High Resolution X-ray Diffraction for In-line Monitoring of Ge MOSFET Devices

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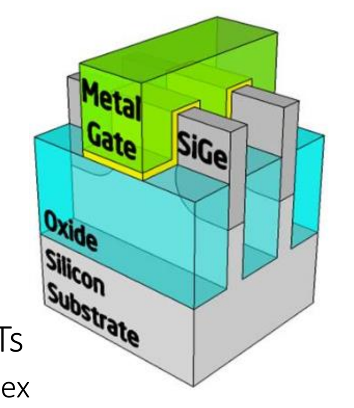
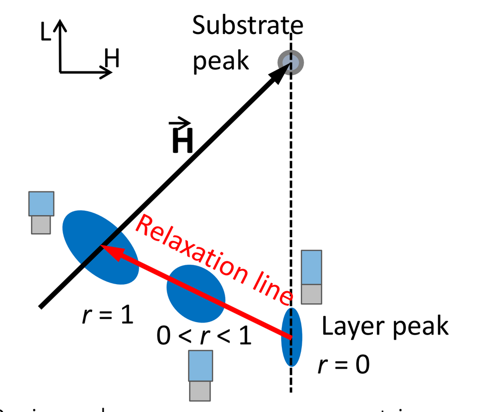
Introduction

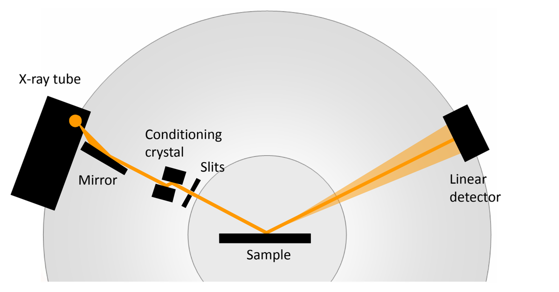


- The semiconductor industry is moving from 2D planar devices to 3D fin-shaped field effect transistors (FinFETs)
  - Keep Moore's law alive for logic at 22 nm nodes and below
  - Increase performance and reduce power consumption
- Many challenges in the fabrication of FinFETs
  - Multiple patterning lithography, new and complex materials, processes and integration schemes
- Serious challenges for established characterization and metrology techniques / tools used for R&D and process control
- We discuss the analysis of Ge MOSFET structures using high-resolution X-ray diffraction (HRXRD)[6]

RSMs with 1D detector

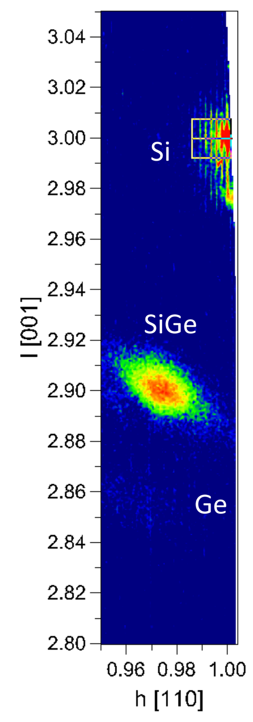


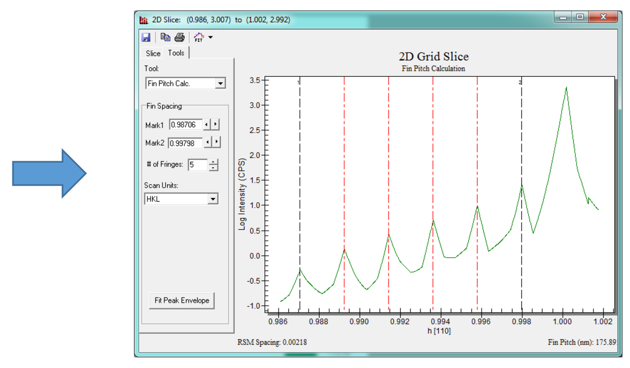
- Reciprocal space maps on asymmetric reflections are used to determine in-plane and out of plane lattice parameters from one measurement
  - Composition and relaxation can then be determined
- Information is also obtained on any lateral periodicity, e.g. fin structures
- Traditionally very slow so only used for R&D
- Recent advances mean these can be performed in small areas in minutes



