# Lattice mismatched semiconductor integration for Si micro- & nanoelectronics

innovations for high performance microelectronics

## Compliant Ge nanoheteroepitaxy on patterned Si(001)


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## Nanoscience, Lichtenwalde, Germany (2012)

# Overview

- *Motivation: Mobile data communication*
  Electronic-Photonic ICs: Need for ultrafast Ge photodetectors …

- *Advanced heteroepitaxy approaches for nano-objects*
  Nanocontact heteroepitaxy: use of compliant substrate effects…

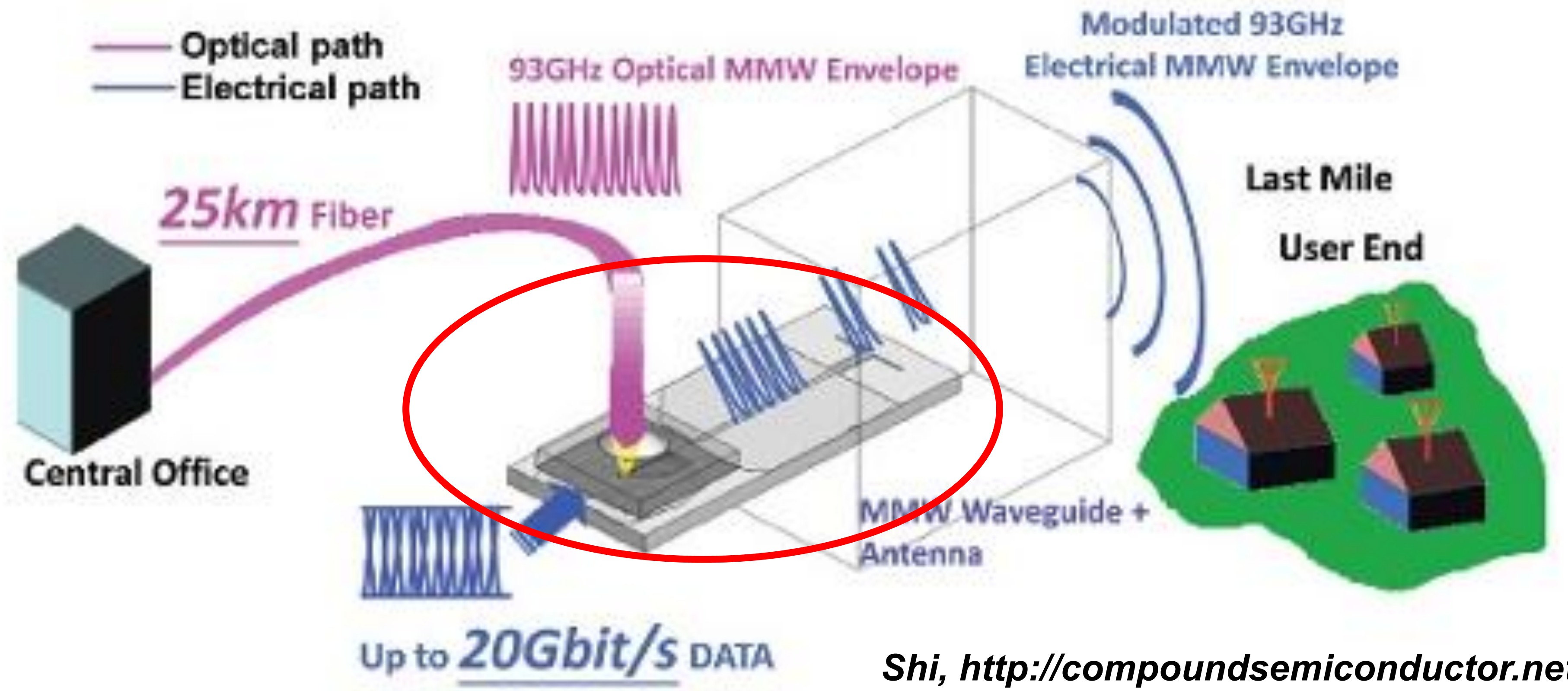
- *Complex top-down processing with nano-growth control*
  optical litho and selective CVD processes on 8“Si tools…

- *Hunting the “myth” of compliant substrate effects*
  the example of the Ge / Si nanostructures as a case study…

- *Summary: theory of nanoheteroepitaxy is oversimplification*
  growth mask effects, shape stabilities, microstrain effects etc.

# Motivation

## Mobile data communication: Radio over fibre



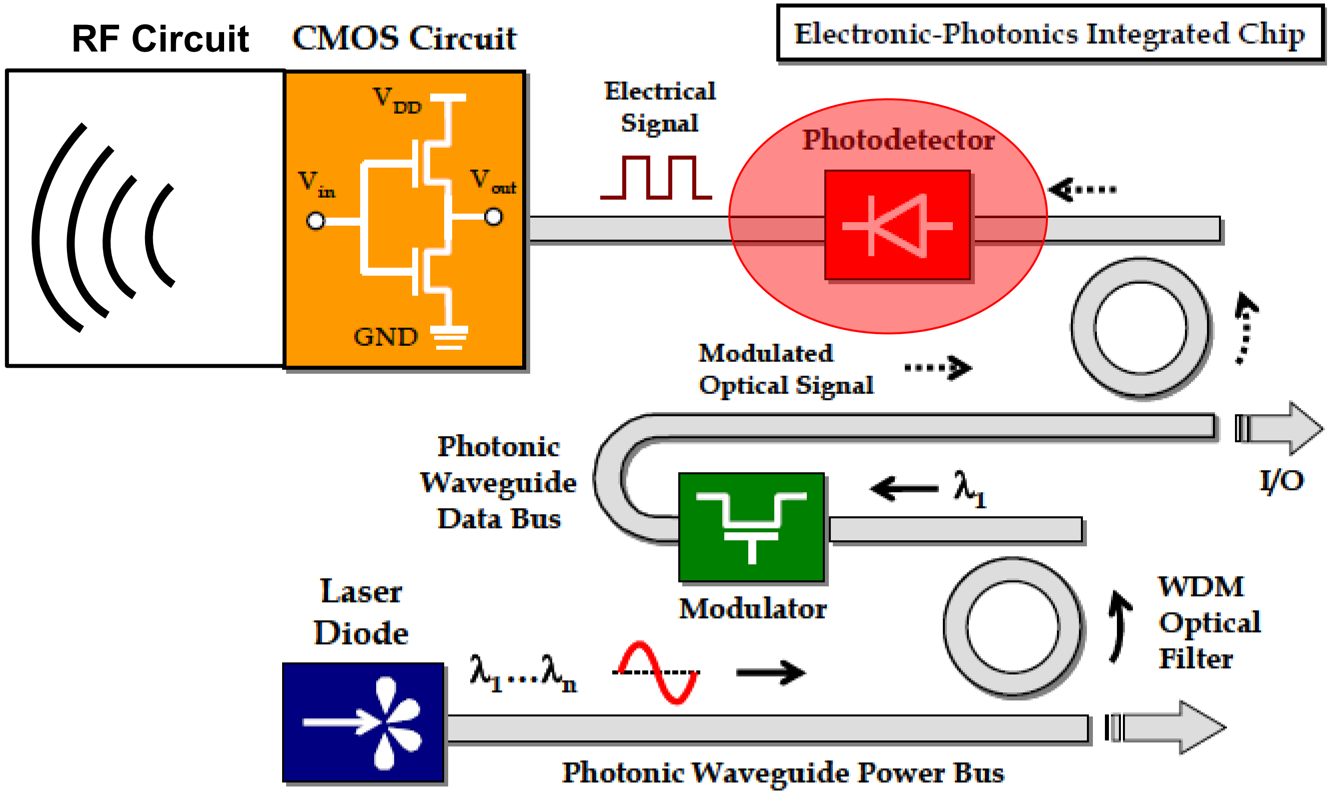

*Shi, http://compoundsemiconductor.net*
*Shi et al., NPG Asia Mater. 3 (2011) 41*

**Merging electronics and photonics on Silicon**

# Motivation

## Mobile data communication: EPICs are needed…

### Look inside an Electronic-Photonic Integrated Circuit…



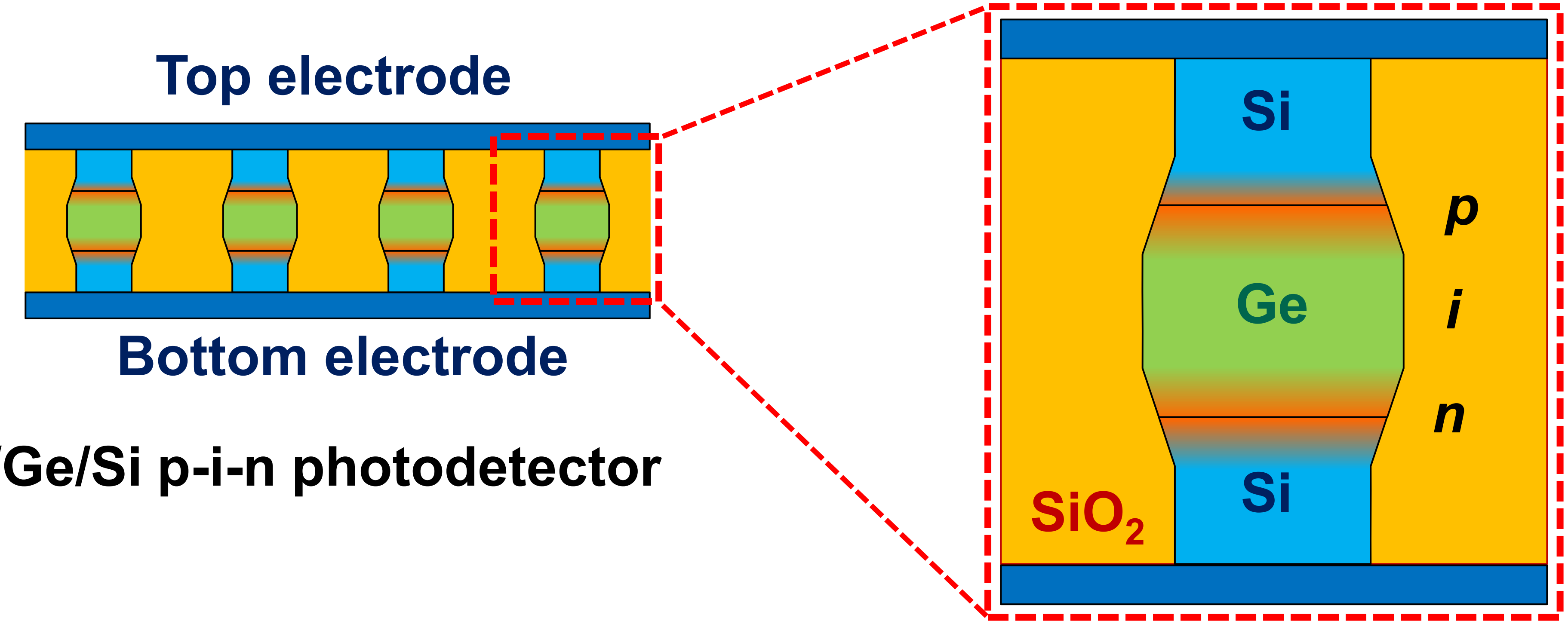

**High performance, high speed photodetectors**

**become bottleneck in RoF data transmission…**

# Motivation

## Ge Micro- and Nanocluster photodetector (PD) arrays…




Si/Ge/Si p-i-n photodetector

**High-speed and high-power photodetector is a must**

Ge photodetectors within Si CMOS technology

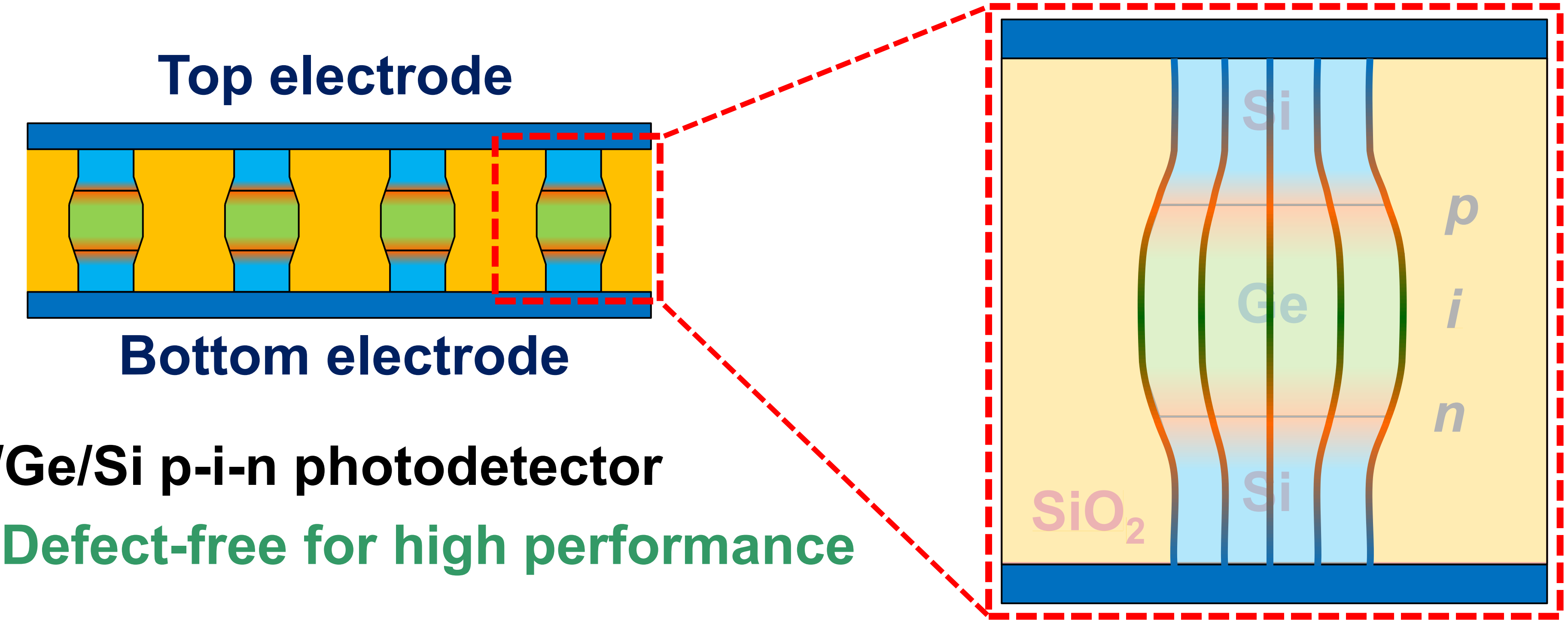
→ Band gap around telecommunication wavelength

