ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

csem centre suisse d'électronique et de microtechnique

L-NESS

Marriage Between Incompatible Couples:
Mismatched Materials

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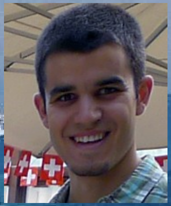
PHYSICS OF NEW MATERIALS

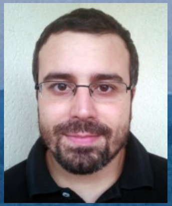
http://www.pnm.ethz.ch

Claudiu V. Falub

Thomas Kreiliger



Alfonso G. Taboada

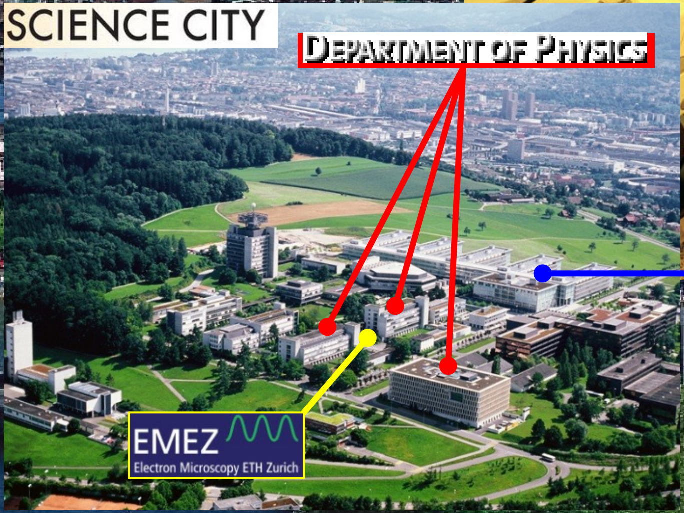


Elisabeth Müller

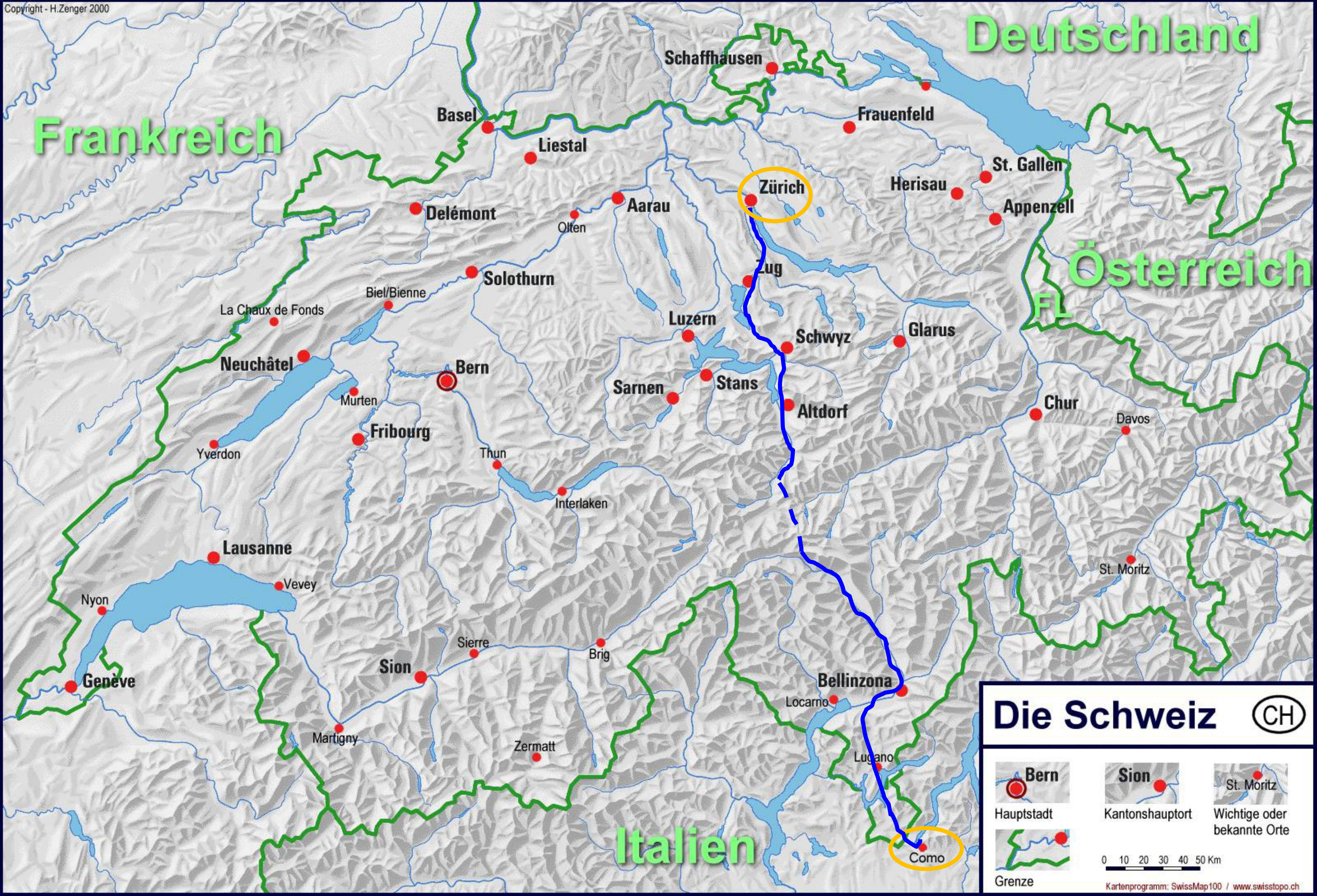
Hans von Känel

Frontiers In Research: Space and Time

860 m^2



FIRST CENTER FOR MICRO- AND NANOSCIENCE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Luzern
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Sarnen
Murten
Altdorf
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Davos
Fribourg
Yverdon
Thun
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Locarno
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Como
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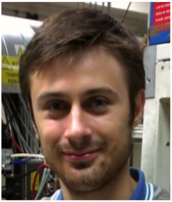
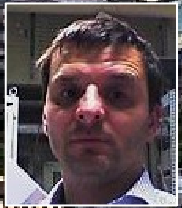
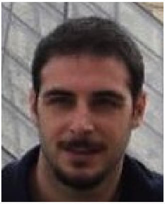
Bern
Hauptstadt
Sion
Kantonshauptort
St. Moritz
Wichtige oder bekannte Orte
Grenze
0 10 20 30 40 50 Km
Kartenprogramm: SwissMap100 / www.swisstopo.ch

Collaborations


Fabio Isa


Daniel Chrastina


Giovanni Isella


Fabio Pezzoli

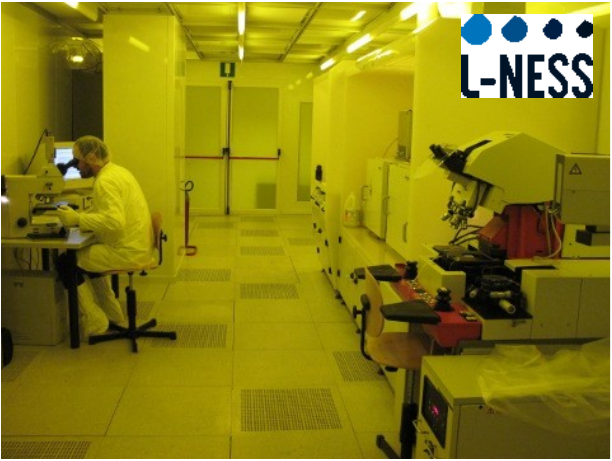

Anna Marzegalli


Roberto Bergamaschini

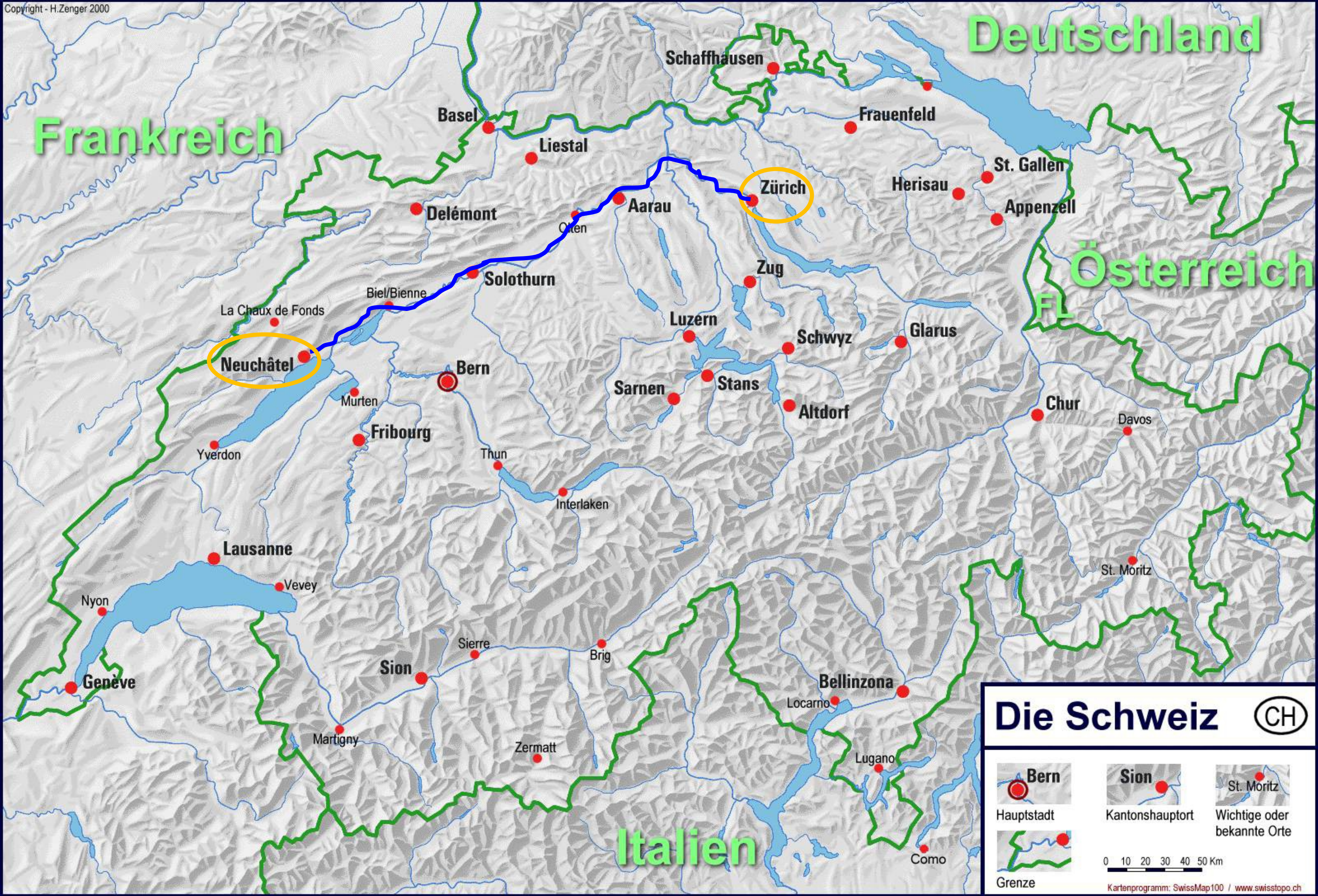

Emiliano Bonera


Leo Miglio

L-NESS: Laboratory for Epitaxial Nanostructures on Silicon and Spintronics (Como, Italy)



UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA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Wichtige oder bekannte Orte
Grenze
0 10 20 30 40 50 Km
Kartenprogramm: SwissMap100 / www.swisstopo.ch

