2D & 3D ADVANCED TRANSMISSION ELECTRON MICROSCOPY FOR SEMICONDUCTOR CHARACTERIZATION

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3DAM, TEM for FEOL SiGe Stacked Nanowire

- **STEM imaging, Electron tomography**
  
- **EDX, EELS-STEM for composition & doping**
  
- **TEM (N-PED) for strain measurements**
• **Introduction, multidimensional TEM**

• **Strain measurements in a TEM**
  - Principle & performances of N-PED
  - Application to 3DAM sample (strain and composition measurements)

• **Electron tomography**
  - Software
  - Application to 3DAM sample

• **Analytical electron tomography**

• **Summary**
INTRODUCTION, ANALYTICAL STEM TECHNIQUES, 2D & 3D

- Modern TEM capabilities:
  - Fast EELS or EDX acquisition in STEM mode
  - Composition measurement, quantification
INTRODUCTION, STRUCTURAL TEM TECHNIQUES, 2D & 3D

- Modern TEM capabilities:
  - Fast NBED pattern acquisition
  - Strain measurement, orientation & phase identification

EDS detectors

ADF detectors

Fast Camera
CCD, CMOS, pixel array detector
TRANSMISSION ELECTRON MICROSCOPES @ LETI USED IN THESE STUDIES

FEI Titan Themis 80-200 kV
XFEG gun, Monochromator, Cs Probe Corrector, Super X, Holography, GATAN Energy Filter, FEI CETA CMOS Camera

FEI Titan Ultimate 80-200-300 kV
XFEG gun, Monochromator, Cs Probe & Cs Image Correctors, Holography, GATAN Energy Filter, GATAN OneView CMOS Camera
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• **Summary**
Why the use of precession for measuring strain?


N-PED: Higher Convergence Angle → Smaller Probe size (<1nm) → Higher Resolution
Higher Convergence Angle → Larger disks = longer edges = better detection of circle → Higher precision
Many more electron spots/disks
Why the use of precession for measuring strain?

- To avoid dynamical diffraction effects.
STRAIN MEASUREMENTS IN A TEM

- References:

Use of a standard Si/SiGe multilayer sample


Test structure with SiO$_2$/Si$_3$N$_4$ dummy gates and recessed SiGe S/D


N-PED precision ~ 0.02 – 0.05 %
Spatial resolution ~ 1-3 nm
**N-PED, APPLICATION TO 3DAM SAMPLES**

- **RAMAN at $\lambda = 532$nm (penetration depth of 1 $\mu$m)**
  - The frequency shift ($\Delta \omega_{\text{Si-Si}}$) for multilayer blanket corresponds to a **Ge concentration of around 31%**
  - Assumption: the multilayer is pseudomorphic, no relaxed layer

- **Can we confirm by N-PED that the blanket sample is made of biaxially strained Si$_{69}$Ge$_{31}$ layers?**

- **N-PED experiment:**
  - FIB (low kV) sample preparation
  - HRSTEM imaging to measure the layers
  - PACBED* to measure the foil thickness: 104 nm +/- 2 nm
  - N-PED acquisition and data processing (2 nm resolution)
  - EDS-STEM: SiGe quantification test / RAMAN (k-factor)

- **Mechanical simulation by finite element modelling (FEM) to estimate the strain relaxation of the FIB foil:**
  - 3D Model using COMSOL software
  - Si/SiGe layers thicknesses: HRSTEM imaging
  - FIB foil thickness: PACBED
  - Composition: RAMAN
  - 3D model projection over the foil thickness direction such that the experimental N-PED strain maps can be directly compared

* Positioned Averaged Convergent Beam Electron Diffraction

*IV_IMEC_DEV01 (Blanket multilayer)*
- SiGe/Si/SiGe/Si on Si substrate
N-PED, APPLICATION TO 3DAM SAMPLES

Strain maps acquired by PED are shown for the [220] and [002] directions.

3D Model using COMSOL software

3D model projection over the foil thickness direction
A good fit is obtained between PED and FEM for a **Ge content of around 31%** as measured by Raman. The Ge content measured by a quantitative EDS treatment in Esprit (k-factor) was 30 % using K line of the Ge peak, **EDS Quantification is in good agreement with RAMAN if we use K lines for both Si and Ge elements**.
N-PED, APPLICATION TO 3DAM SAMPLES

- Ge composition map (EDS-STEM)

The edges of the SiGe layers exhibit a higher intensity of the HAADF signal, which corresponds to a higher Ge content. Effect of condensation during the fin etching?

- N-PED strain measurements

Strain maps acquired by N-PED are shown for the [220] and [002] z directions.

IV_IMEC_DEV02 (Embedded Multilayer Fins)
- In between fins = SiO₂ to the top
- Surface planarized
- Arrays of fins

30 at. % of Ge in the center of the SiGe layers, 50 at. % on the sides
N-PED, APPLICATION TO 3DAM SAMPLES

- Relaxation along the Fin width [220] $\varepsilon_{xx}^{PED}$

The strain profile along the dotted blue line shows that the $\varepsilon_{xx}$ strain ranges from 1 to 1.2 % in the center of the SiGe layers. This level corresponds to full relaxation of the structure along the fin width.

