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Si Quantum Dots via Rapid Ge Diffusion During High Temperature Oxidation of Si/SiGe Nanostructures

Emily Turner[1]

Keshab R. Sapkota[2], Christopher Hatem[3], Ping Lu[2], Joaquin Pizarro Junquera[4], George T. Wang[2], Kevin S. Jones[1]

1 University of Florida, Gainesville, FL
2 Sandia National Laboratories, Albuquerque, NM
3 Applied Materials Inc., Gloucester, MA
4 Universidad de Cádiz, Cadiz, Spain

SWAMP Research Group

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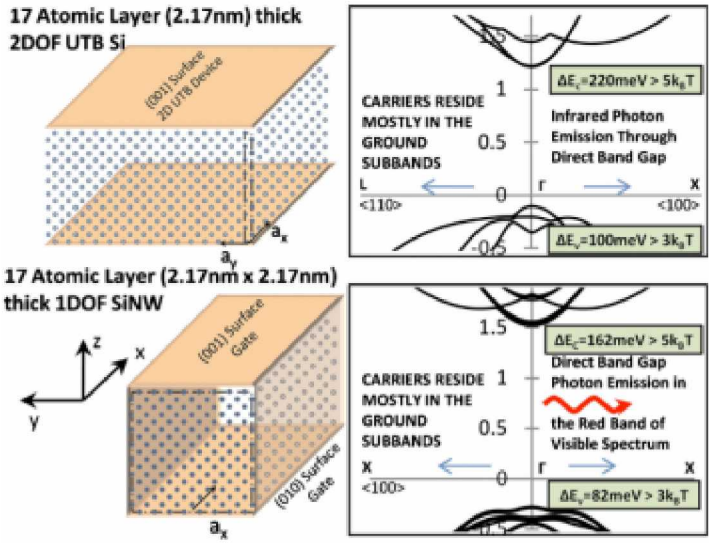
Outline

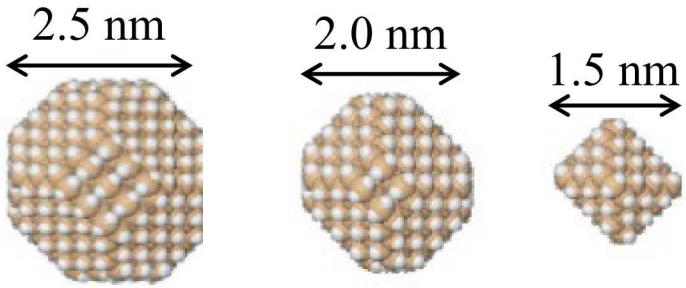
- Introduction
  - *Si and SiGe for quantum applications*
  - *Enhanced diffusion of Ge along Si/SiO_2 interface*
- Oxidation of Si/SiGe fin structures
- Oxidation of Si/SiGe pillar structures
  - *Method for FIB cross section fabrication of 3-D nanostructures*
  - *Si dot formation during oxidation*
- Conclusions

Si and SiGe for quantum applications

- Si/SiGe quantum structures have potential as on-chip optical sources, microelectronics, & quantum computing
- Interesting material property changes as dimensions decrease to quantum sizes
- Fabricating on-chip quantum structures challenging



Theoretical calculations suggesting Si may transition from having indirect to direct bandgap properties when spatially confined [2]



DFT analysis of Si-H QDs for electronic structure information [1]

[1]Hapala, P. *et al*. Theoretical analysis of electronic band structure of 2- to 3-nm Si nanocrystals. *Phys. Rev. B - Condens. Matter Mater. Phys.* **87,** 1–13 (2013).

[2]M. O. Baykan, S. E. Thompson, and T. Nishida, "Strain effects on three-dimensional , two-dimensional , and one-dimensional silicon logic devices..," *J. Appl. Phys*., **108,** 1–24, (2010).