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Collaborations

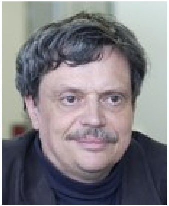
Philippe Niedermann

Antonia Neels

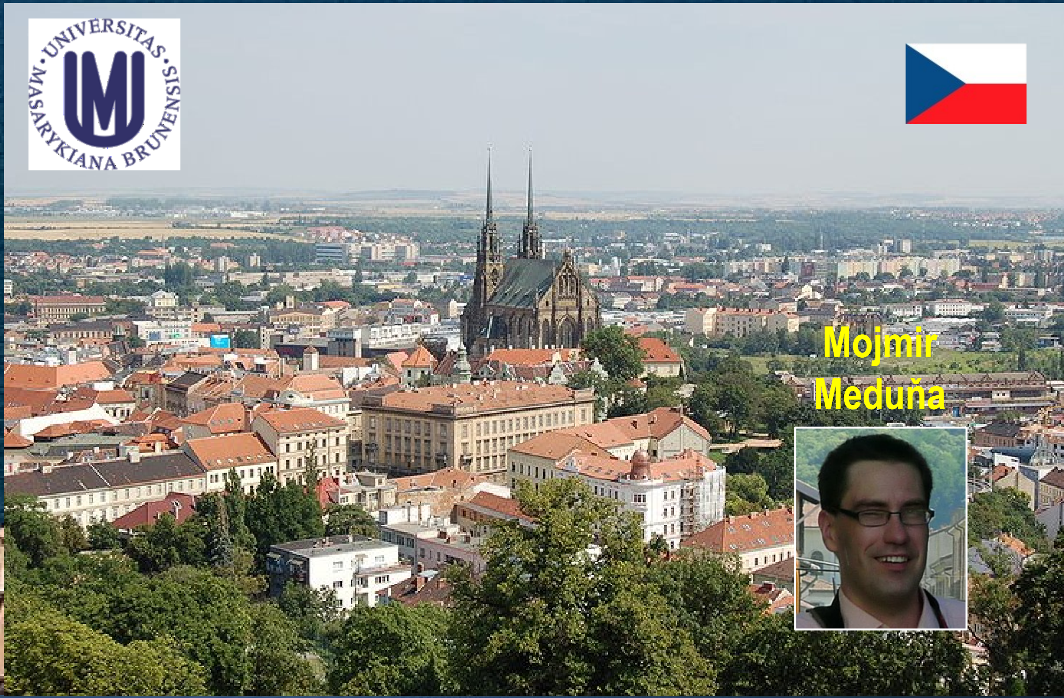
Aurélie Pezous

Rolf Kaufmann

Alex Dommann

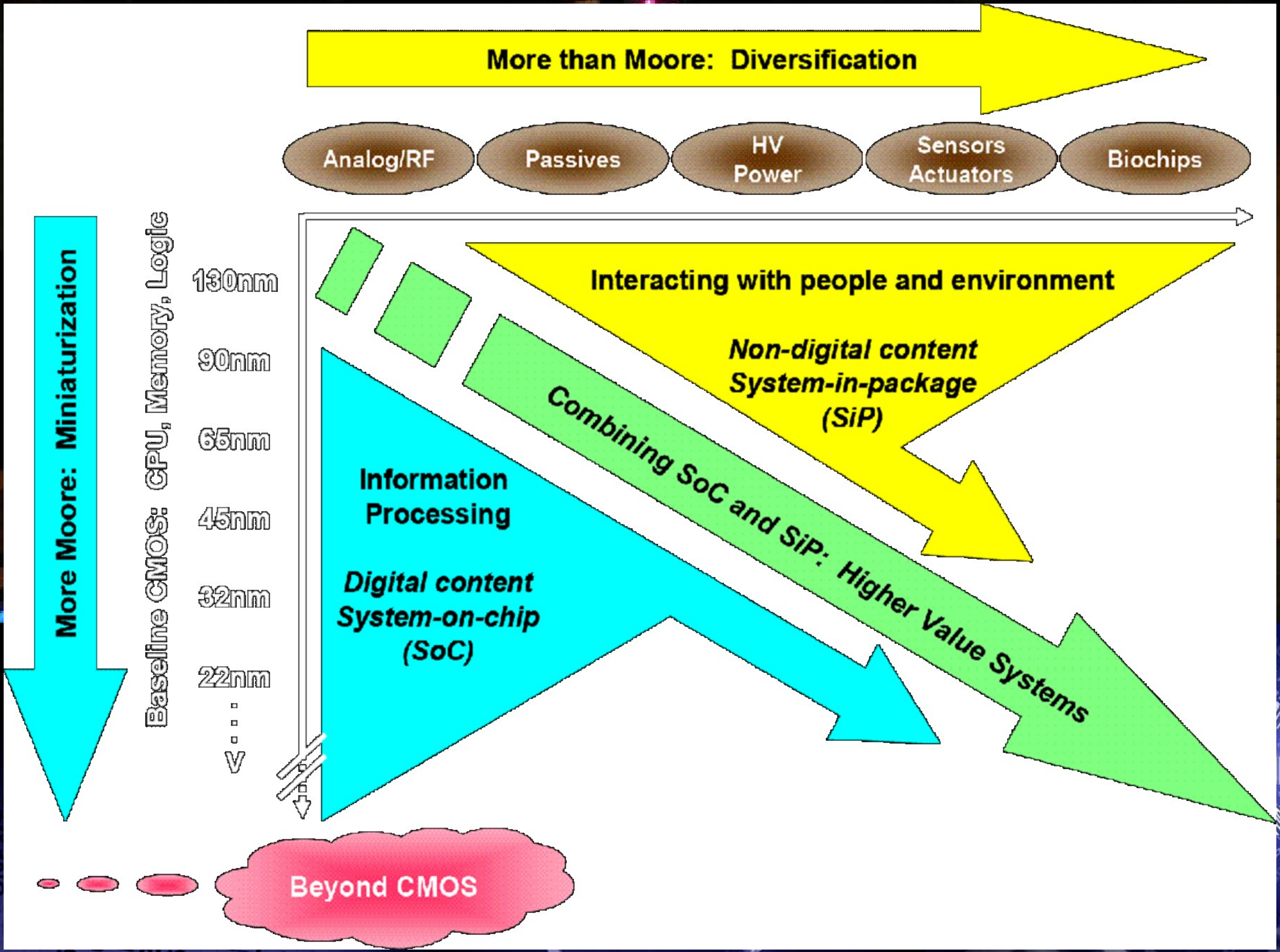


UNIVERSITAS MASARYKIANA BRUNENSIS



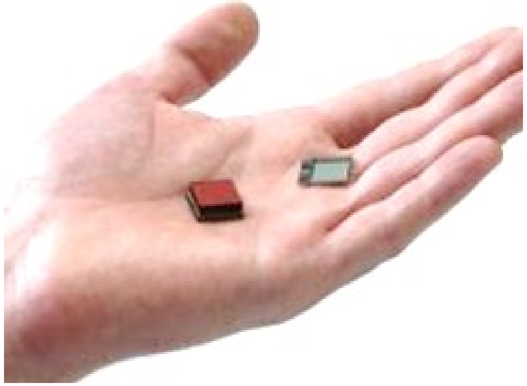
Mojmir Meduňa

International Roadmap for Semiconductors



Motivation: Integrated Miniaturized X-ray Systems

nano-tera.ch



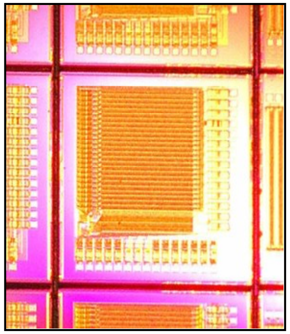
"NEXRAY"

- Next Generation X-Ray Systems
- High resolution/sensitivity
- Ge as conversion layer
- No bump-bonding (monolithic integration)

Fast, programmable X-ray sources

Ge layers for high-energy X-ray detection

Single-photon solid-state X-ray detection



Phase contrast X-ray imaging

EMPA
Materials Science & Technology

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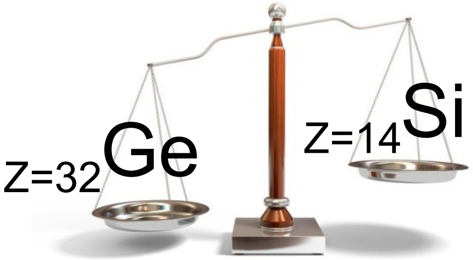
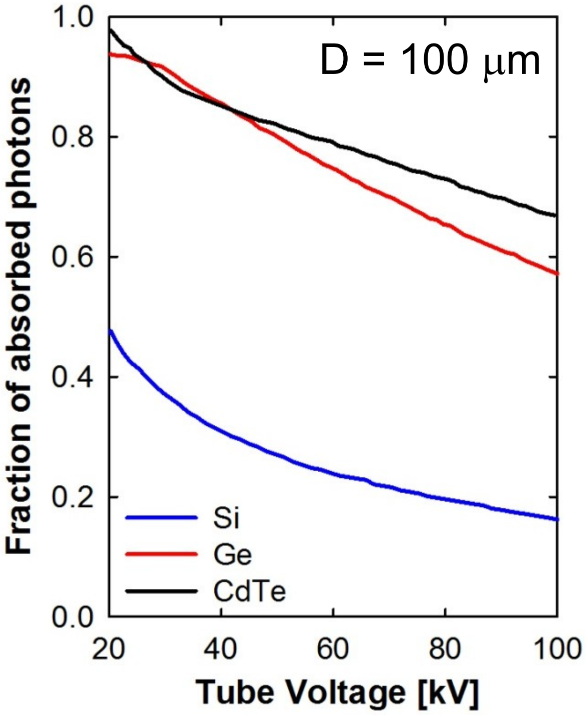
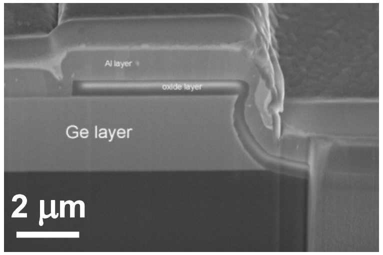
Motivation: Next Generation X-Ray Detectors

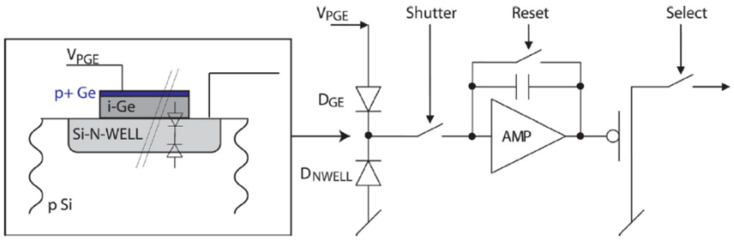
- Why Germanium?



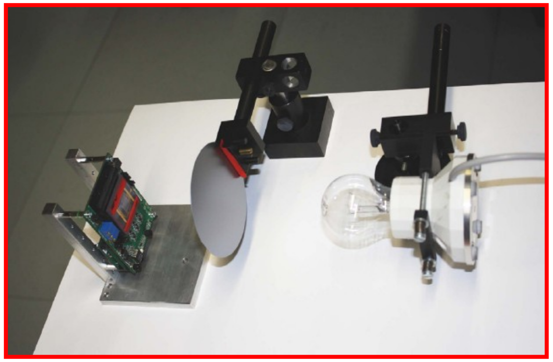


- Monolithic integration of a 3 μm Ge film with CMOS for IR radiation was demonstrated at ETHZ/CSEM

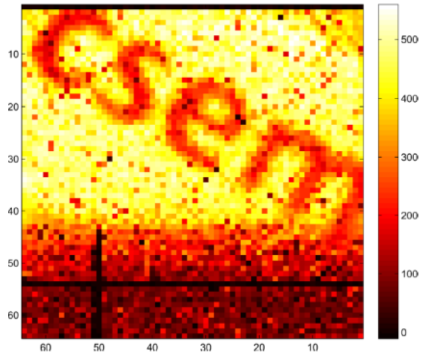




64×64 pixel IR sensor with integrated Ge photodiodes



⇨

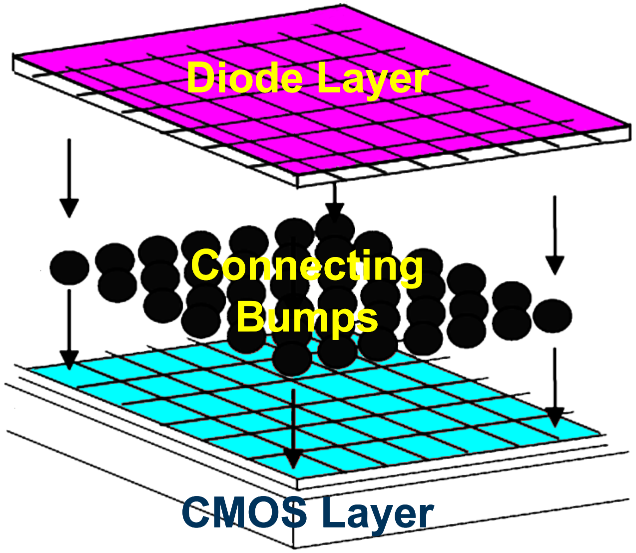


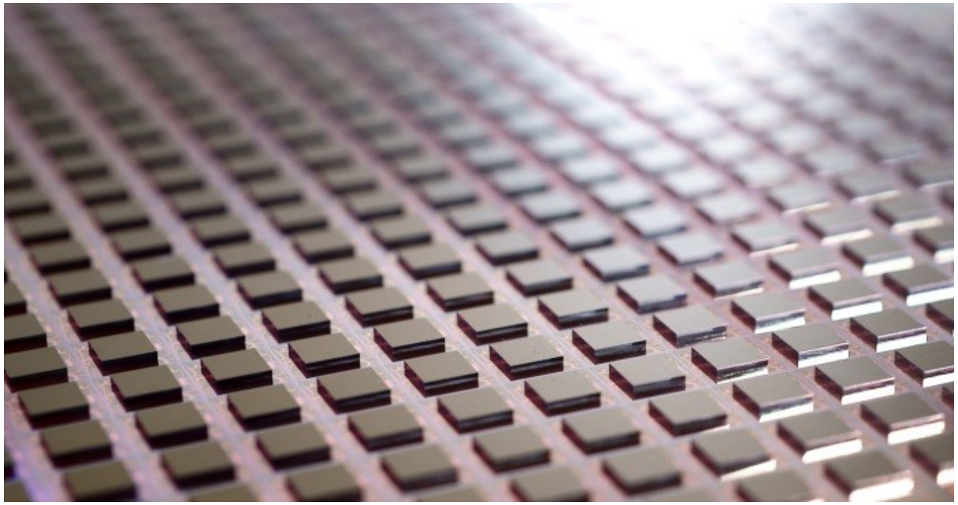
R. Kaufmann *et al*., J. Appl. Phys. **110**, 023107 (2011)

For X-rays → SUPER THICK (> 50 μm !!!) high quality (i.e. dislocations, uniformity) Ge epilayers

Integration of Mismatched Materials: State-of-the-art

A. Wafer Bonding



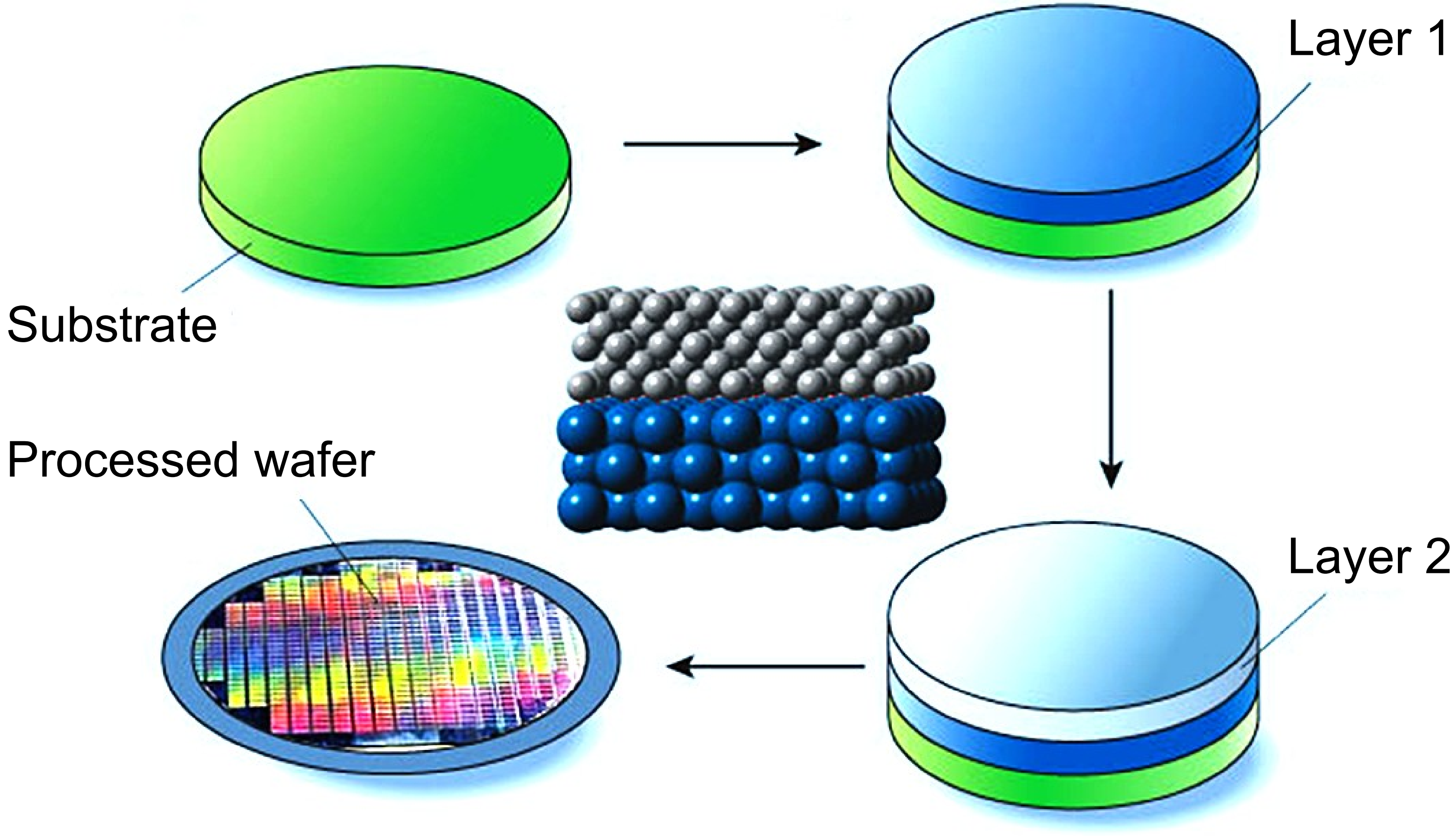


☹ Debonding may occur at large ΔT

☹ Expensive bump-bonding required

Integration of Mismatched Materials: State-of-the-art

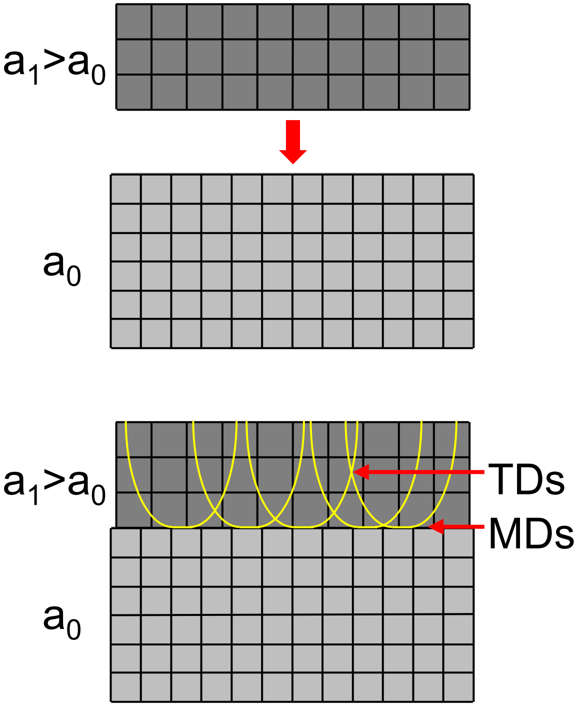
B. Monolithic Integration (HETERO-EPITAXY)