→ Monolithic integration in Si CMOS fab is feasible

→ Ge Micro- & Nanocluster PD array: high speed & performance

# Motivation

## Defect-free Ge Micro- & Nanoclusters by compliance




**Si/Ge/Si p-i-n photodetector**

→ Defect-free for high performance

**Nanoscience: Defect-free Ge PD arrays by compliant growth**

→ Defects act as scattering, recombination, trapping centres

→ Interface as well as threading dislocations problematic

→ Defect-free Ge micro- and nanocluster arrays by compliance

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  **Nanocontact heteroepitaxy: use of compliant substrate effects…**

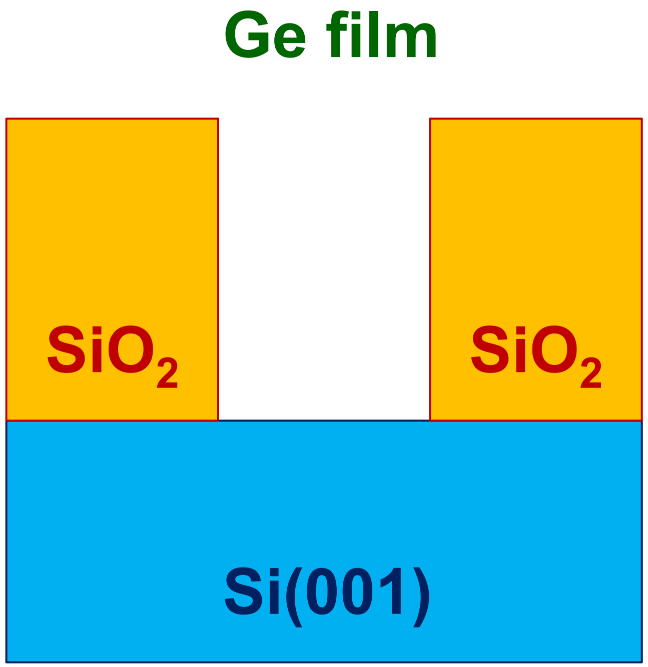
- ***Complex top-down processing with nano-growth control***
  **optical litho and selective CVD processes on 8“Si tools…**

- ***Hunting the “myth” of compliant substrate effects***
  **the example of the Ge / Si nanostructures as a case study…**

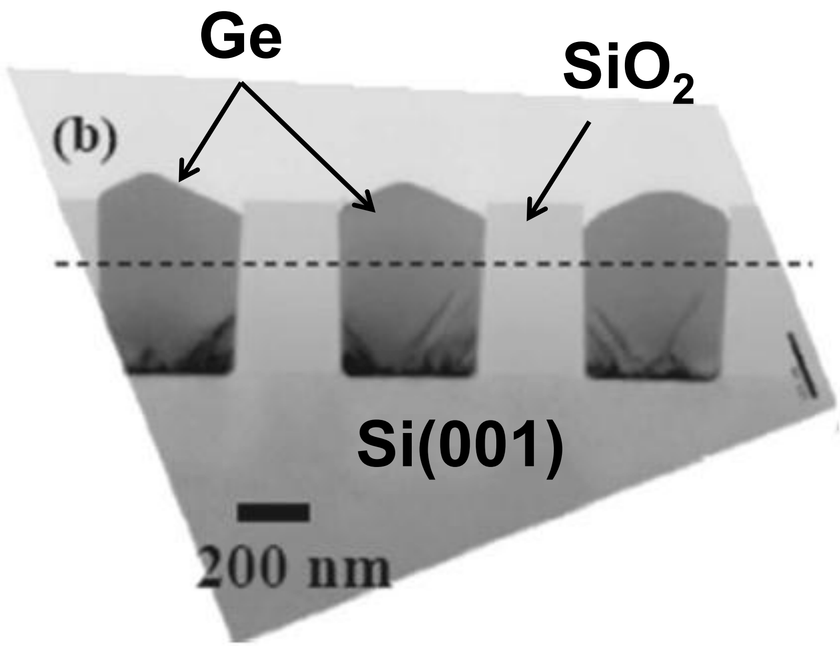
- ***Summary: theory of nanoheteroepitaxy is oversimplification***
  **growth mask effects, shape stabilities, microstrain effects etc.**

# Advanced heteroepitaxy approaches

## Nanocontact approaches – Aspect ratio trapping




Selective Ge growth




→ Threading dislocations trapped inside $SiO_2$ trench
→ Stacking faults in Ge after coalescense
→ Lattice plane tilt

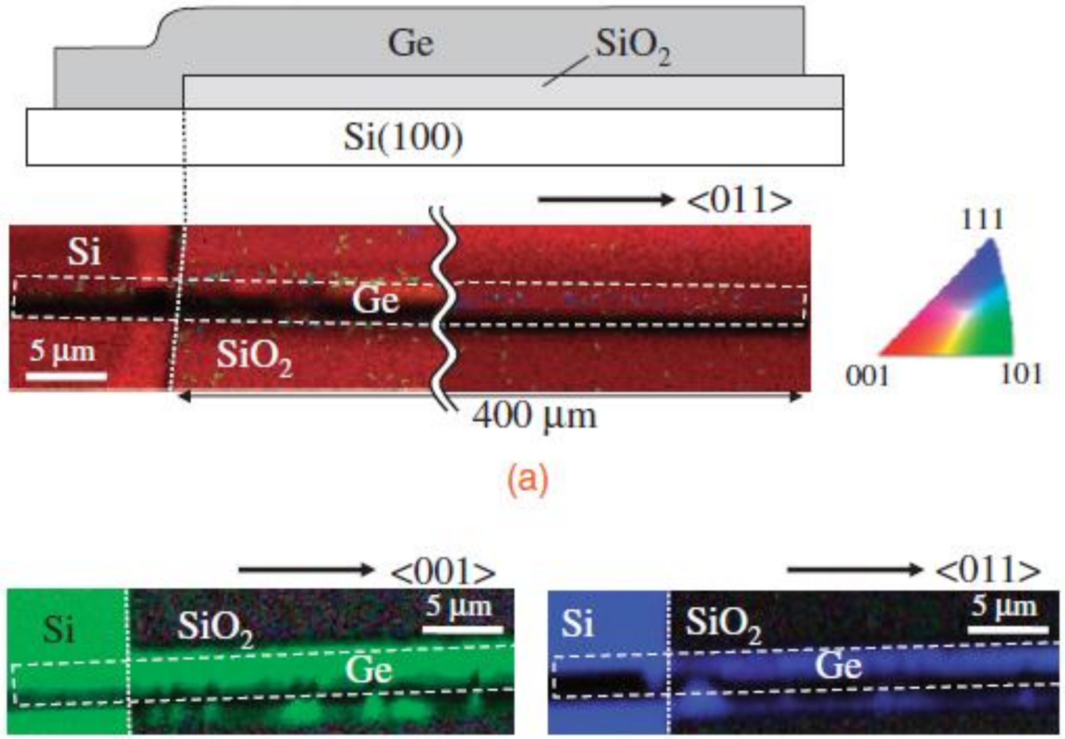
*J.-S. Park et al., Appl. Phys. Lett. 90, 052113 (2007)*
*P. Zaumseil et al., J. Appl. Phys. 106, 093524 (2009)*

# Advanced heteroepitaxy approaches

## Nanocontact approaches – Epitaxial lateral overgrowth


**Liquid phase epitaxy**




→ Dislocations filtered out

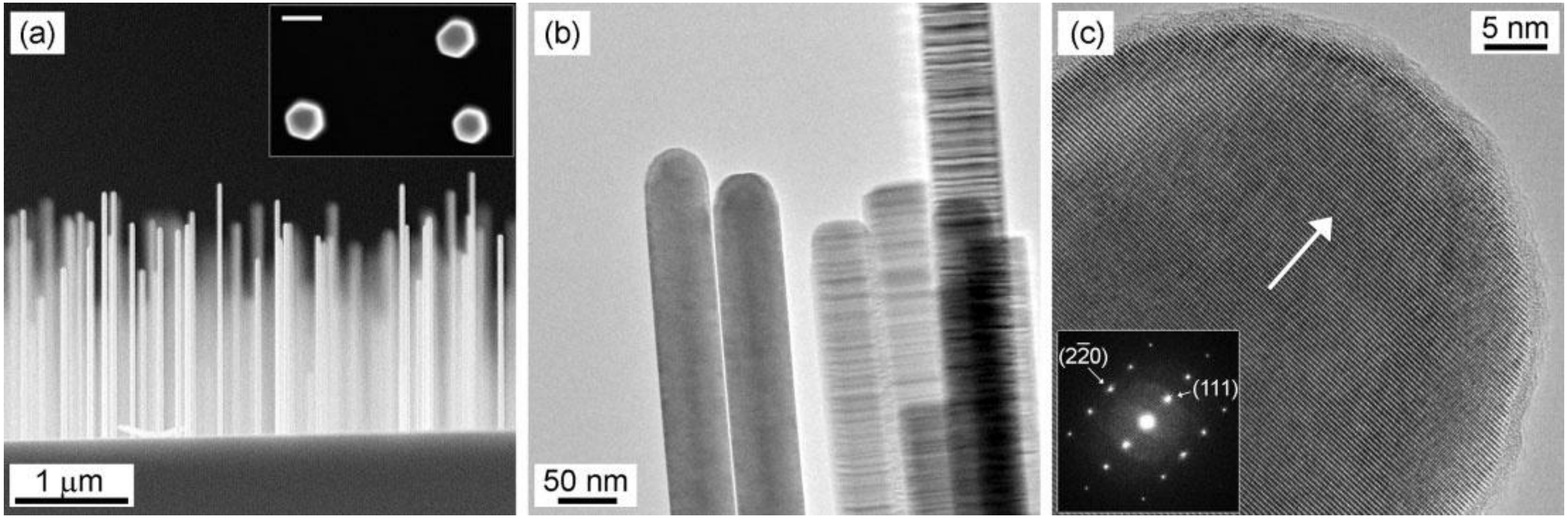
→ Limited Si interdiffusion

→ Single crystalline Ge

*M. Miyao et al., Appl. Phys. Express 2, 045503 (2009)*
*T. Tanaka et al., Appl. Phys. Express 3, 031301 (2010)*

# Advanced heteroepitaxy approaches

## Nanocontact approaches – III-V nanowires on Si(001)




→ **Very small cross section → efficient lateral relaxation**

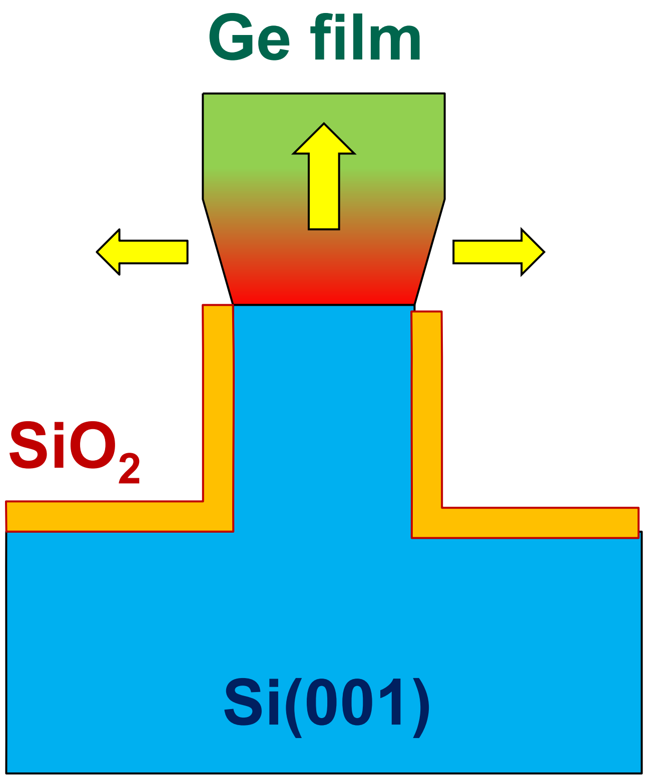
→ **Freedom to combine lattice mismatched materials**

*M. Heurlin et al., Nano Lett. 11, 2028 (2011)*
*E.P.A.M. Bakkers et al., MRS Bulletin 32, 117 (2007)*
*M. T. Björk et al., Appl. Phys. Lett. 80, 1058 (2002)*

# Advanced heteroepitaxy approaches

## Nanoheteroepitaxy based on compliant substrate effects




→ **Theory developed by various authors:**

- **H. Richter et al.:** J. Appl. Phys. 75, 657 (1994)
- **Zubia *et al.*:** *J. Appl. Phys.* 85, 6492 (1999)

