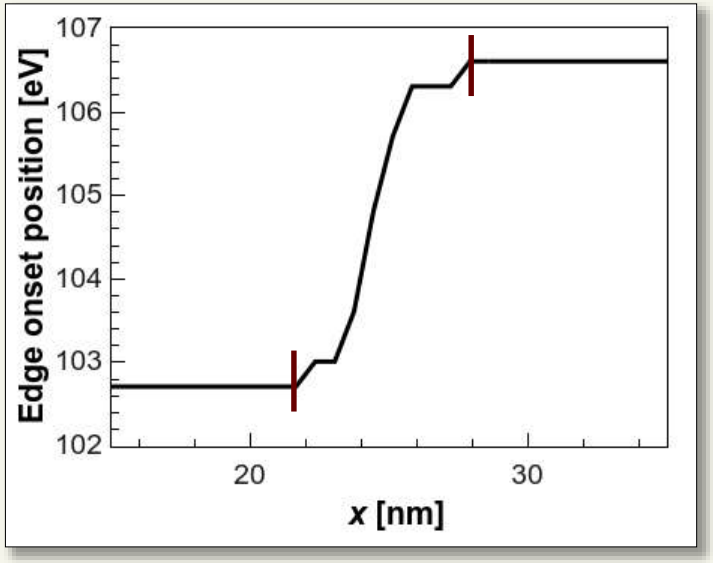


- EELS fine structure (ELNES) reflects local unoccupied density of states
  - Semiconductor → insulator
  - Edge onset → minimum energy needed to excite core shell e^-
  - Band gap widens, core levels depressed relative to E_F[1]
    - Charge transfer from Si → C/O
    - Onset shifts to higher energy

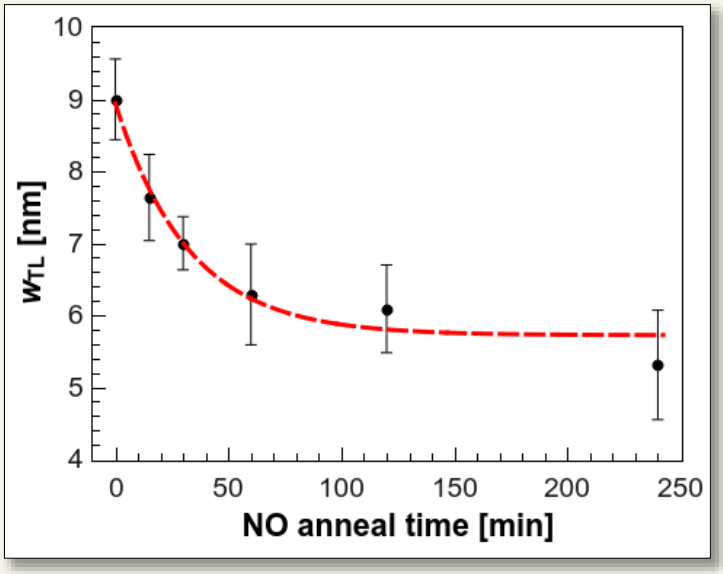
[1] D. Muller, Ultramicroscopy **78,** 163 (1999).

Si-$L_{2,3}$ chemical shift

- Track inflection point of edge onset across interface[1]
- Gradual and monotonic shift
  - Si bonding changes gradually and uniformly across the interface