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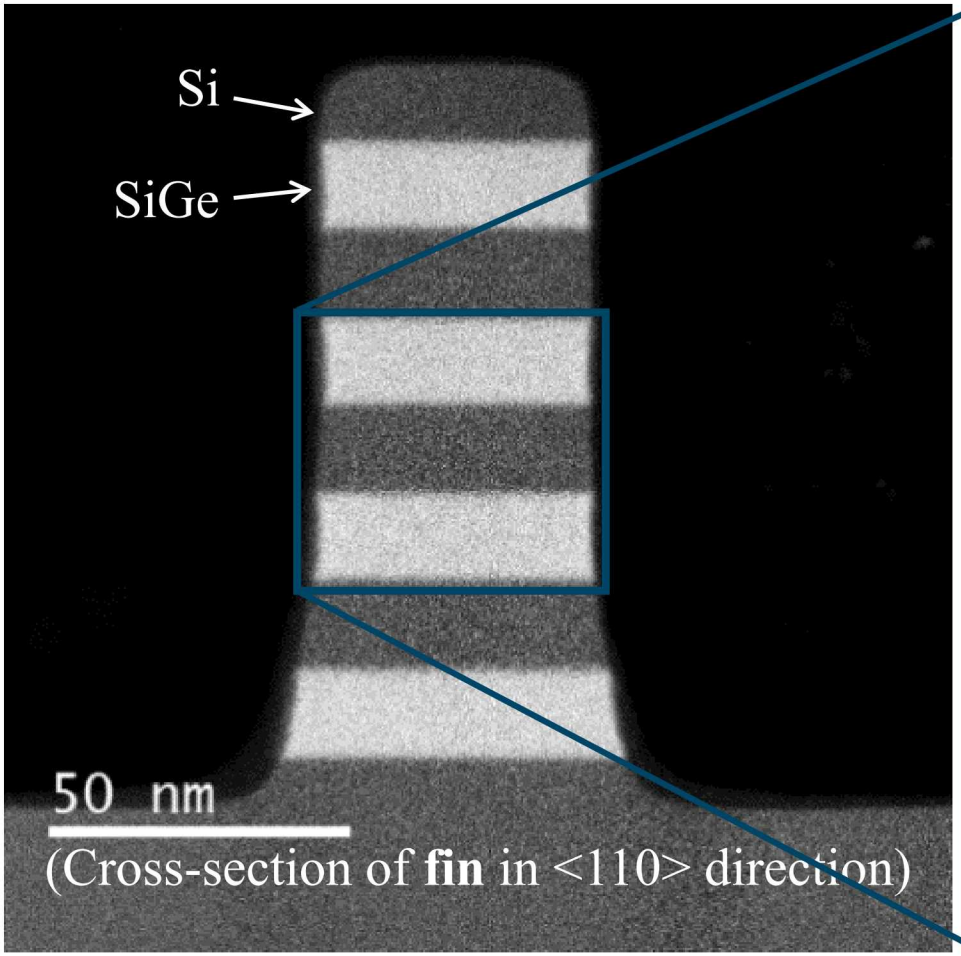
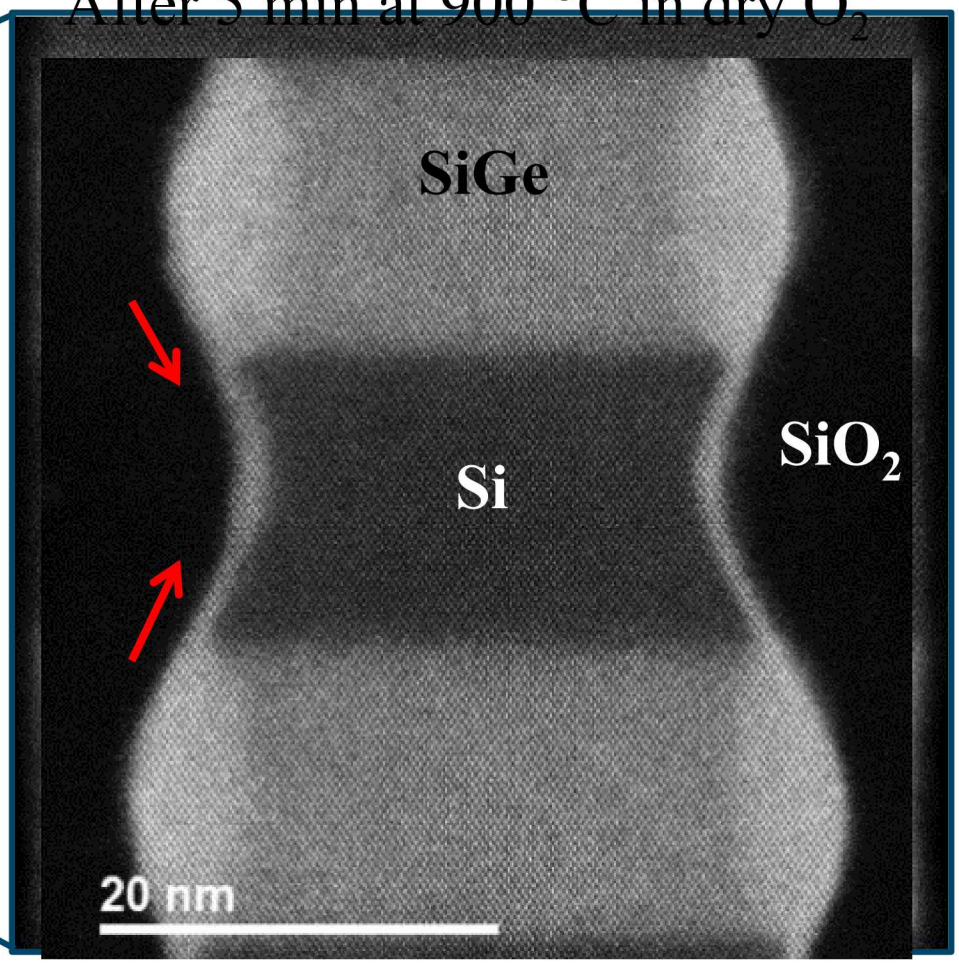
Enhanced diffusion of Ge along Si/SiO_2 interface

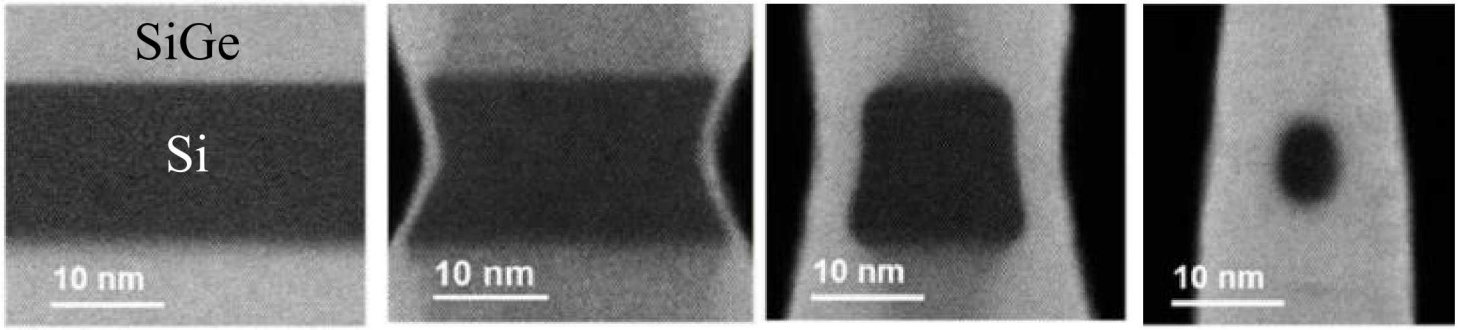




Brewer, W. M. *et al.* Lateral Ge Diffusion During Oxidation of Si/SiGe Fins. *Nano Lett.* **17,** 2159–2164 (2017).