Key Problems of Hetero-Epitaxy

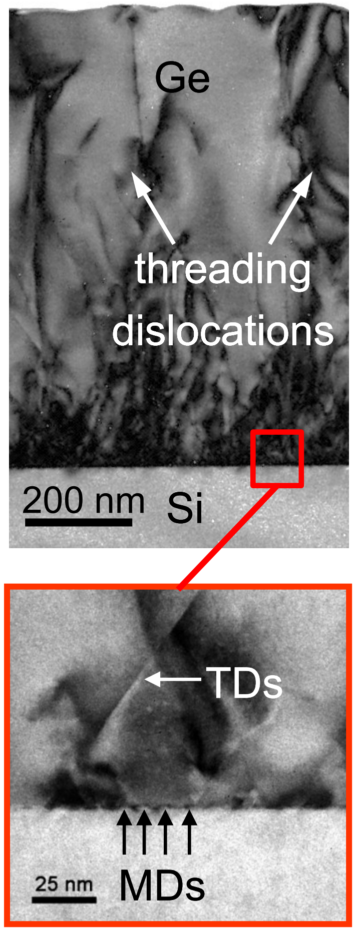
Dislocations

(lattice mismatch)



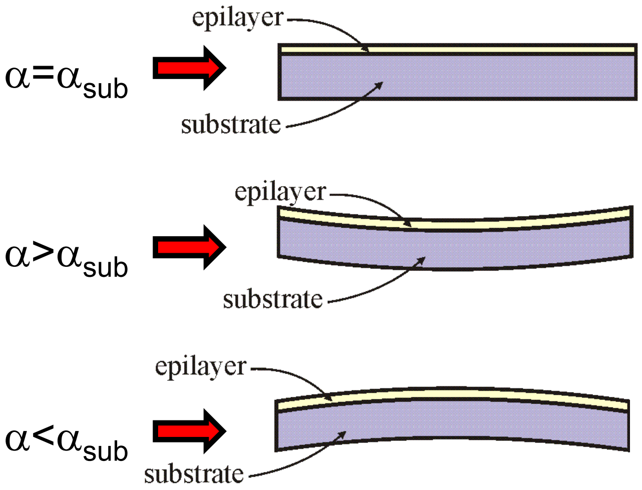
TDs – threading dislocations

MDs – misfit dislocations

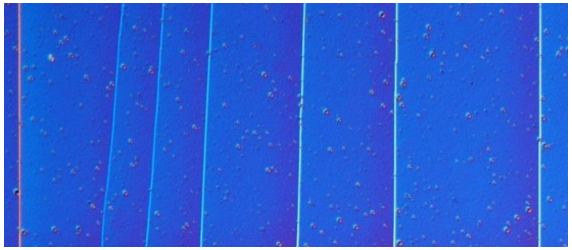


Wafer Bowing & Cracks

(thermal mismatch)



Nomarski top view micrograph

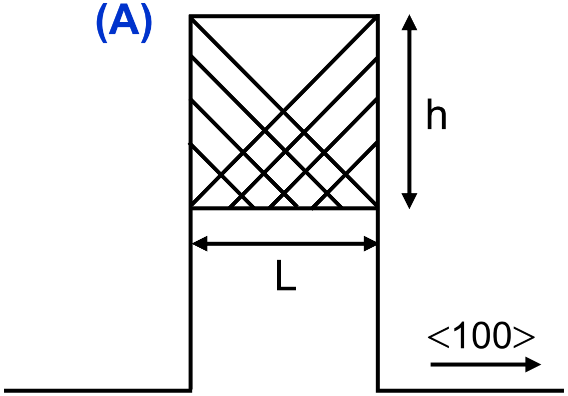


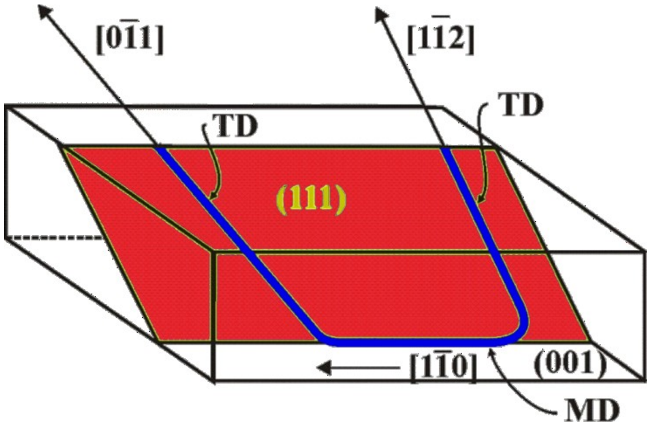
30 µm Ge/Si(001)

Dislocations Control by Substrate Patterning

- S. Luryi, E. Suhir, APL **49**, 140 (1986) → critical thickness increases very much with the reduction of the lateral dimension of the patterned areas
- (A) E.A. Fitzgerald, N. Chand, J. Electron. Mater. 20, 839 (1991) → Epitaxial Necking (GaAs on Si)
- (B) T.A. Langdo et al., APL 76, 3700 (2000) → Epitaxial Necking (Ge on Si)
- (C) J.S. Park et al., APL 90, 052113 (2007) → Aspect Ratio Trapping (ART)

(A)





60-degree dislocations

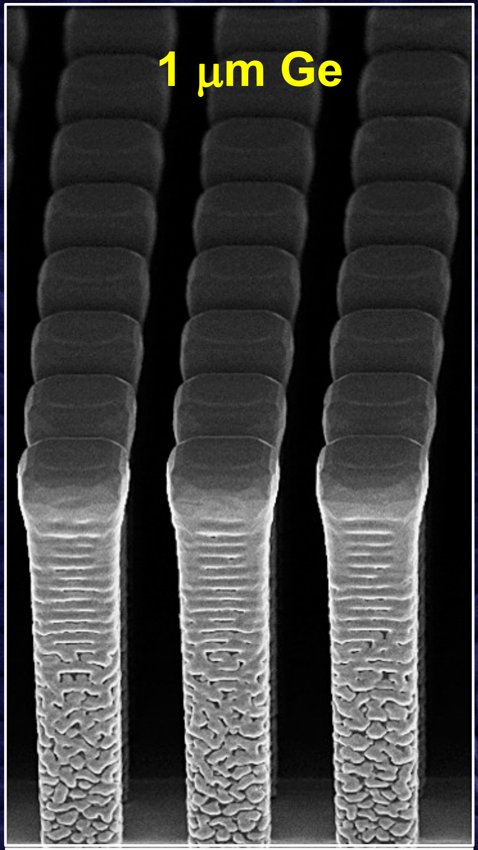
A.E. Blakeslee, MRS Symp. Proc. **148**, 217 (1989)

J.W.Matthews et al., JAP **41**, 3800 (1970)

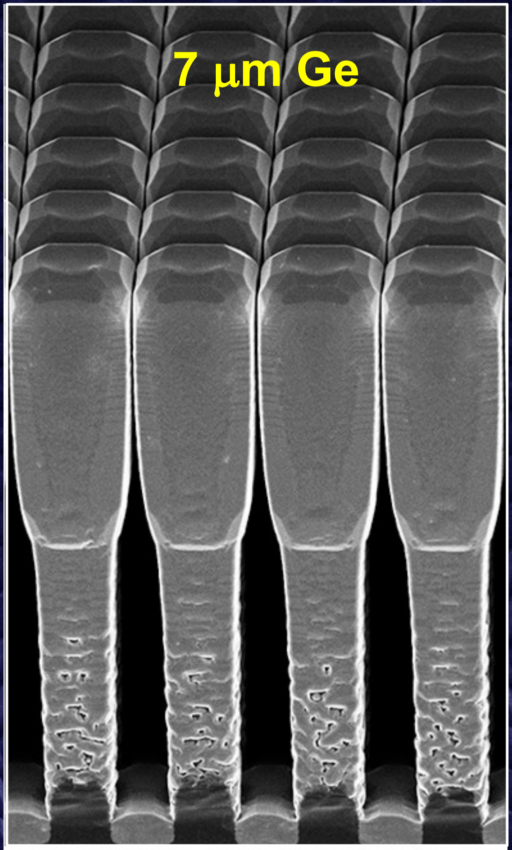
Growth on Patterned Si Wafers

Si “**pilars**”
(DRIE)

Ge growth (~4 nm/s)
(LEPECVD)

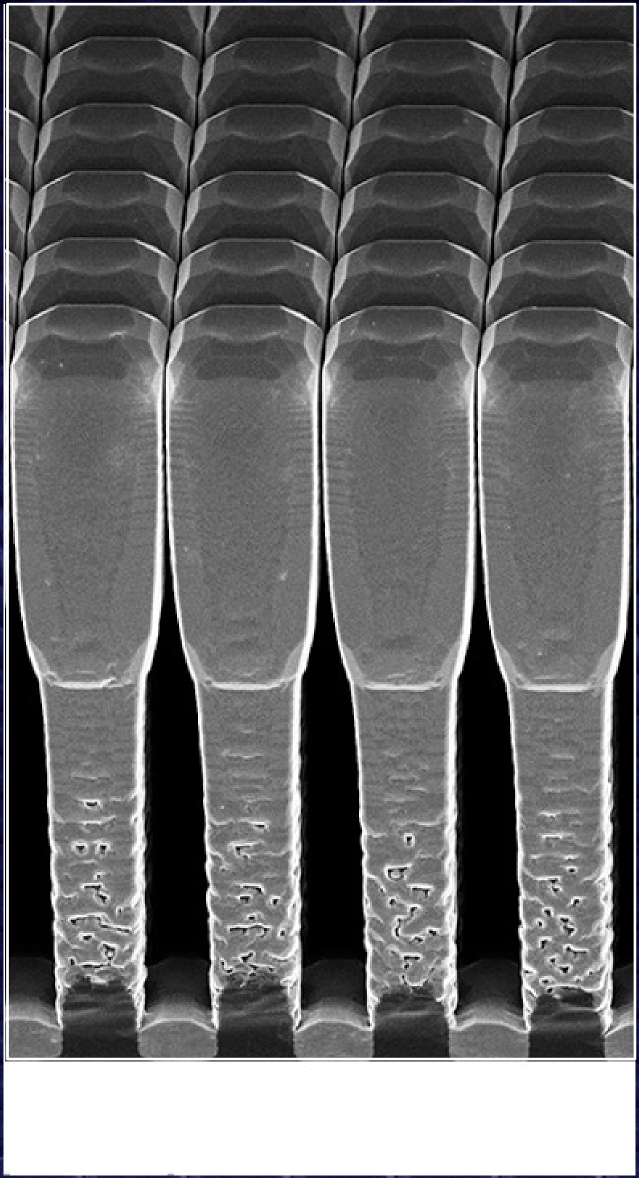


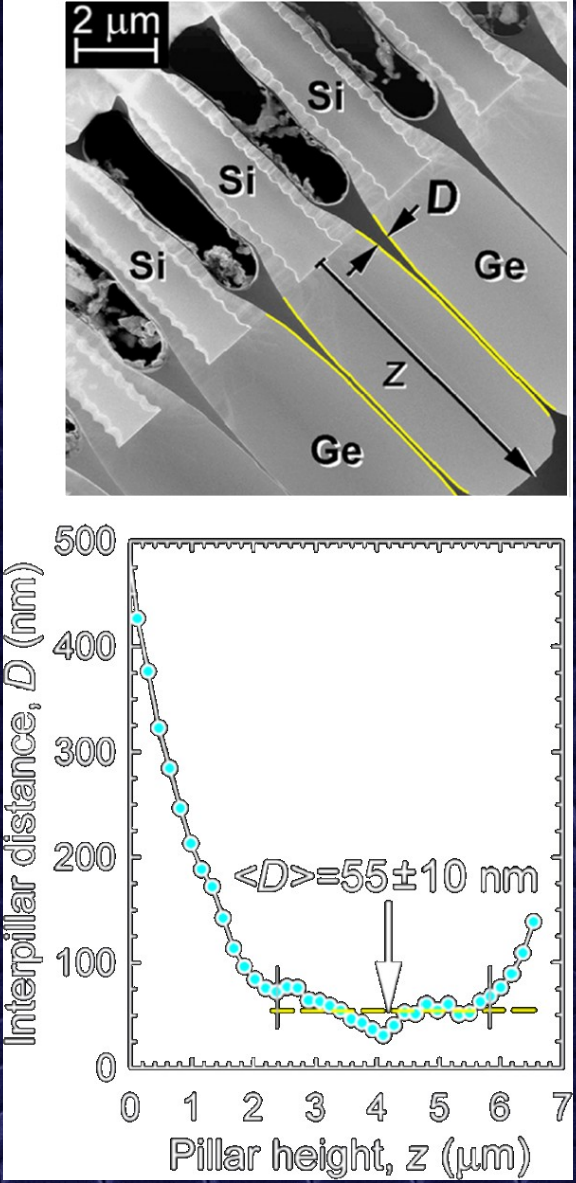
Ge “**towers**”
(Quenched Lateral Growth)