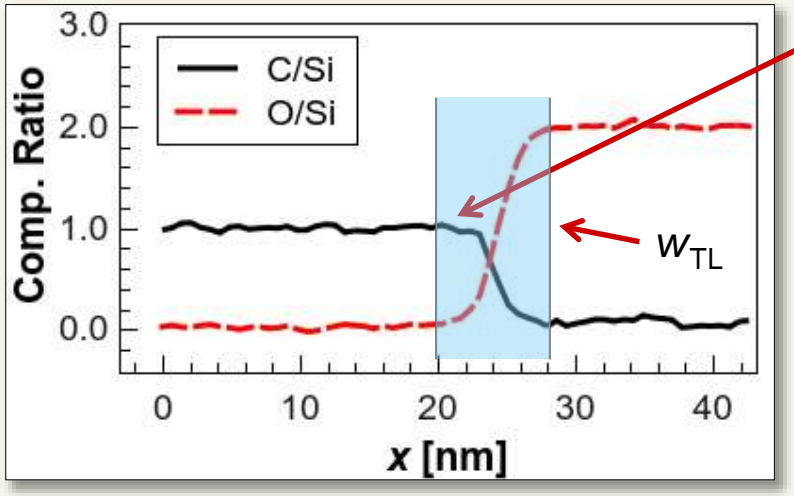
- Significant NO anneal improvement
  - Best method to track transition layer
  - (Relatively) insensitive to spectral noise
- Characterizes bonding instead of composition



[1] D. Muller, P. Batson, and J. Silcox, Physical Review B **58**, 11970 (1998).

w_{TL} from composition ratios

- Plot profiles of atomic ratio maps:



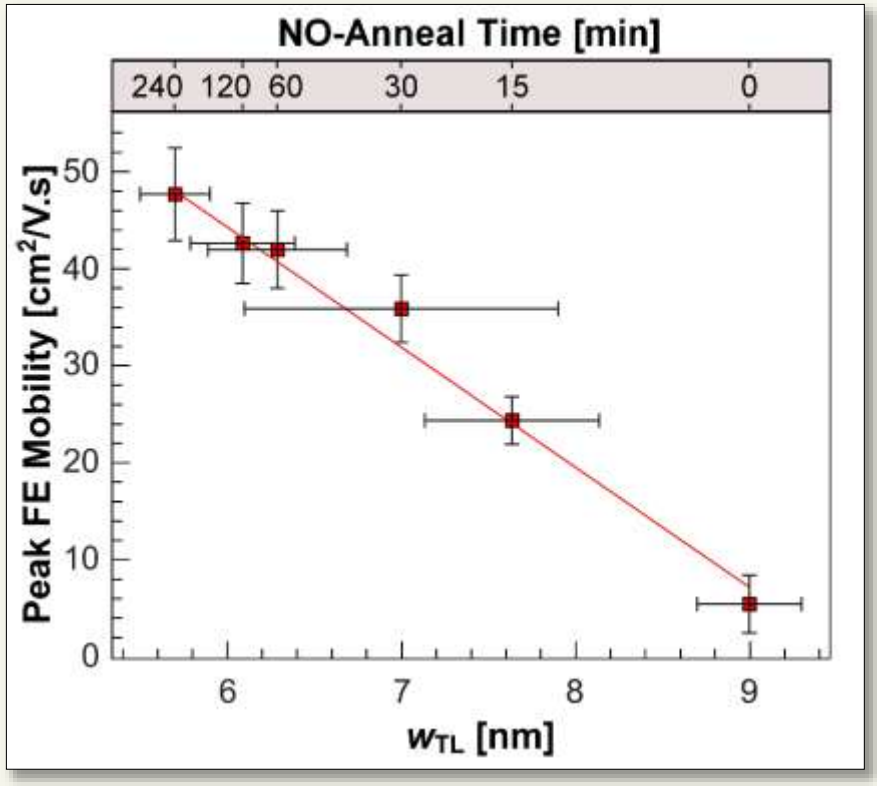
No excess C at interface

$\pm 2.5\%$

- Results:
  - Narrower w_{TL} as function of NO-anneal time
  - Trend agrees with chemical shift method
  - No excess carbon signal

NO-anneal results

- w_{TL} correlates inverse-linearly μ_{FE}
  - Confirming previous work results by Biggerstaff *et al.* with systematic samples
- NO-anneal removes/passivates mobility-limiting defects
  - Compositionally and electronically
- **Conclusions:**
  - w_{TL} decreases with increasing NO anneal time
    - New chemical shift of Si-$L_{2,3}$ edge onset was most reliable method
    - No excess C on either side of interface



