INSIGHT-DRIVEN PROCESS DEVELOPMENT: FROM FUNDAMENTALS TO APPLICATION

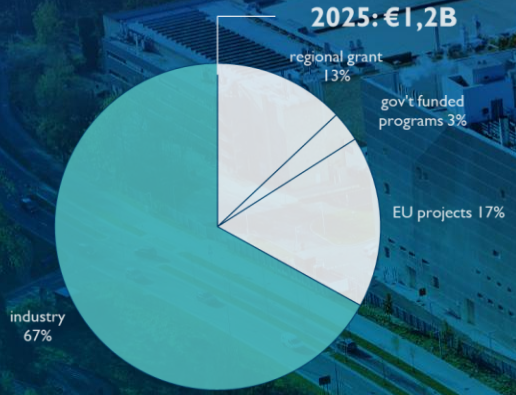
T NUYTTEN


As a **world-leading R&D** hub, we aspire to achieve the impossible and aim for **disruptive innovation**. We maximize societal impact by creating **smart sustainable solutions** that enhance **quality of life**.
At imec, we shape the future.
imec

talented employees

~6500 skilled people

~100 nationalities



world-class infrastructure

~12,000m2 cleanroom
+6,000m2 cleanroom expansion

€3,5B investment
+€2,5B additional investment

over 250 tools

24/7 operation

global ecosystem

- Equipment Suppliers
- Material Suppliers
- Design & System Companies
- IDMs & Foundries
- Academia and RTO
- Start-Ups & SMEs

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imec is a global organization

● R&D ● Representative office

our impact extends across key application domains

compute

health

automotive

industry

consumer electronics

aerospace & security

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compute

health

automotive

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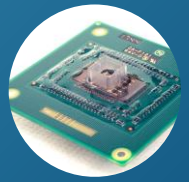
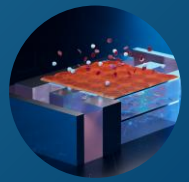
consumer electronics

aerospace & security



DNA sequencing

process analytic technology

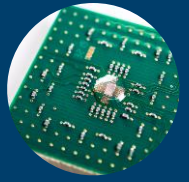


blood brain barrier

neuroprobe

140 GHz radar in deeply-scaled CMOS

integrated photonics for on-chip lidar



edge-AI chip

CMOS-based NIR and SWIR imagers

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Our impact extends across key application domains

