# TEM CHARACTERIZATION OF THE TRANSITION LAYER IN NO, P, AND N-PLASMA PASSIVATED 4H-SIC/$SIO_2$ MOS DEVICES

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Monday, March 18, 2013

2013 March APS Meeting - A23.00002

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

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# Motivation and Background

- SiC: Very promising for high temperature, high power, and high radiation environments
  - 4H polytype (bulk): $\boldsymbol{E_g} = 3.23\ \mathrm{eV},\ \boldsymbol{\mu_e} \approx 850\ \frac{\mathrm{cm}^2}{\mathrm{V{\cdot}s}},\ \boldsymbol{\varepsilon} = 10,\ \boldsymbol{\kappa} = 3.7\ \frac{\mathrm{W}}{\mathrm{cm}\cdot{}^\circ\mathrm{C}}$
  - MOSFET devices limited by poor channel carrier mobility and reliability
  - Best $\boldsymbol{\mu_{FE}}$: 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)[⧫]
  - 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 $\mu$, 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

[◊] G. Liu *et al.*, IEEE Electron. Dev. Lett. **34**, 181–183 (2013).
[⧫] 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?

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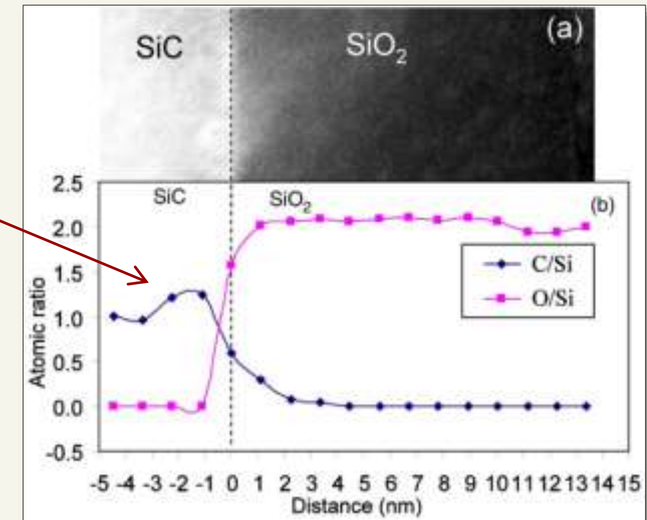
# Outline

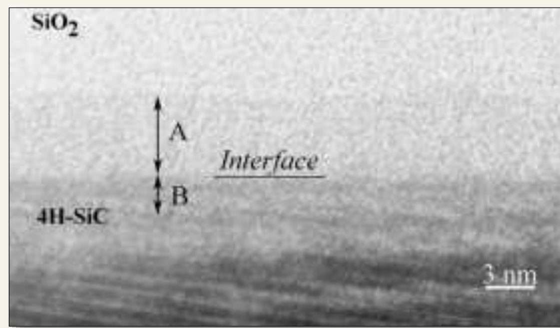
- Characterization of transition layer in NO-annealed 4*H*-SiC MOSFETs
  - J. Taillon *et al.*, *J. Appl. Phys.* 113, 044517 (2013).
  - Experimental Methods
    - TEM with HAADF-STEM and EELS Spectrum Imaging
  - Transition layer width results
    - Traditional measurements
    - Chemical shift measurement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

- Comparison with P and N-plasma passivated 4*H*-SiC devices
  - Preliminary results

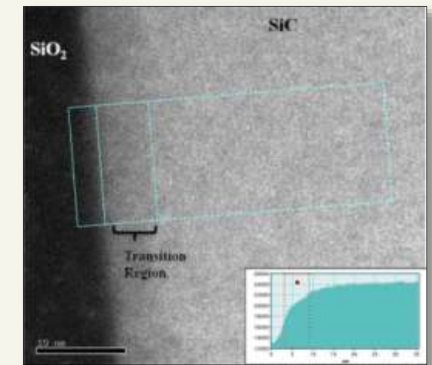
# Previous Work

- 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).