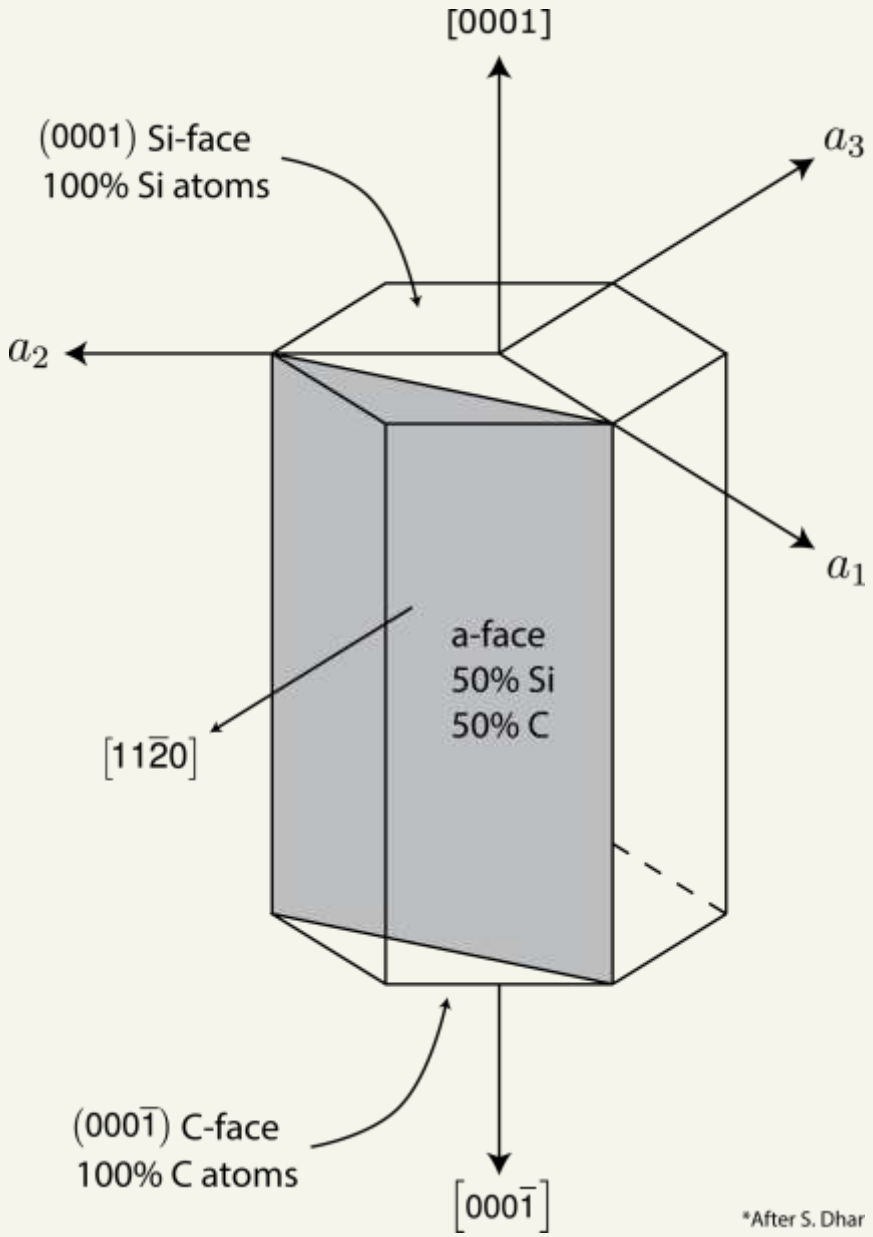
J. Taillon, L. Salamanca-Riba, *et al.*, *J. Appl. Phys.* 113, 044517 (2013).

