This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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2020 VIRTUAL MRS® SPRING/FALL MEETING & EXHIBIT

November 27 – December 4, 2020

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2020 VIRTUAL MRS® SPRING/FALL MEETING & EXHIBIT

Tracking interfacial disorder in SiGe qubit material

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Tracking interfacial disorder in SiGe qubit material

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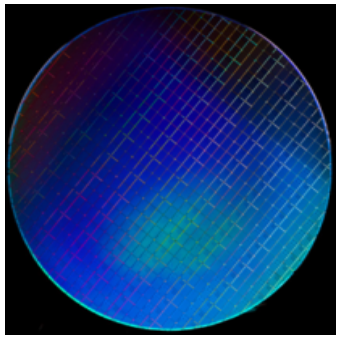
Center for Integrated Nanotechnologies — CINT — Discovery, Performance, Integration, Education — Sandia, Los Alamos

Background

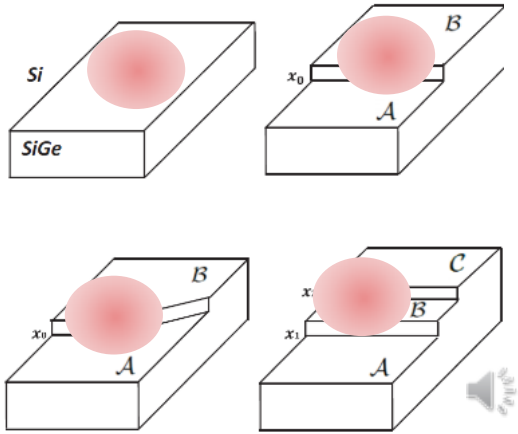
Intel 300 mm Isotopic pure SiGe



- **Si is great platform for spin qubits**
  - **Strengths: Si foundry compatibility &** isotopic purity (Intel, HRL)
    - Challenge: degenerate conduction band (CB), multiple valleys

- **For SiGe e- spin qubits**
  - **CB valleys split (degeneracy gone) in quantum dot**
    - Challenge: Valley splitting is suppressed by atomic-scale interface disorder [1-4]

- **Atomic-scale interface disorder is natural feature in thin films**
  - Smooth layer growth *requires* atomic steps on surface
  - Hence, inevitable valley e- interaction with atomic steps



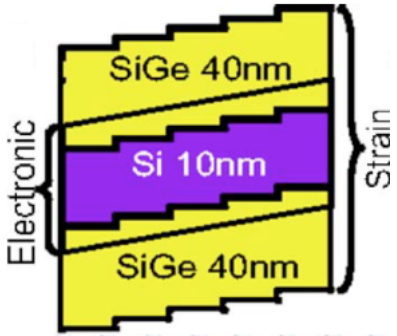
✓ **Disorder in Si leads to decoherence**

✓ **Control over disorder indicates potential platform for spin qubits**

[1] *Appl. Phys. Lett.* **112**, 243107 (2018), [2] *Nature Physics* **3**, 41 (2007)
[3] *Phys. Rev. B* **75**, 115318, [4] *RMP* ***85****, 961* (2013)

Challenge

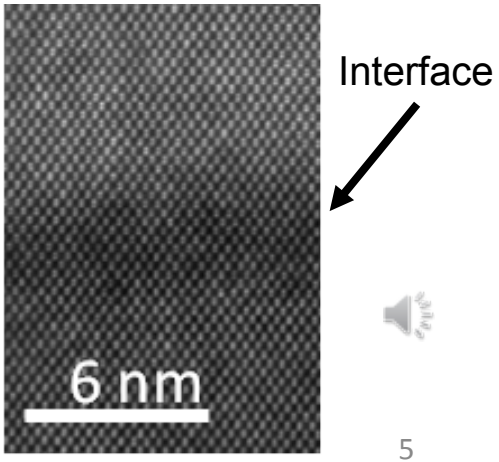
Control over valley splitting will require intricate knowledge and understanding of atomic-steps in heterostructure interfaces