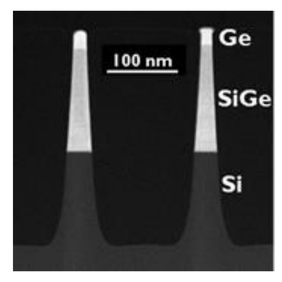
- A linear (1D) detector is used in place of the point (OD) detector and analyzer crystal
- Allows simultaneous measurement over a large range of 2θ angles
  - Resolution is limited by the width of the diffracted X-ray beam
- RSMs now collected in the same time as single Omega-2Theta scans
- Automated analysis of RSMs in now possible

Results: Using 1D detector



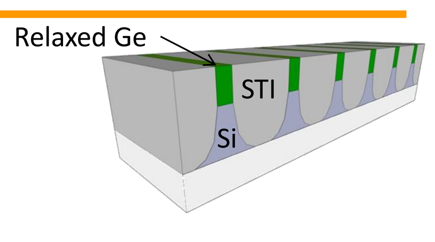


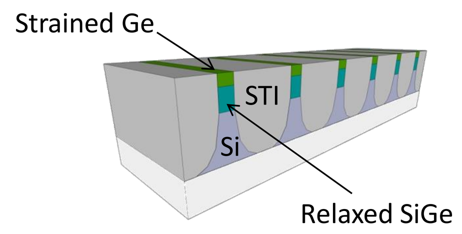
- Ge on SiGe on Si fins
- 113 RSM collected using 1D detector
- Additional fin information now available from the satellites around the Si peak
  - Pitch = 176nm
- Fin information correlates with TEM (right)
- Other information still available from single map

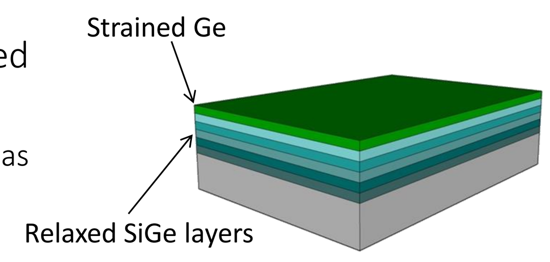


Samples

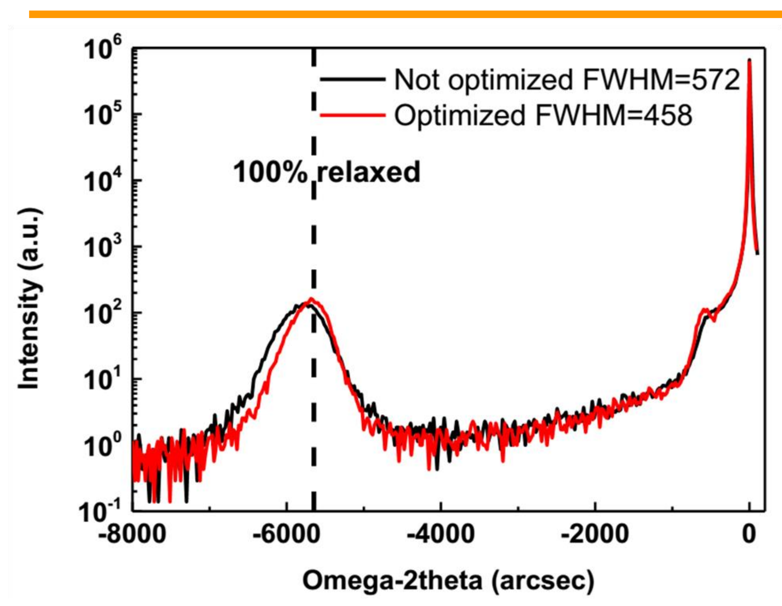
1. Relaxed Ge[2]
   - Relaxed Ge grown selectively in trenches of STI after a Si recess.
   - To reduce threading dislocation density, Ge was overgrown then made smooth using CMP process
2. Strained Ge on relaxed SiGe buffer[3]
   - Deposition of strain relaxed SiGe buffer layer (Ge content ~ 70%) into STI trench after Si recess
   - Ge deposited on top of SiGe
   - Ge layer was strained with respect to relaxed SiGe buffer layer
3. Strained Ge on multiple relaxed SiGe layers[4]
   - Commercially available strain relaxed SiGe buffer layers used as template
   - Strained Ge layer deposited on top of SRB
   - Blanket wafer only