→ **Advanced heteroepitaxy process:**

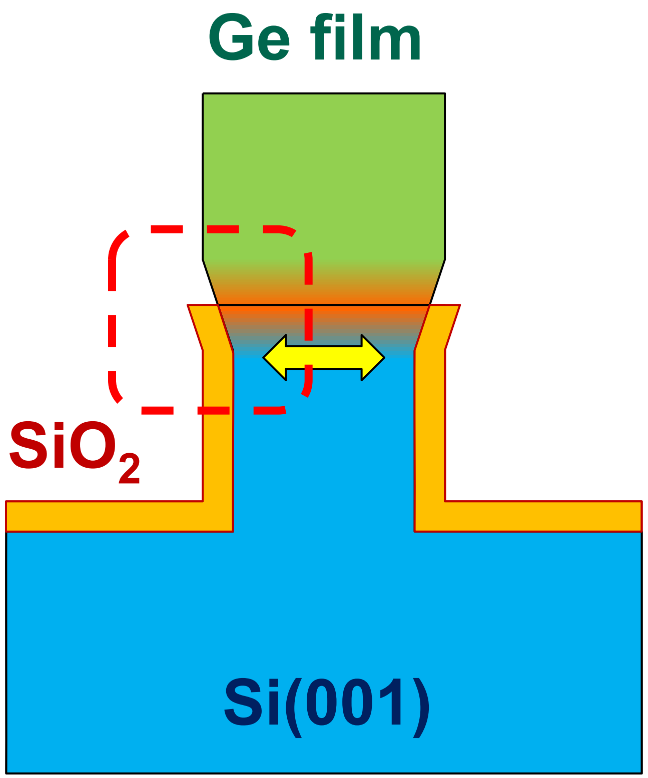
- Free-standing Si nanostructures
- Selective Ge growth

→ **Nanocontact heteroepitaxy features:**

- Glide out of defects from epi-layer
- 3D strain relief mechanisms active
- Limited to nanocontact area

# Advanced heteroepitaxy approaches

## Nanoheteroepitaxy based on compliant substrate effects

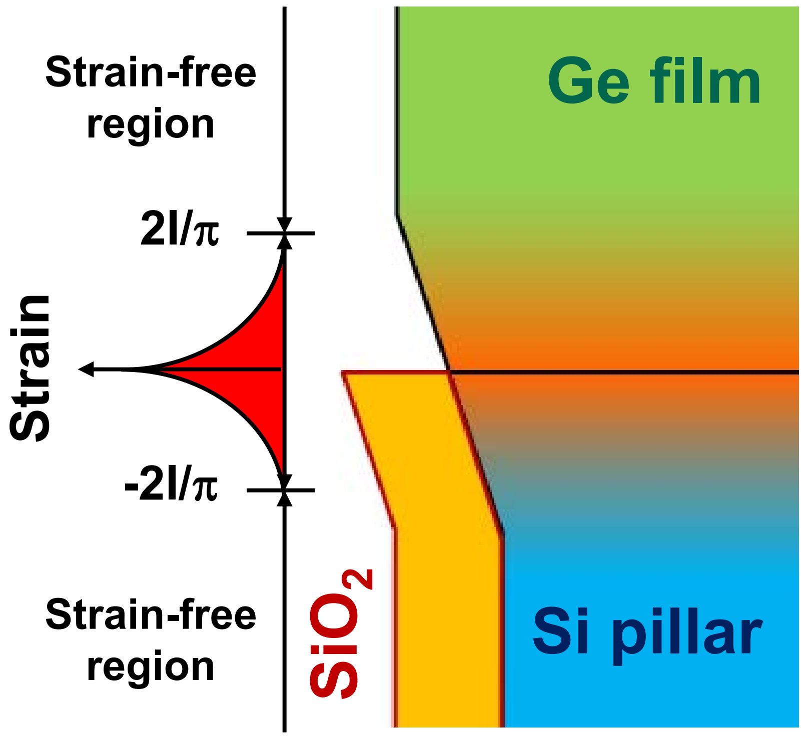



→ **Theory of Nanoheteroepitaxy:**

- Compliance: misfit strain partitioning between substrate & film nanostructure
- Strain level in epi-film below defect nucleation energy for plastic relaxation
- In other words, vision is to completely avoid defects in lattice mismatched film

# Advanced heteroepitaxy approaches

## Nanoheteroepitaxy based on compliant substrate effects




**Challenge**

→ The larger the misfit, the smaller pillars required for compliance

→ Mismatch of 4.2% in the Ge/Si(001) requires feature of ~50nm and less

*Y.H. Lo et al., Appl. Phys. Lett. 59, 2311 (1991)*
*A. Fischer & H. Richter, J. Appl. Phys. 75, 657 (1994)*
*D. Zubia et al., J. Appl. Phys. 85, 6492 (1999)*

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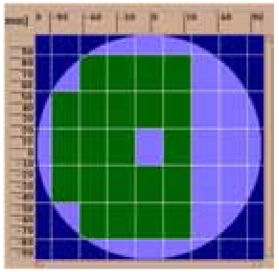
# Experimental

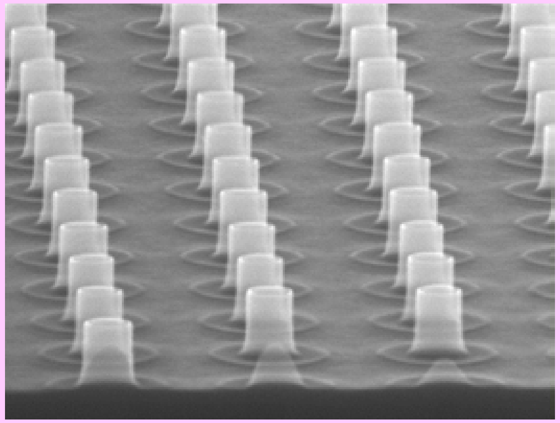
## Scientific approach : 8” Si BiCMOS prototyping line

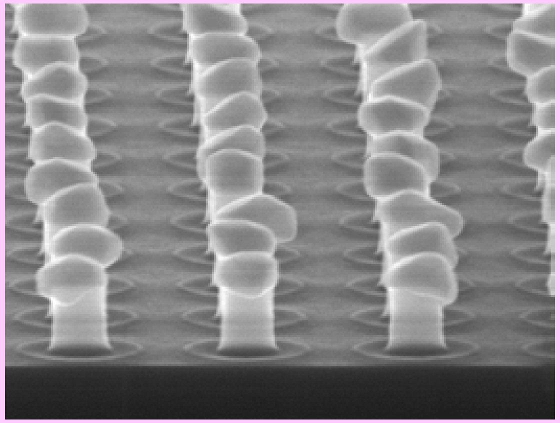


**Lithography (J. Bauer)**

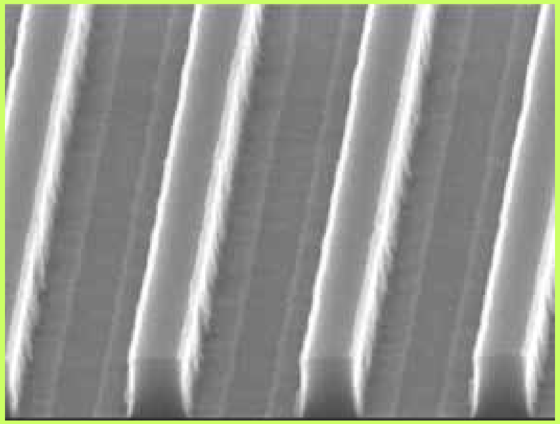
**Ge RP-CVD (Y. Yamamoto)**

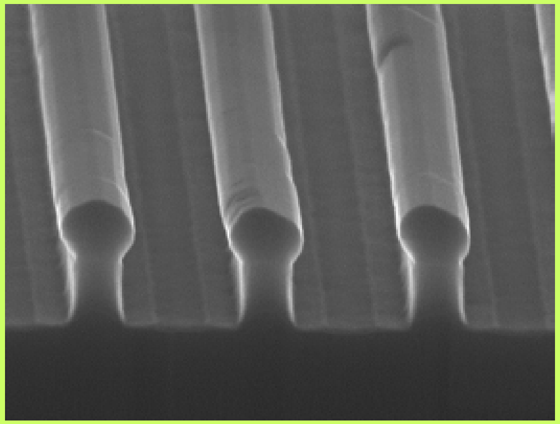
**Dot structure**





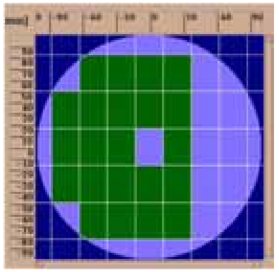
**Line structure**





# Experimental

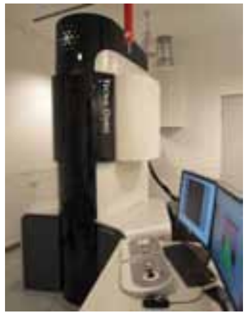
## IHP Technology (Tillack) & Material (Schroeder) Department



Lithography
(J. Bauer)

Ge RP-CVD
(Y. Yamamoto)

Scanning electron microscopy
(G. Morgenstern)



Transmission electron microscopy
(A. Schubert)

Synchrotron Studies – ESRF
(G. Kozlowski, P. Zaumseil)

Raman Spectroscopy
(G. Kozlowski)


Finite Elelemnt Method simulation
(G. Kozlowski)

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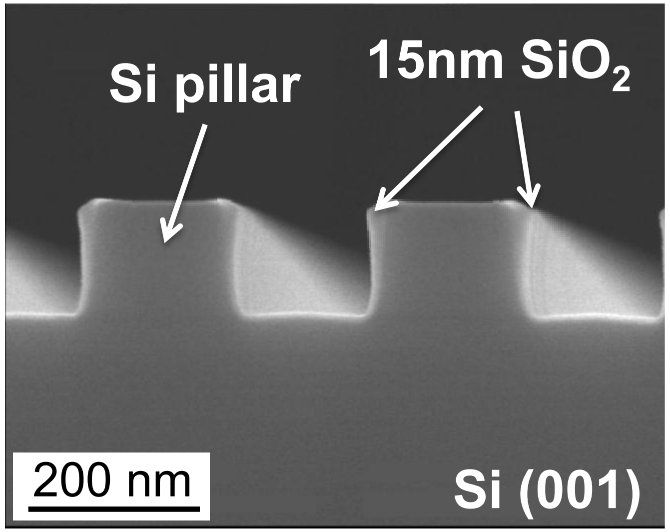
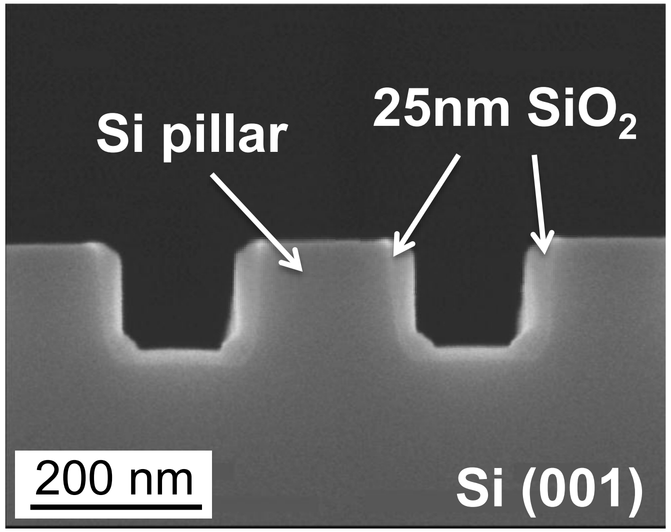
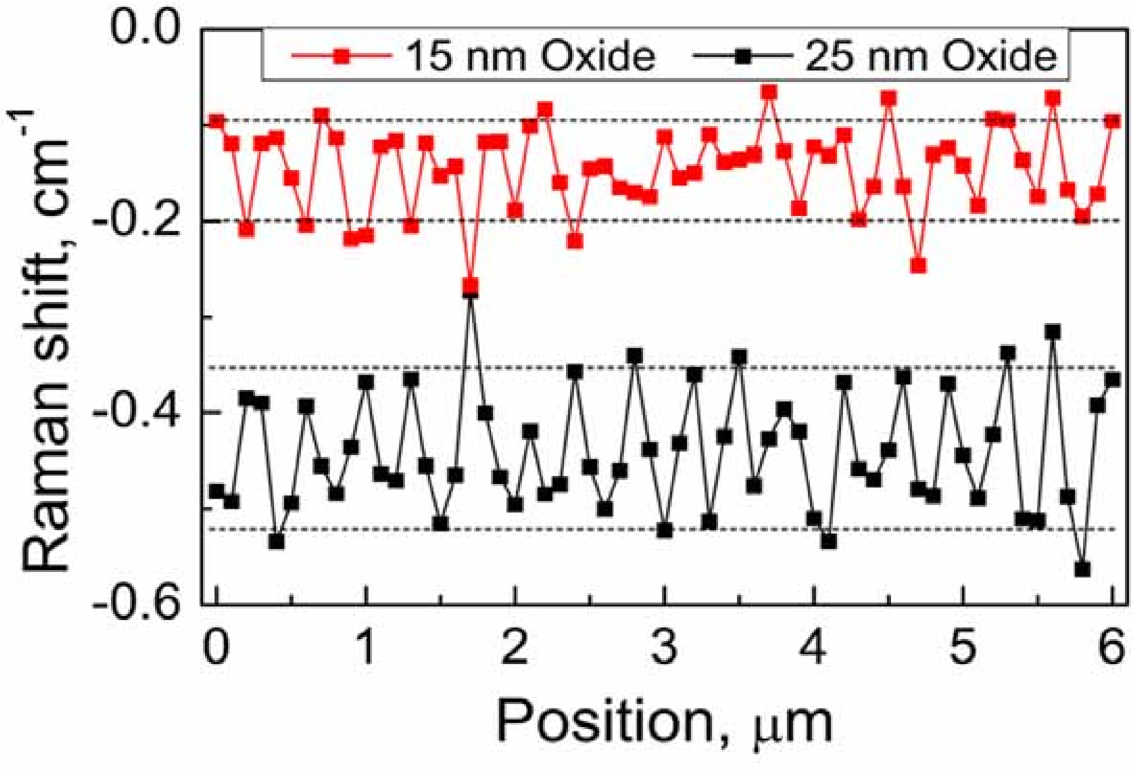
# Results and Discussion

## Strain field investigation:Si nanostripes with $SiO_2$ mask




SEM




Raman (UV)