LEPECVD: “Low Energy Plasma Enhanced CVD” (H. von Känel, ETH-Zürich)

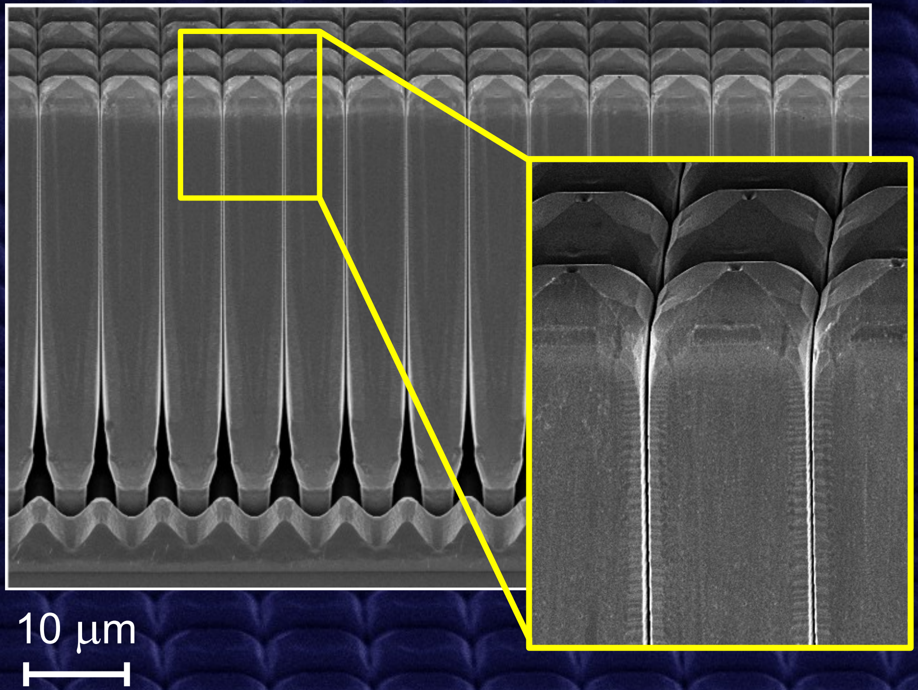
New Growth Mechanism: Self Limiting Lateral Growth

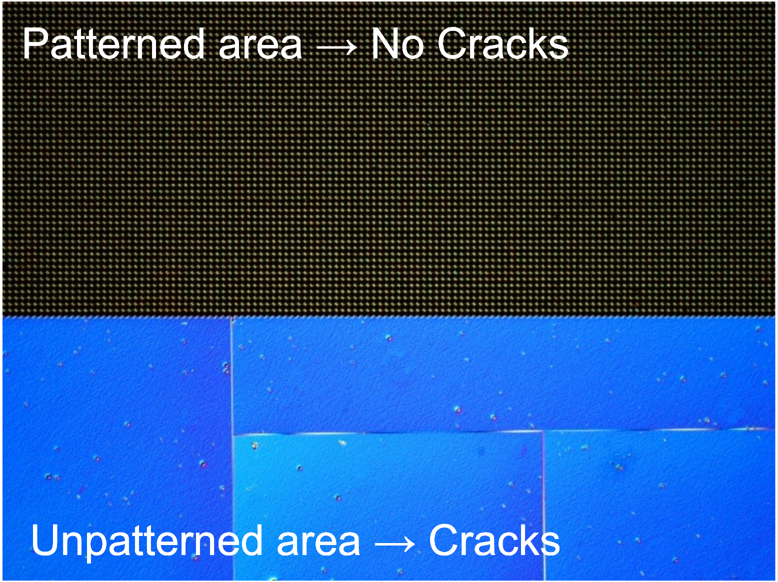




Unlimited Layer Thickness

Ge "towers": **50 µm (!)**



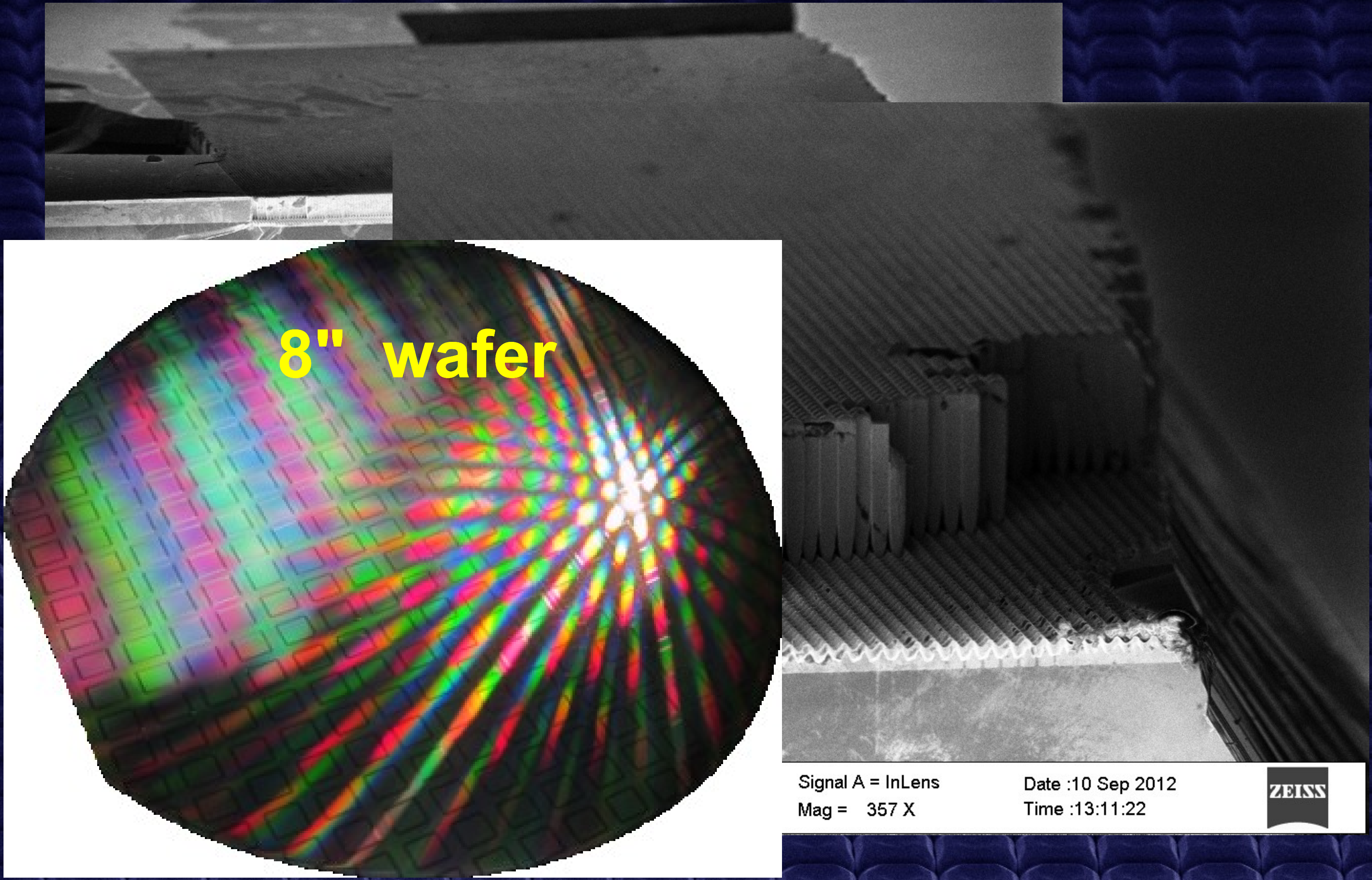


__100 µm__ thin pre-patterned 8" CMOS wafer completely covered with __20-µm-tall Ge towers__ → __very small bowing!__

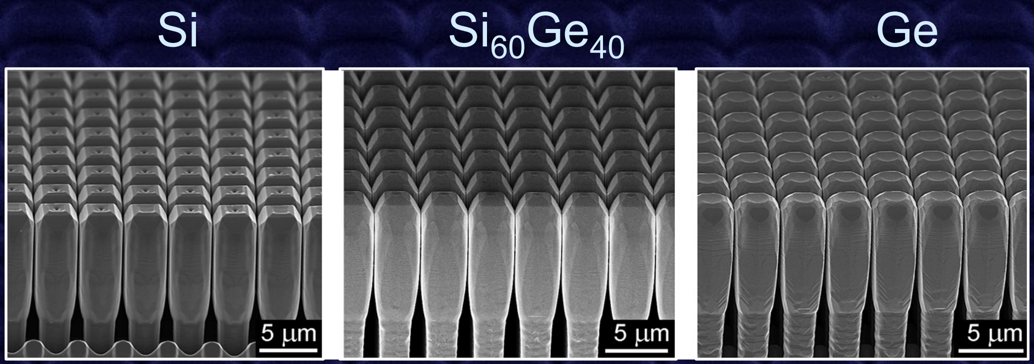
- Cracks don't propagate into the patterned area
- Elimination of the wafer bowing