Recent work

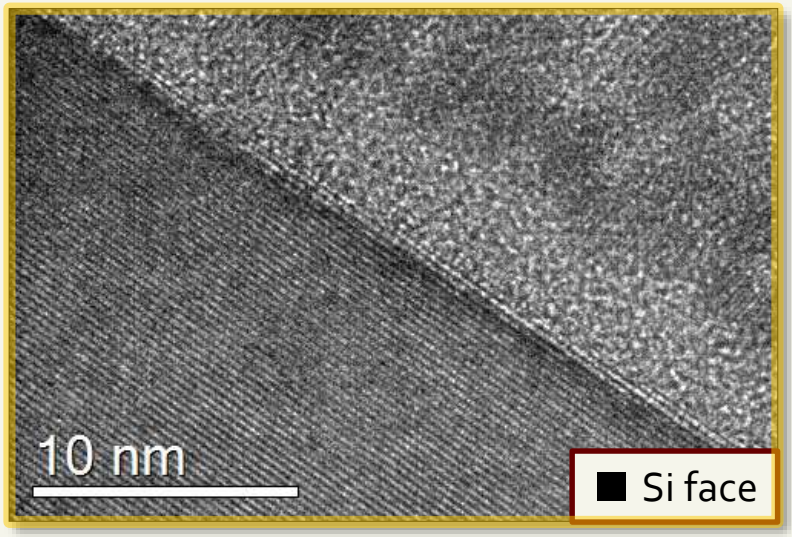
Device Process / Crystal face	NO	P	N2P
Si - (0001)	X	X	X
a - $(11\bar{2}0)$	X	X	
C - $(000\bar{1})$	X		