compute

logic

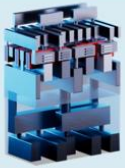
memory

interconnect

litho

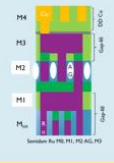
other

NS



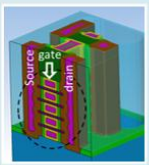
CFET

Nano-IC

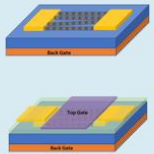


LNA EUV

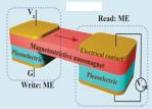
2D FET



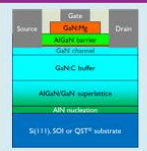
CNT FET



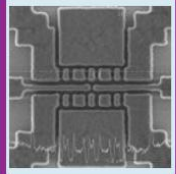
Spin logic



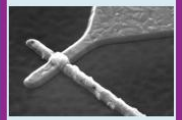
GaN Power



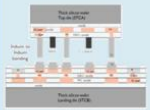
Spin QB



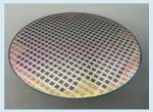
SC QB



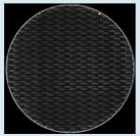
3Di



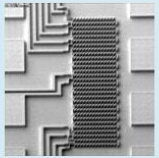
D2W



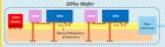
W2W



RDL

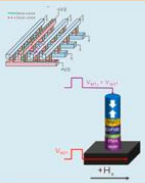


OIO

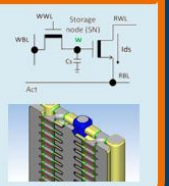


Adv RF

MRAM

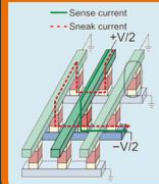


DRAM

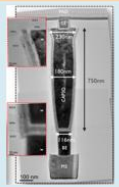


HNA EUV

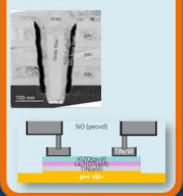
SCM



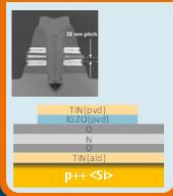
FeRAM



FeFET



NAND



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Fundamental process insight
on materials and interfaces
as innovation driver

Ge segregation causes roughness disparity / mitigation by passivation

Ge atoms segregating into the Si, during the initial stages of the Si layer growth, driven by more energetically favorable Ge-terminated surfaces

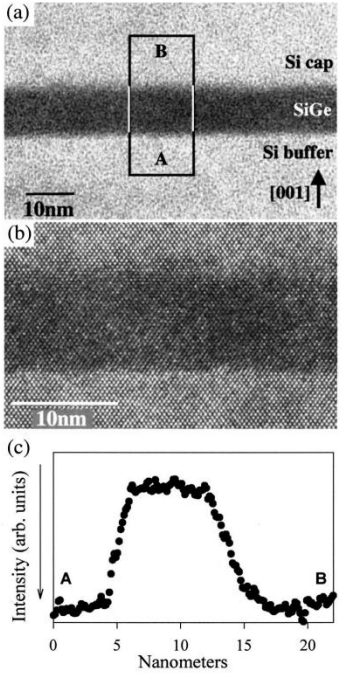


FIG. 1. (a), (b) 002 and high resolution [110] images of SiGe channel in Si matrix, and (c) inverted intensity profile across the region outlined in (a).

Norris J Appl Phys 86 7183 (1999)

- Ge atoms preferentially replacing Si atoms at the surface to minimize the surface free energy.
- DFT simulations further confirmed that Ge-terminated structures are energetically favored over Si-terminated structures by 0.38 eV per dimer.

- Mitigation: surface treatments with hydrogen (H) or chlorine (Cl)
- The higher bond dissociation energy of Si–H and Si–Cl than that of Ge–H and Ge–Cl results in more stable Si-terminated surfaces, limiting Ge segregation.

- SiGe-to-Si interface can be improved by passivation (Cl or H) – as also confirmed by XRR
- This passivation provides better starting surfaces and limits the Ge segregation
- Theoretical study on self-limiting process: Fukatsu Appl Phys Lett 59 3103 (1991)