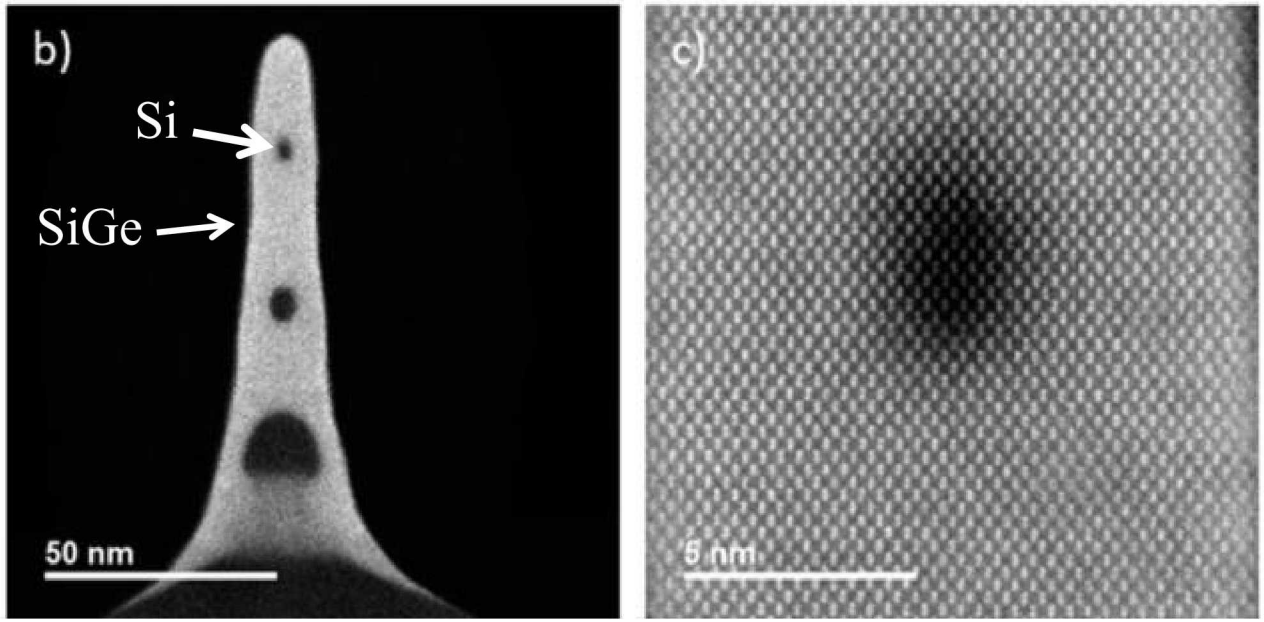
Si nanowire formation during 900 °C oxidizing anneal

- Fin cross section during oxidation at 900 °C in O_2



Before oxidation | 5 minutes | 20 minutes | 45 minutes

- Unexpected formation of lateral Si nanowires down to 2 nm in diameter!



Brewer, W. M. *et al.* Lateral Ge Diffusion During Oxidation of Si/SiGe Fins. *Nano Lett.* **17,** 2159–2164 (2017).

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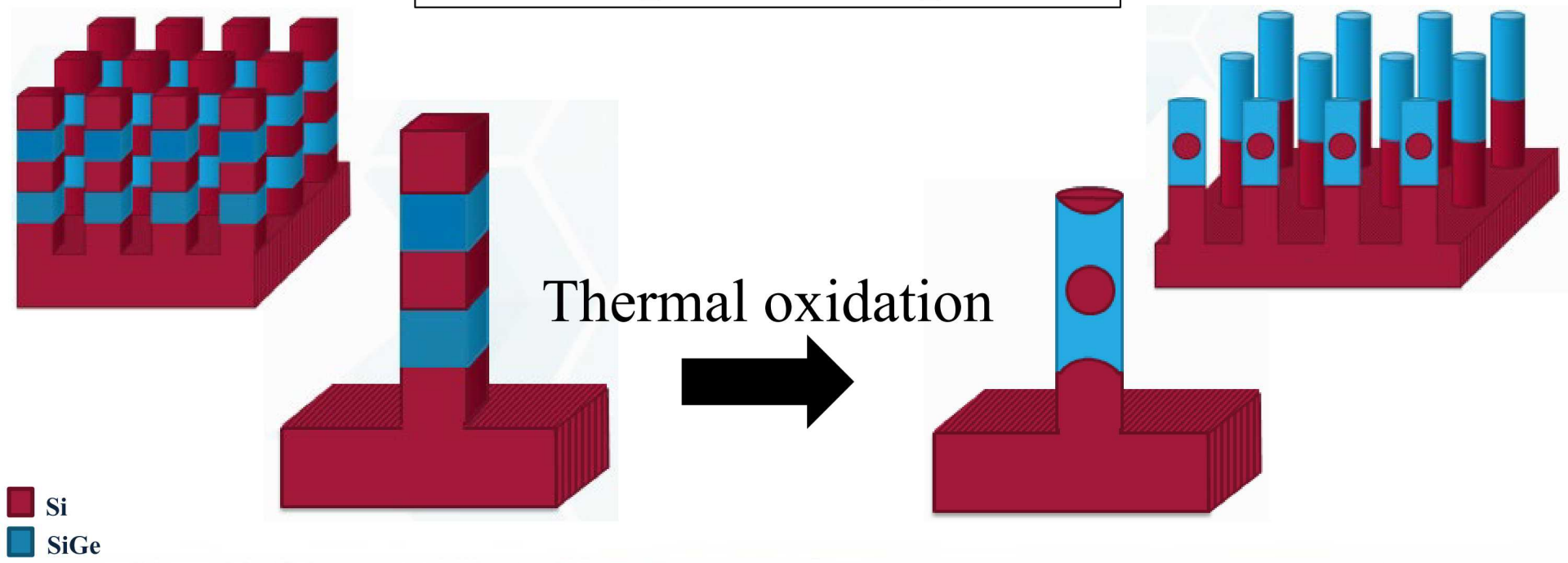
Enhanced Ge diffusion for novel fabrication method

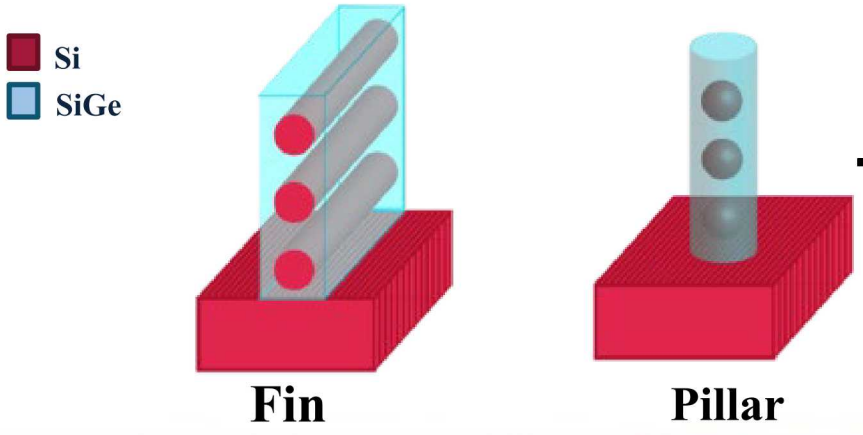
- Need scalable methods for on-chip Si nanostructures with dimensions <10nm
- Can we extend the use of this enhanced Ge diffusion process to create 0D structures (quantum dots) in addition to lateral 1D nanowires?