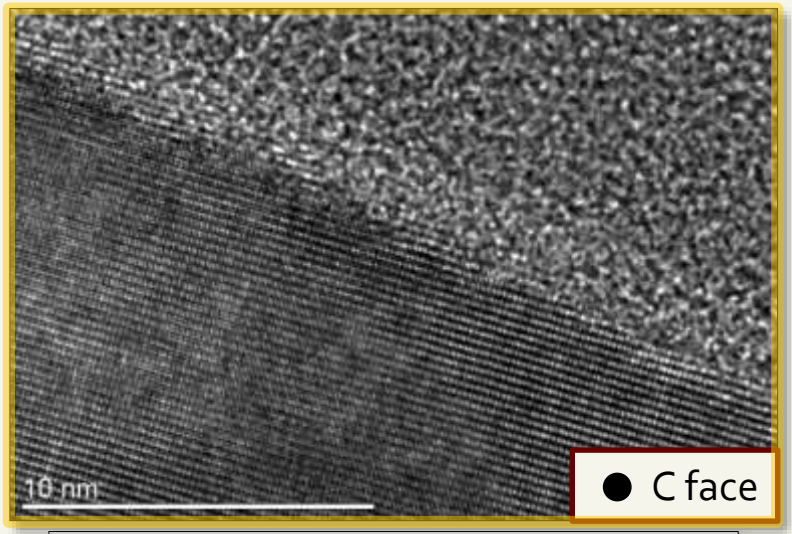
Crystal orientations

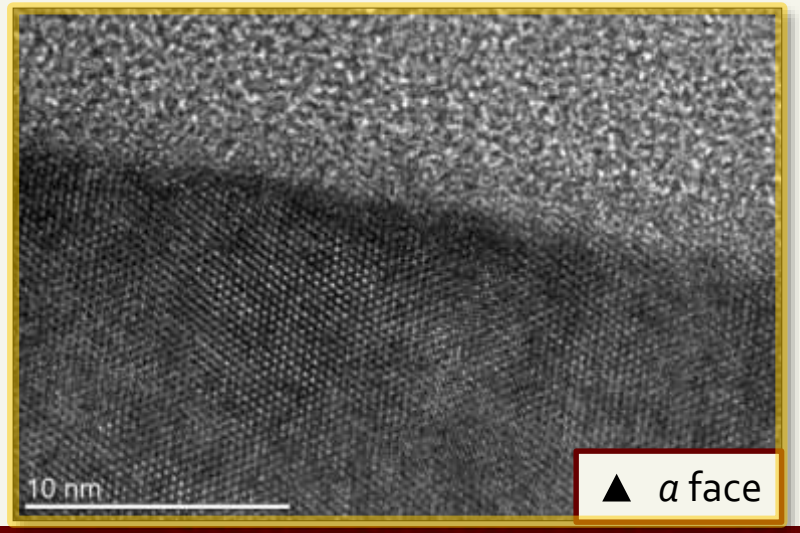
- Three faces investigated:
  - (0001) – Si face
  - $(000\bar{1})$ – C face
  - $(11\bar{2}0)$ – *a* face
- Miscut on Si and C faces
  - 4° or 8°
- No miscut on *a* face