Appl. Phys. Lett. ***90****, 092109 2007*

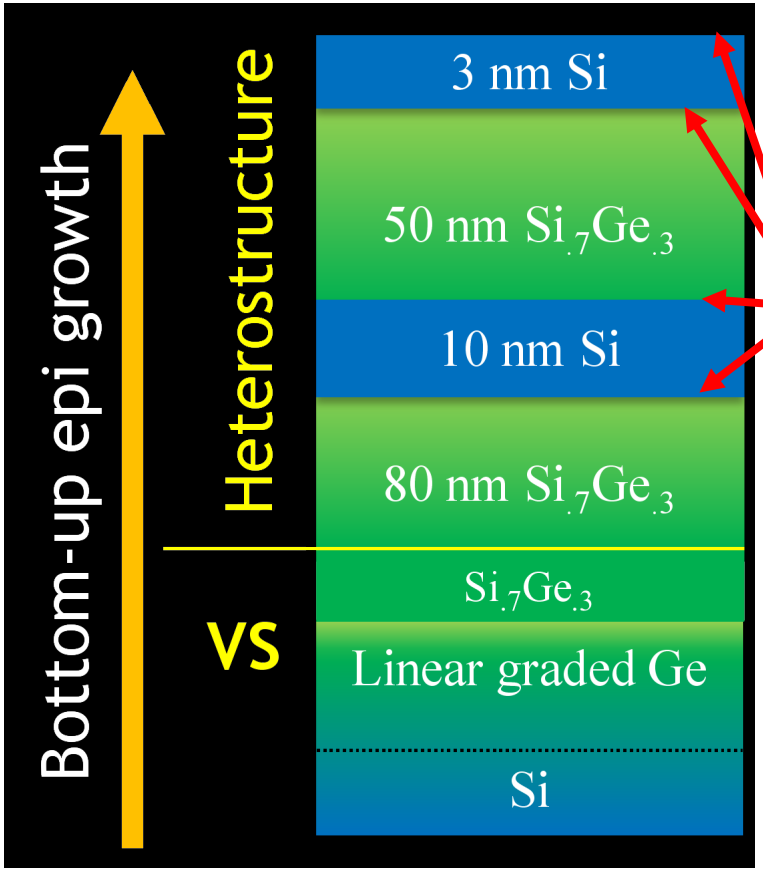
➢ **Buried interfaces are challenging to measure in 3D**

- **Common methods,**
  1. Cross-sectional TEM provides 2D structure info.
  2. AFM measurements of final surface must be extrapolated to 3D



✓ **Our approach: image surfaces that become buried interfaces as layered structure is deposited**

Strategy



What is our proposed solution to this materials science problem?