Jung Appl Surf Sc 690 162553 (2025) and refs therein

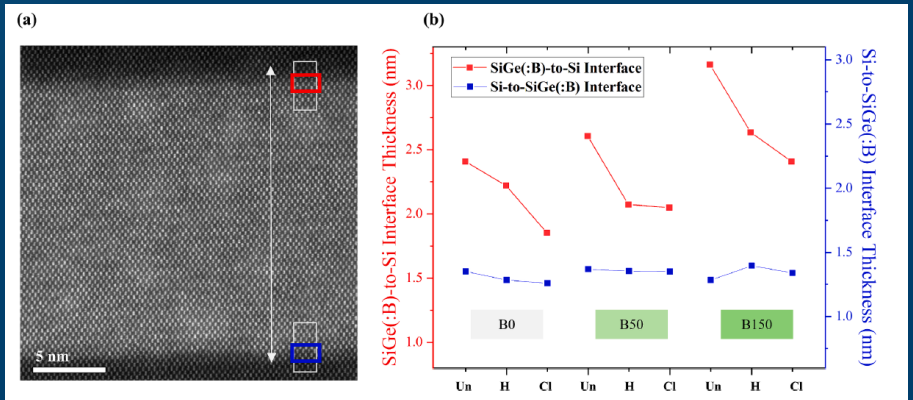
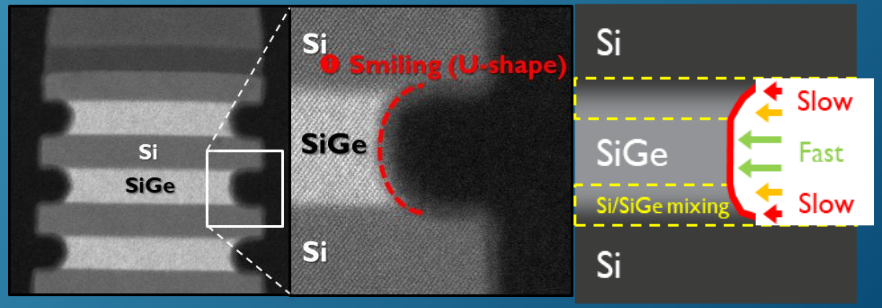
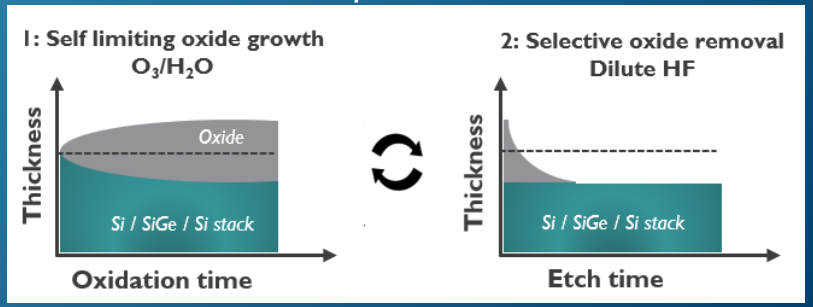
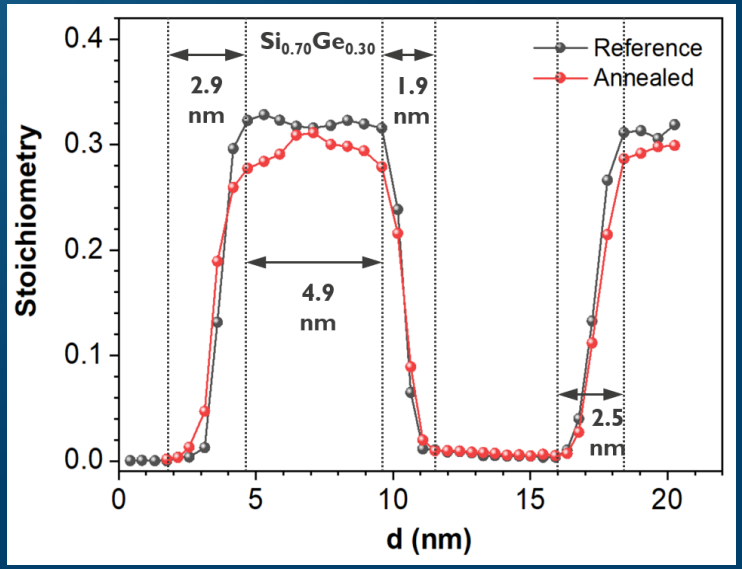


Fig. 7. (a) Cross-sectional STEM image highlighting the regions used for interface analysis. The blue box indicates the Si-to-SiGe(:B) interface, and the red box indicates the SiGe(:B)-to-Si interface. (b) Calculated Si-to-SiGe(:B) and SiGe(:B)-to-Si interface thicknesses, based on different surface treatments (untreated (Un), H-treated (H), and Cl-treated (Cl)) and B concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

At imec: Ge diffusion profile characterization in Si/SiGe/Si stacks







- Non-uniform selective cavity etch due to Ge out diffusion / intermixing at the Si/SiGe and SiGe/Si interfaces
- A wet ALE approach is combined with ICP-MS to probe the Ge diffusion profile with 5 Å spatial resolution
- The Ge intermixing layer extends 2-3 nm into the Si channel,
- Clear elevated Ge background levels in the channel region: SiGe1%