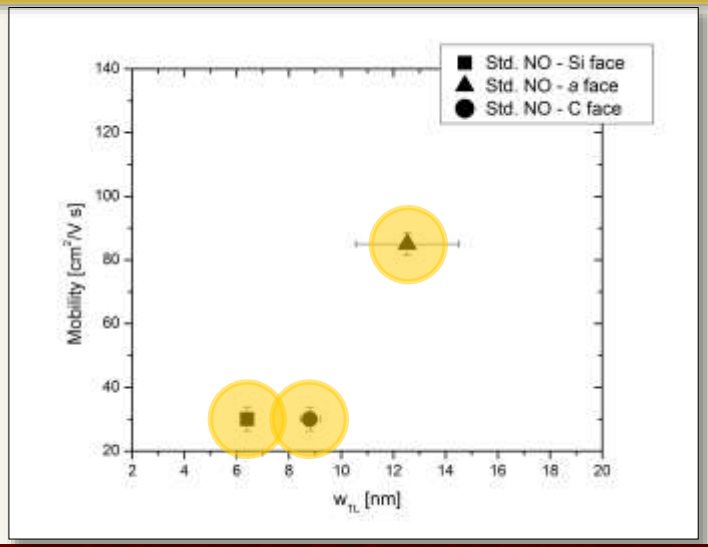


NO anneal


10 nm
■ Si face


10 nm
● C face

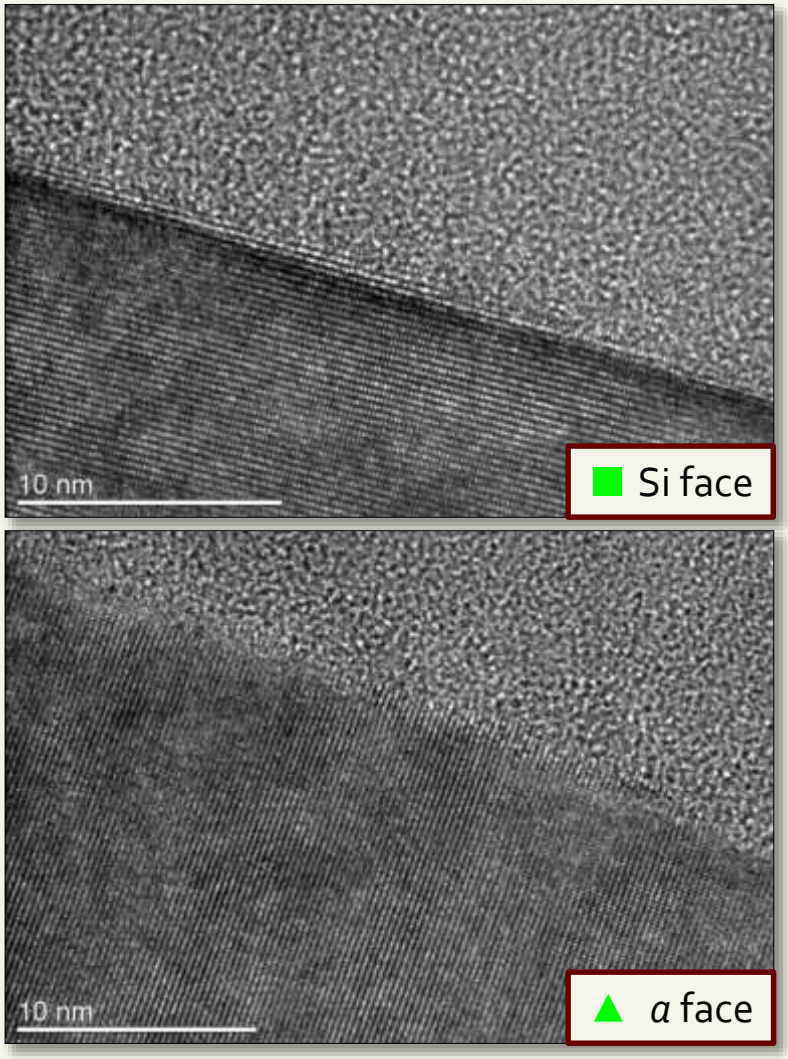

10 nm
▲ a face

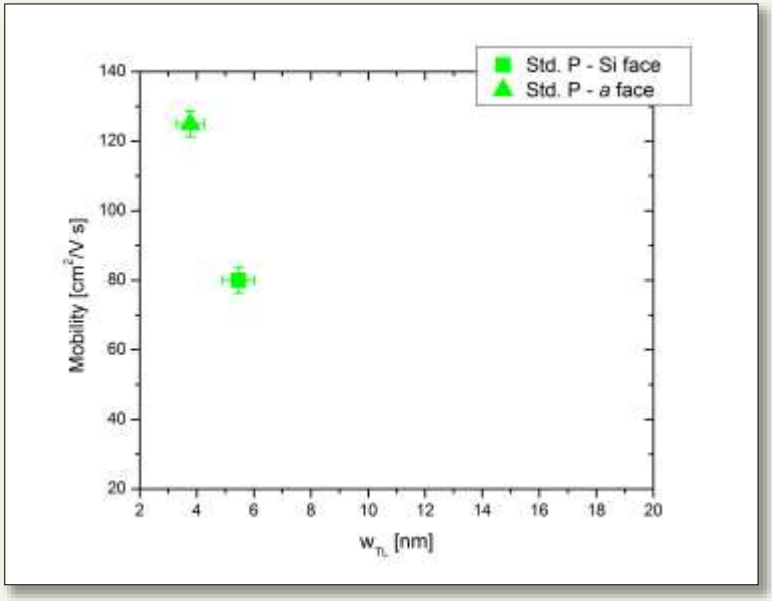

Std. NO - Si face
Std. NO - a face
Std. NO - C face
Mobility [cm²/V s]
w_TL [nm]
140
120
100
80
60
40
20
2
4
6
8
10
12
14
16
18
20

Recent work

Device / Process / Crystal face	NO	P	N2P
Si - (0001)	X	X	X
a - $(11\bar{2}0)$	X	X	
C - $(000\bar{1})$	X		