Very High Surface Filling

Ge “towers”: **50 μm (!)**

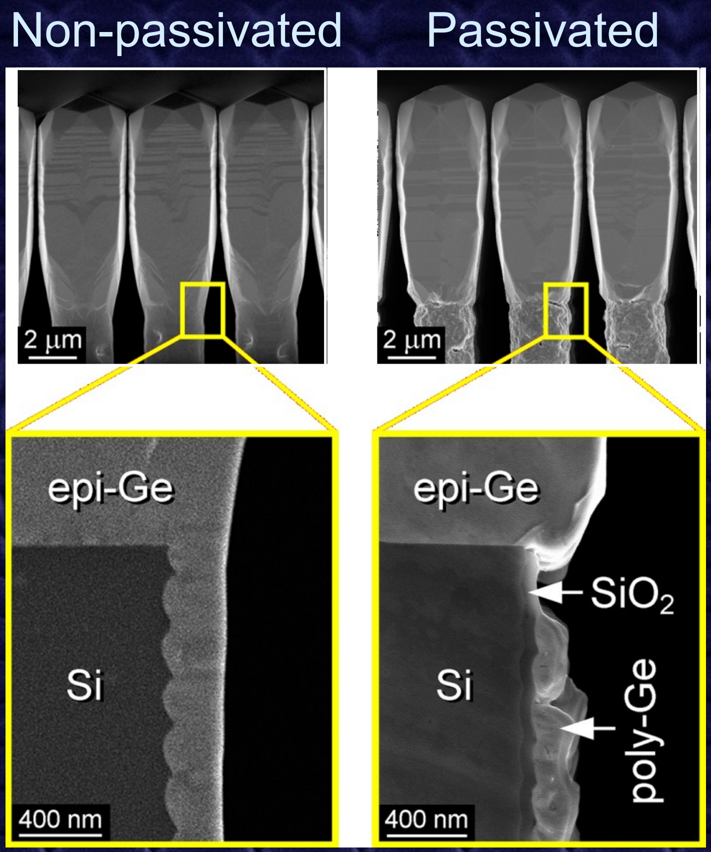


Ubiquity of the Epitaxial Growth Mode

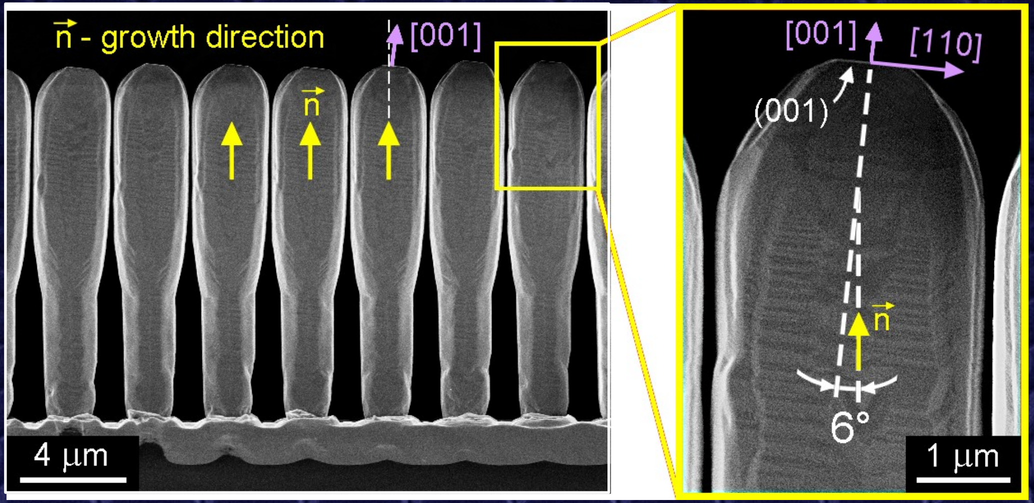

Si

$Si_{60}Ge_{40}$

Ge

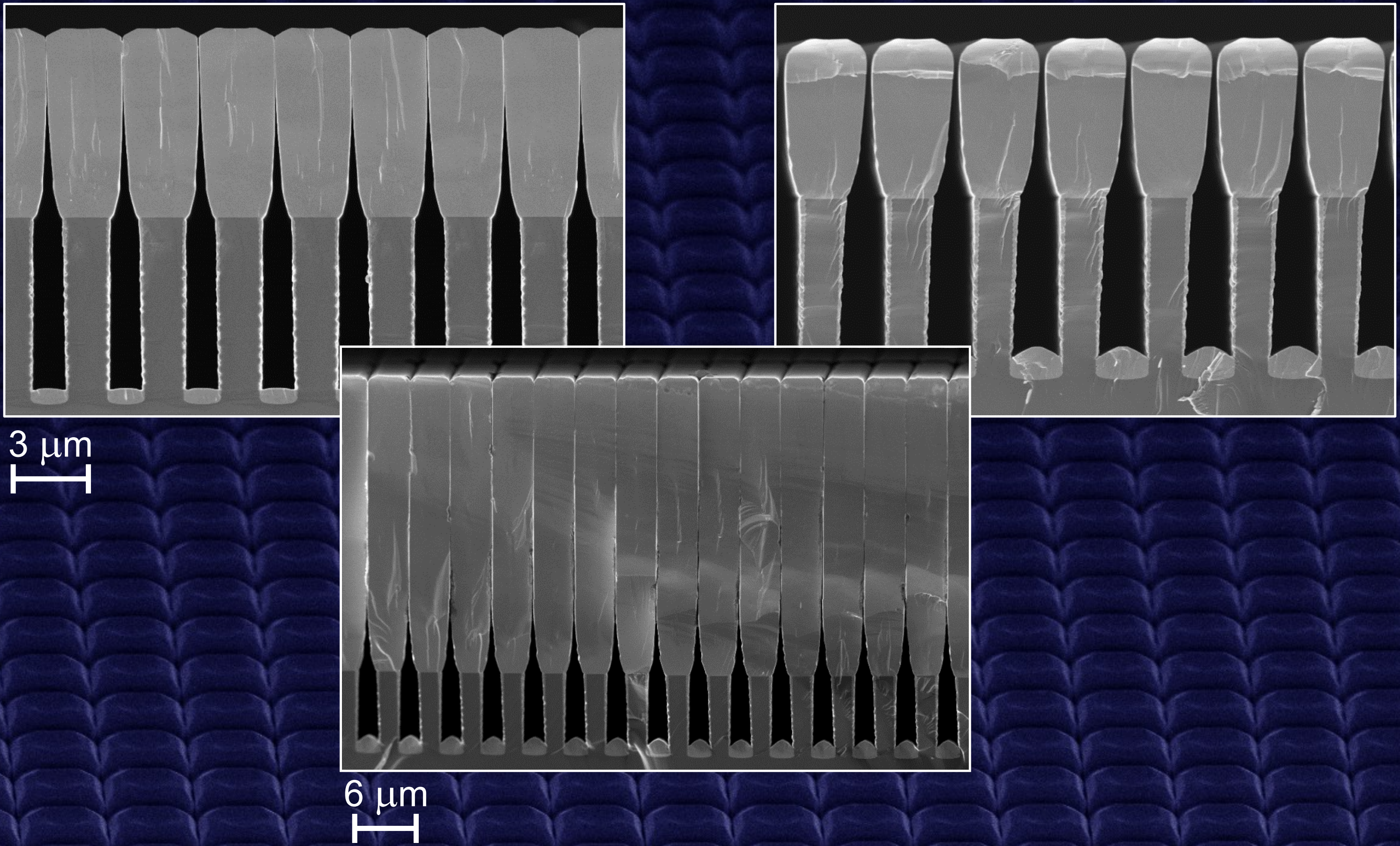

Non-passivated

Passivated



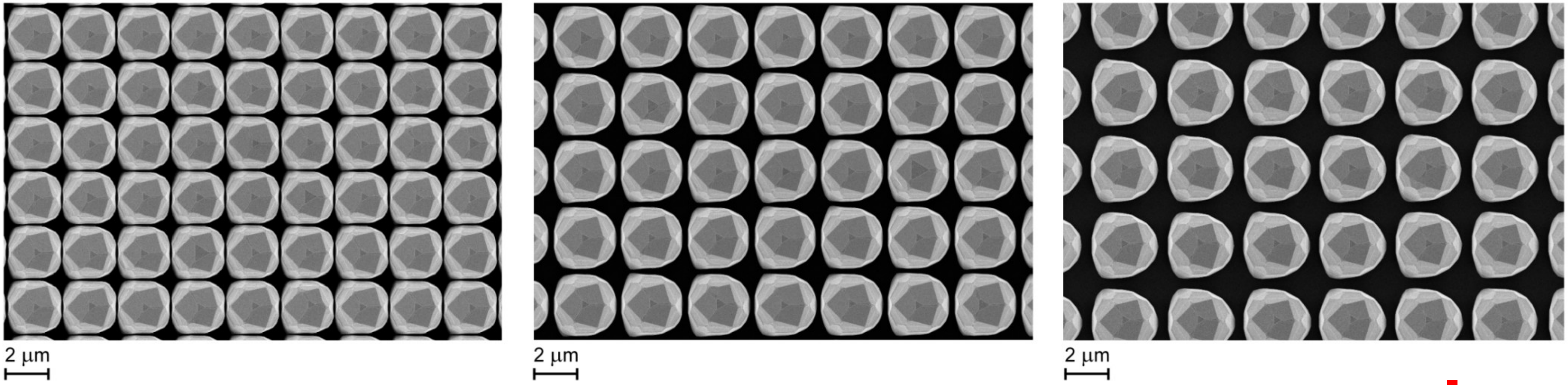
Ge towers are obtained for different thermal/lattice mismatch, substrate miscut, geometry of the patterns (e.g. pillars, ridges), initial facet distribution (passivated or not), smootheness of the pillar sidewalls !

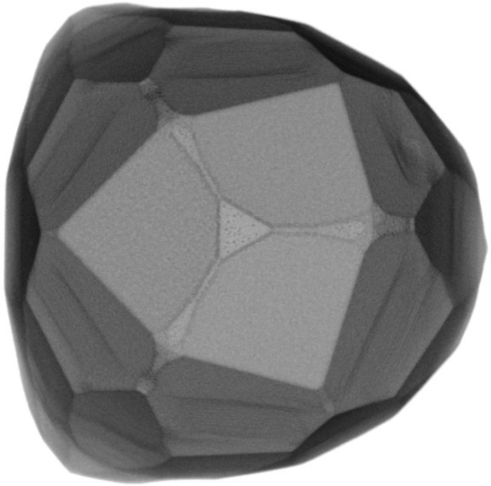
Growth of Germanium on Si Ridges

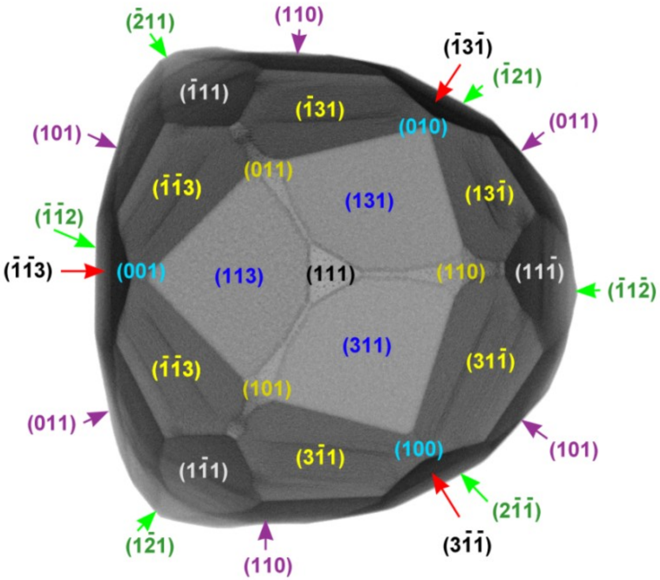


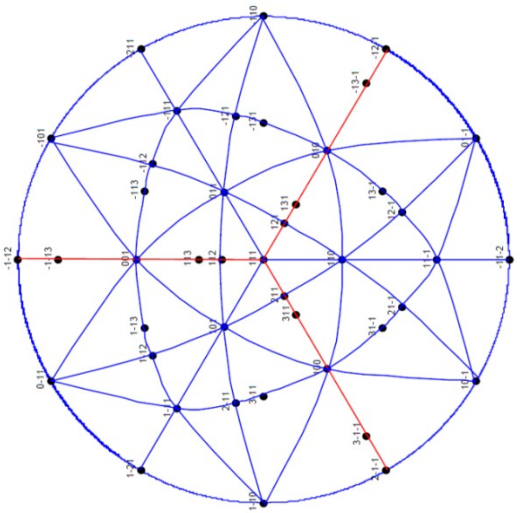
⇒ **Growth of Ge on Si ridges is similar to that on Si pillars**

Growth of Germanium on Si(111) substrates







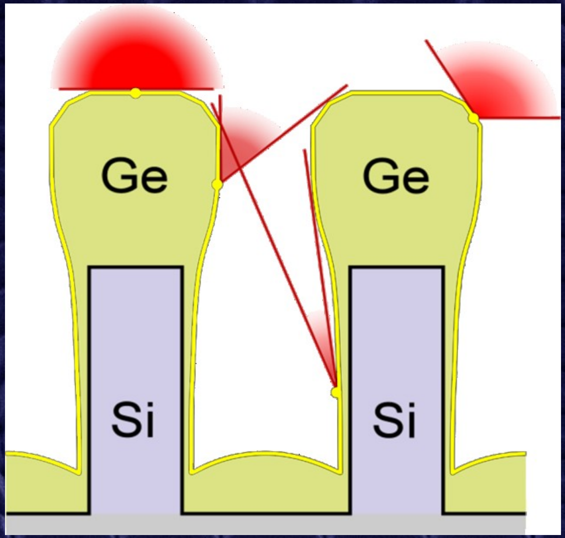


From Isolated Pillars to Closely Spaced Pillar Array

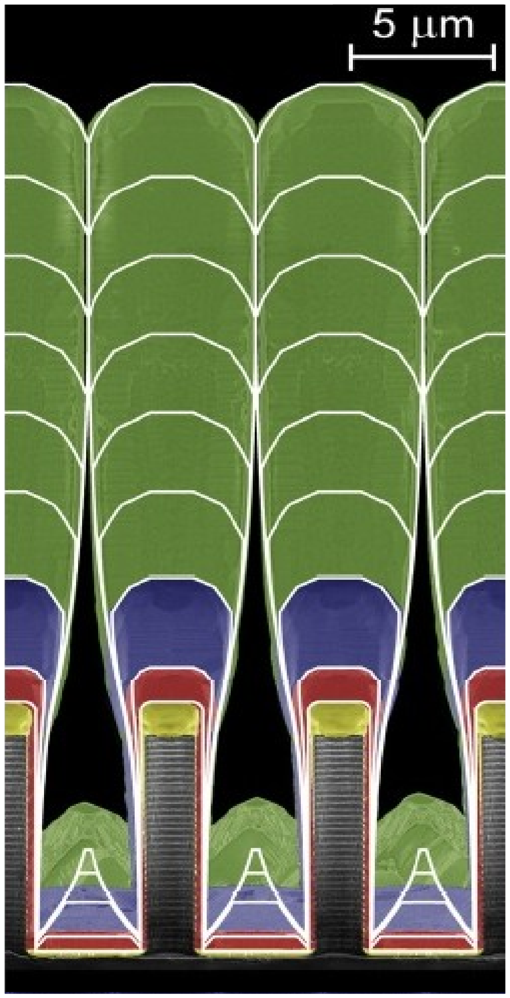
1) High deposition rate (~ 4 nm/s)

⇒ Short diffusion length

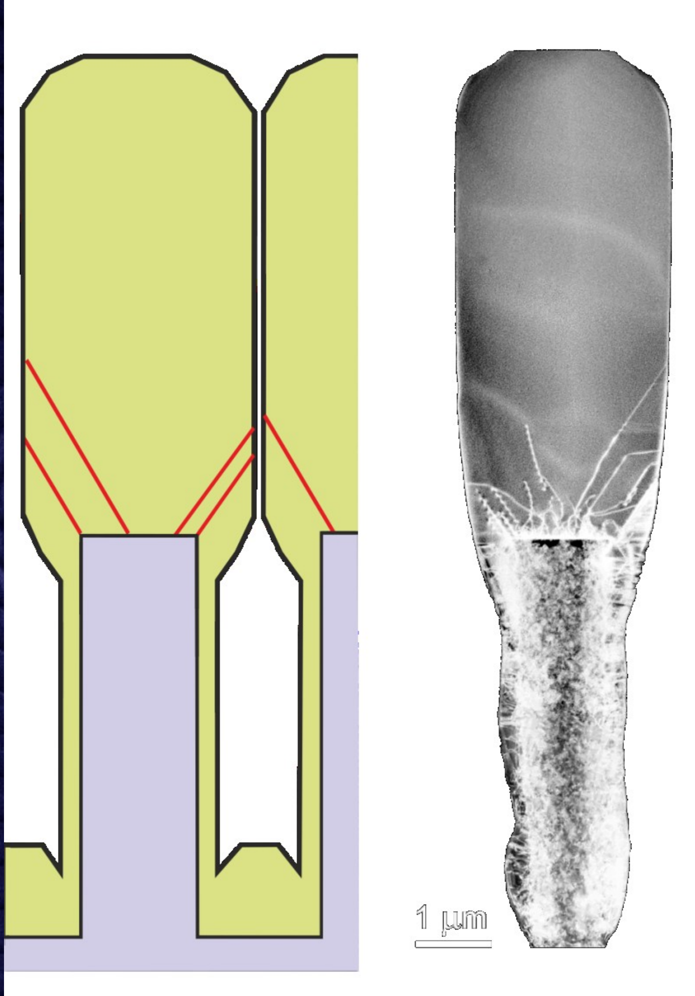
2) Mutual flux shielding



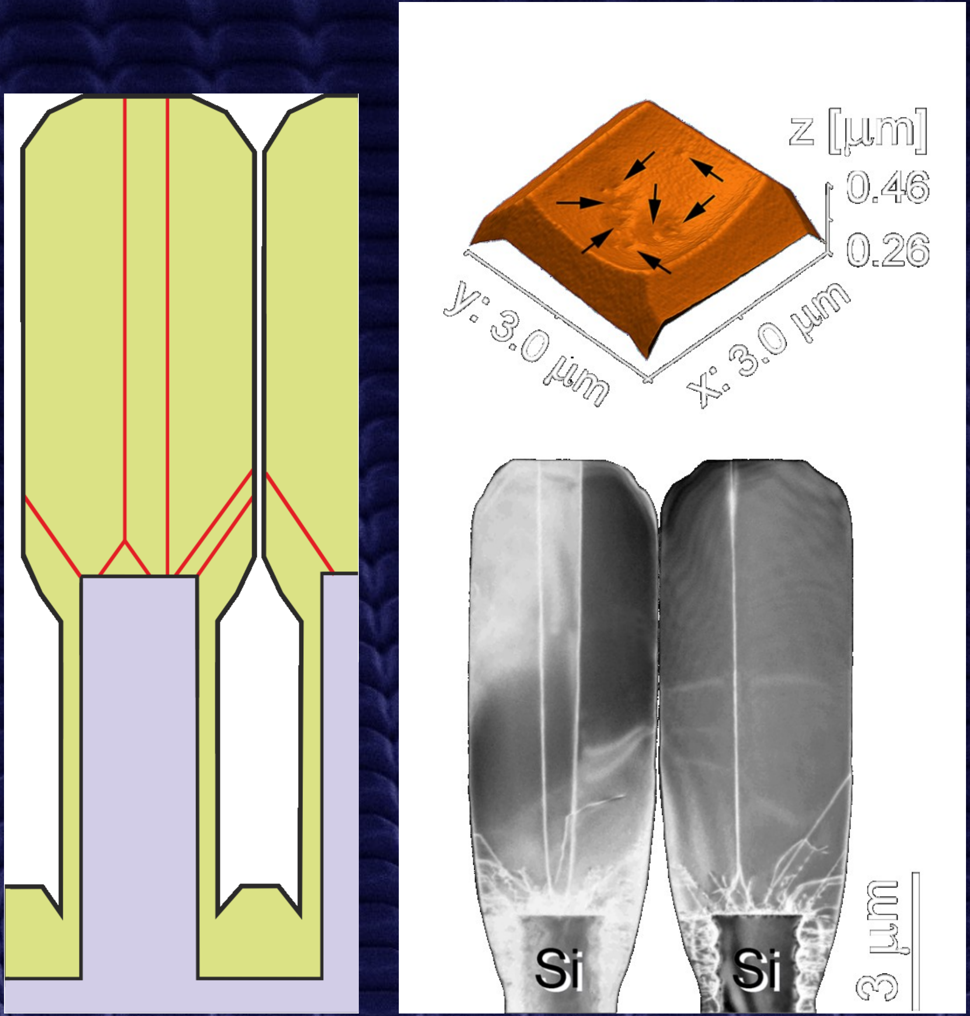
Modelling based on the rate equation for the adatom phase