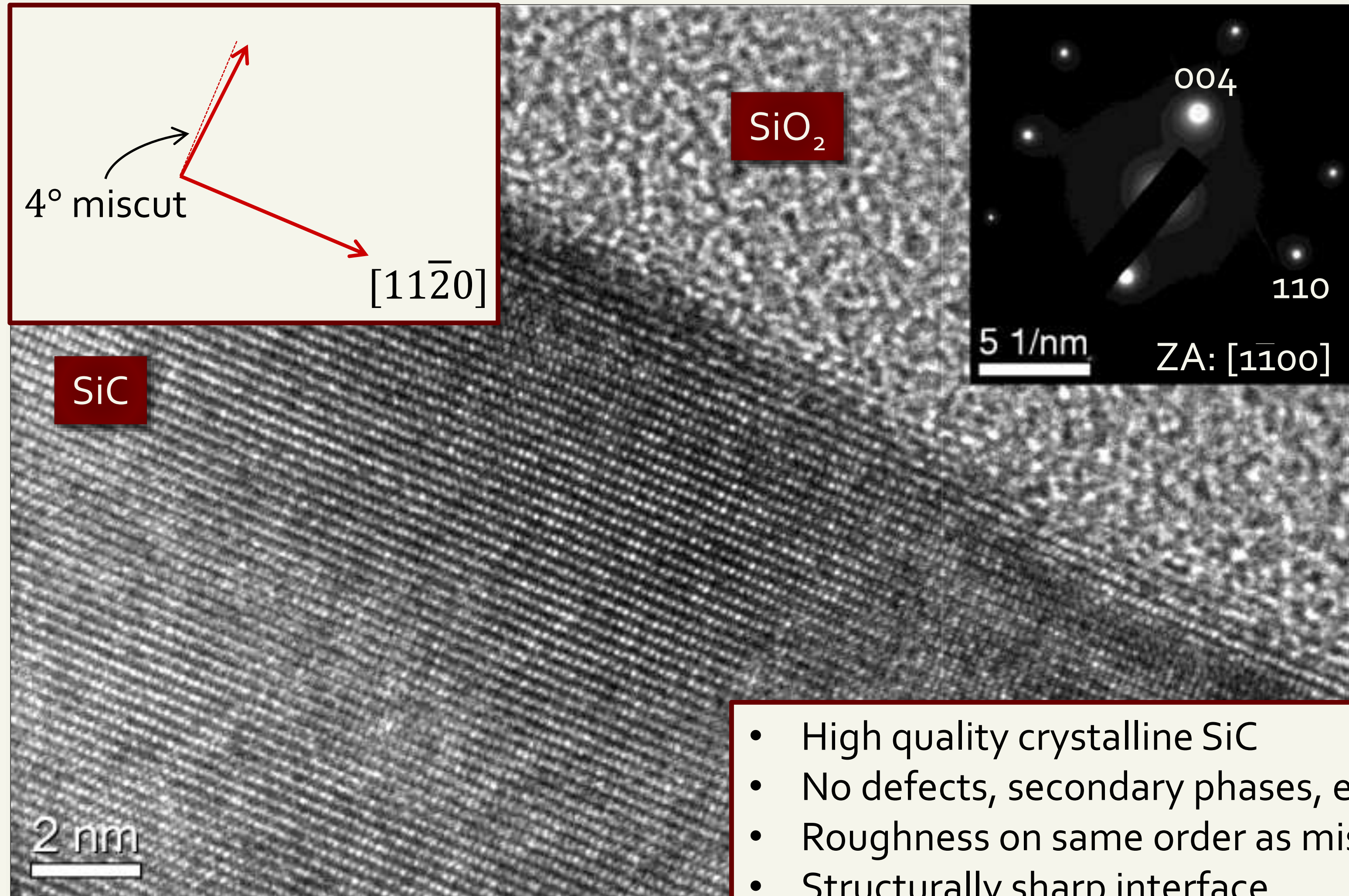



  - Transition layer width ($w_{TL}$) lowered by NO post-anneal
    - Measured with HAADF-STEM intensity profiles
    - Inverse linear correlation between $w_{TL}$ and mobility
    - T. Biggerstaff, *et al*. Appl. Phys. Lett. **95**, 032108 (2009).