→ **Strain in Si nanopillar prior to Ge growth**

→ **Oxide thickness dependent**

***Kozlowski et al., J. Appl. Phys., 110 (2011) 053509***

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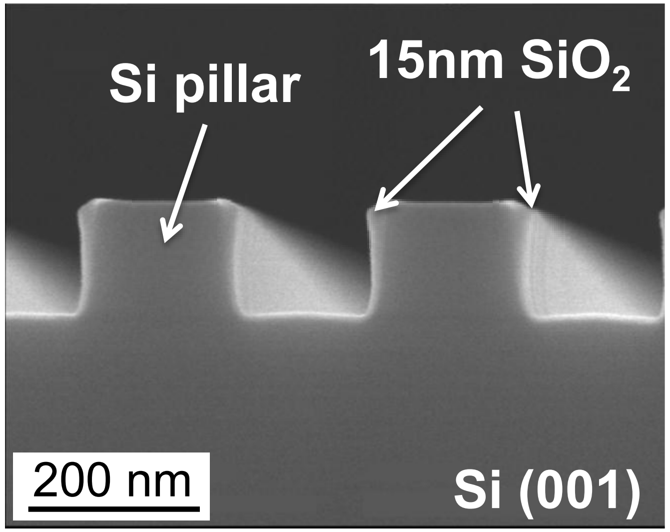
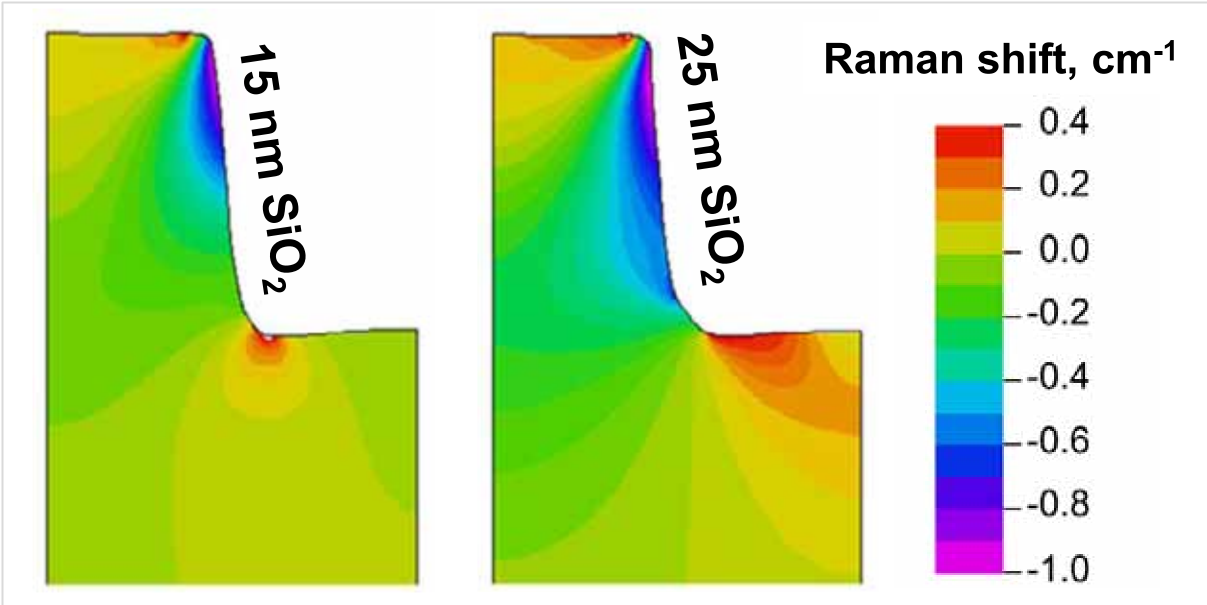
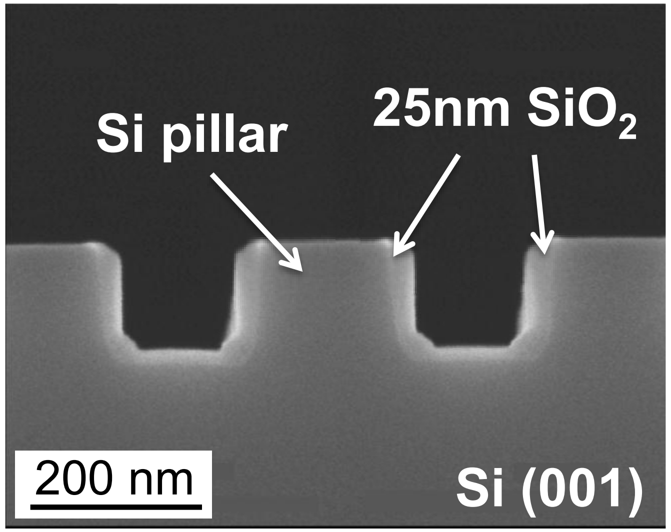



FEM: $TO_2$

SEM




→ Strain in Si nanopillar prior to Ge growth

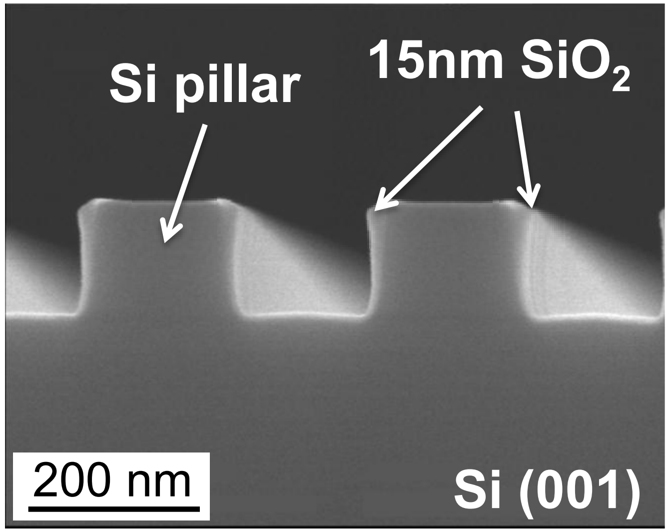
→ Oxide thickness dependent

→ Signal dominated by $TO_2$ mode

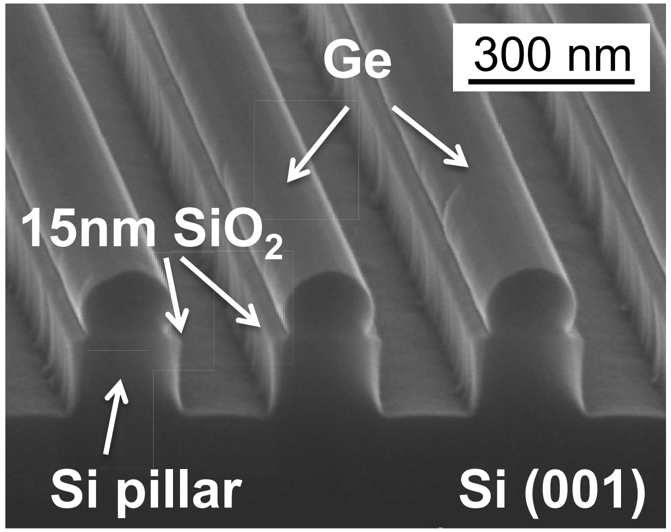
*Kozlowski et al., J. Appl. Phys., 110 (2011) 053509*

# Results and Discussion

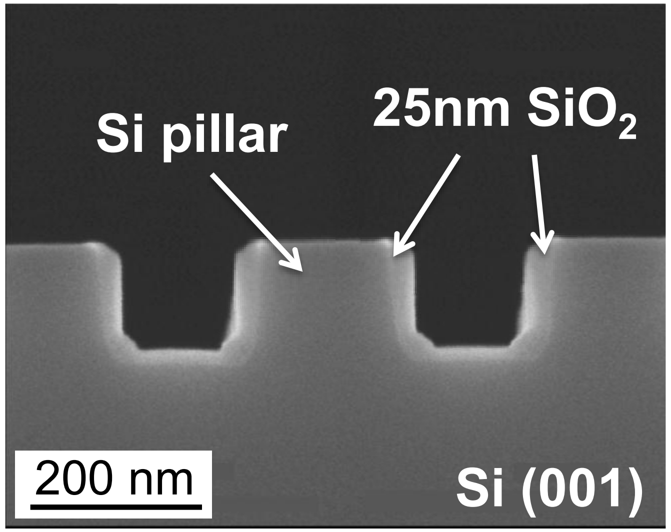
## Strain field investigation – Ge/Si nanostripes

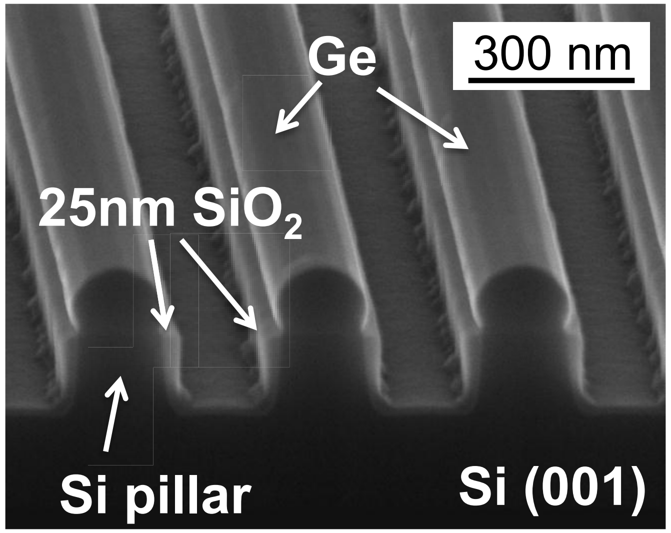



Deposition




SEM



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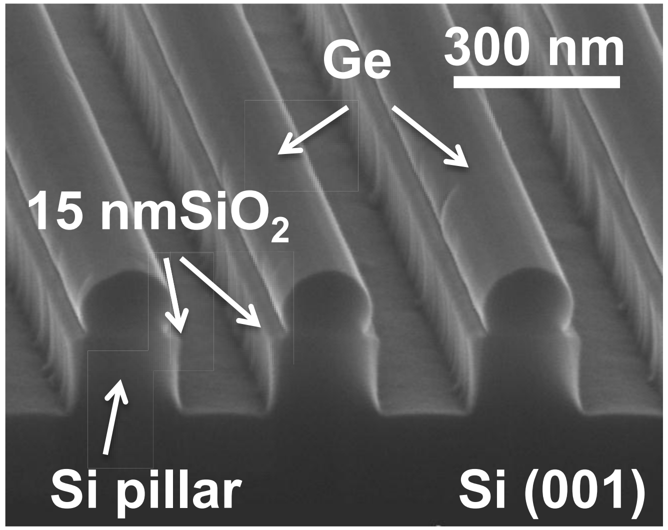
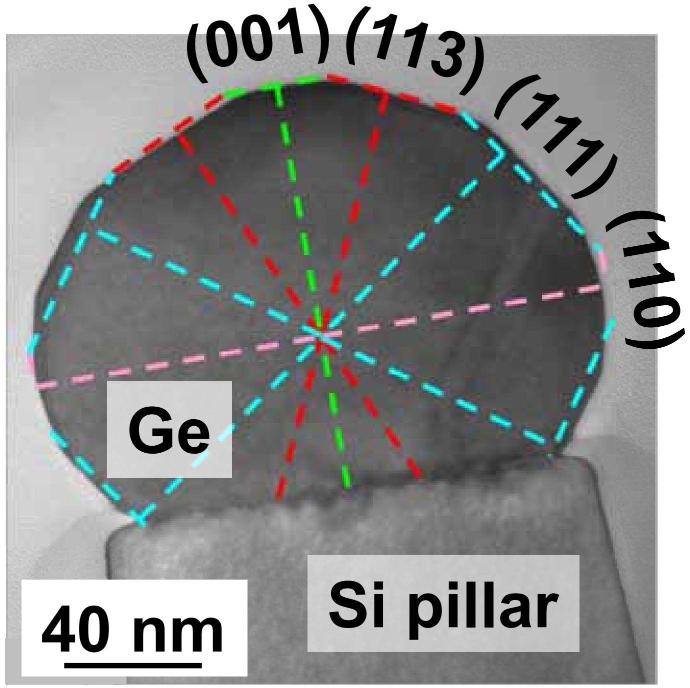
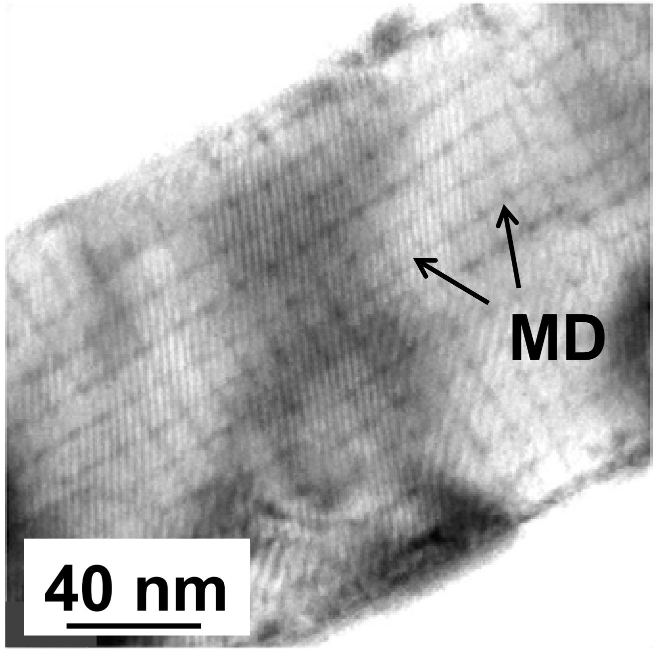
## Strain field investigation – Ge/Si nanostripes