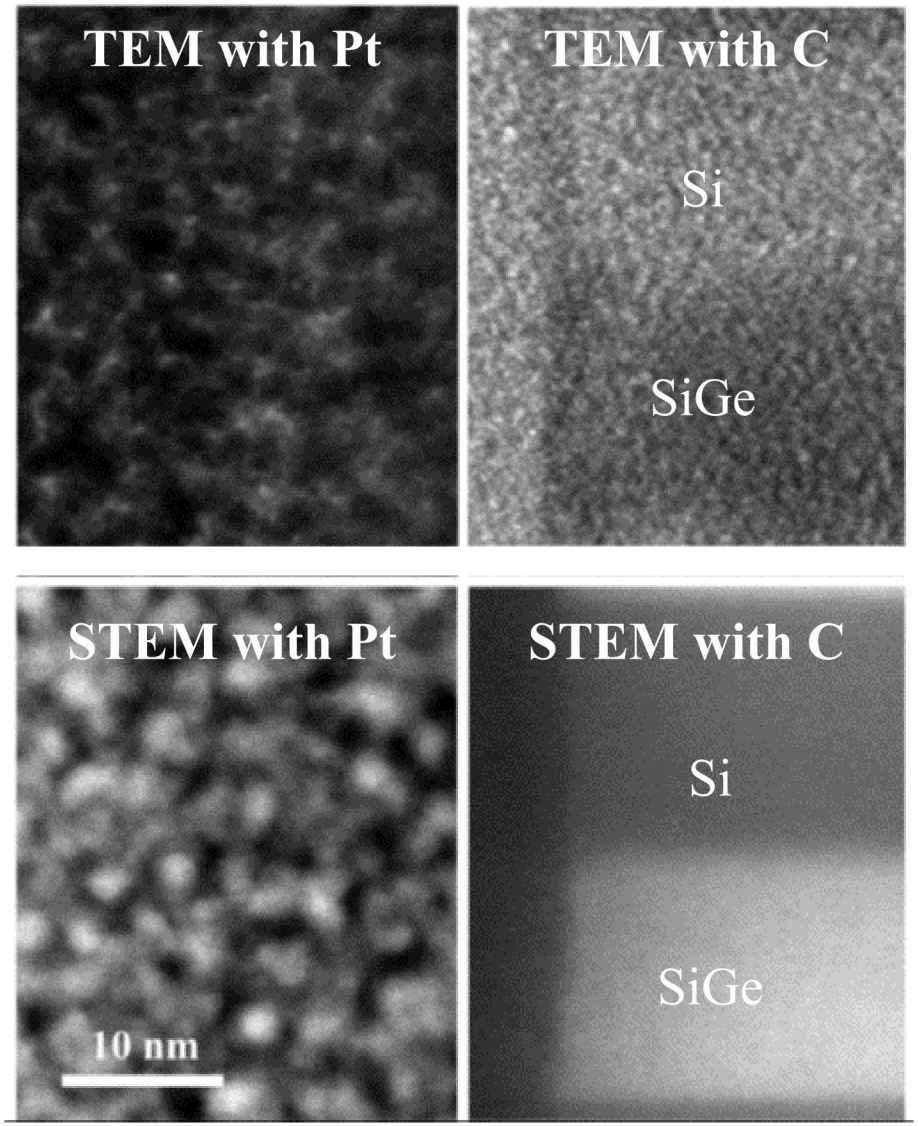
Next step: Si/SiGe pillars



FIB Cross Sectioning of 3-D nanostructures

- Typically use a protective material like C and/or Pt to avoid ion beam damage during preparation
- Works very well for bulk and 2-D nanostructures (e.g. fins)
- Causes obstruction of 3-D nanostructures (e.g. nanopillars, vertical nanowires, QDs) during TEM analysis





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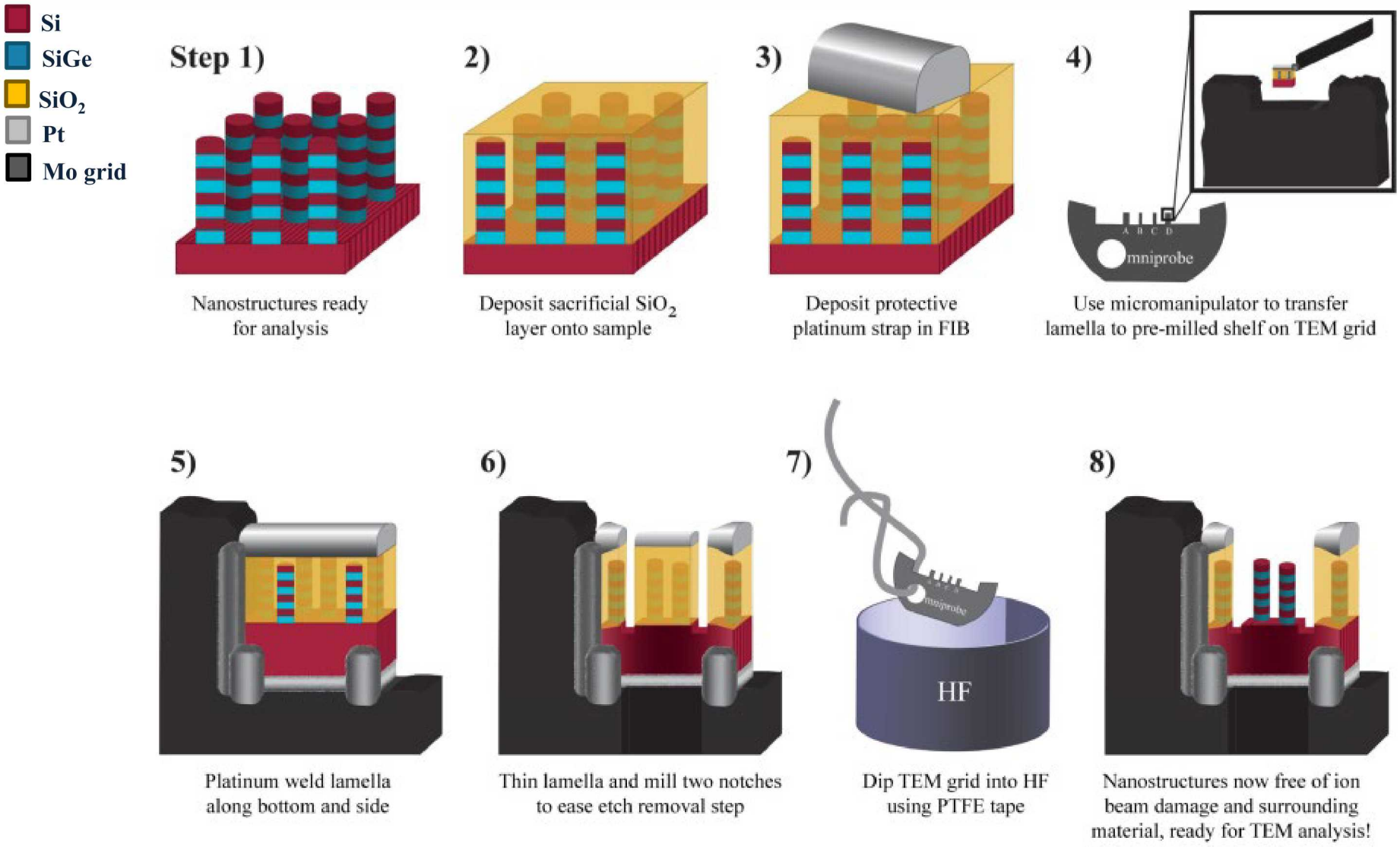
Method for 3-D nanostructure characterization



