

Structural Characterization of Strained Silicon Substrates by X-Ray Diffraction and Reflectivity

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- Motivation
- Wafer structure and measurement details
- Results
 - Strain
 - Thickness
 - Tilt and twist
- Conclusion

- Strained Si technology gaining commercial acceptance
- Strained Si substrates require careful characterization
- X-ray diffraction and reflectivity are robust techniques sensitive to:
 - Parallel strain
 - Perpendicular strain
 - Tilt
 - Twist
 - Thickness

X-ray diffraction (XRD)

- Reciprocal space mapping precision = 12 arc sec.
- Strain measurement accuracy of ~1%
- Measurement time < 5 min.

X-ray reflectivity (XRR)

- Beam divergence = 0.003°
- Thickness measurement accuracy of ~1%
- Measurement time < 5 min.

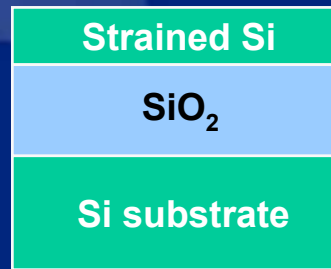
All measurements performed with a Philips X'Pert PRO

Bulk strained silicon



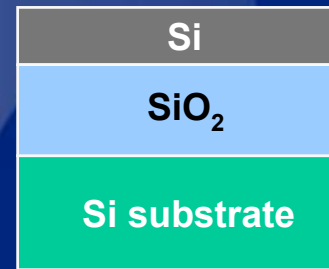
- 32% relaxed SiGe
- Layer has **same** crystal lattice as substrate

Strained Si on insulator (SSOI)



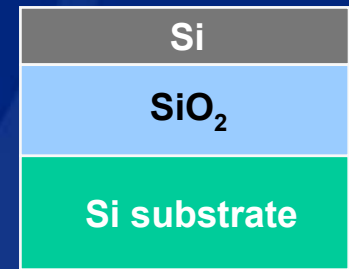
- **No SiGe**
- Layer has **different** crystal lattice from substrate