# HRTEM of Transition Layer



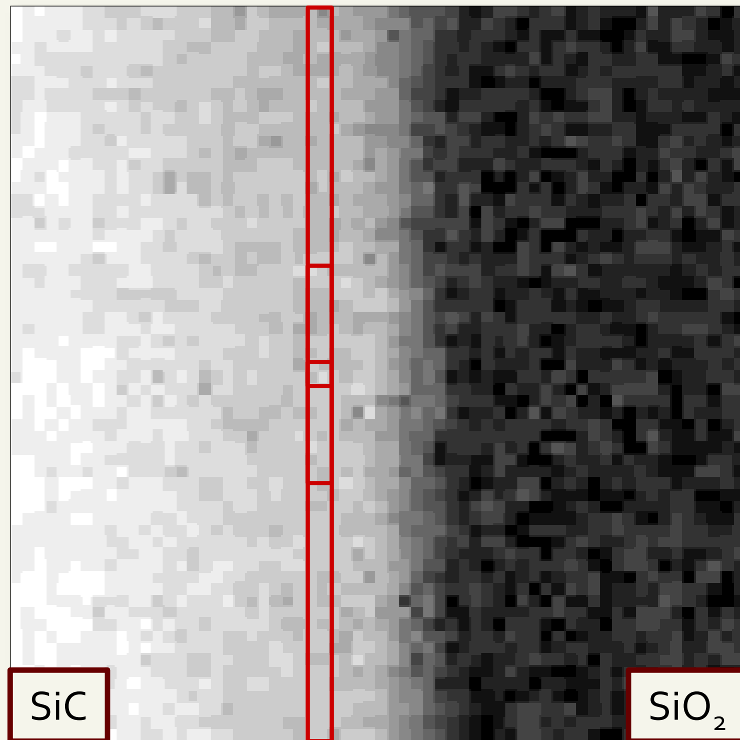

- High quality crystalline SiC
- No defects, secondary phases, etc.
- Roughness on same order as miscut
- Structurally sharp interface

# Transition Layer Width Measures

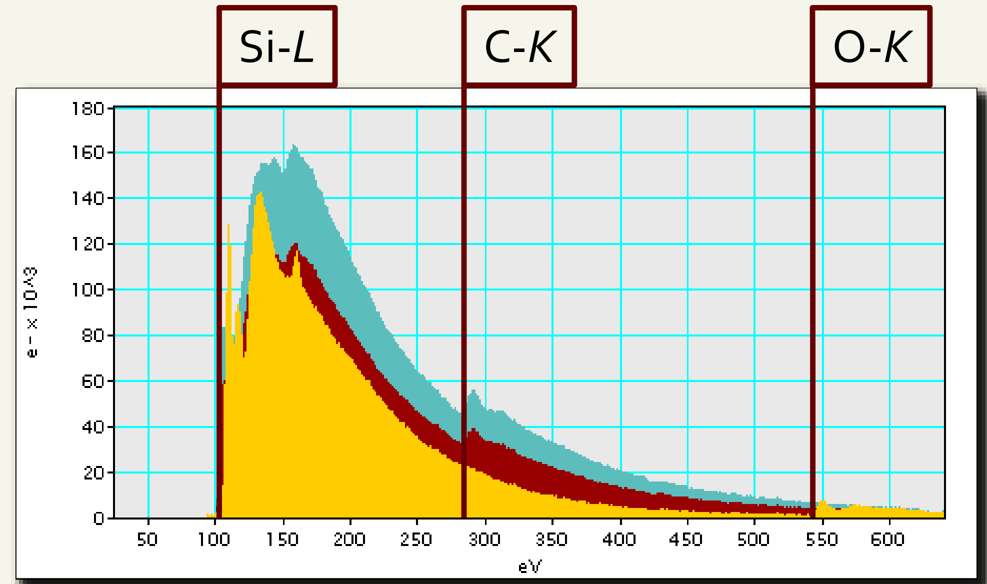
- Chemical shift of Si-$L_{2,3}$ EELS edge
  - Well-documented shift in edge onset energy (SiC: 100 eV; $SiO_2$: 104 eV)
    - G. Auchterlonie, *et al.* Ultramicroscopy, **31**, 217 (1989).
  - Reveals information about local Si bonding
- Relative composition ratios from EELS ($^{C}/_{Si}$ and $^{O}/_{Si}$)
  - Eliminates many sources of systematic error[1]
- HAADF-STEM image intensity profiles
  - HAADF reveals Z-contrast from variations in atomic composition