Turner, E. M. *et al.* Wet-chemical Etching of FIB Lift-out TEM Lamellae for Damage-free Analysis of 3-D Nanostructures *Ultramicroscopy.* (2020).

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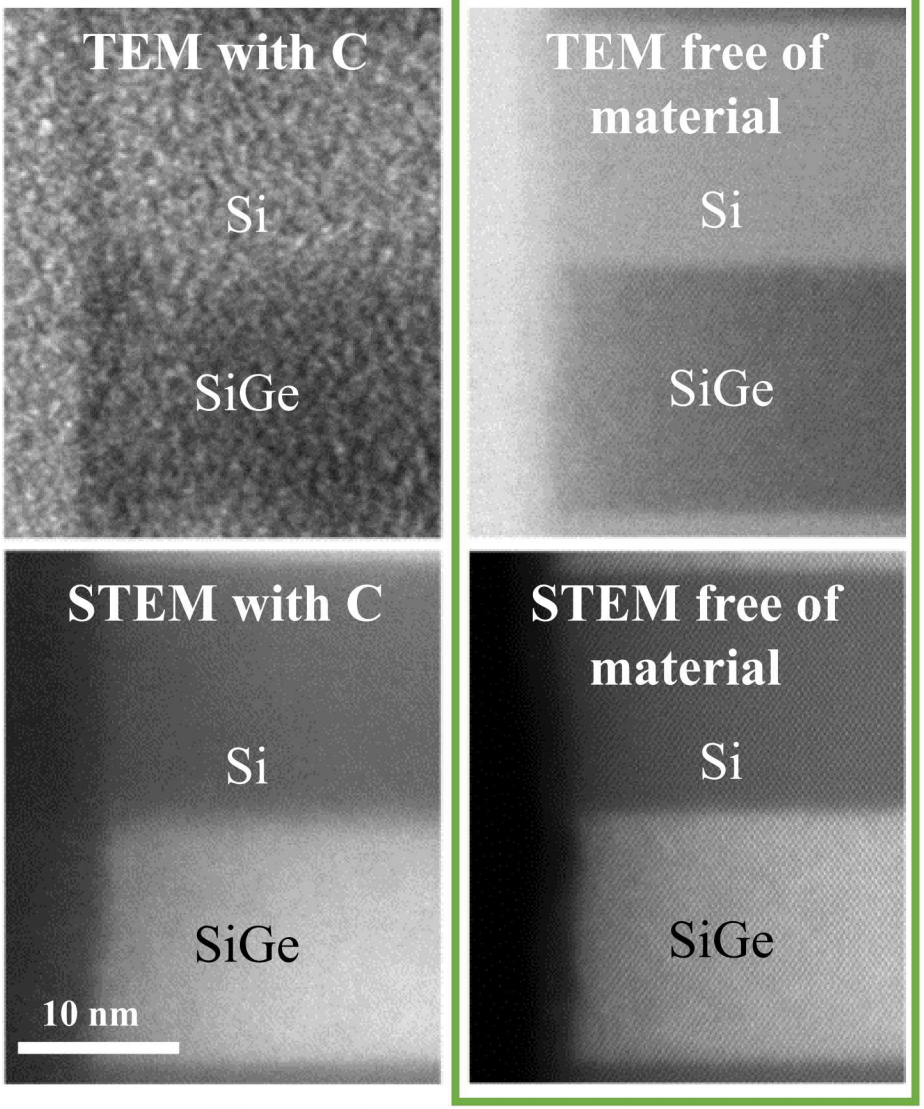
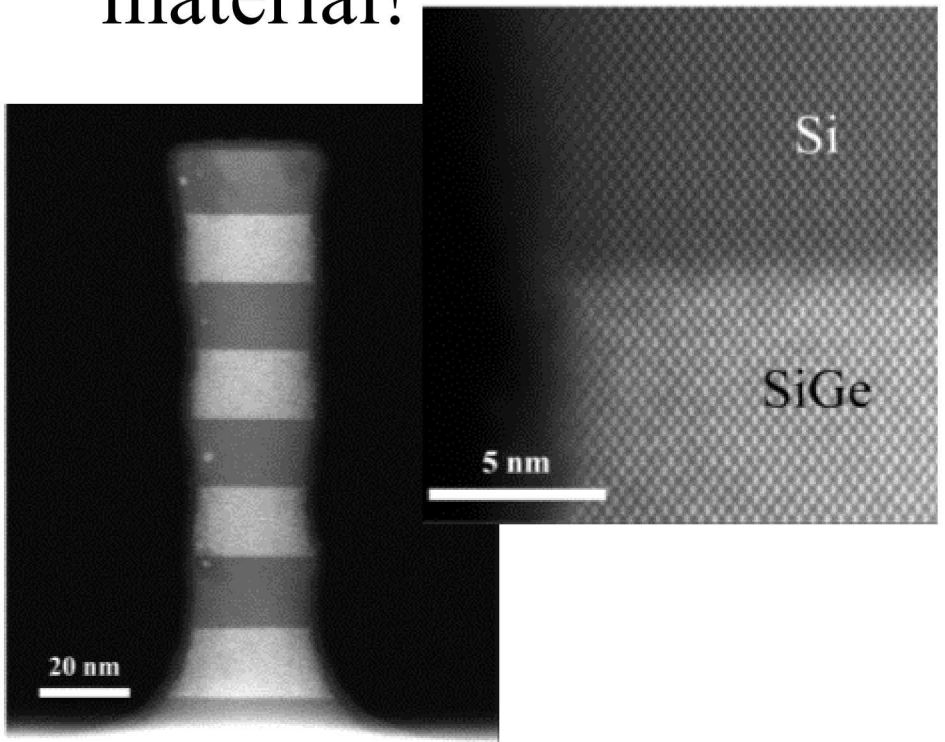
Results of new wet etch method