**SEM**




**Cross section TEM**




**Plane view TEM**

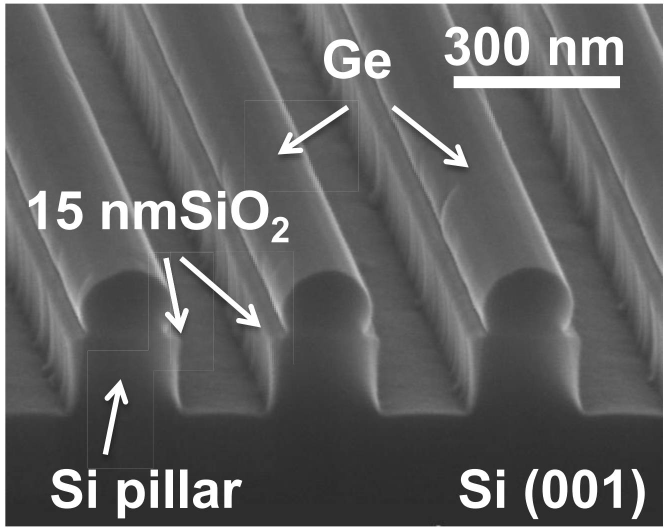
- → Good fit to Equilibrium Crystal Shape
- → Misfit dislocation network at Ge/Si interface
- → Relaxed Ge growth…

*Kozlowski et al., J. Appl. Phys., 110 (2011) 053509*

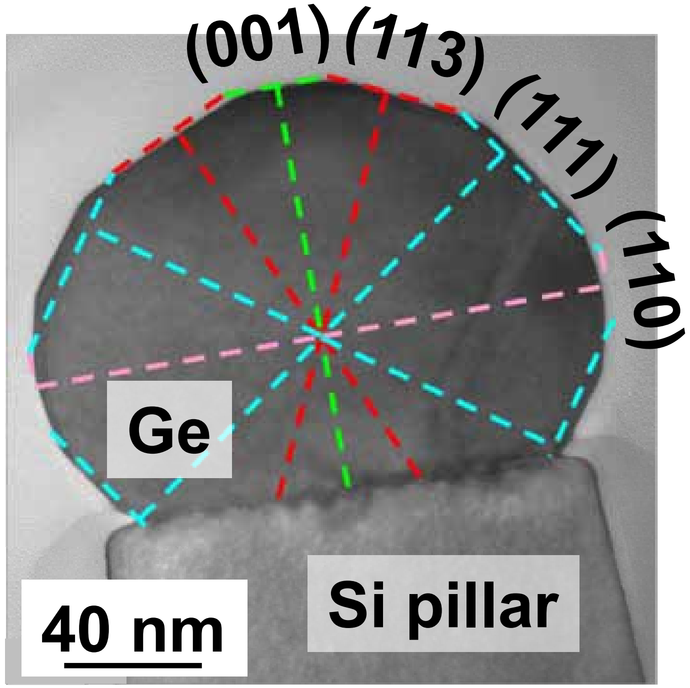
 

# Results and Discussion

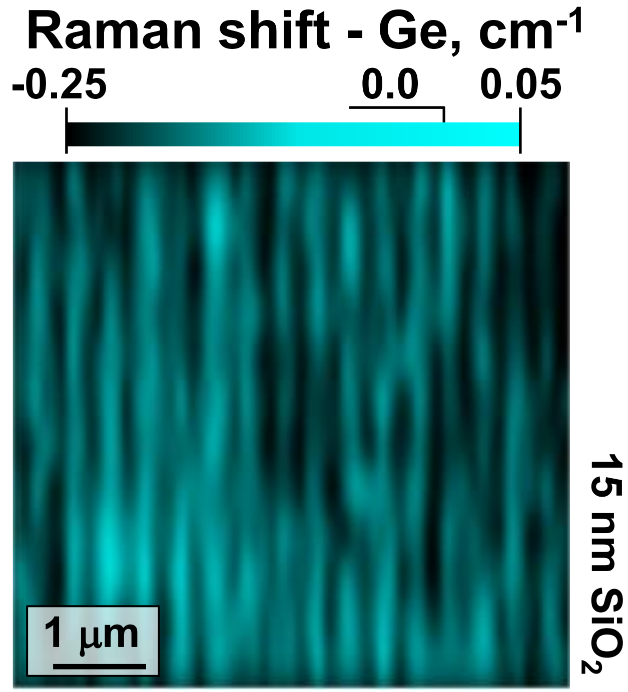
## Strain field investigation – Ge/Si nanostripes




**SEM**




**Cross section TEM**




**Raman spectroscopy**

→ Good fit to Equilibrium Crystal Shape

→ Misfit dislocation network at Ge/Si interface

→ Relaxed Ge growth… with residual strain

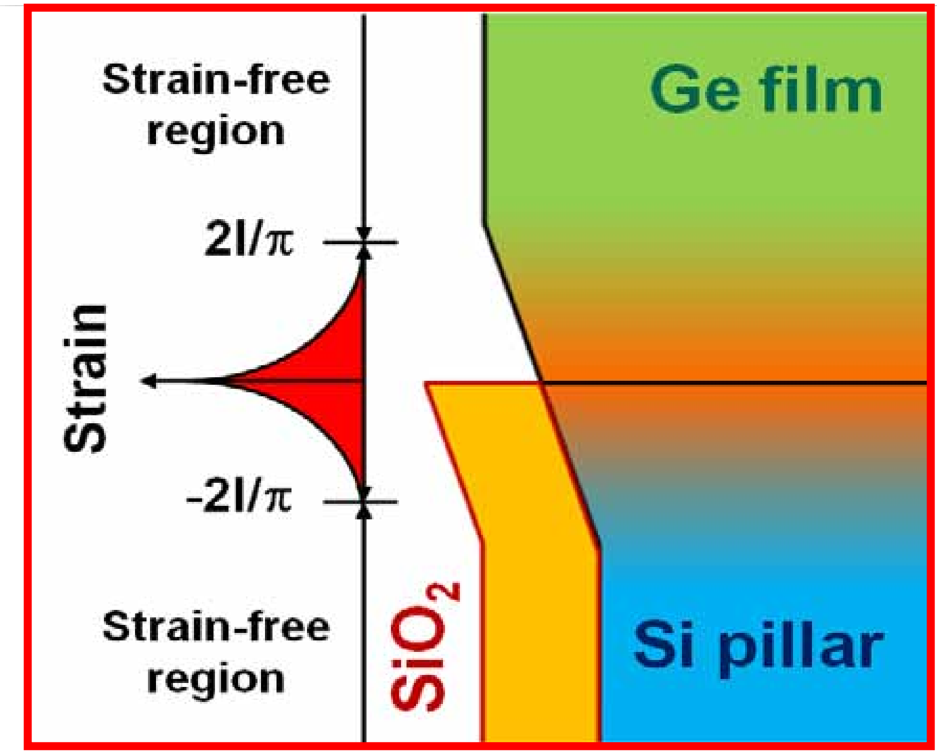
*Kozlowski et al., J. Appl. Phys., 110 (2011) 053509*

# Results and Discussion

## Compliance verification – Ge/Si structures on Si(001)

→ Ge nanoclusters on ~50 nm wide Si nanopillars

→ Diameter expected to trigger strain partitioning phenomenon





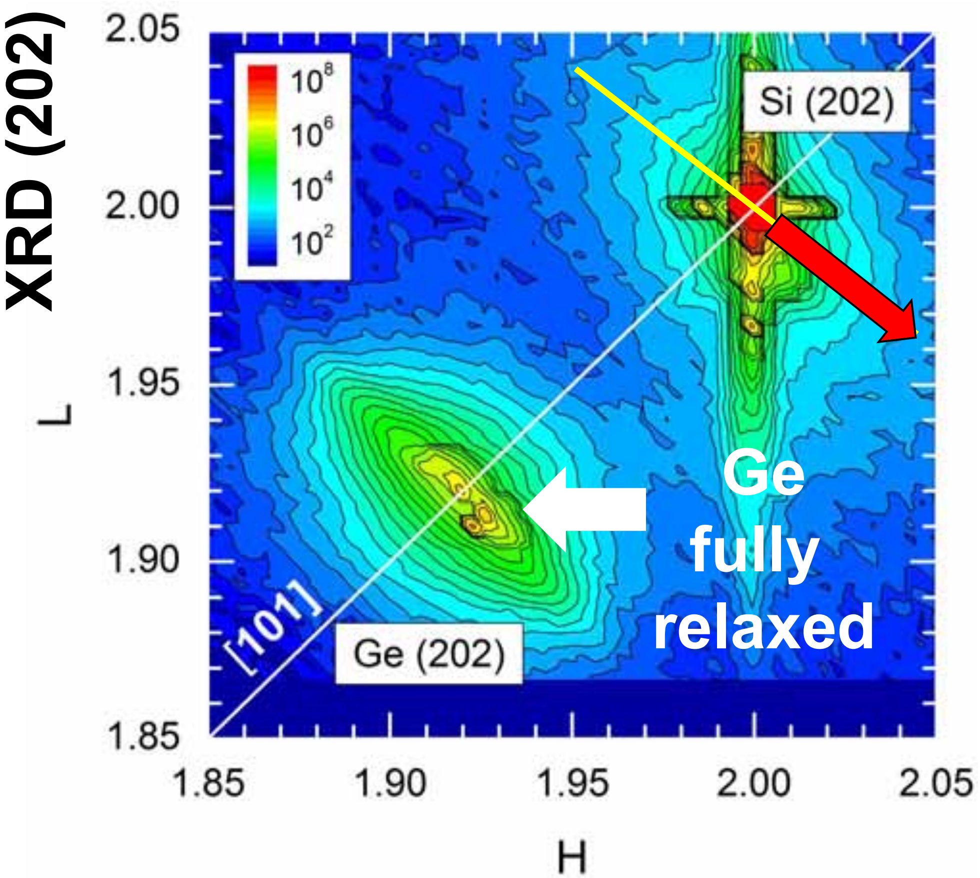
**<u>Advanced materials science characterization on the nano-scale:</u>**

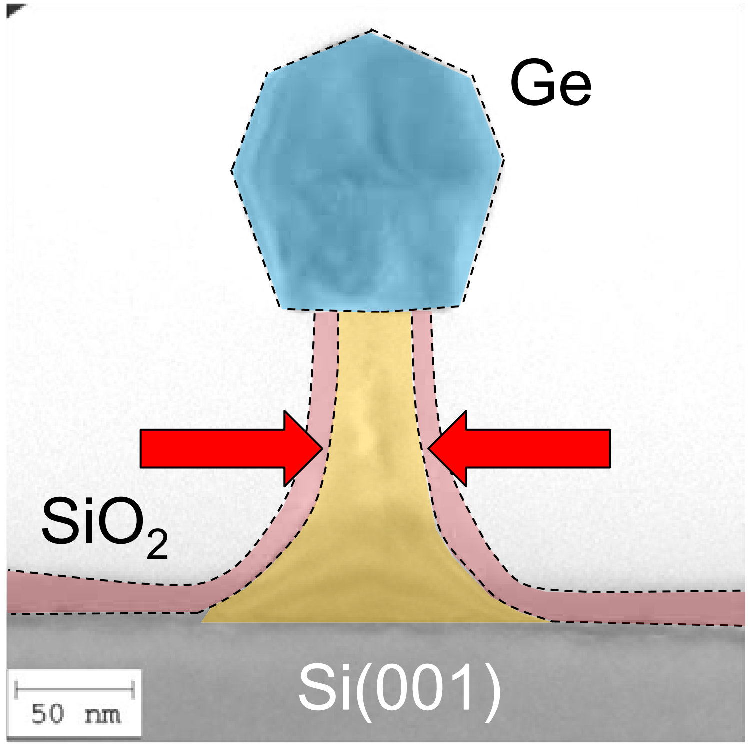
**Structure and defects on the nano-scale by non-destructive XRD**

# Results and Discussion

## Compliance verification – Ge/Si structures on Si(001)

XRD (202)