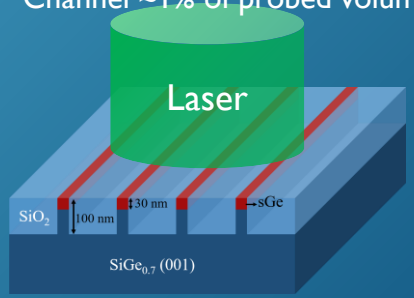
Agilent 8900 MS/MS

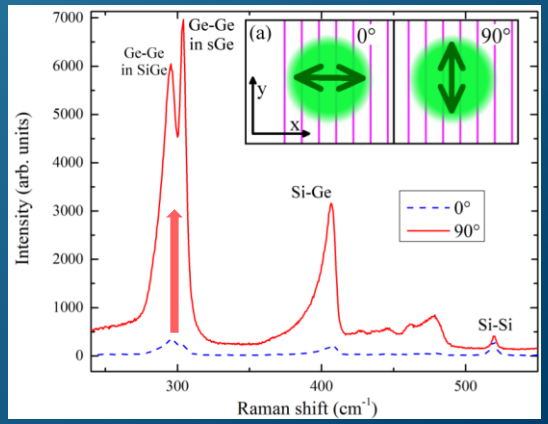
Courtesy D. van Dorp

Nanofocusing of light

Making deep sub-wavelength structures visible again

Channel ≈1% of probed volume

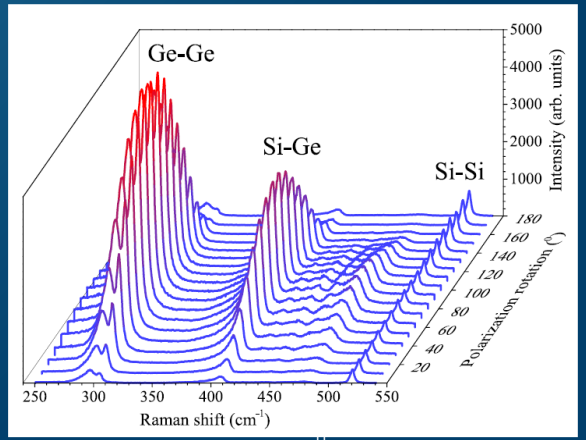


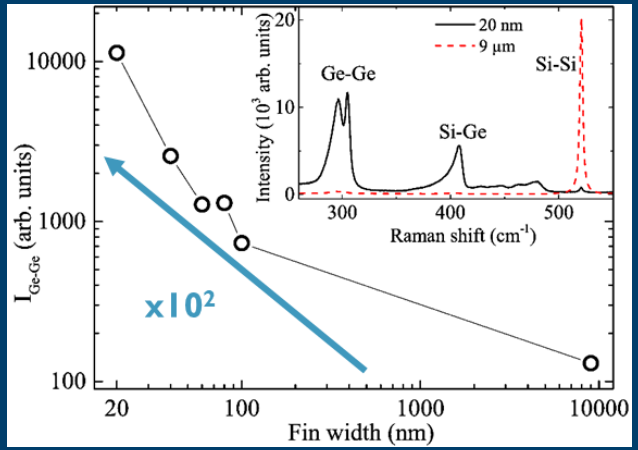


Configuration:

- Fully automatic 300mm stage with autofocus
- 325 405 473 532 633 nm laser excitation
- Motorized laser and Raman polarization kit
- Multipoints: coordinate-based wafer maps that can run without analyst supervision