SOI by wafer bonding

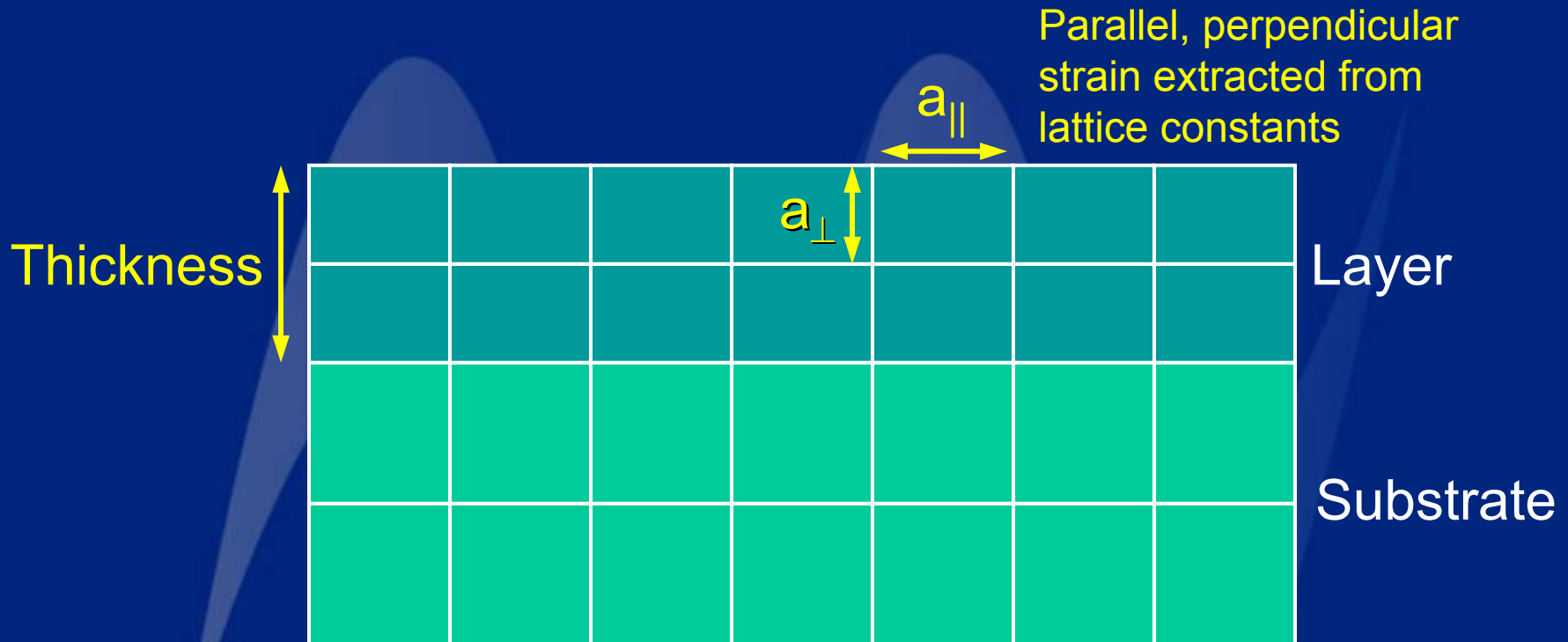


- No strain
- Layer has **different** crystal lattice from substrate

SOI by SIMOX

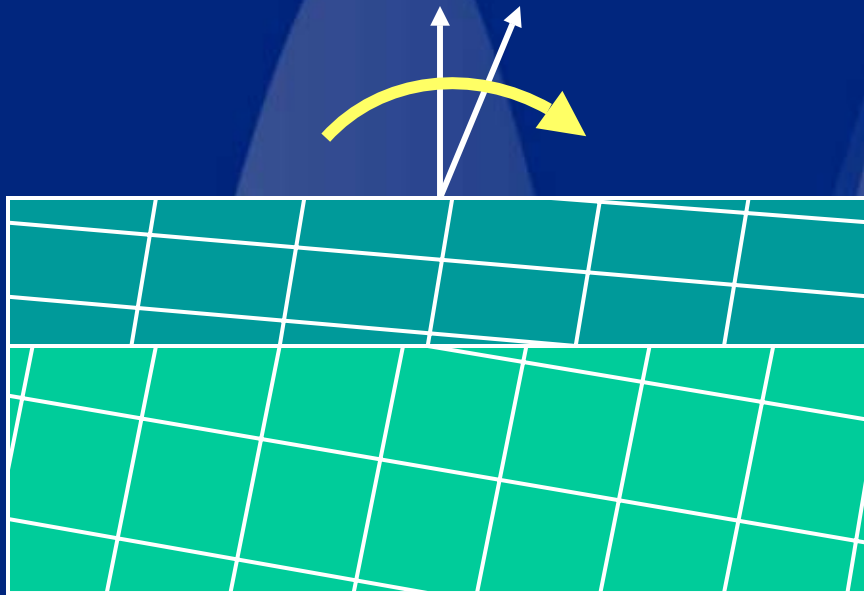


- No strain
- Layer has **same** crystal lattice as substrate

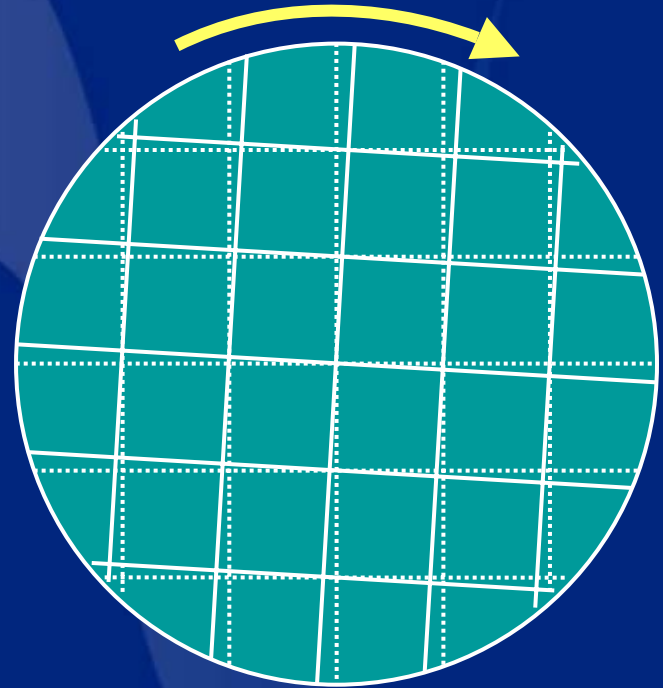


Strain and thickness are critical parameters for bulk strained silicon and SSOI substrates