TEM

**(202) Bragg reflection – Strain in Si nanopillar**

**→ In-plane compressive → $SiO_2$ growth mask**

***Kozlowski et al., Appl. Phys. Lett., 99 (2011) 141901***

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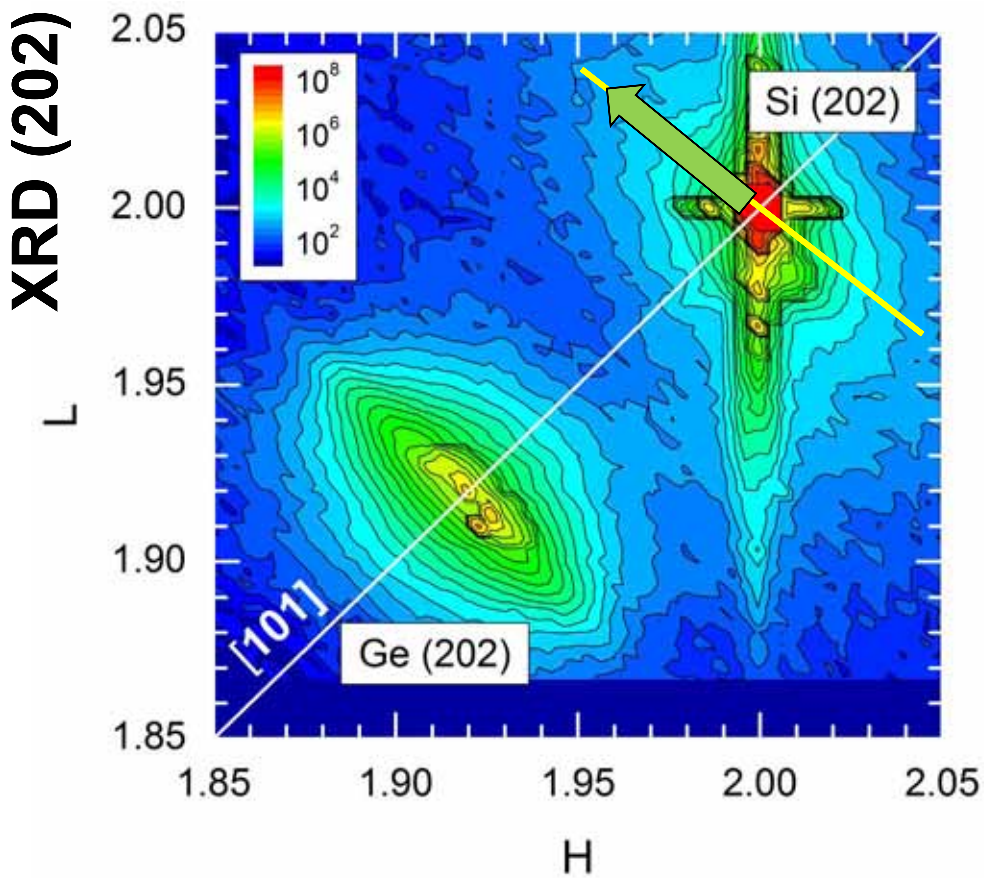
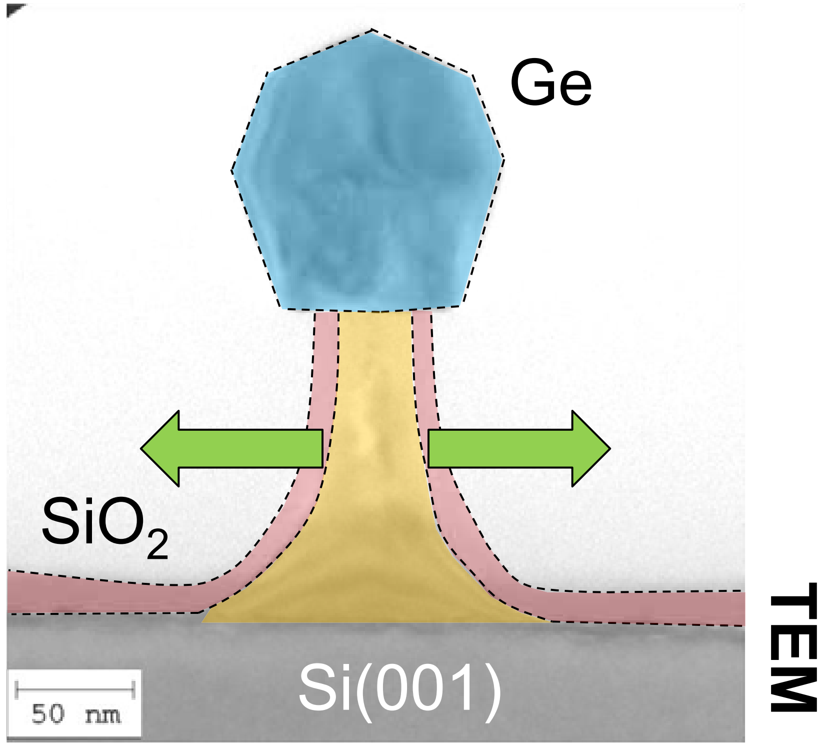
## Compliance verification – Ge/Si structures on Si(001)




**(202) Bragg reflection – Strain in Si nanopillar**

**→ In-plane compressive → $SiO_2$ growth mask**

**→ In-plane tensile → epi-Ge → CS effects**

***Kozlowski et al., Appl. Phys. Lett., 99 (2011) 141901***

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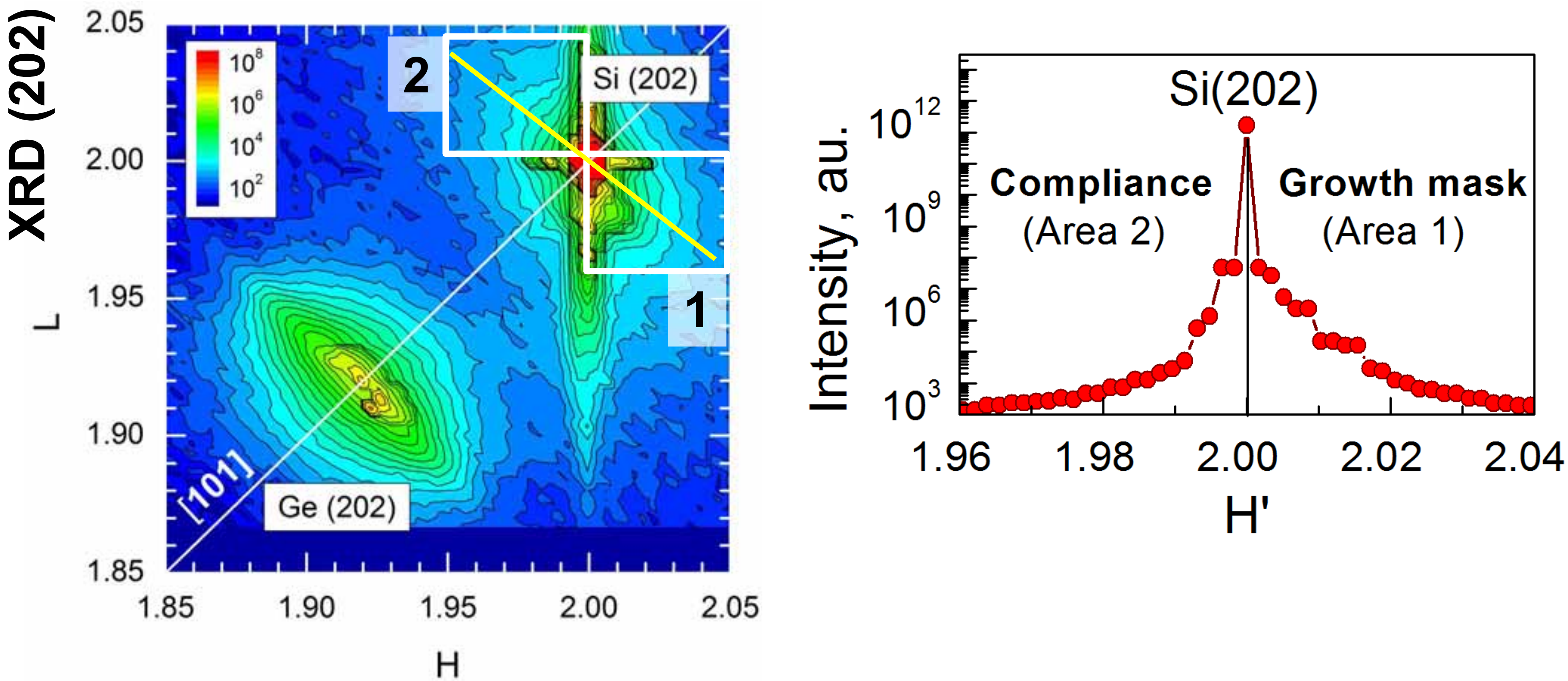
## Compliance verification – Ge/Si structures on Si(001)




**(202) Bragg reflection – Strain in Si nanopillar**

**→ In-plane compressive → $SiO_2$ growth mask → Dominant**

**→ In-plane tensile → epi-Ge → CS effects → Minor**

***Kozlowski et al., Appl. Phys. Lett., 99 (2011) 141901***

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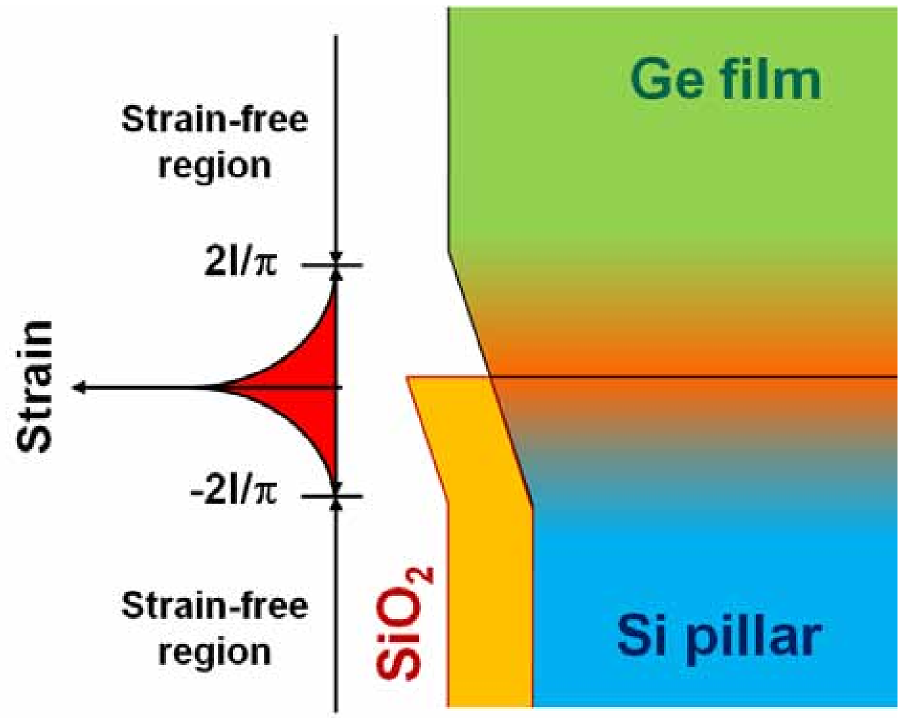


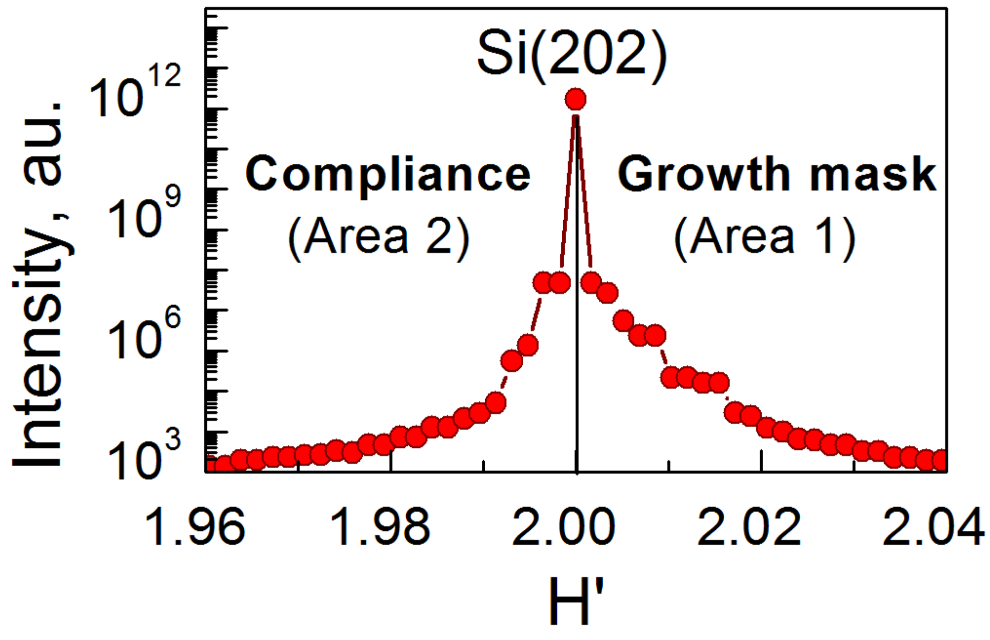


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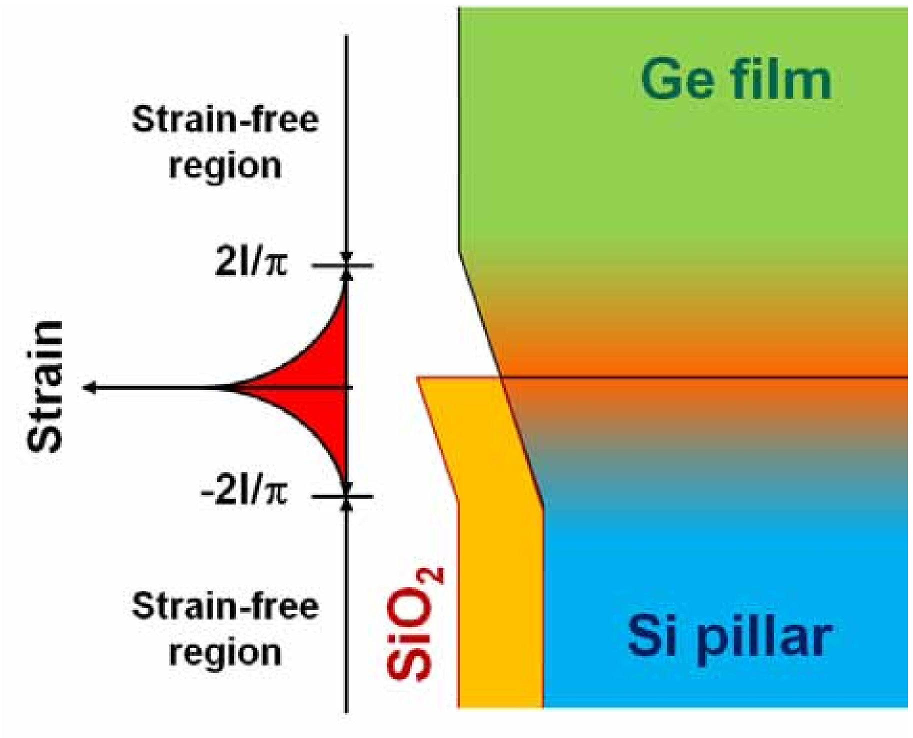
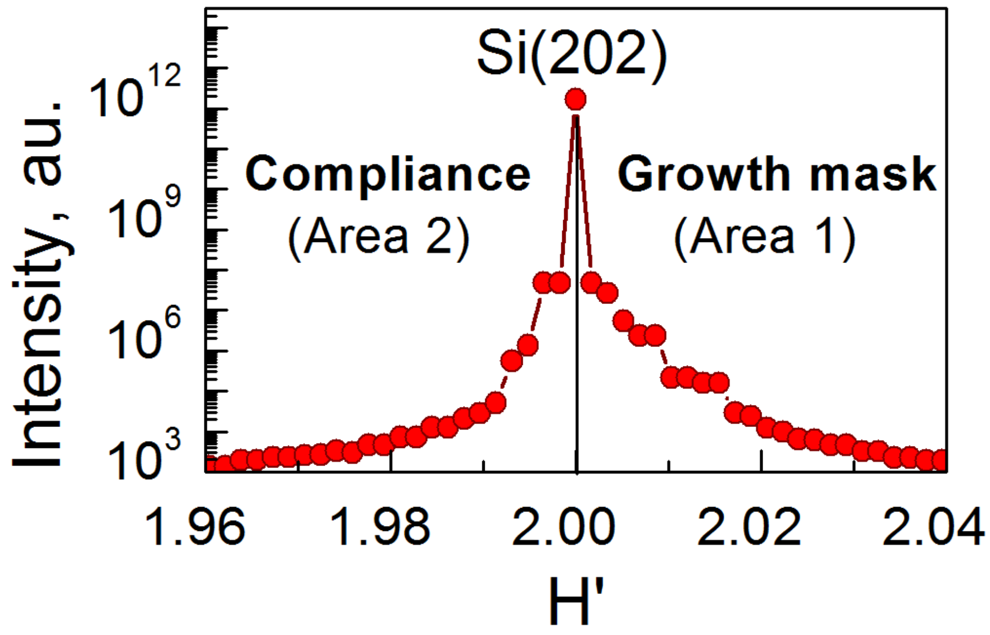