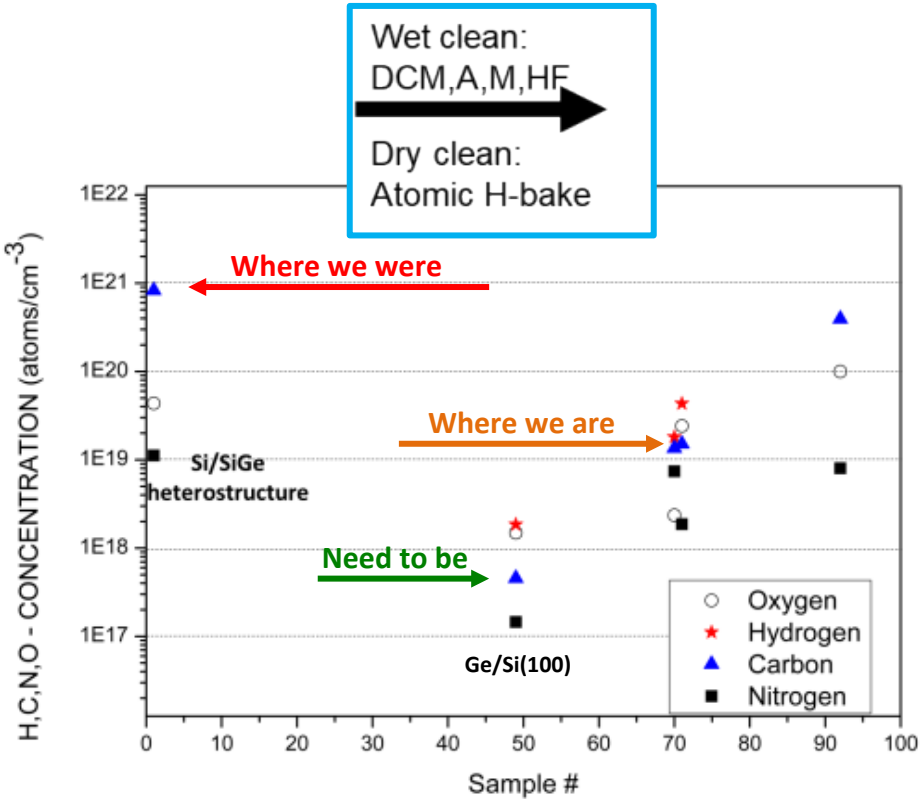
Grow a heterostructure and Image interface with STM after MBE growth

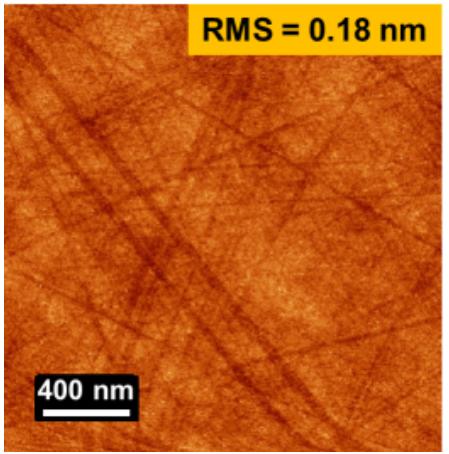
look at interfaces as they form - get 3D atomic resolution view of interface

not possible by other techniques

Substrate material

Adventitious contamination

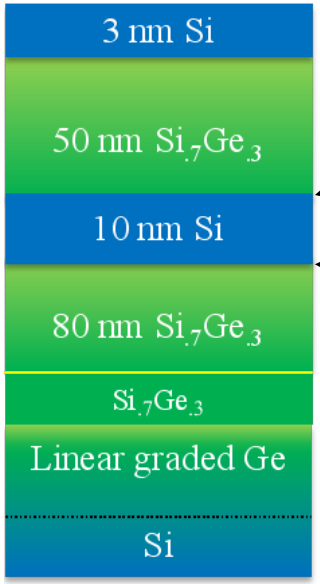




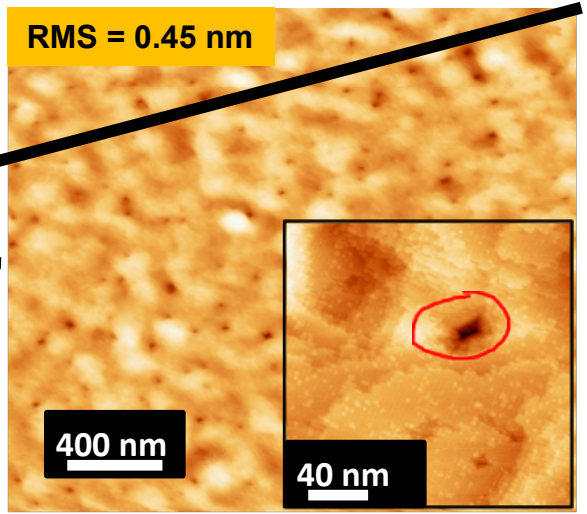
Foundation to grow heterostructure

Extensive C mound formation at interface if surface cleaning is not done properly