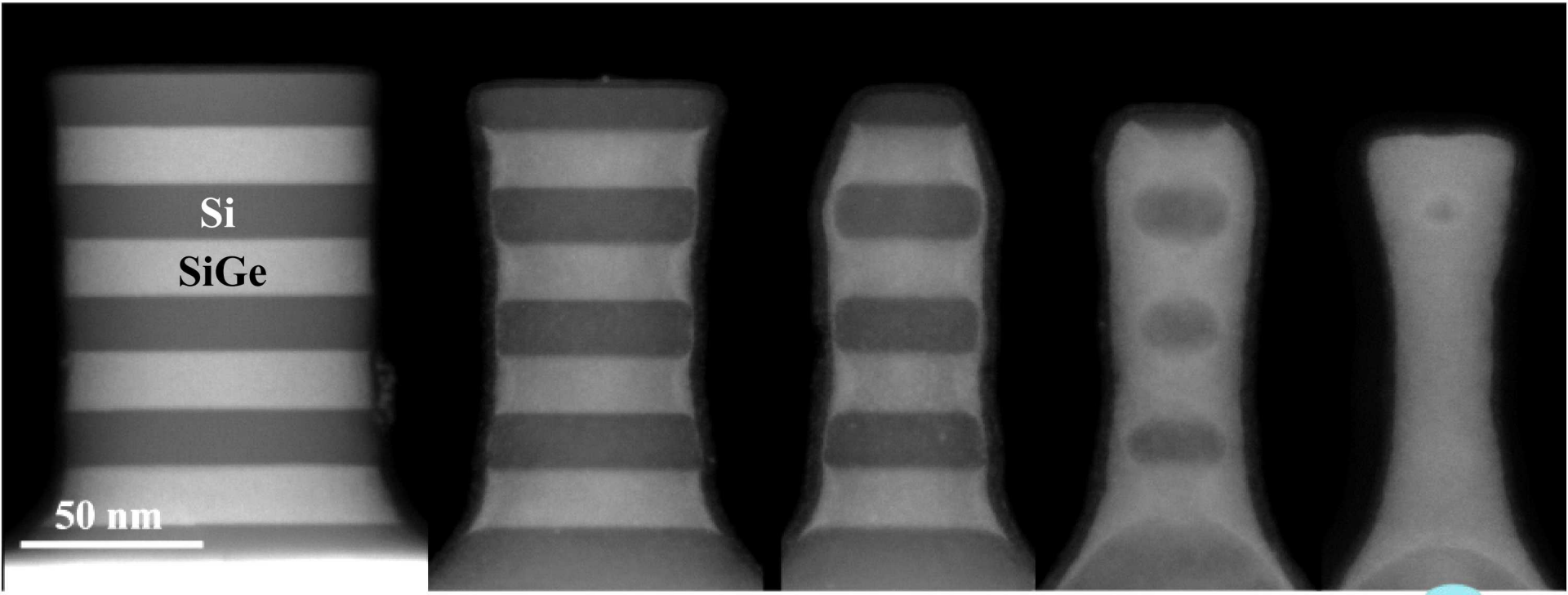
- Now able to image 3-D nanostructures without damage or obstructing material!