- Strain along the [002] direction $\varepsilon_{zz}^{PED}$

The strain profile along the dotted blue lines shows that the $\varepsilon_{zz}$ strain ranges from 1.3 to 1.7 % in the center of the SiGe layers. This level of strain is:

- Higher than the one for a fully Si$_{70}$Ge$_{30}$ relaxed layer ($\varepsilon_{zz} \sim 1.15\%$),
- Lower than the one for a Si$_{70}$Ge$_{30}$ fin with no relaxation along the fin length ($\varepsilon_{zz} \sim 2.04\%$)

In between fins = SiO$_2$ to the top
- Surface planarized
- Arrays of fins
OUTLINE

• Introduction, multidimensional TEM
• Strain measurements in a TEM
  • Principle & performances of N-PED
  • Application to 3DAM sample (strain and composition measurements)
• Electron tomography
  • Software
  • Application to 3DAM sample
• Analytical electron tomography
• Summary
ELECTRON TOMOGRAPHY GUI

- **Purpose**: User-independent, fast and efficient process for 3D reconstruction
- **Electron tomography software**:
  - Get benefit from Graphics processing unit (GPU)
  - Adapted to needle-shaped samples/on-axis tomography holder

1. Automated $x$, $z$ and tilt axis measurements

2. Apply & check alignment

3. Reconstruction using FBP* or SIRT** (Astra Toolbox)

- **Mix of 3 techniques**
  - cross-correlations between neighboring projections
  - common line algorithm to get a precise shift correction in the direction of the tilt axis
  - intermediate reconstructions to precisely determine the tilt axis and shift correction in the direction perpendicular to that axis

* : filtered backprojection ** : simultaneous iterative reconstruction technique
• Application to 3DAM sample

Acquisition IV_IMEC_DEV02 (Embedded Multilayer Fins)
• 30 projections from -90° to +90°
• Frame size: 2048x2048 pixels
• Frame time: 20sec
• Pixel size: 133pm
**ELECTRON TOMOGRAPHY GUI**

- Application to IMEC sample

Acquisition IV_IMEC_DEV02 (Embedded Multilayer Fins)
- 30 projections from -90° to +90°
- Frame size: 2048x2048 pixels
- Frame time: 20sec
- Pixel size: 133pm

Tilt series

Aligned tilt series

3D reconstruction (SIRT)
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• **Summary**
• Challenge: monitor As dopant implantation process in a silicon Fin structure
• Experimental & EELS data processing setup:
  • Needle shaped FIB sample preparation, on-axis holder (2050 Fischione)
  • 23 HAADF STEM images & 23 fast Dual EELS maps projections (between -90° and +90°)
  • PCA denoising and extraction of O K, As L_{2,3} and Si K elemental tilt series

ANALYTICAL ELECTRON TOMOGRAPHY

HAADF STEM
23 projections x 546x512 pixels

EELS STEM ROI
23 projections x 60x90 pixels

PCA and pseudo EELS quantification

23 sets of 3 elemental maps
ANALYTICAL ELECTRON TOMOGRAPHY

- Use of the home-made software for alignment (with HAADF STEM)
- Rescaling & Zero-padding of the elemental maps
  - HAADF & EELS STEM data fusion
- Application of the shifts in x and y from the HAADF-STEM alignment
- 3D reconstruction (next slide)
ANALYTICAL ELECTRON TOMOGRAPHY

HAADF STEM image of the needle shaped specimen including the FinFET

Elemental maps of Silicon, Oxygen and Arsenic at 70°

3D SIRT reconstruction obtained with the 23 elemental projections

a) Overlay of 3D elemental volumes
b) x,y slice through the As elemental reconstruction showing As clustering
ANALYTICAL ELECTRON TOMOGRAPHY

- Microscopy & Microanalysis US conference in August
  - J. Sorrel & Z. Saghi, Correlative HAADF-STEM and EDX-STEM tomography for the 3D morphological and elemental analysis of FinFET semiconductor devices.
  - M. Jacob & Z. Saghi, Multivariate analysis and compressed sensing methods for spectroscopic electron tomography of semiconductor devices

- Batch-processing of the 3D dataset: Spectral unmixing using MSA (NMF, VCA)
- Total variation minimization algorithm (TVM) 3D reconstructions and more
- Better quality reconstruction of the As precipitates, Fin sidewall = metrology

Identification of three chemical phases in the sample: Si, SiO$_2$ and As

EDS STEM data set

SIRT/TVM comparison

Si \hspace{2cm} O \hspace{2cm} As

\[
\text{SIRT: } \min_{f} \|Af - p\|_2^2
\]

\[
\text{CS: } \min_{f} \|Af - p\|_2^2 + \|T(f)\|_1
\]
SUMMARY

• **Strain measurements**
  - N-PED used as a standard technique at LETI
  - Combine TEM local measurement with a non-destructive technique (RAMAN) and mechanical modelling

• **(Analytical) Electron tomography**
  - Software: user-independent, fast and reliable
  - Still some work to extract 3D quantitative information from reconstructed volumes
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Thank you for your attention

3rd 3DAM Metrology Workshop at Minatec Campus, Grenoble, March, 15th 2019

2nd European FIB Network Workshop
Grenoble, France
June 19th-20th, 2018
http://www.eu-f-n.org/2018-grenoble