STM of Si/SiGe heterostructure

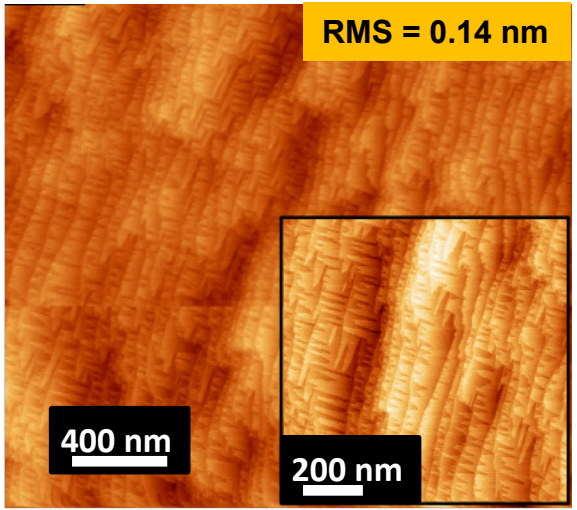


Top surface of relaxed SiGe buffer layer

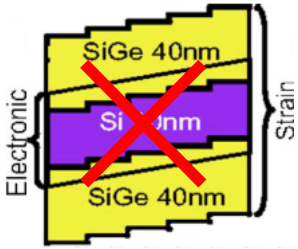


Metastable features < 1nm deep

Strained-Si quantum well top surface

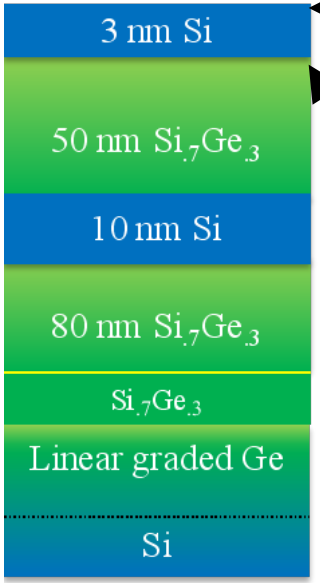


Dense atomic steps with nonuniform distribution

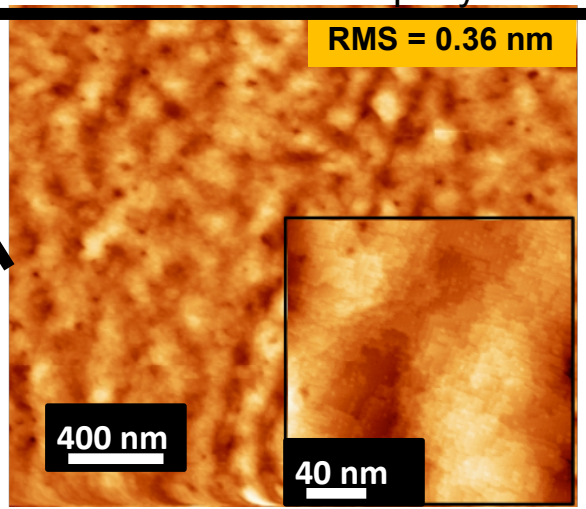


- **Regrowth doesn't follow miscut!**
- **The top of the Si well obeys some other order, with step bunches and step waves → NOT LOCAL MISCUT**