Dislocation Management by Epitaxial Necking

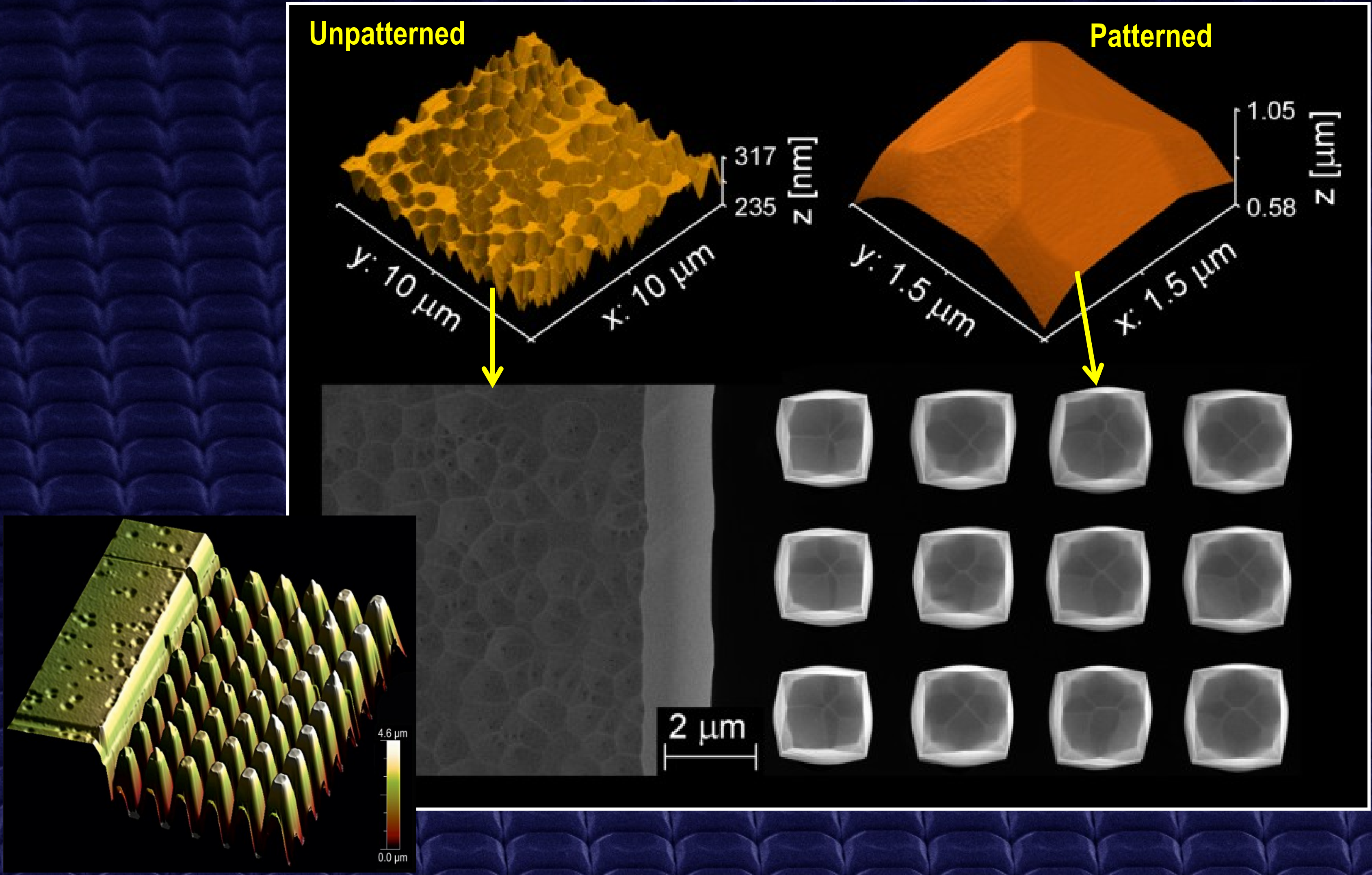


“60°Dislocations”

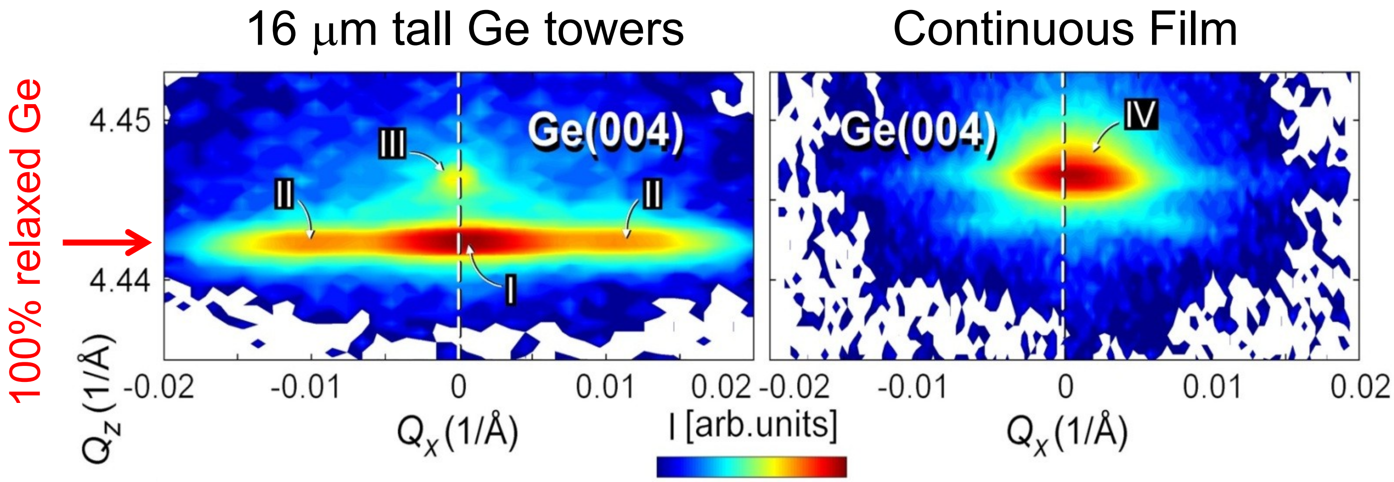


“Growth Dislocations”

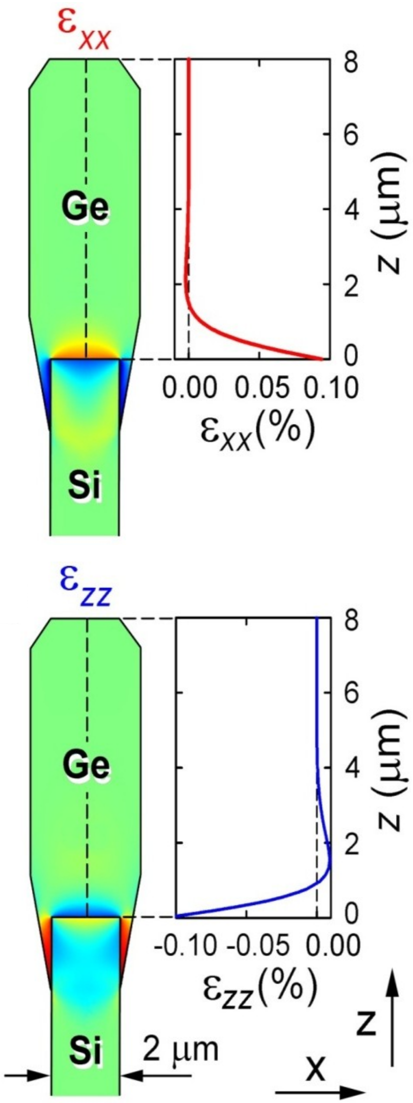
Dislocation Management by Surface Facetting

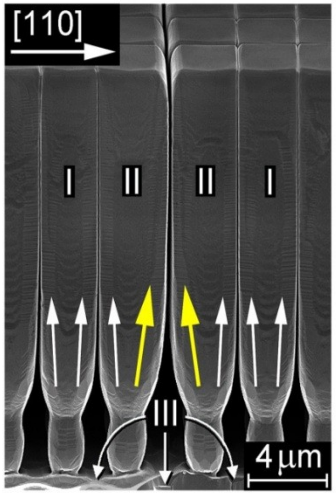


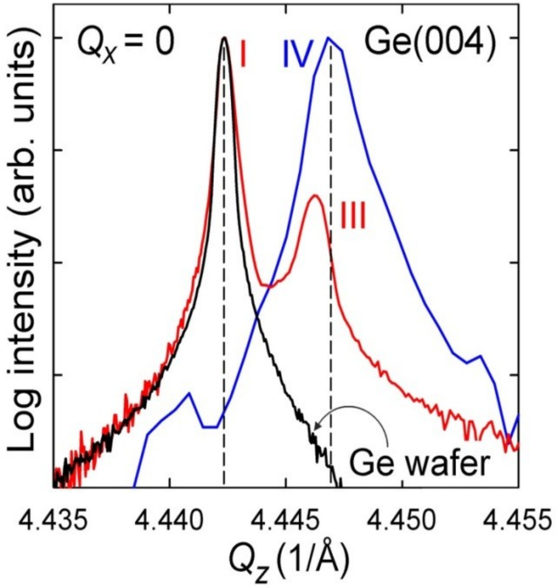
Assessment of the crystalline quality (HRXRD)