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

# Spectrum Imaging

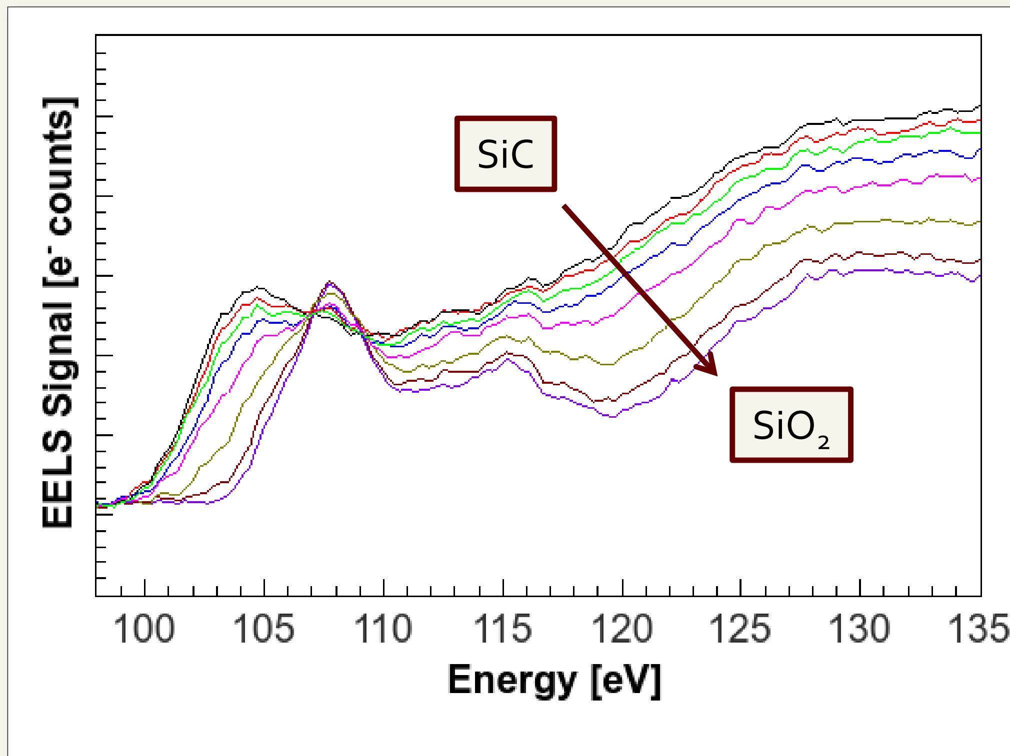



Spectrum Image
*(60 minute anneal)*




Background-subtracted spectrum
*(60 minute anneal)*

# Si-$L_{2,3}$ Chemical Shift

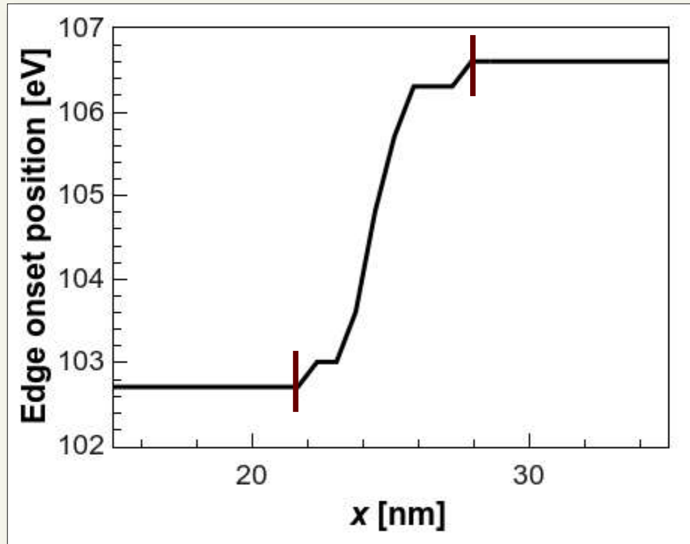



- EELS fine structure (ELNES) reflects local unoccupied density of states
  - Edge onset → minimum energy needed to excite core shell $e^-$
  - Semiconductor → insulator
  - Band gap widens, core levels depressed relative to $E_F$[1]
    - Charge transfer from Si → C/O