**(202) Bragg reflection – Strain in Si nanopillar**

→ In-plane compressive → $SiO_2$ growth mask → **Dominant**

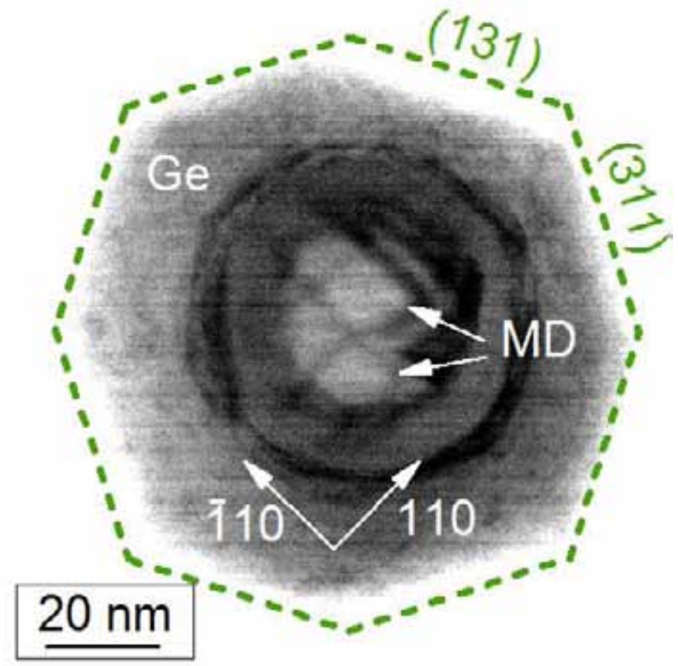
→ In-plane tensile → epi-Ge → CS effects → **Minor**

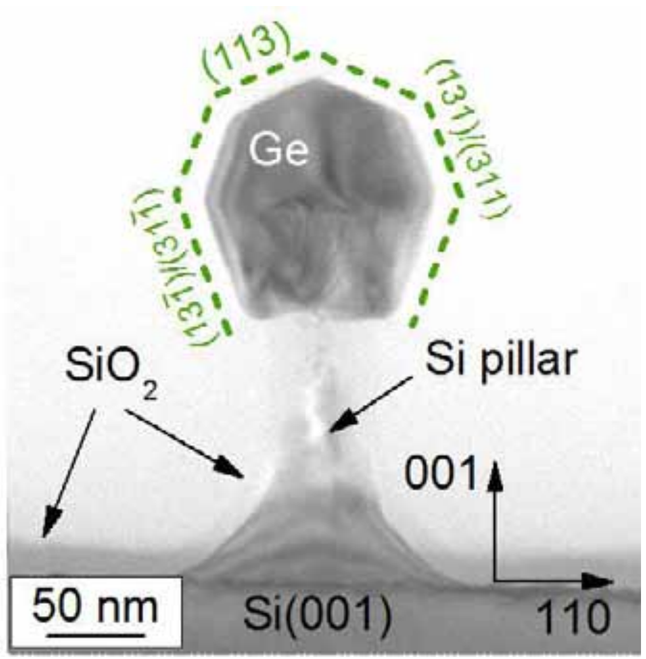
**$SiO_2$ growth mask limits the compliance of Si nanopillars**

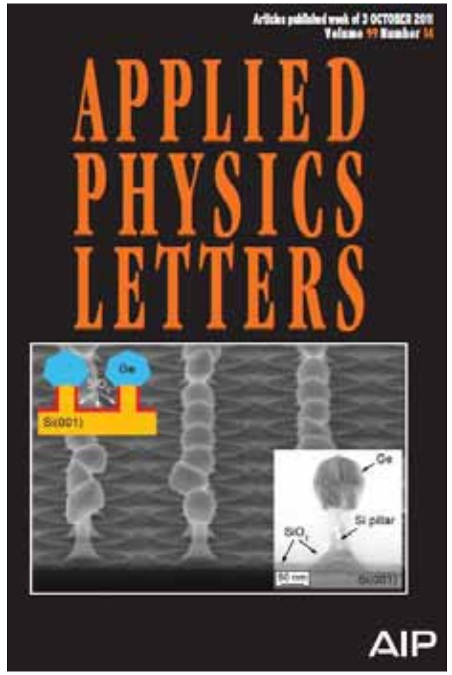
# Results and Discussion

## Compliance verification – Ge/Si structures on Si(001)

**TEM**




*Kozlowski et al., Appl. Phys. Lett., 99 (2011) 141901*

**Main strain relaxation mechanism: plastic relaxation via MDs**

→ **Misfit dislocations (MDs) at Ge / Si interface**

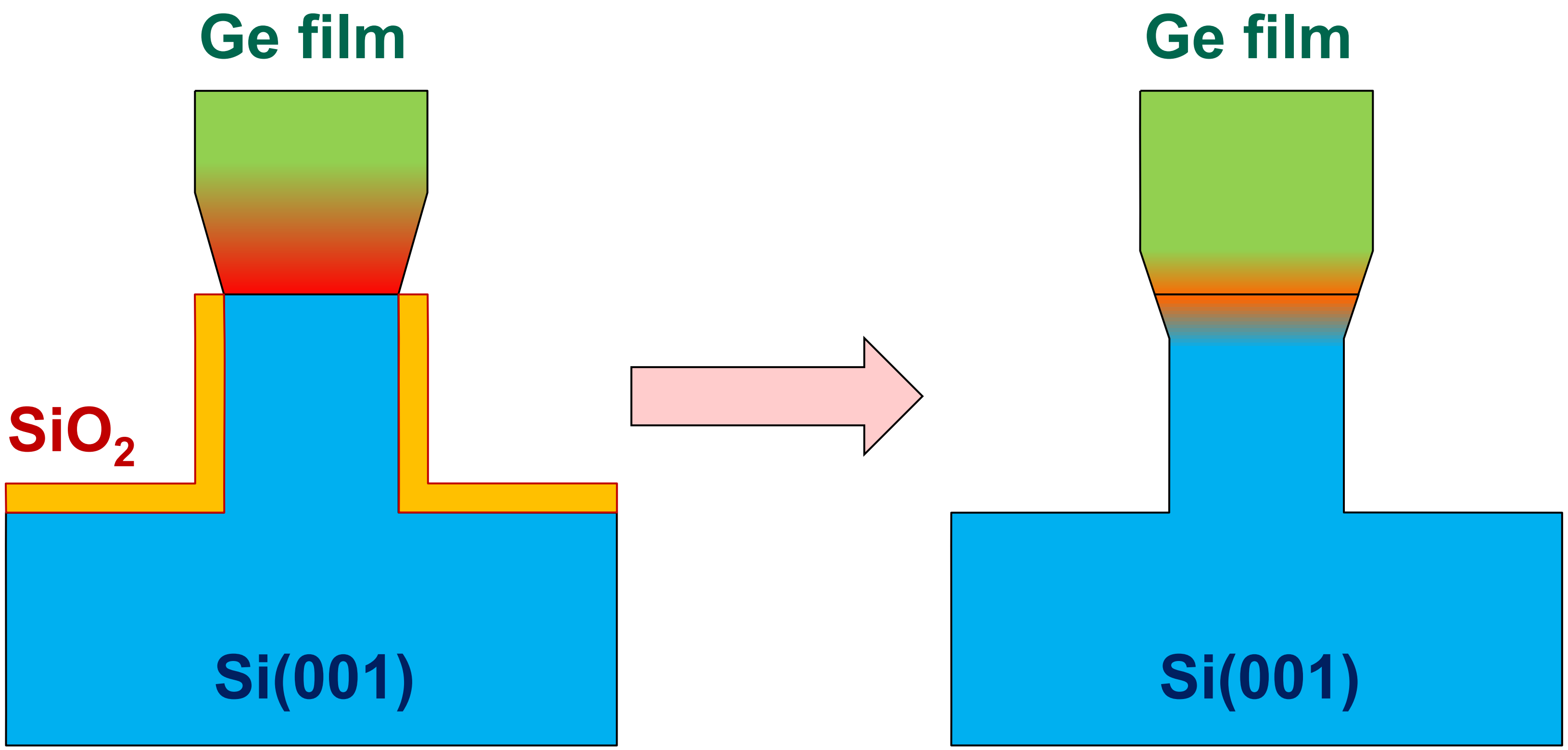
→ **High quality symmetric Ge cluster**

# Results and Discussion

## Compliance verification – Ge/Si structures on SOI(001)

→ Compliance limited by growth mask (Ge/Si on Si(001))

→ Ge/Si structures without additional growth mask

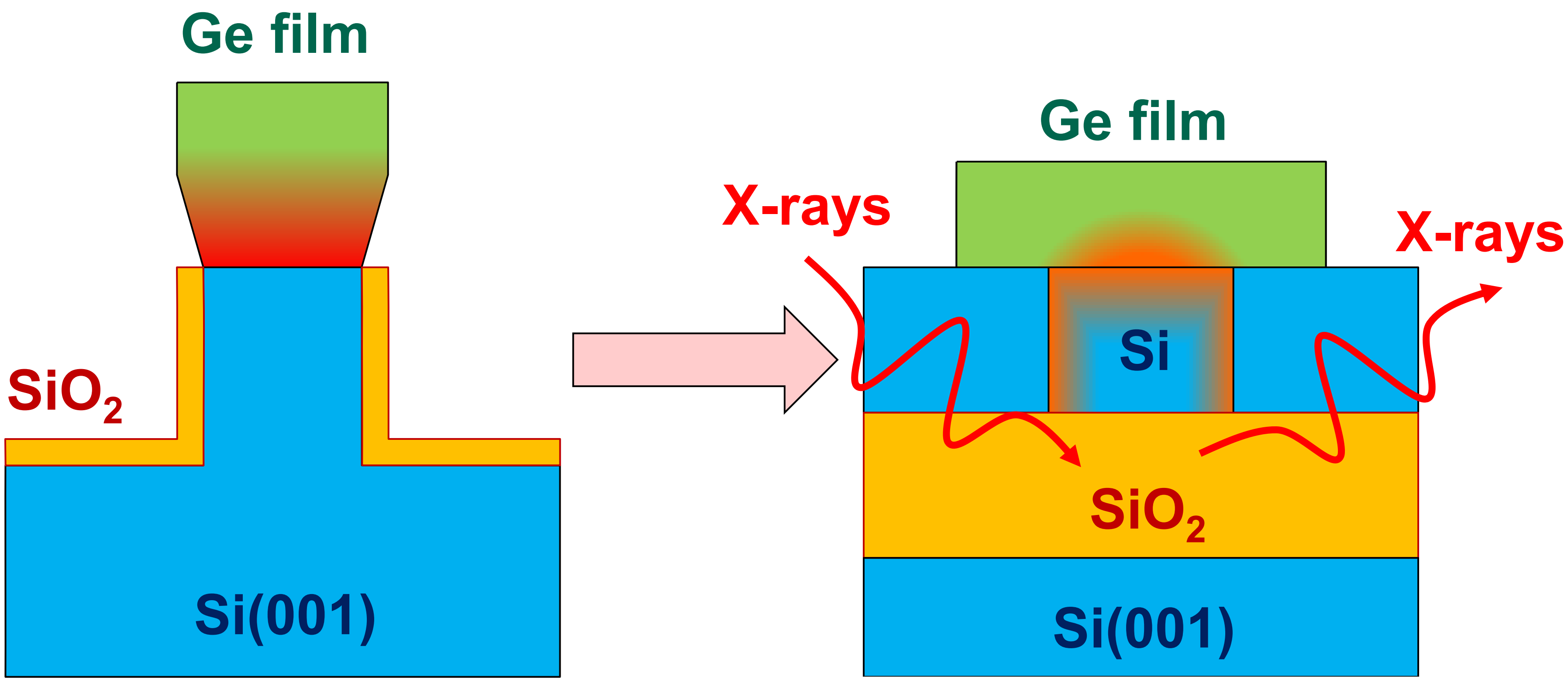


# Results and Discussion

## Compliance verification – Ge/Si structures on SOI(001)

- → Compliance limited by growth mask (Ge/Si on Si(001))
- → Ge/Si structures without additional growth mask
- → Si islands on SOI substrate
- → Selective growth triggered by patterning down to $SiO_2$