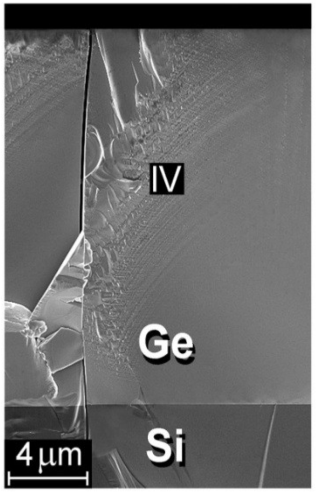

16 µm tall Ge towers

Continuous Film

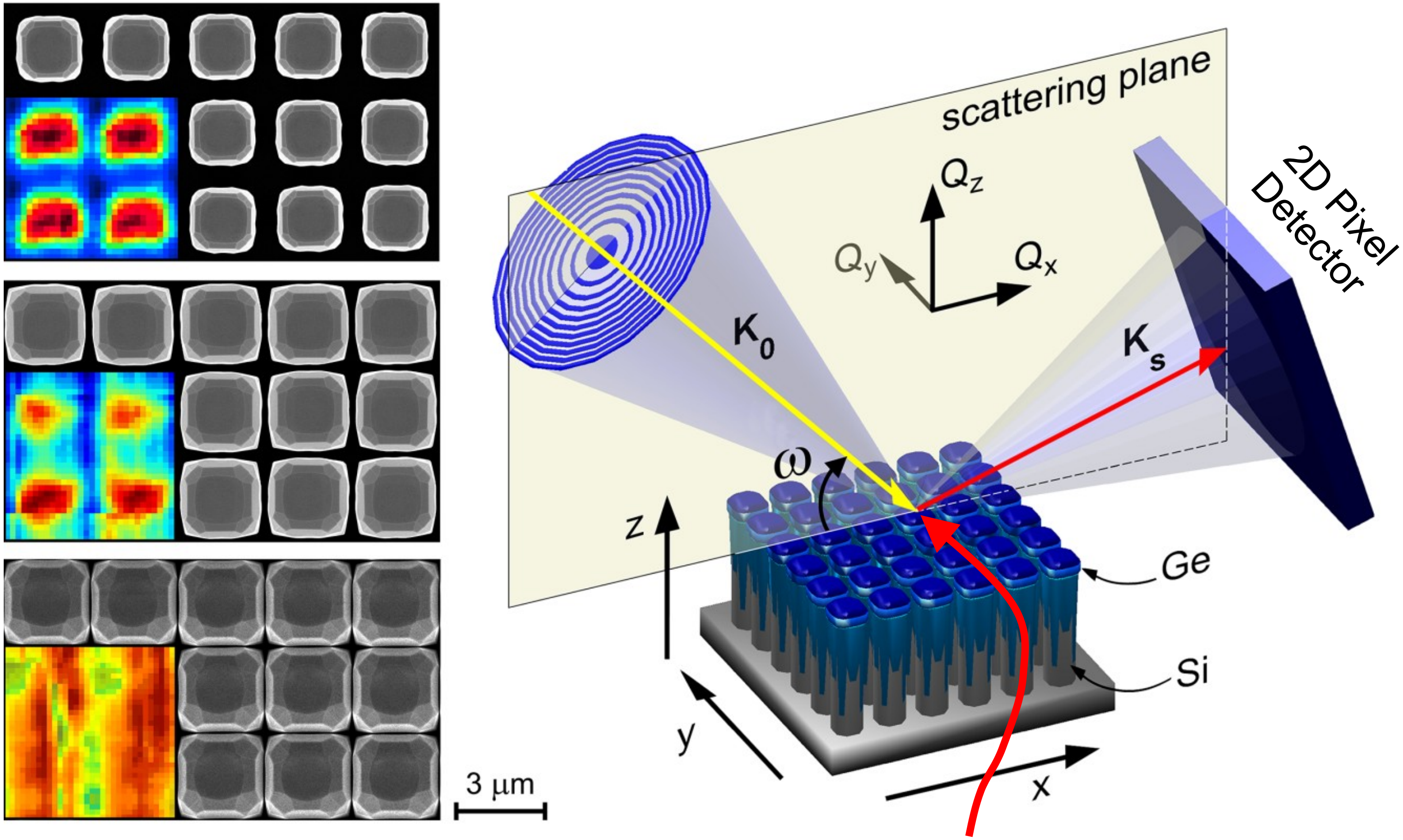








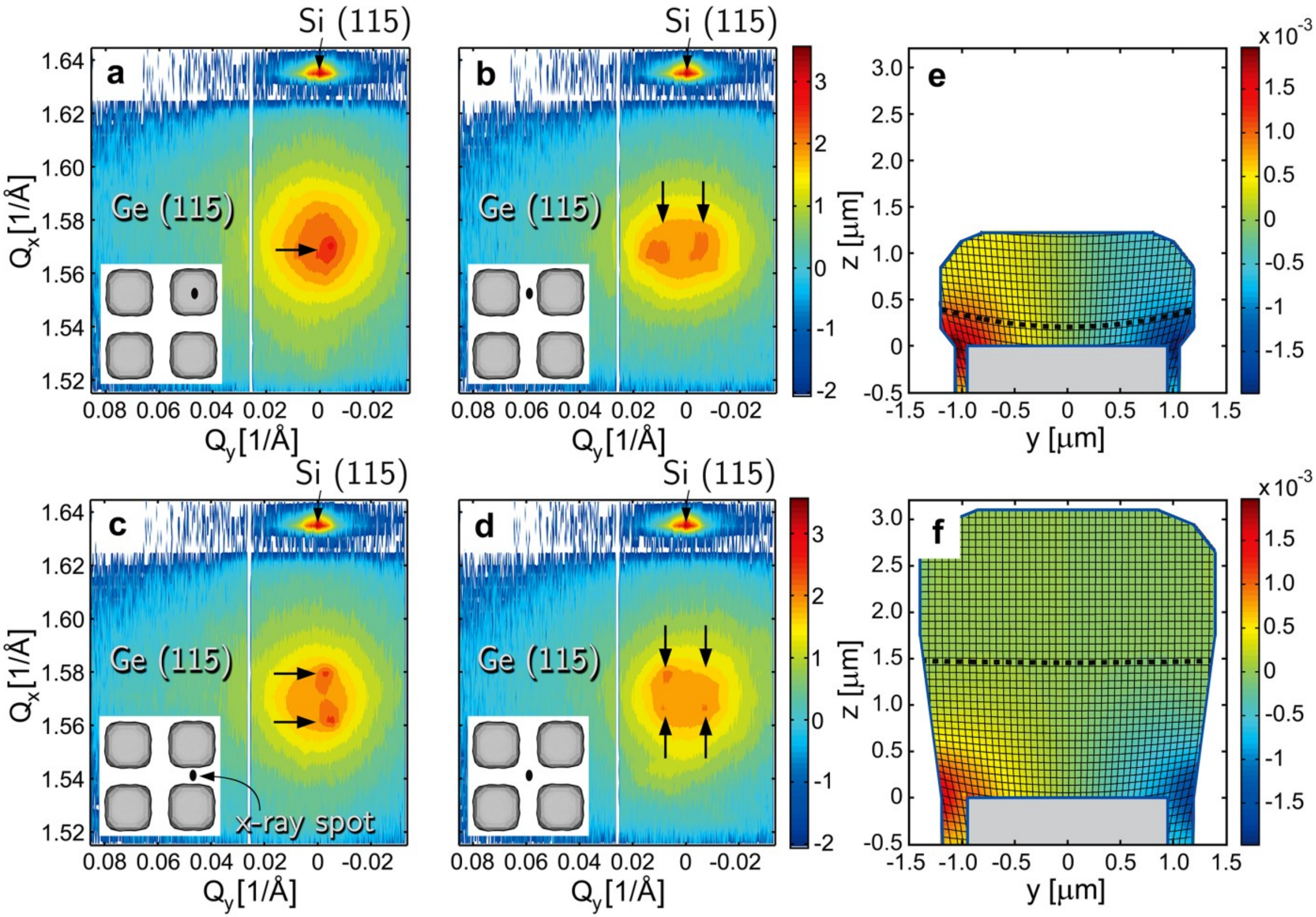
Three Dimensional Nanodiffraction of Ge Crystals



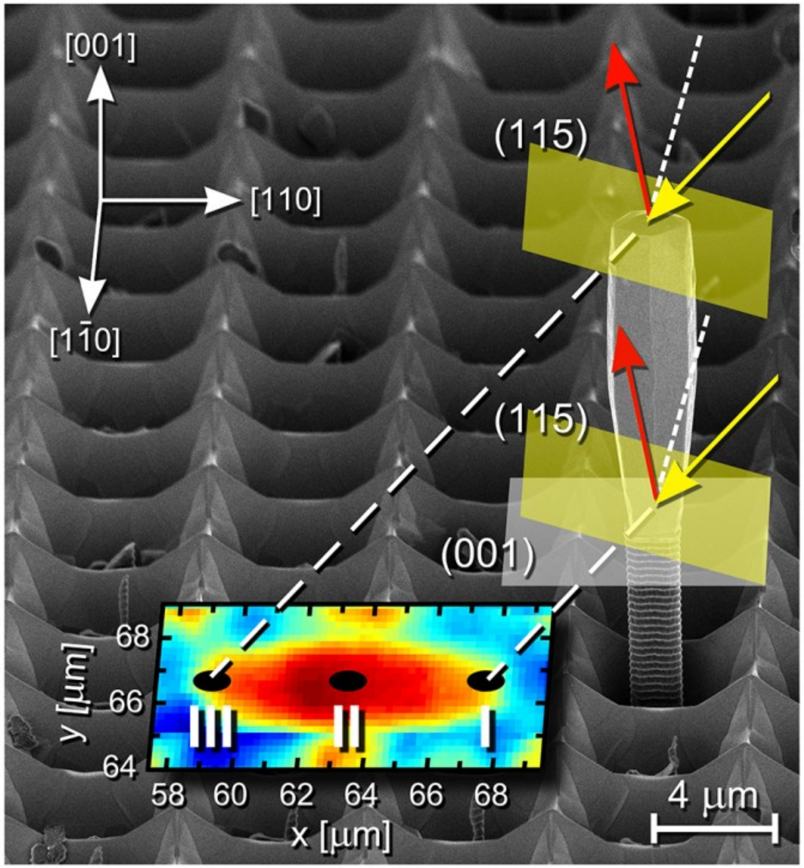
X-ray beam

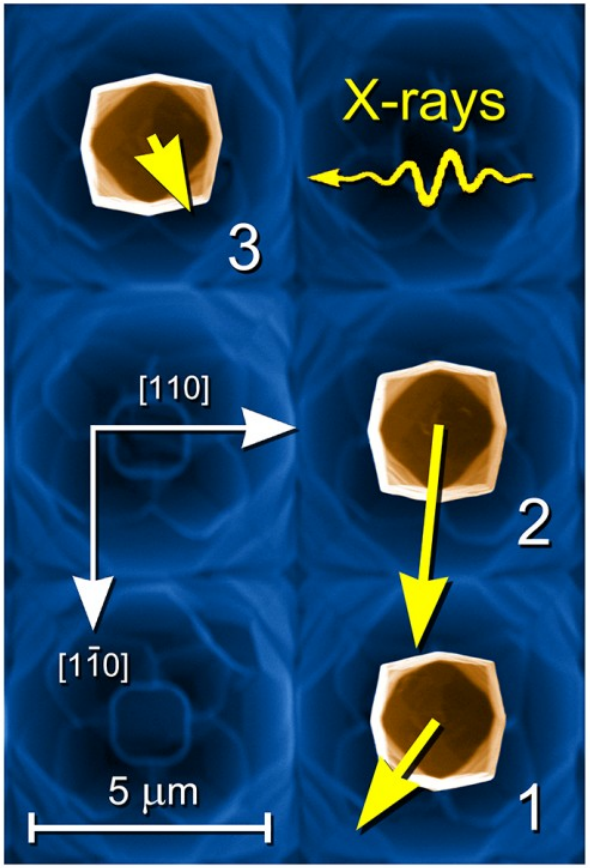
~ 300×500 nm

Three Dimensional Nanodiffraction of Ge Crystals

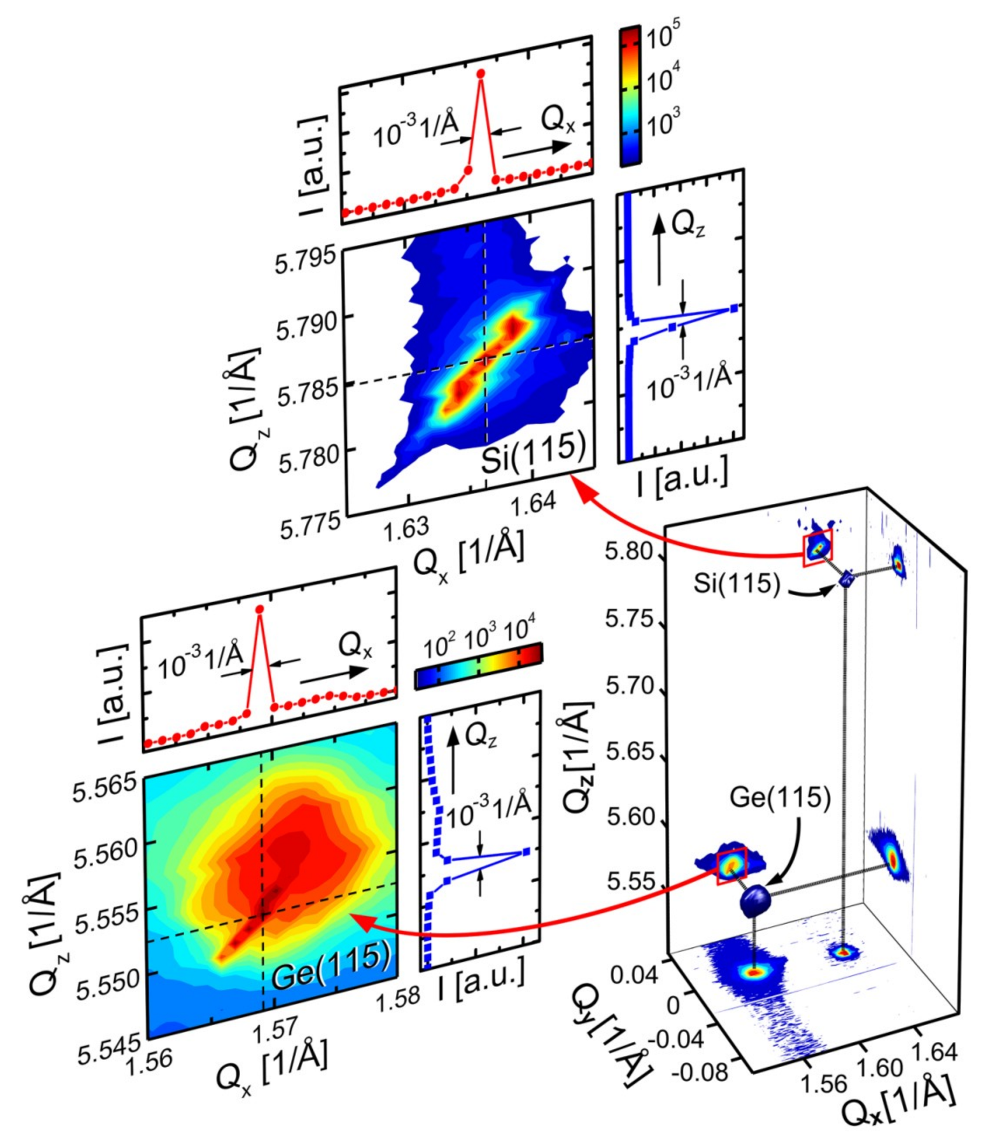


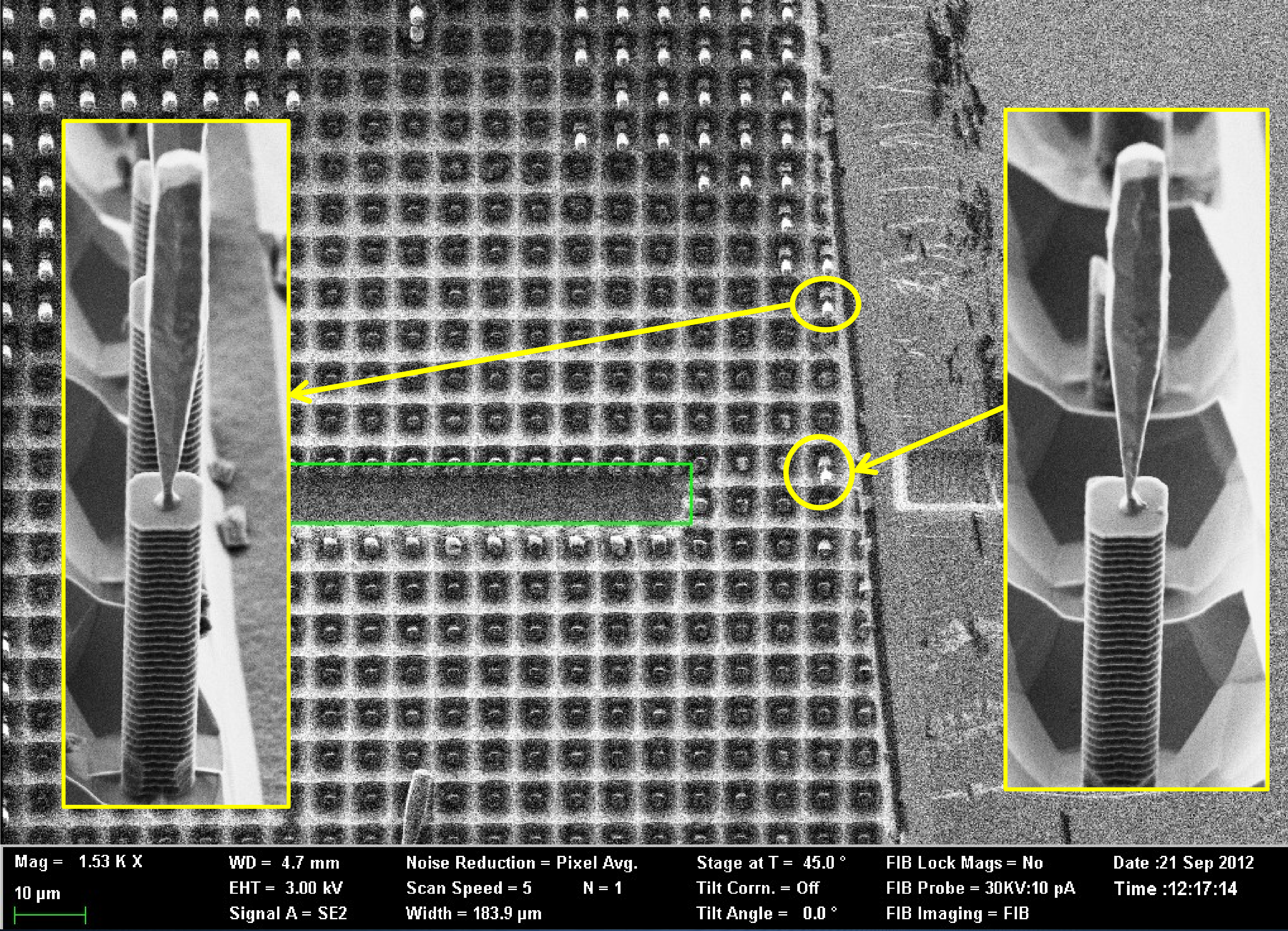
Nanodiffraction of Isolated Ge Crystals





Nanodiffraction of Isolated Ge Crystals





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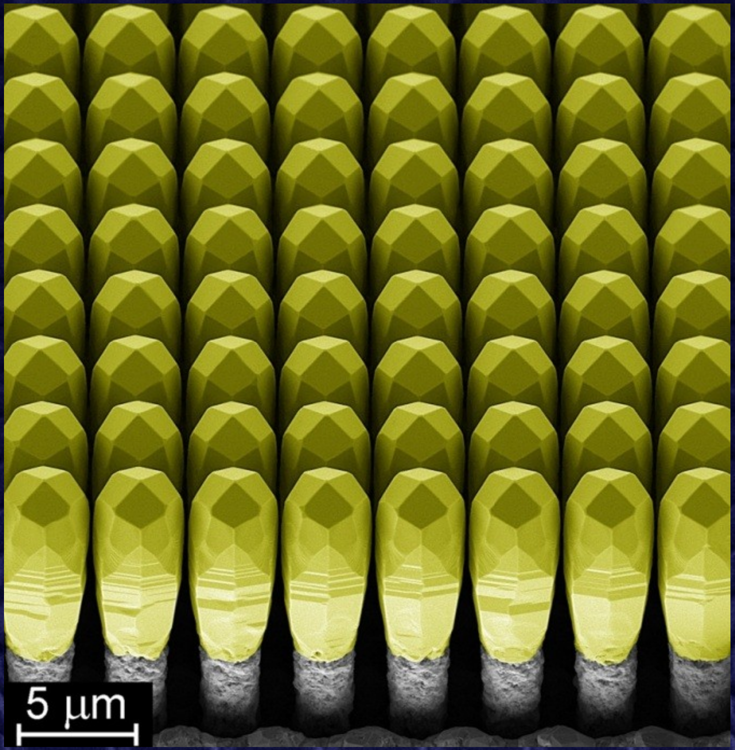
Strain and Dislocations Free Ge Crystals



TUNABLE QUASIPERFECT MATERIALS !