Tilt

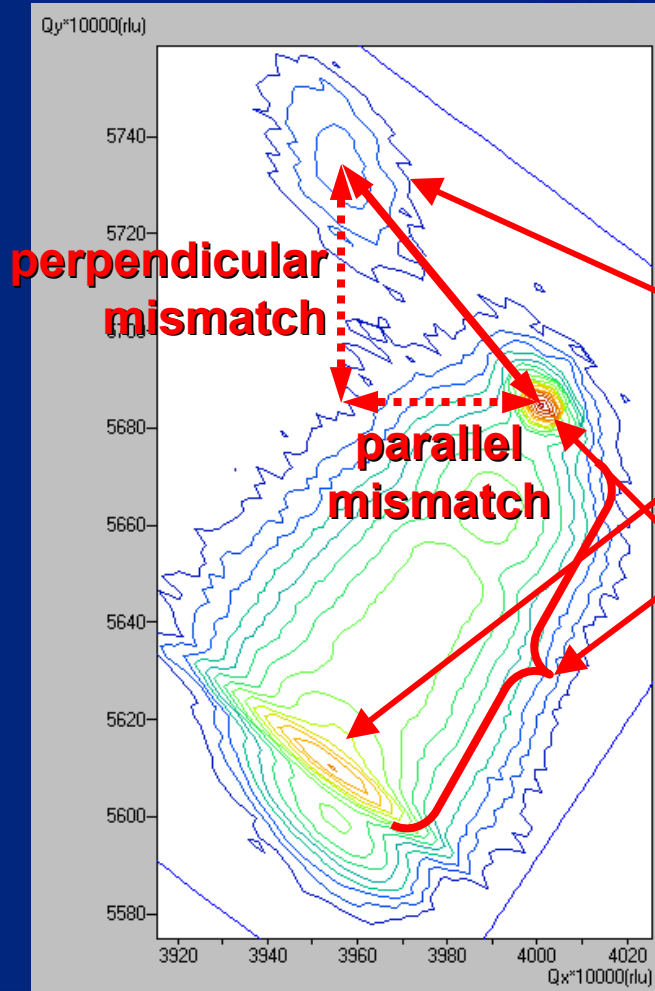


Twist



Tilt and twist are key parameters for bonded wafers

How Strain Is Determined



- Rocking curves are not accurate
- Measured with four {224} reciprocal space maps to eliminate effect of tilt
- Horizontal offset gives parallel lattice constant
- Vertical offset gives perpendicular lattice constant
- Combining the lattice constant information gives parallel and perpendicular strain and composition

Bulk strained Si

SSOI

Strained Si
Relaxed SiGe
SiGe Grade
Si substrate

Strained Si
SiO ₂
Si substrate

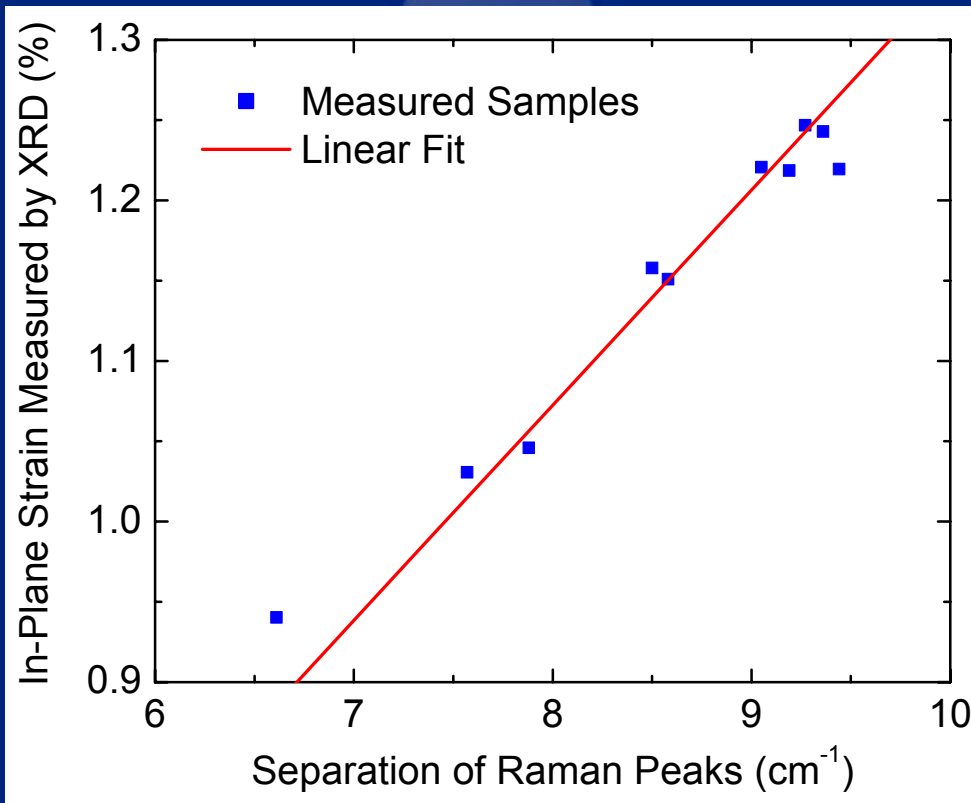
Parallel strain, strained Si	1.28%	1.27%
Perpendicular strain, strained Si	-0.99%	-0.98%
Mismatch, original SiGe cap	1.26%	1.26%