STM of Si/SiGe heterostructure

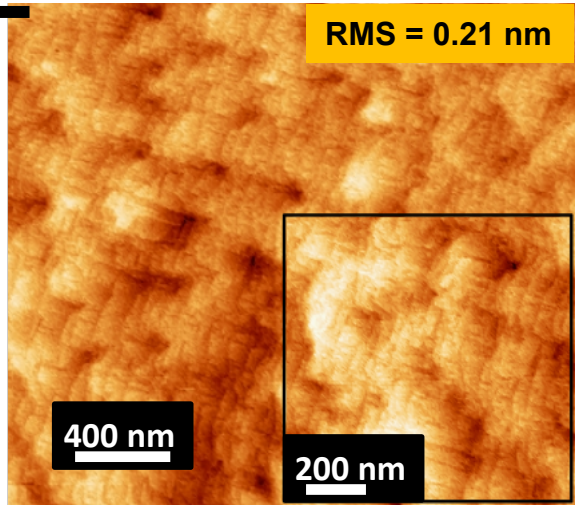


Relaxed SiGe top layer



Isolate s-Si quantum well from disorder at finished top surface and subsequent gate stack

After strained-Si cap – finished heterostructure surface



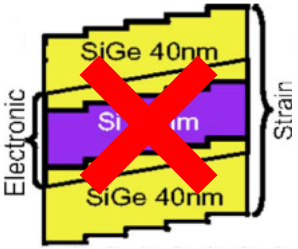
Step formation and possibly metastable step pinning from previous surface

- **No evidence of conformal epitaxial growth**
- **No obvious correlation between interfaces**

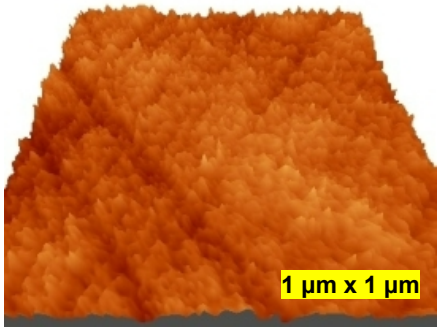
Summary

No obvious correlation between interfaces – Si well does not appear to inherit roughness from substrate.

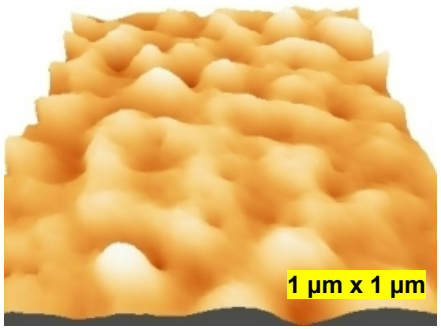
Steps do not follow crystal miscut, rather growth kinetics & local strain.



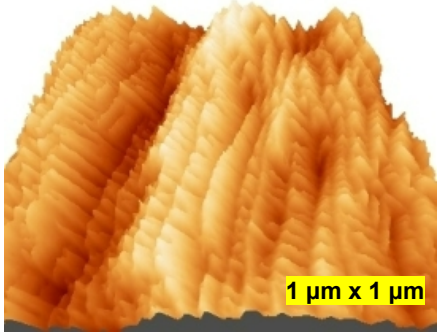
Substrate



SiGe



Si well



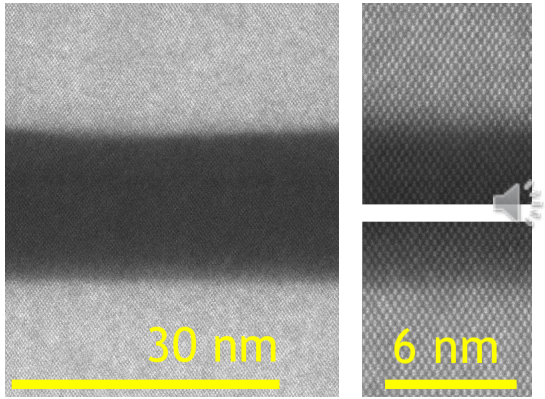
There is no easy way to look at buried interfaces after growth.

Cross-sectional TEM provides 2D structure information

We augment with STM for full 3D picture

Si well interface →

SiGe interface →



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- **Soft, Biological & Composite Nanomaterials –** Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.
- **Quantum Materials Systems –** Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.