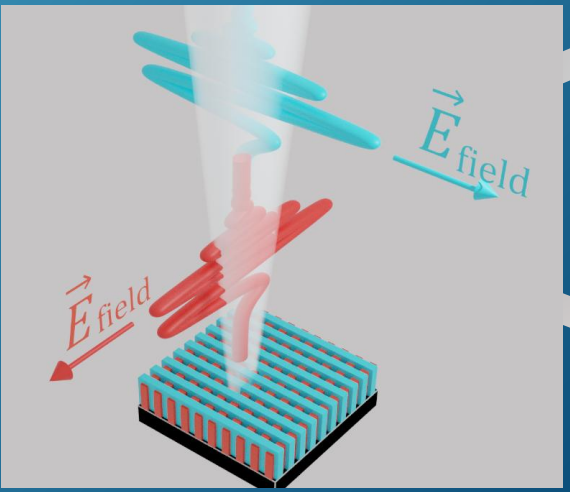
- Raman response dictated by geometric properties: critical dimension, pitch
- Allows for isolation of the signal of the ROI
- All strengths of Raman are re-enabled at the nanometer scale
- Opens path for Raman dimensional metrology

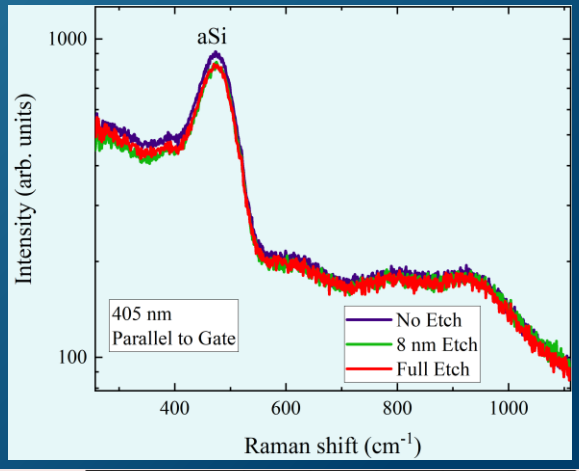




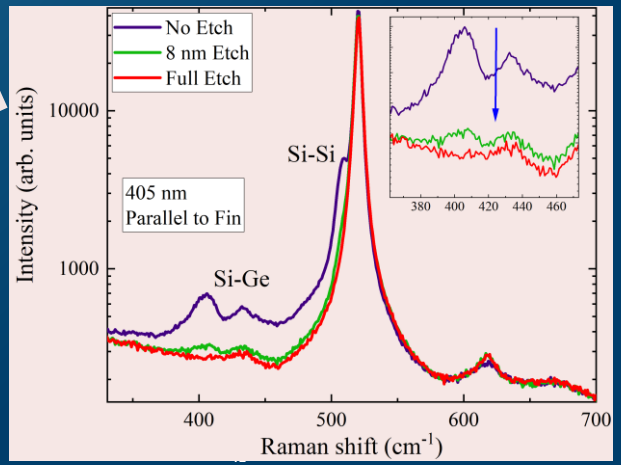
Kuhn FCMN 2013
Nuytten Appl. Phys. Lett. **106** 033107 (2015)
Bogdanowicz Appl. Phys. Lett. **108** 083106 (2016)
Gawlik Appl. Phys. Lett. **113** 063103 (2018)
Nuytten APL Mat. **6** 058501 (2018)
Nuytten Appl. Phys. Lett. 125 053506 (2024)
Nuytten US 12,216,057B2

Tunable selectivity for 3D volumes

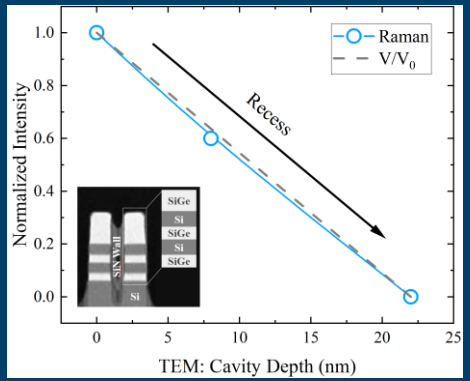




- All samples show identical aSi signature
- No SiGe visible at all



- Sensitivity to SiGe recess
- No aSi visible at all (!)