    - Onset shifts to higher energy

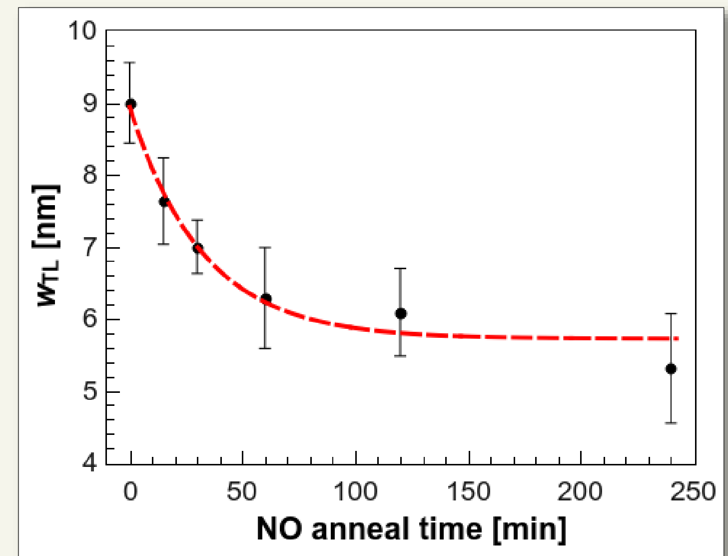
[1] D. Muller, Ultramicroscopy **78**, 163 (1999).

# Si-$L_{2,3}$ Chemical Shift

- Track inflection point of edge onset across interface[1]
- Gradual and monotonic shift
  - Bonding changes, possible strain
  - Implies a mix of Si-C and Si-O bonding



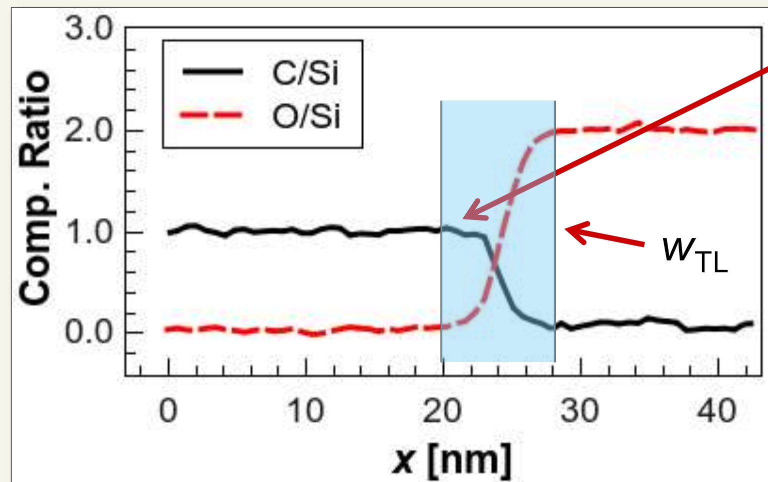

- Significant NO anneal improvement
  - Best method to track transition layer
  - (Relatively) insensitive to spectral noise
- Characterizes bonding instead of composition