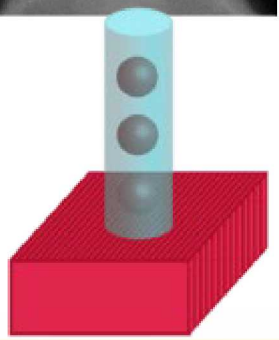
30 nm diameter Si/SiGe pillar

Evolution of Si/SiGe **pillar** during oxidation

Unoxidized **pillar** 5 min ox 10 min ox 20 min ox 35 min ox

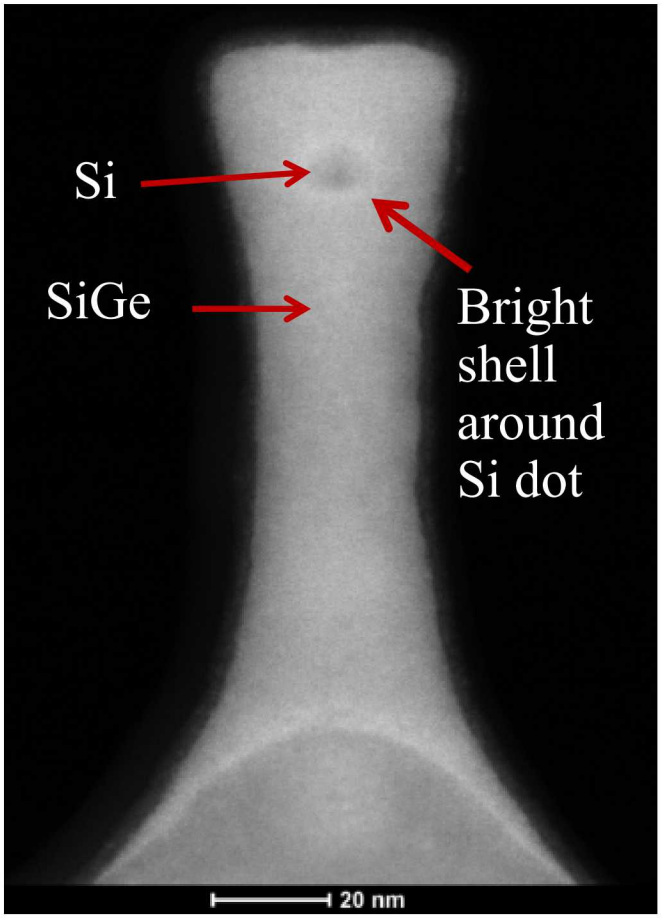


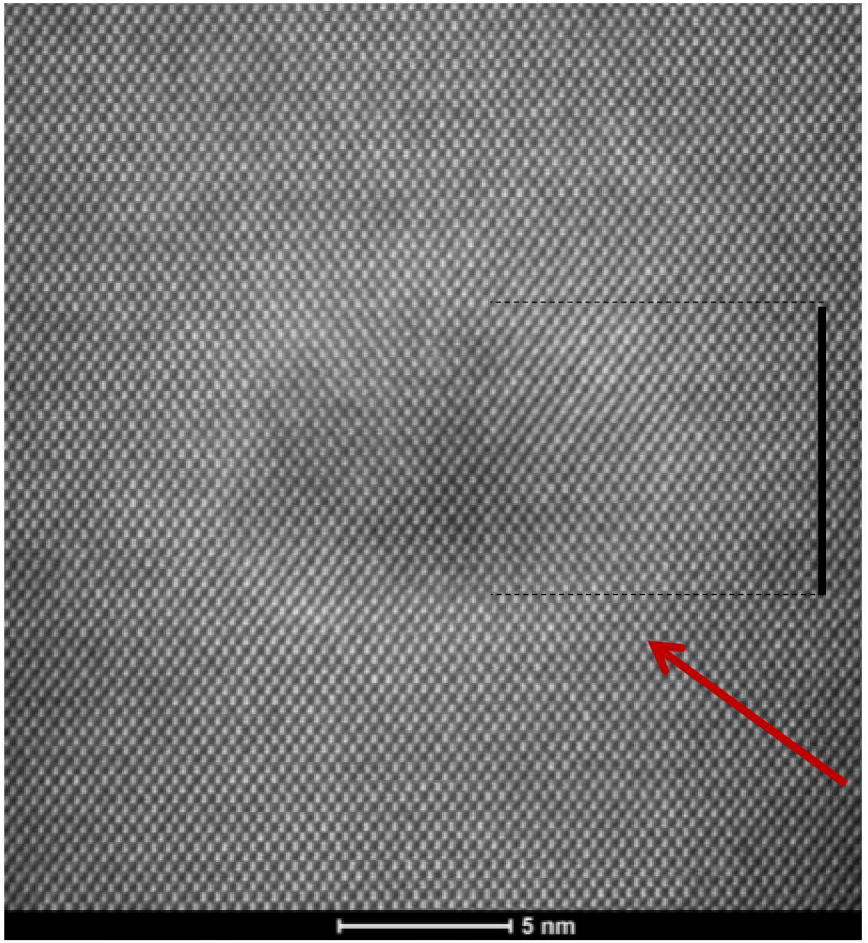
- HAADF STEM images of Si/SiGe pillars after oxidation at 900 ˚C in dry O_2 for a range of oxidation times
- Ge diffusion results in **Si dots encapsulated in SiGe pillars!**



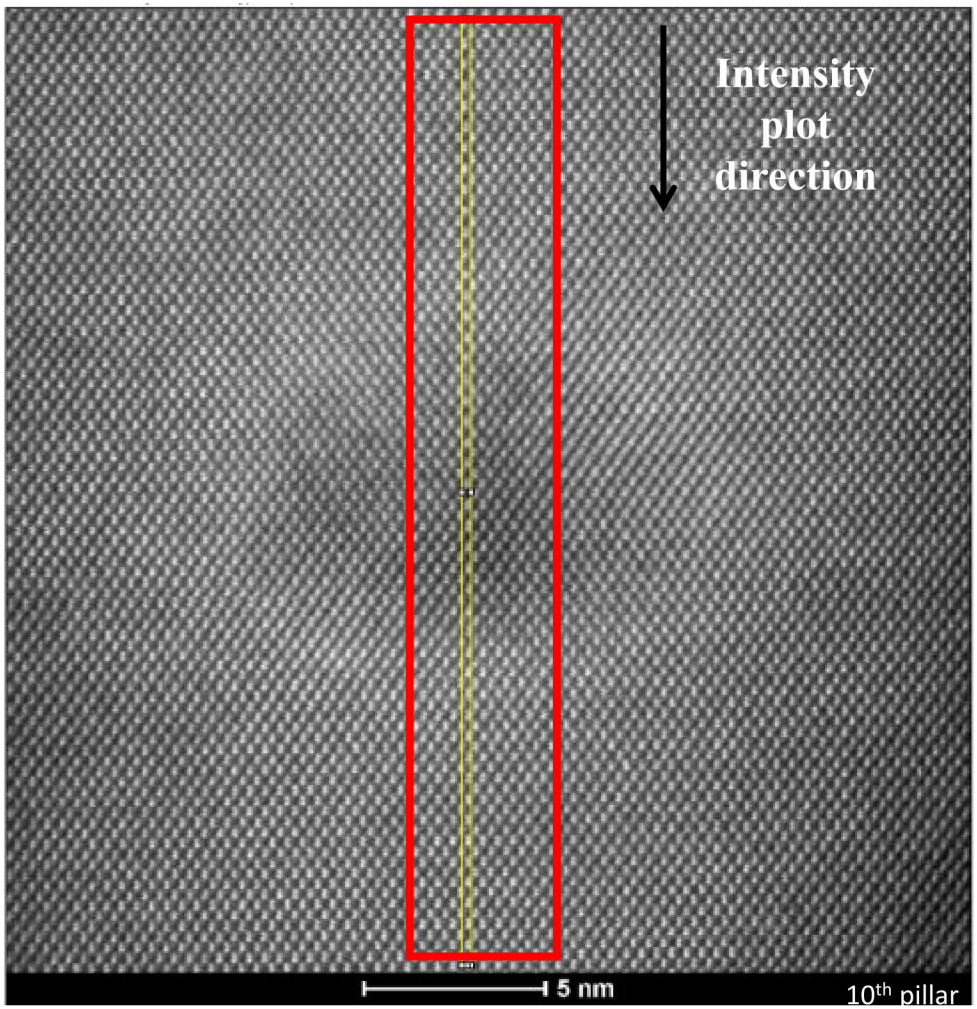
STEM of encapsulated Si dot in SiGe

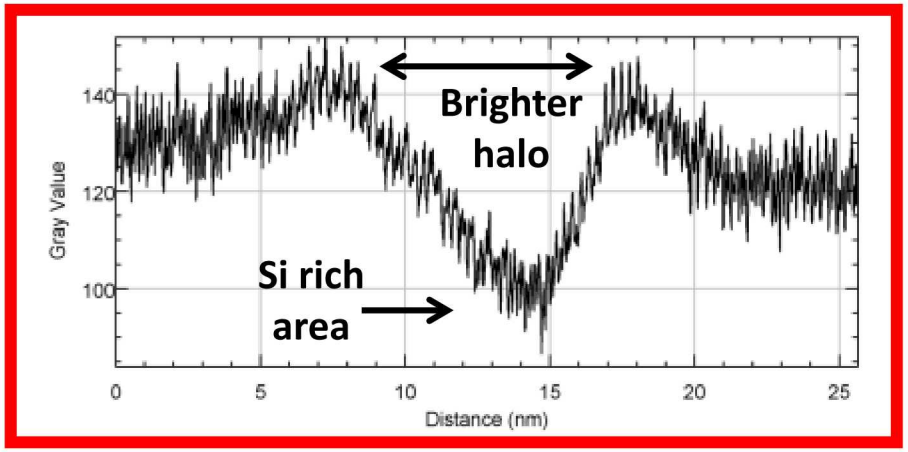
- Si layers fully encapsulated by single crystal SiGe
- **Unexpected Ge rich halo around Si dot**