J. Bogdanowicz et al, Nanoletters 24, 1191 (2024)
Nuytten Appl. Phys. Lett. 125 053506 (2024)
Nuytten US 12,216,057B2

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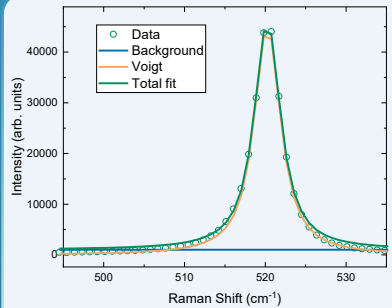
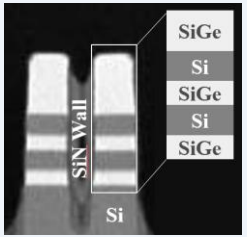
Applications and opportunities
Universal across technology roadmaps

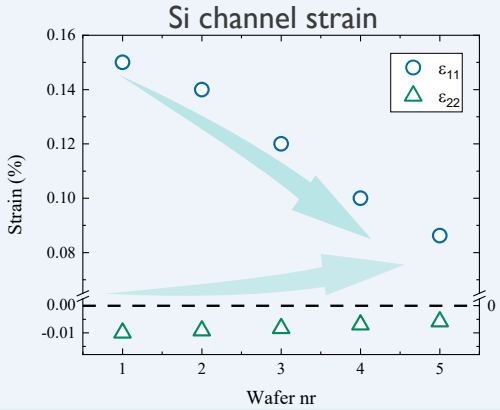
Channel Strain

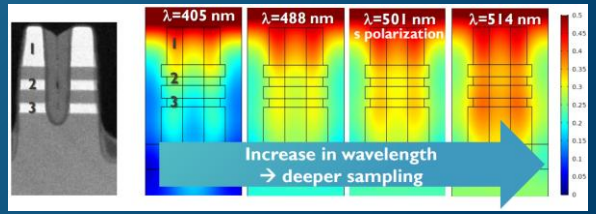


DOE on FS SiGe etch
- Fit cSi at 405 nm coming from channel
- Extract stress and strain

Relaxation:
- Tensile strain along
- Comp. strain across

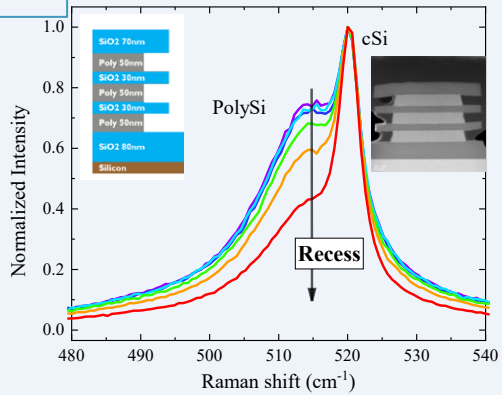


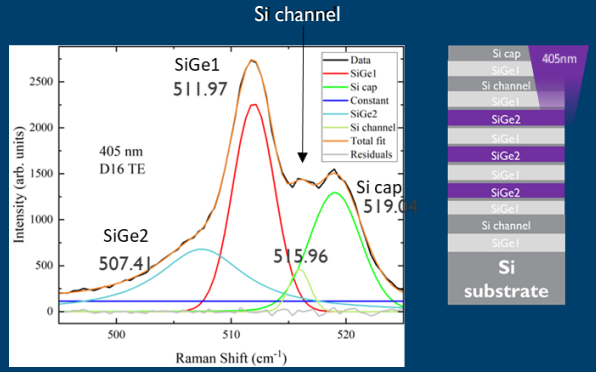




Memory stack CD

Universally applicable when signal can be isolated





Strain along channel (ε_{11})	+1.6%
Strain across channel (ε_{22})	-0.1%

Summary

- Continued semiconductor innovation will require deep process understanding
- Fundamental insight is critical for enabling breakthrough technology development
- Illustrations of this philosophy include the leverage of advanced metrology for insight into nanoscale interface phenomena

Acknowledgements

embracing a better life