[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:



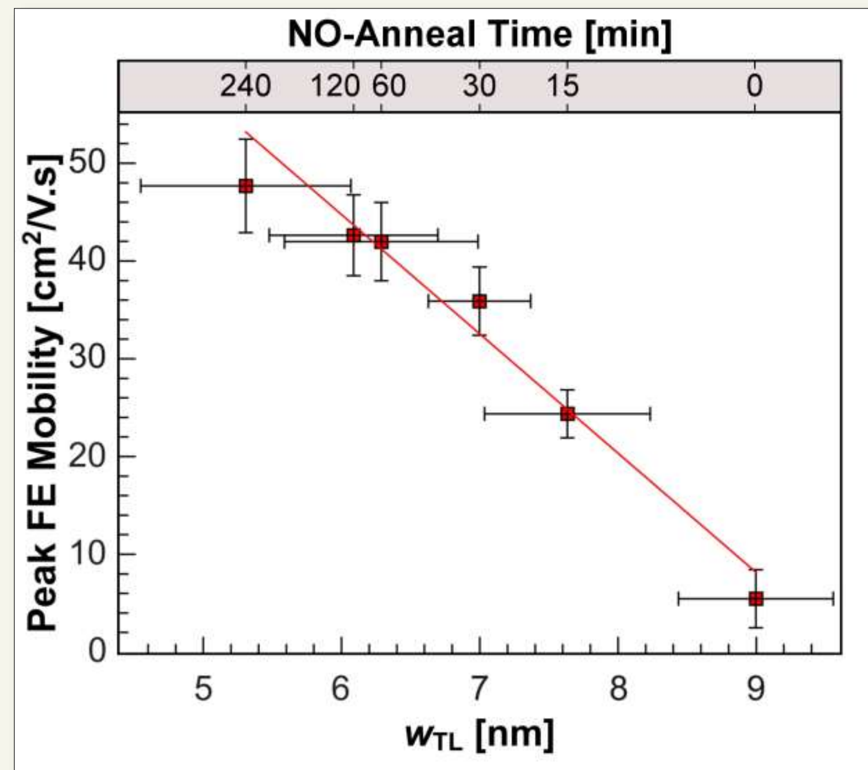

*No excess C at interface*

$\pm 2.5\%$

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

# Electronic measurements/Conclusions

- $w_{TL}$ correlates inverse-linearly $\mu_{FE}$
  - 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).