- Parallel and perpendicular strain obey Poisson relationship to within ~2%

$$\epsilon_{\perp} = -\frac{2\nu}{1-\nu}\epsilon_{\parallel} \quad \nu_{\text{Si}} = 0.28$$

- Strain in SSOI is fully preserved
- No strain detected in bonded or SIMOX SOI

- Raman spectroscopy sensitive to parallel strain only
- Parallel strain by Raman given by: $\epsilon = c\Delta\omega$
- Previous reports: **scalar $c = 0.123$** [Tsang et al., *J. Appl. Phys.* 75, 8098 (1994)]



Correlation of Raman shift to strain

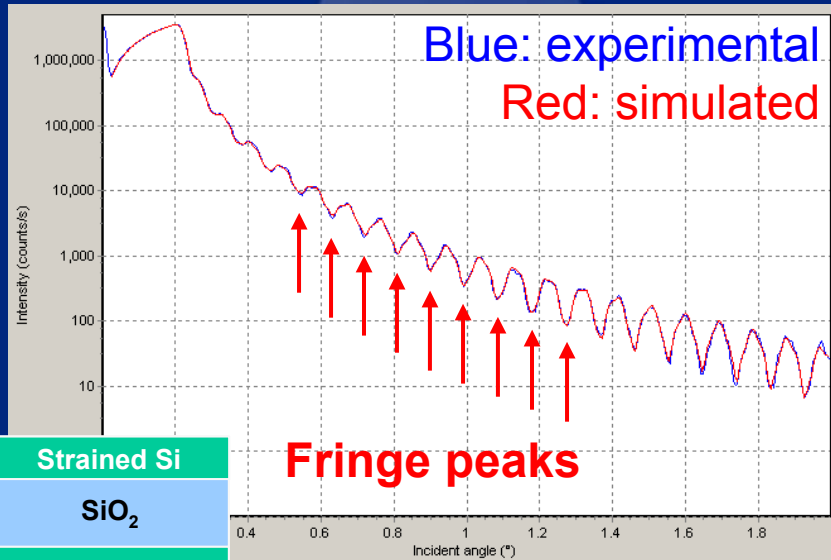
- Ten SSOI samples investigated
- Strain measured **directly** by XRD
- No assumptions made

Scalar $c = 0.134$

How Thickness Is Determined

X-ray reflectivity (XRR)

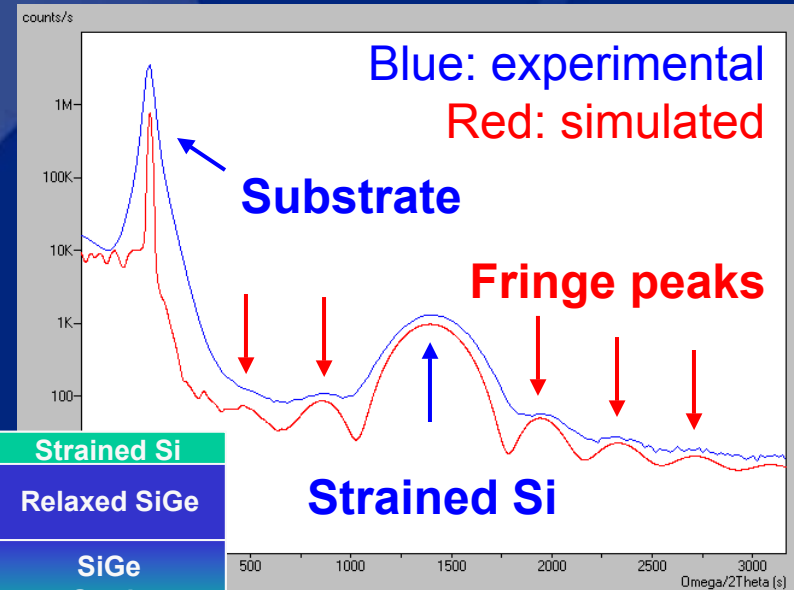
- Fringe spacing determines thickness
- Can also determine density, roughness
- More sensitive to thin layers than XRD