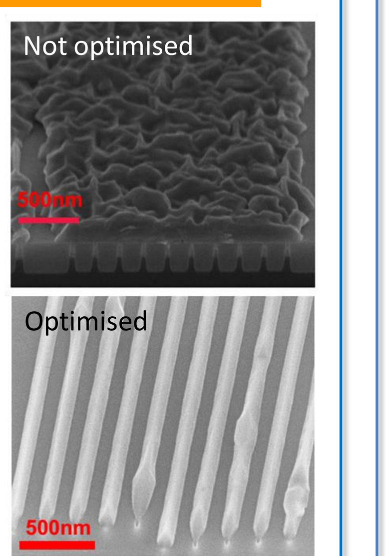






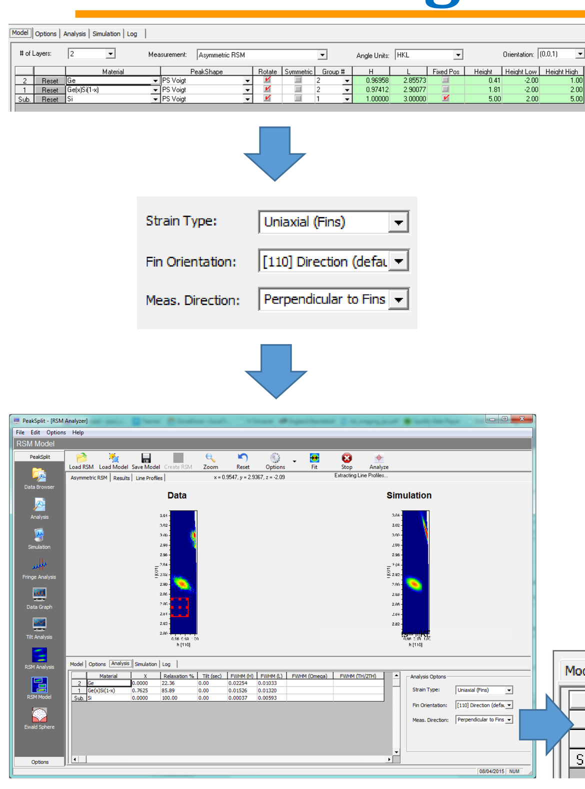
Results: Relaxed Ge

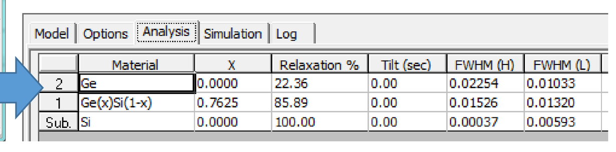




- Position within Omega-2Theta scans show 100% relaxed films
- FWHM of Omega scans indicate quality of layer
- Optimised layer shows lower FWHM and illustrated by SEM image (right)
- HRXRD can be used to investigate and control layer quality within relaxed epilayer structures