P anneal

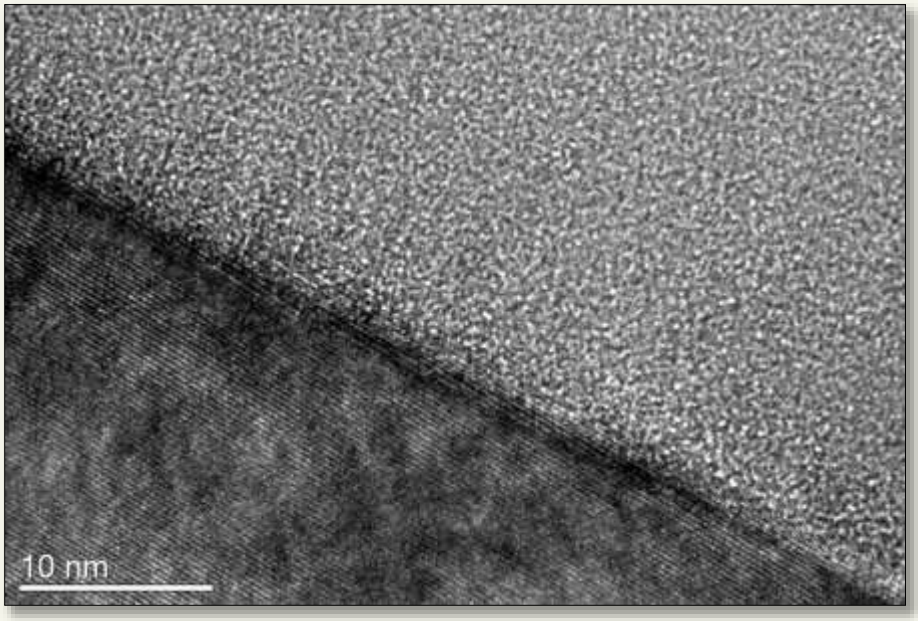

10 nm
Si face
10 nm
a face

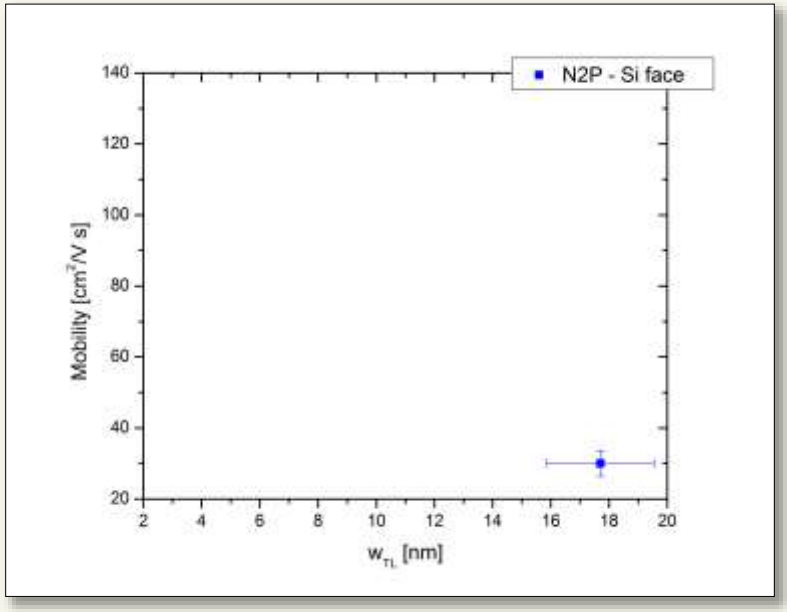

Std. P - Si face
Std. P - a face
Mobility [cm²/V s]
140
120
100
80
60
40
20
2
4
6
8
10
12
14
16
18
20
w_TL [nm]