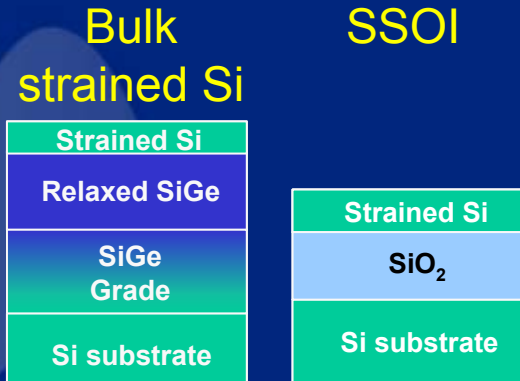
Strained Si
SiO ₂
Si substrate

X-ray diffraction (XRD)

- Fringe spacing determines thickness
- Less sensitive to thin layers than XRR, requires higher dynamic range

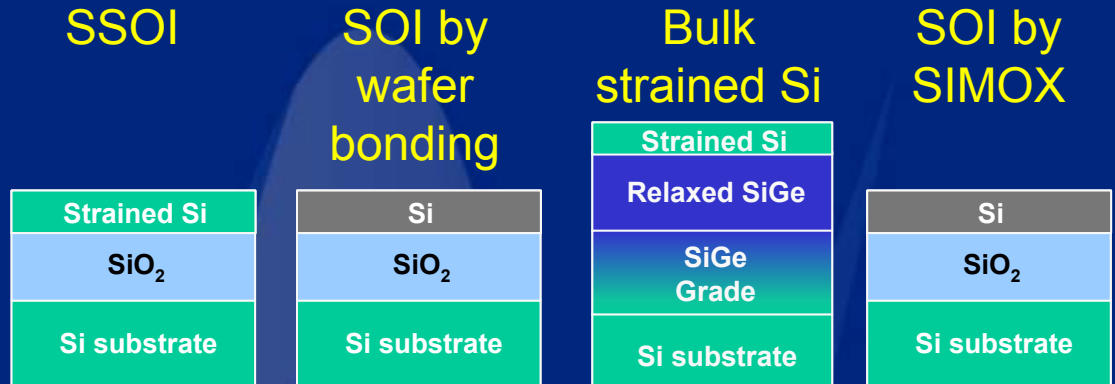


Strained Si
Relaxed SiGe
SiGe Grade
Si substrate



Strained Si thickness, XRR	530 Å	455 Å
Strained Si thickness, XRD	512 Å	—

- Difference of ~3% between XRR and XRD
- XRR will have higher accuracy due to higher sensitivity
- First demonstration of strained Si thickness measurement by XRD without synchrotron radiation
- **Routine monitoring of strained Si substrates by XRD and XRR is possible**



Tilt of Si layer <i>wrt</i> Si substrate	0.22°	0.12°	0.02°	< 0.01°
Twist of Si layer <i>wrt</i> Si substrate	-0.68°	-0.19°	—	< 0.01°

- Tilt and twist measured with x-ray diffraction
- Both bonded substrates have **appreciable** tilt and twist, since layer and substrate are formed from **different** crystal lattices
- Bulk strained Si and SIMOX SOI have **negligible** tilt and twist since layer and substrate are formed from the **same** crystal lattice

- Complete structural parameters were measured for bulk strained Si and SSOI by x-ray diffraction and reflectivity
 - Strain
 - Thickness
 - Tilt and twist
- Strain measurements correlated with Raman
 - More accurate value of strain scalar determined
- X-ray diffraction and reflectivity are suitable for routine strained Si monitoring
 - No need for synchrotron x-ray source