RSM Fitting

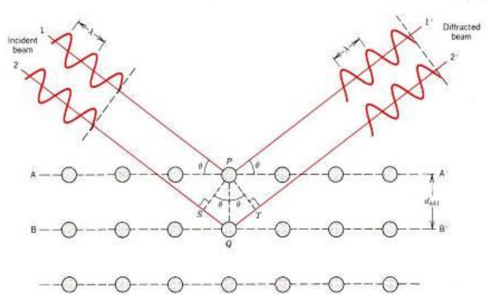




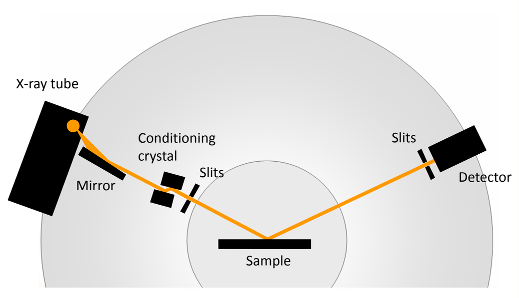
- RSM fitting can now be automated
- Create a model with peak bounds in reciprocal space
- Select strain type
  - Uniaxial and biaxial both supported
- Peak locations and heights are fit in 3D to determine position within RSM
- Fit positions are used to determine composition and relaxation of each peak
- Fit widths give information on defect density

HRXRD: Fundamentals

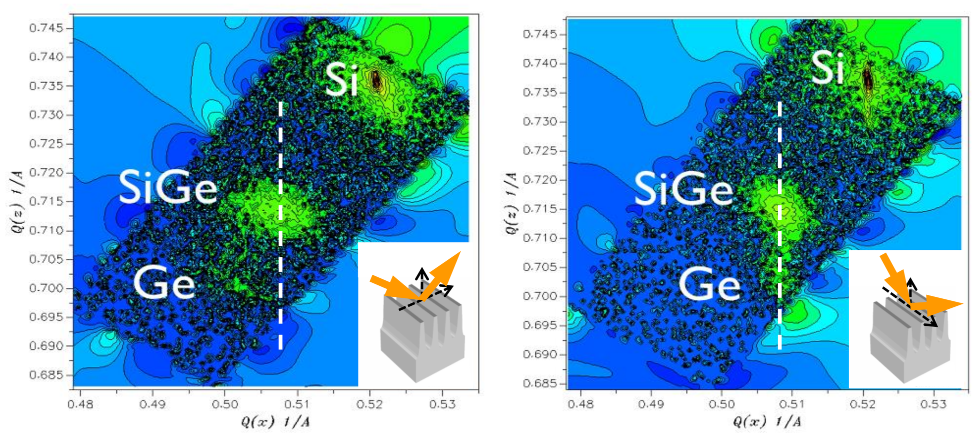
- X-rays have similar wavelengths to the distances between atoms in solids.
  - Scattered X-rays are characteristic of the properties of materials and structures at atomic length scales
  - X-ray diffraction arises from constructive scattering from periodic arrangement of atoms in single crystal materials
- Measurement and simulation of HRXRD spectra is straightforward and well established[5]
  - It does not depend on variable material properties (such as *n* & *k* optical constants) but on first principle theory



$2d \sin \theta_B = \lambda$



Results: Strained Ge on SiGe



- SiGe peak is shifted in Q_x in both cases indicating relaxation
- Ge peak is shifted from SiGe peak when measuring across fins but not shifted when measuring along fins
  - Uniaxial relaxation of Ge layer across fins
- Relaxation across the fins depends on fin width[6]