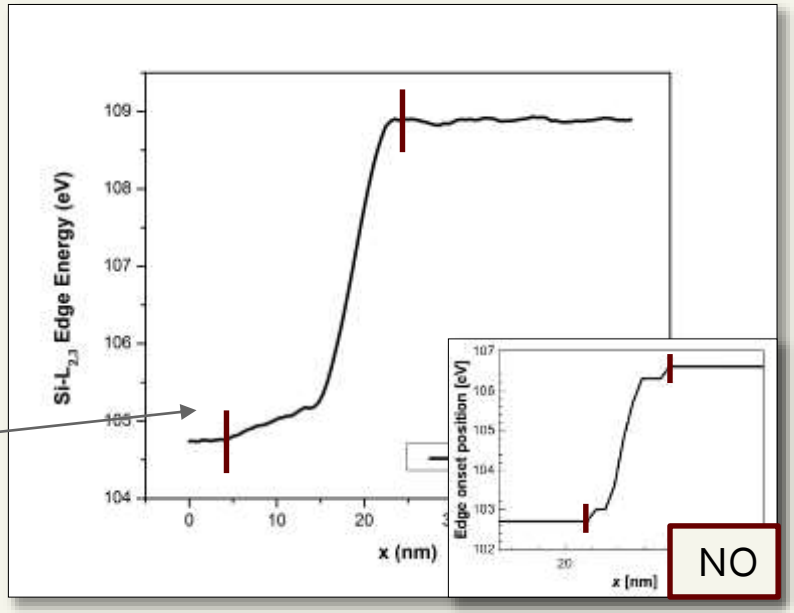
Recent work

Device Process / Crystal face	NO	P	N2P
Si - (0001)	X	X	X
a - $(11\bar{2}0)$	X	X	
C - $(000\bar{1})$	X		

N2P anneal



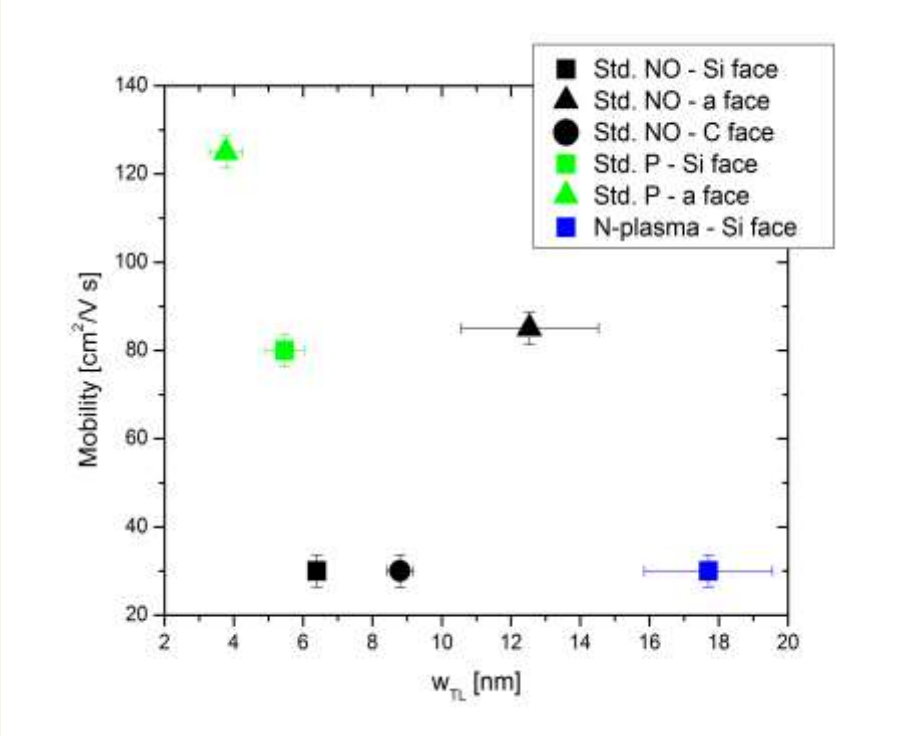




Asymmetric chemical shift not observed in any other samples

Preliminary conclusions

- NO, P, & N-plasma samples:
  - Large variation in μ and w_{TL}
  - Less obvious trend
    - Suggests different μ trend than NO samples alone
  - *a*-face and P-anneal samples have higher μ
  - N2P sample is anomalous
    - Additional roughness, and asymmetric chemical shift



Acknowledgements

- ARL Contracts W911NF-11-2-0044 and W911NF-07-2-0046.
- NSF Graduate Research Fellowship Grant DGE 1322106
- NISPLab at UMD – supported by NSF and MRSEC
- Dr. Joshua Schumacher at NIST

THANK YOU

Questions and comments?