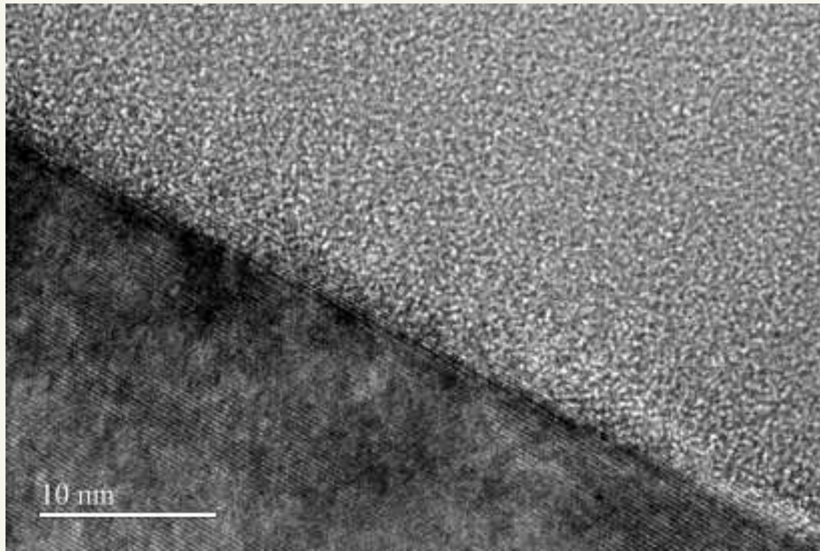
# Latest Samples

| Treatment | Processing time | Crystal face | Mobility $[\frac{cm^2}{V\,s}]$ |
|---|---|---|---|
| NO | 2 hours | Si | 42 [1] |
| P | 4 hours | Si | 80 [1] |
| N-plasma | 6 hours | Si | 30 [2] |

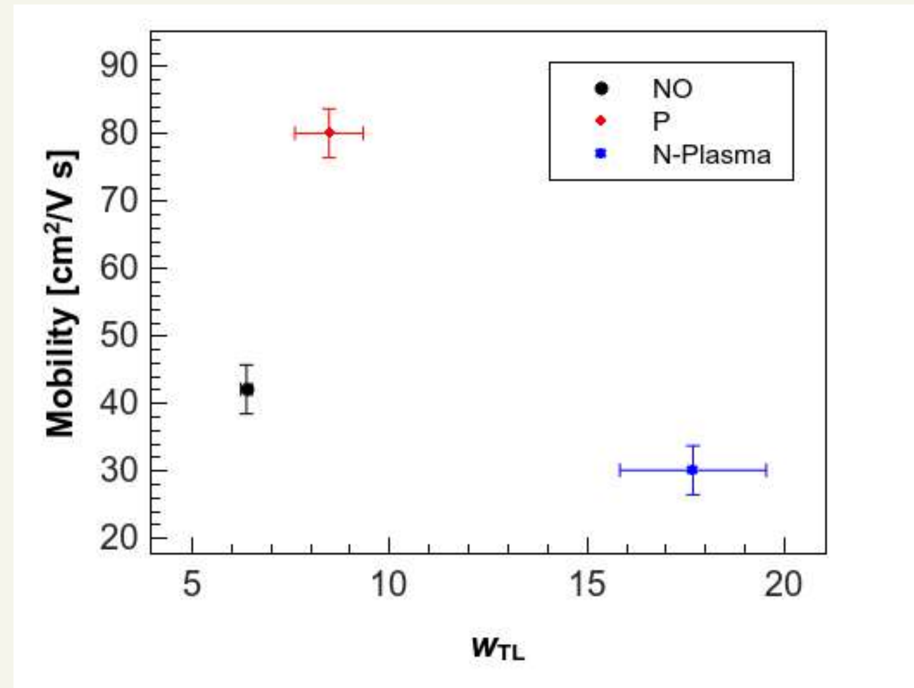
*Sample processing performed at Auburn and/or Rutgers*

1 G. Liu *et al.*, IEEE Electron. Dev. Lett. **34**, 181–183 (2013).
2 S. Dhar *et al.*, Unpublished.

# Preliminary Results




*Example HRTEM of N-plasma treated sample*



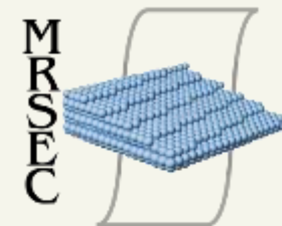

$w_{TL}$ measured by chemical shift of Si-$L_{2,3}$ edge across interface

# Conclusions

- NO-anneal:
  - Increase in anneal time
    → Decrease in $w_{TL}$
  - No excess carbon at interface
  - Introduced new $w_{TL}$ measurement method
- NO, P, & N-plasma
  - Large variation in $\mu$
  - Preliminary results suggest different $\mu$ trend than NO samples alone
  - Research is ongoing

# Acknowledgements


- ARL Contracts W911NF-11-2-0044 and W911NF-07-2-0046.
- NISPLab at UMD – supported by NSF and MRSEC
- Dr. Joshua Schumacher and Mike Hernandez at NIST



# THANK YOU

Questions and comments?