HRXRD for FinFET processes

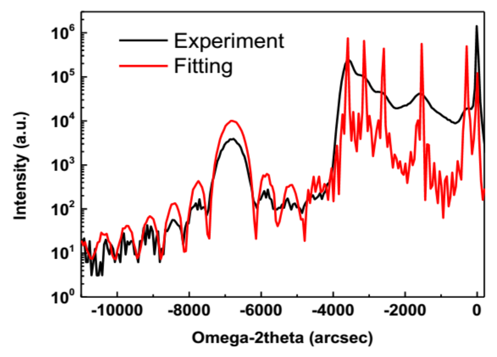
Fin Parameter	Capability	Notes
Pitch	Quantitative (green)	Position of fundamental grating rods in H-scan
Pitch walking	Quantitative (green)	Intensity ratio of harmonic grating rods in H-scan
Fin width	TBD	Intensity modulation of grating rods
Fin sidewall angle	Quantitative (green)	Splitting of L-scans through high-order grating rods
SiGe fin thickness	Quantitative (green)	Period of interference fringes in L-scan along 0-th order grating rod (defect free epi)
SiGe fin composition	Quantitative (green)	Position of peak in L-scan along 0-th order grating rod
SiGe fin strain/relaxation	Quantitative (green)	Position of layer peak envelope in RSMs of symmetric (vertical component) and asymmetric (horizontal & vertical components)
SiGe fin defectivity	Qualitative (yellow)	Lack on interference effects and layer peak broadening in RSMs

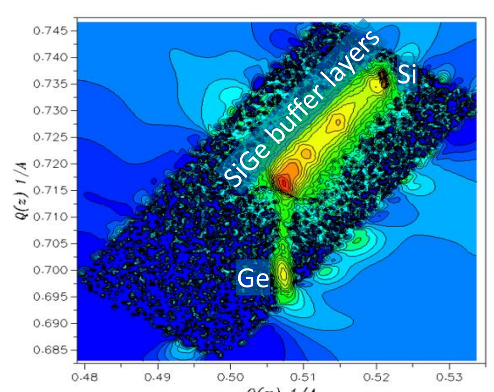
Quantitative (green) Qualitative (yellow) No capability (red)

Equipment: JVX7300LSI

- JVX7300LSI **Small & Large-Spot** X-Ray Metrology tool for:
  - **10nm** node and below Si R&D and process development
  - In-Fab, in-line production process monitoring of semiconductor applications:
    - SiGe, III-V and GaN on Si FinFET analysis, defect density, epilayer thickness, composition and relaxation on **blanket** and **product** (patterned) wafers
    - High-K / metal gate crystallinity / thickness / density
- Advanced 300mm scanning tool for: **HRXRD, XRR, WA-XRD, GI-XRD, In-Plane XRD**
- All tool configuration, alignment and measurement is **fully automatic**
- JVX7300LSI is a **dual source system**
  - **M channel (<0.2mm beam) or S channel (<50µm beam) available**
  - Use the large beam for HRXRD alignment to Si substrate and then automatically transfer to small spot source for measurement. Allows much faster and more precise alignment.
    - Can use large beam HRXRD for blanket or large arrays of structures
  - Large spot also used for XRR and XRD as these are generally blanket applications within R&D, giving much higher throughput

Results: Ge on SRB Layers





- Ge thickness fringes present in Omega-2Theta scan
  - Layer is fully strained
  - Sets upper limit on dislocation density in Ge layer of ~ 10^5 cm^{-2}
  - Can determine layer thickness from these fringes
    - ~30nm in this example
- SiGe SRB peaks gives composition of SiGe buffer layers
- Ge peak position shows no Q_x shift from last buffer layer
  - No relaxation
- SiGe SRB peak positions indicate
  - Composition of buffer layers
  - All layers fully relaxed
    - Shift in Q_x in each subsequent buffer

Conclusions

- High-resolution XRD delivers valuable information on nanostructures relevant to FinFET devices
- Composition and relaxation of complex structures can be obtained from single reciprocal space maps collected on asymmetric reflections
- The latest generation of lab / fab tools can yield good quality data in minutes not several hours
  - Including symmetric & asymmetric RSMs using 1D detectors
- In-line X-ray metrology tools, like the JVX7300 series, enable advance materials and process development and provide novel solutions for production monitoring

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