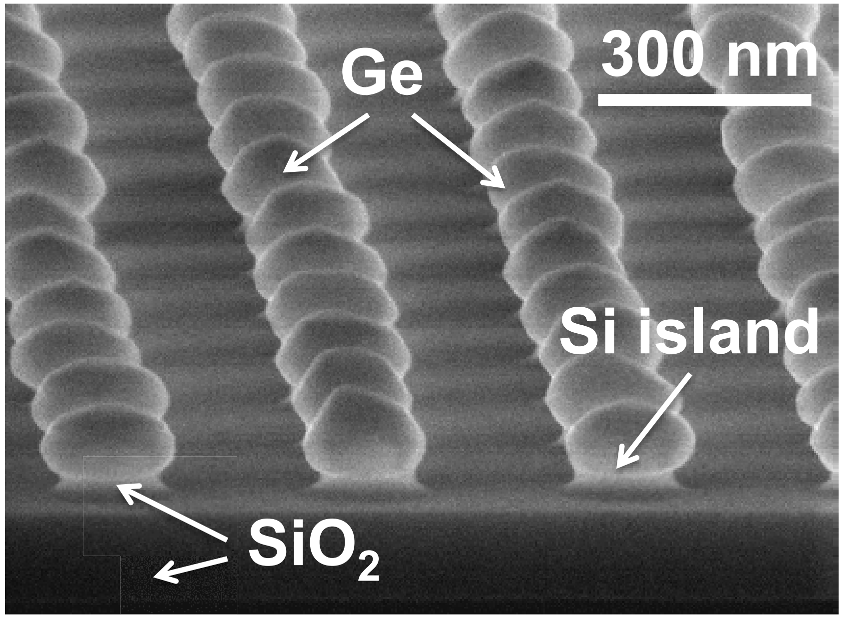



Box oxide as X-ray mirror

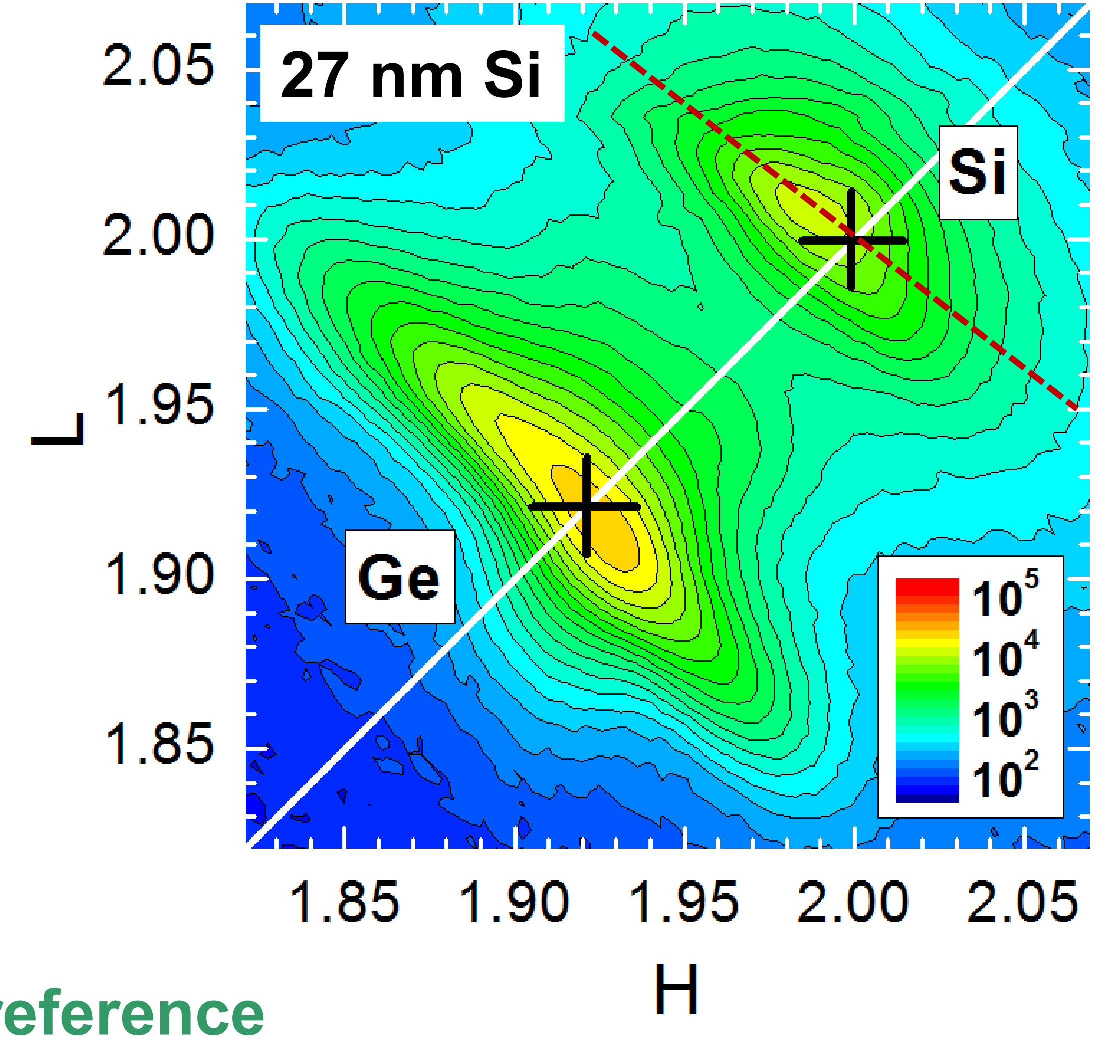
# Results and Discussion

## Compliance verification – Ge/Si structures on SOI(001)

**SEM**




**XRD (202)**




→ Peaks shifted away from reference

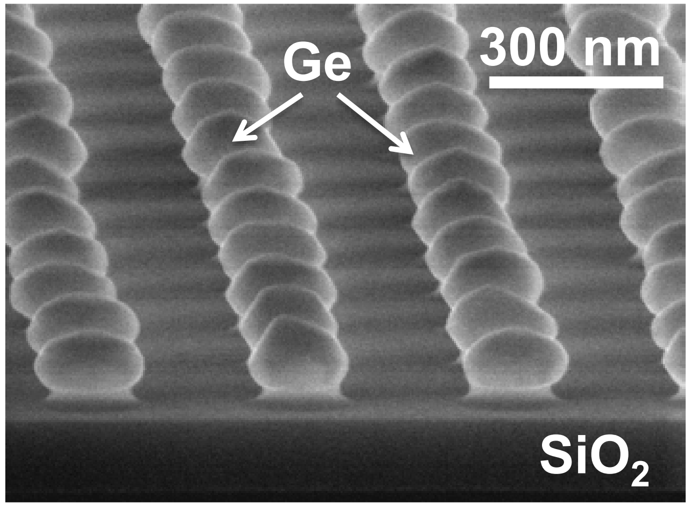
→ Compliance observed → Effect stronger for thinner Si islands

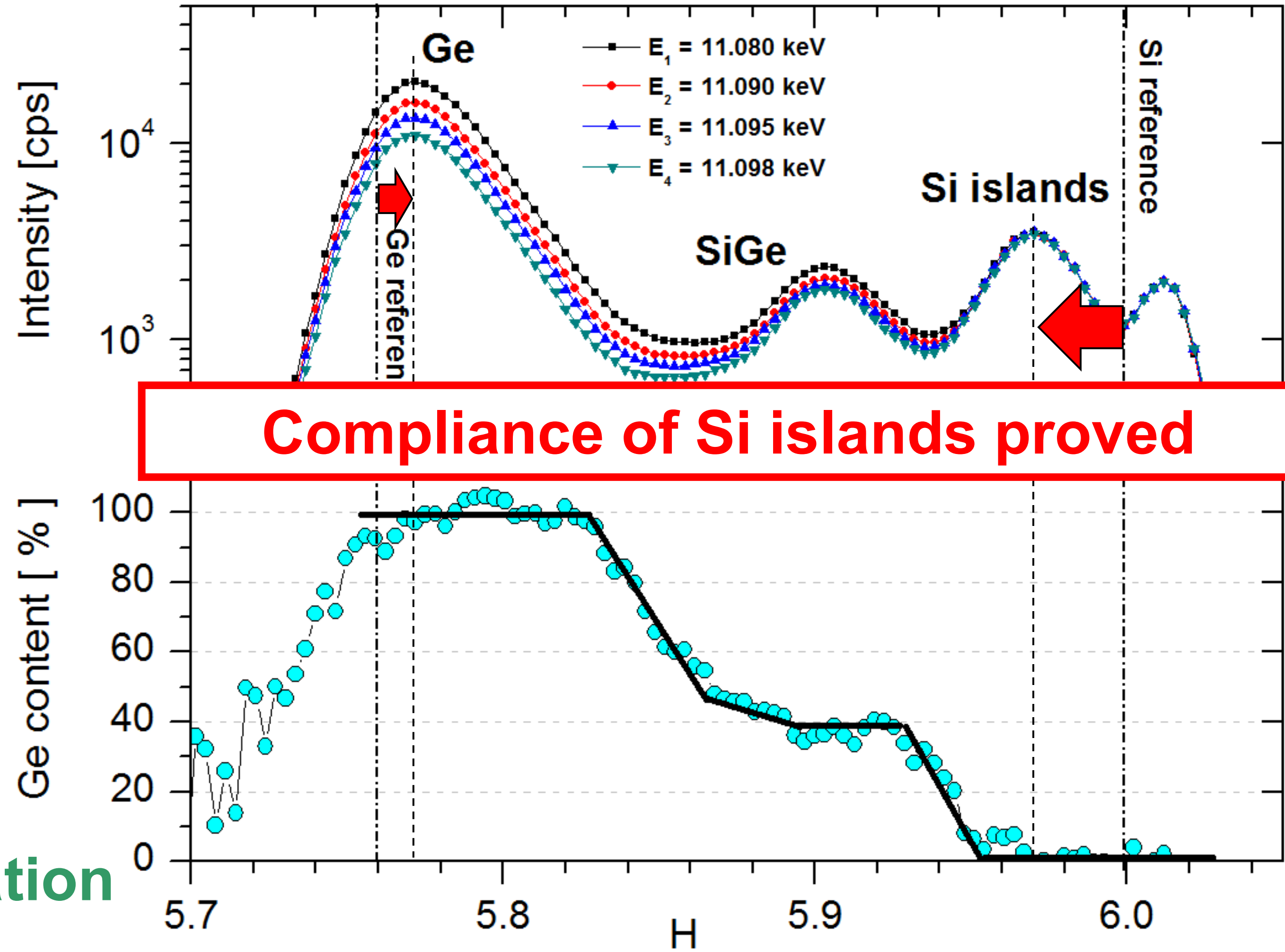
# Results and Discussion

## Compliance verification – Ge/Si structures on SOI(001)

**SEM**

**54 nm thick Si**




**Compliance of Si islands proved**

→ Compressed pure Ge

→ Tensile strained pure Si

→ Additional plastic relaxation and SiGe formation…

**Strain partitioning phenomenon within Nanoheteroepitaxy theory not yet sufficient to completely avoid defects.**

# Overview

- *Motivation: Mobile data communication*
  Electronic-Photonic ICs: Need for ultrafast Ge photodetectors …

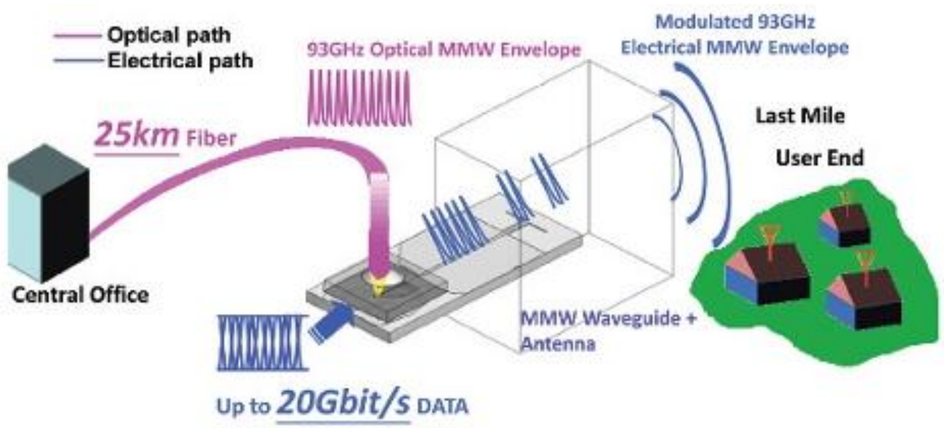
- *Advanced heteroepitaxy approaches for nano-objects*
  Nanocontact heteroepitaxy: use of compliant substrate effects…

- *Complex top-down processing with nano-growth control*
  optical litho and selective CVD processes on 8"Si tools…

- *Hunting the "myth" of compliant substrate effects*
  the example of the Ge / Si nanostructures as a case study…

- *Summary: theory of nanoheteroepitaxy is oversimplification*
  growth mask effects, shape stabilities, microstrain effects etc.

## Summary

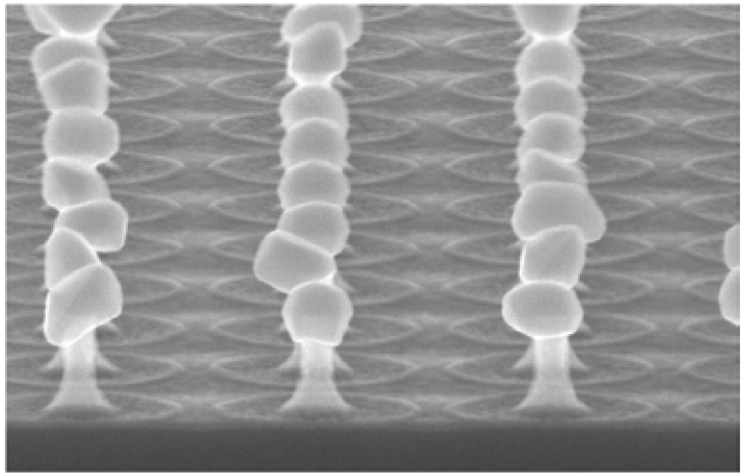



**Mobile data communication:**

**Ultrafast, high performance Ge PD arrays of interest…**

**Characterization on the nano-scale**

**Advanced facilities needed for modern materials science…**



**Growth control on nano-scale**

**compliance proved; limits due to micro-strain fluctuations…**

**Thanks for your attention**

**…and thanks for inviting us !**