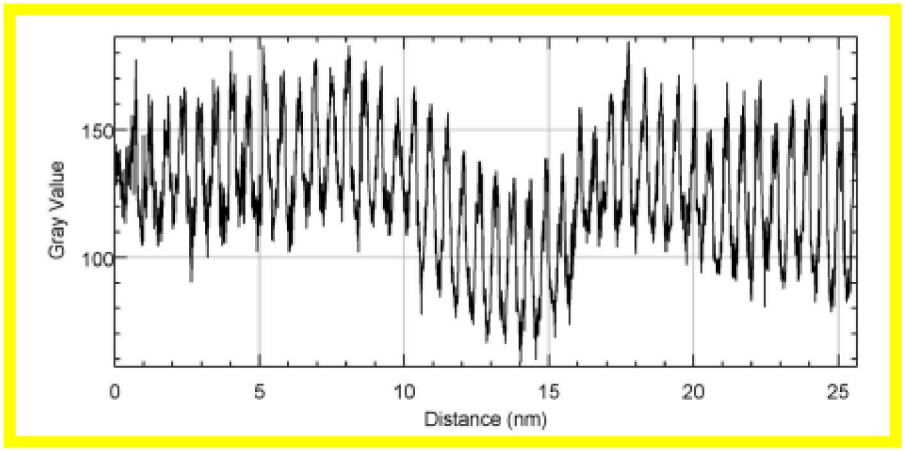




STEM of encapsulated Si dot in SiGe







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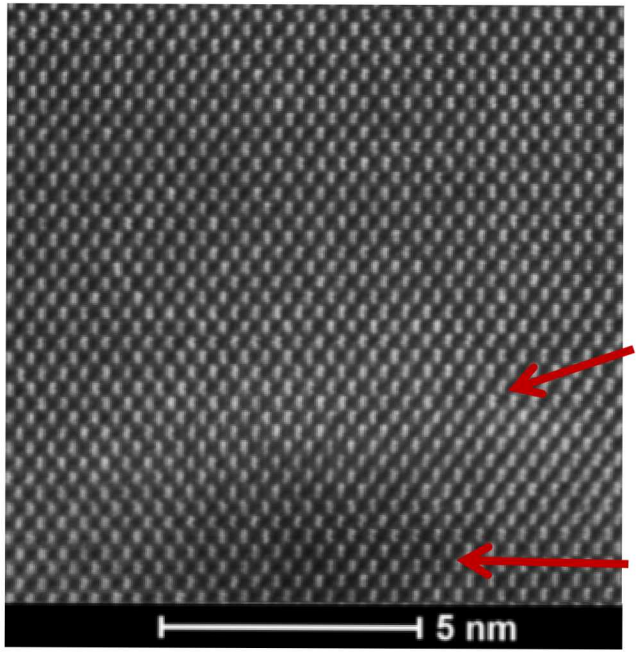
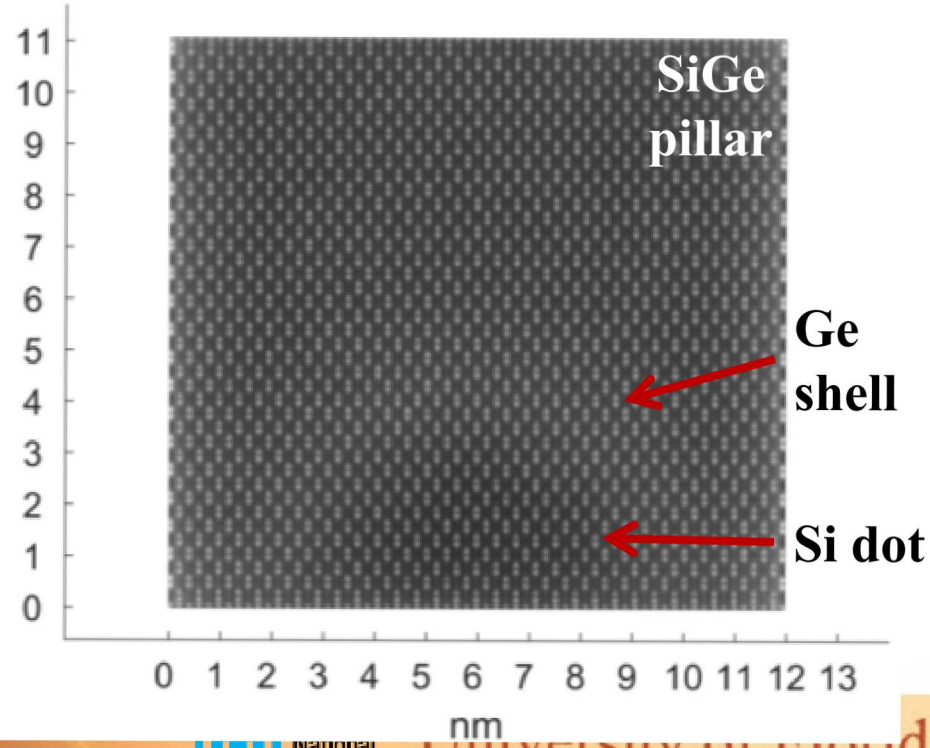
STEM modeling of Si dot and Ge shell

- Is the bright region around the Si dot due to strain or composition?
- If we are able to match a simulated STEM image with the experimental data, can have some confidence about compositional makeup of Si/SiGe pillar

Experimental STEM image



Simulated STEM image



Conclusions

- New method developed for damage free cross sectioning of 3-D nanostructures free of surrounding material
- Novel Ge diffusion also observed in Si/SiGe pillar structures
- Continued oxidation forms encapsulated Si QDs!
- Next steps include investigating electronic structure of QDs
- Enhanced Ge diffusion could pave the way to formation of novel Si (and SiGe) structures for future electronics applications

Emily Turner
emilymturner@ufl.edu
expected graduation FA2020

Acknowledgments

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  - CINT
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