- Unique in the last 40 years of epitaxial work !
- Until recently considered to be impossible !

Scaling Hetero-Epitaxy from Layers to Three-Dimensional Crystals

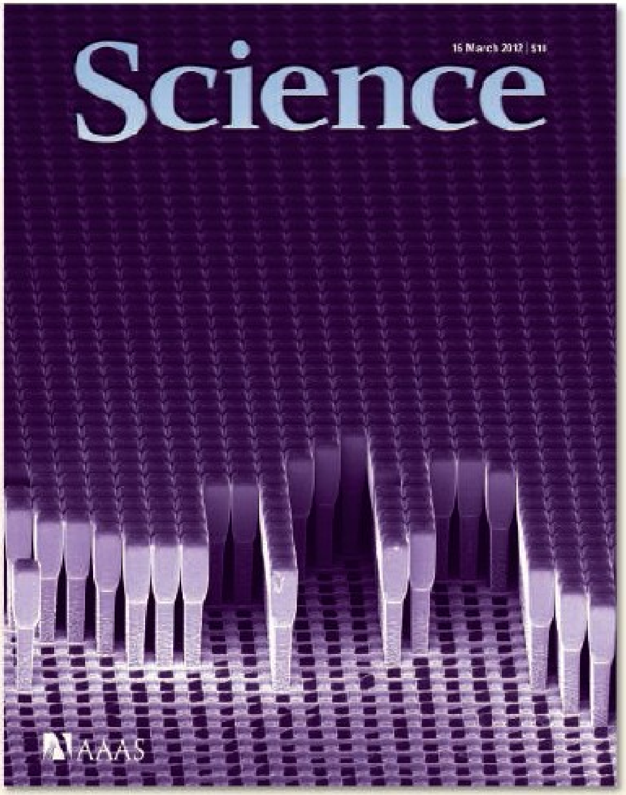
Claudiu V. Falub *et al.*
Science **335**, 1330 (2012);
DOI: 10.1126/science.1217666

SCIENCE VOL 335 16 MARCH 2012

Published by AAAS

8 December 2011; accepted 27 January 2012

www.sciencemag.org



Terracotta Army (China), 3rd century BC

COVER

False-colored scanning electron micrograph of ~8-micrometer-tall germanium crystals, separated by finite gaps, grown onto silicon pillars. In structures like this one, wafer bowing and layer cracking are absent, allowing single-crystal integration of different materials onto a silicon substrate, which serves as a platform for many applications, such as multiple-junction solar cells, x-ray and particle detectors, or power electronic devices. See page 1330.

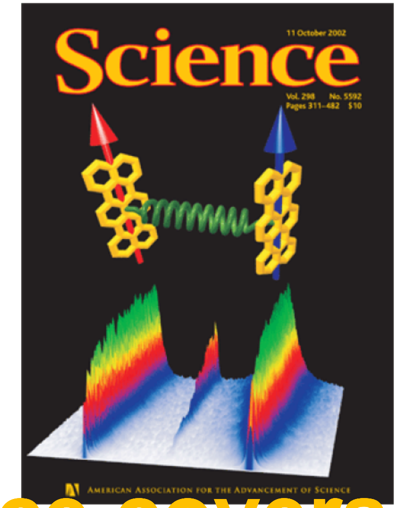
Image: Claudiu V. Falub, Laboratory for Solid State Physics, Swiss Federal Institute of Technology (ETH-Zürich)

4 ETHZ Science covers (1880-2012)

26 July 2002

(Biology)

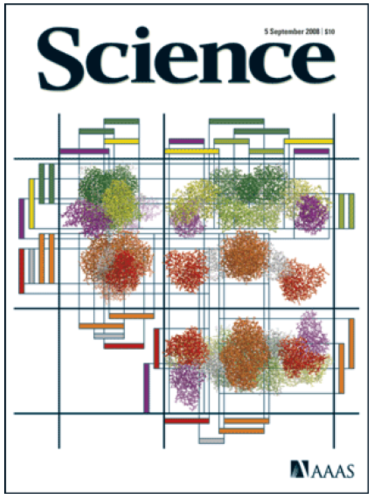
COVER Electron micrograph showing a stalled DNA replication fork in a checkpoint-defective yeast mutant. Aberrant DNA replication is one mechanism postulated to contribute to genome instability. The molecular basis of genome instability and its role in cancer development are the subject of a special feature in this issue. See page 599 [Image: J. M. Sogo et al.]



11 October 2002

(Chemistry)

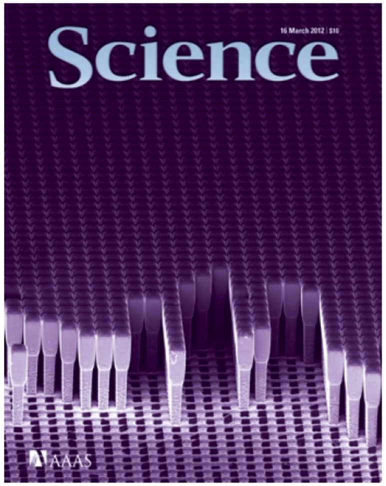
COVER Artist's impression of two nearby molecules that "couple" (upper image), lose their individualities, and give rise to new spectral features (lower image). By combining high-resolution laser spectroscopy and scanning probe techniques it is now possible to look deep into the world of fluorescent molecules even if they are only a few nanometers apart. See page 385 [Image: C. Hettich]



5 September 2008

(Biology)

COVER Mammalian fatty acid synthase, a multienzyme that catalyzes all steps of fatty acid biosynthesis. A blueprint of its atomic structure is shown in three views, and the extent of its functional domains is indicated by colored bars. The versatile segmental construction is also used in other members of this large family of multienzymes, which synthesize natural products such as antibiotics. See page 1315. Image: Marc Leibundgut and Timm Maier/ETH Zurich



16 March 2012

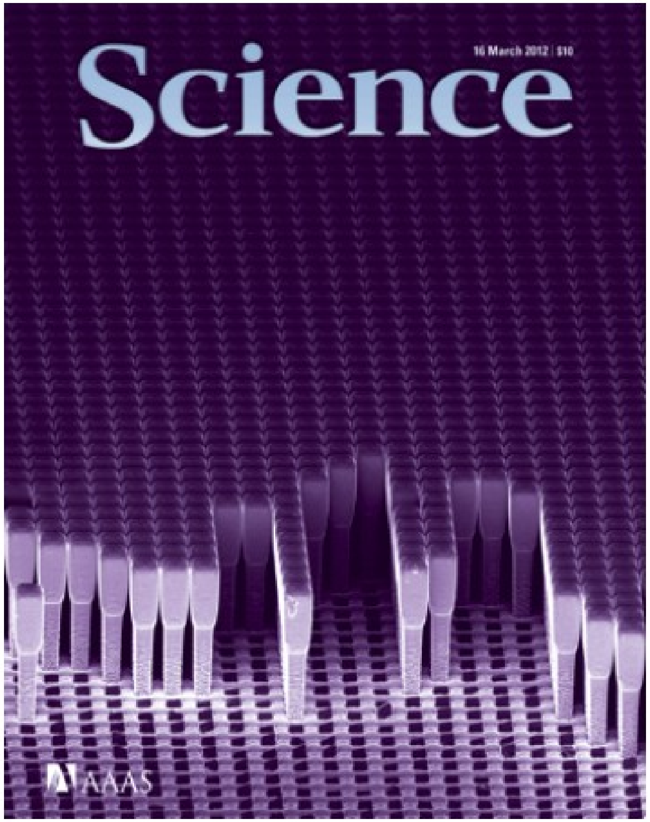
(Physics / Materials Science)

COVER False-colored scanning electron micrograph of ~8-micrometer-tall germanium crystals, separated by finite gaps, grown onto silicon pillars. In structures like this one, wafer bowing and layer cracking are absent, allowing single-crystal integration of different materials onto a silicon substrate, which serves as a platform for many applications, such as multiple-junction solar cells, x-ray and particle detectors, or power electronic devices. See page 1330. Image: Claudiu V. Falub, Laboratory for Solid State Physics, Swiss Federal Institute of Technology (ETH-Zürich)

COVER Low-energy (<10 millielectron volts) electronic spectra of bilayer graphene undergoing nematic phase transition from an isotropic, unperturbed form (top left) to an asymmetric form (bottom right). Electron-electron interactions in suspended graphene layers drive this transition, causing a change in the material's band structure and, thus, its electronic properties. See page 860. [Image: Kostya S. Novoselov/University of Manchester and Yael Fitzpatrick/*Science*]

16 March 2012

12 August 2011



COVER False-colored scanning electron micrograph of ~8-micrometer-tall germanium crystals, separated by finite gaps, grown onto silicon pillars. In structures like this one, wafer bowing and layer cracking are absent, allowing single-crystal integration of different materials onto a silicon substrate, which serves as a platform for many applications, such as multiple-junction solar cells, x-ray and particle detectors, or power electronic devices. See page 1330. Image: Claudiu V. Falub, Laboratory for Solid State Physics, Swiss Federal Institute of Technology (ETH-Zürich)

International Reactions

Neue Art von Halble

Versão para Impressão

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ETH Zurich
Produce Se

Published on March 20, 2012
By Andy Choi

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Perspective scanning electron
Silicon pillars.

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12 March 2012

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PennWell

MARCH 2012

450mm Wafer Transition P. 13

Metrology Beyond 22nm P. 16

Copper Wire Bonding P. 23

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Image: Perspe
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europhysicsnews
THE MAGAZINE OF THE EUROPEAN PHYSICAL SOCIETY

Executive Committee
Merging incompatible materials
EPS directory
Neutrinos... the last mixing angle
Magnetic Resonance Imaging

43/4
2012

Volume 43 · number 4
European Union countries price:
90€ per year (VAT not included)

Merging
incompatible materials

Hans von Känel

EPS

edp sciences

je velmi jednoduchý, stej-
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kud se tak o ptačích dialek-
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samotným, neváhejte a za-
se do projektu Nářečí čes-
trnadů. Jak to udělat, se do-
na *www.strnadi.cz.*

pro vědce posílejte na adresu
y@lidovky.cz

DECKÁ KAVÁRNA

**orujete
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A Jaké jsou výsledky ornito-
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Malostranské náměstí 21,
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celar@zelenykruh.cz. mat

**or pro mladé
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A Sekce pro děti a mládež
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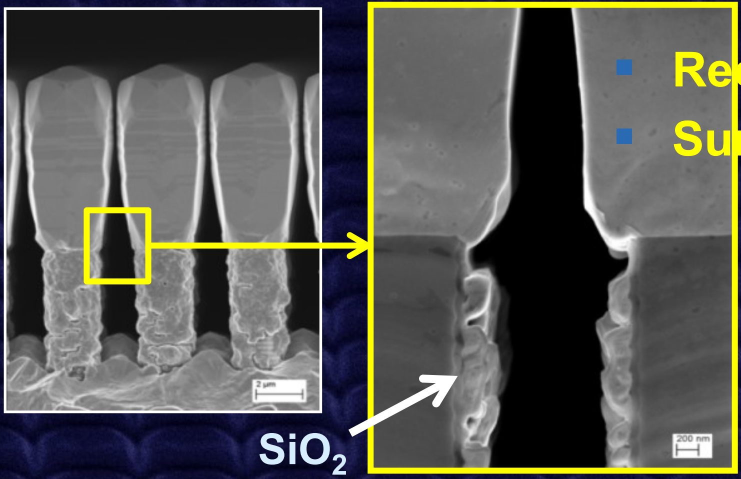
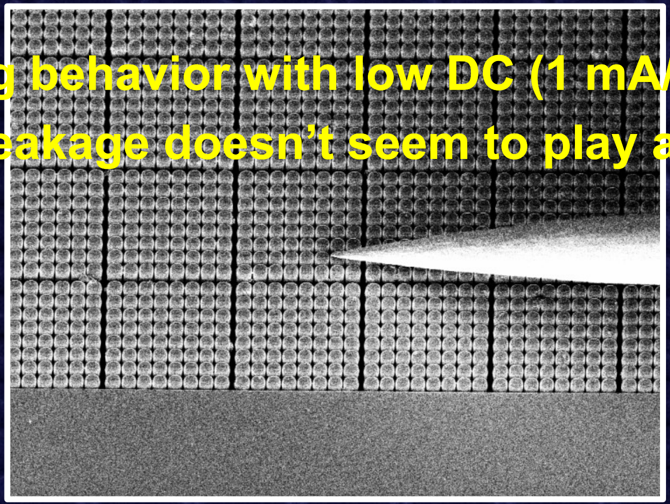
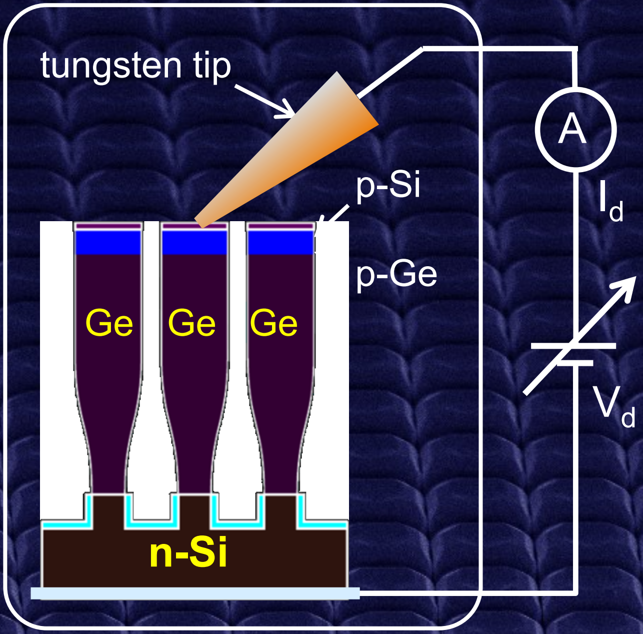
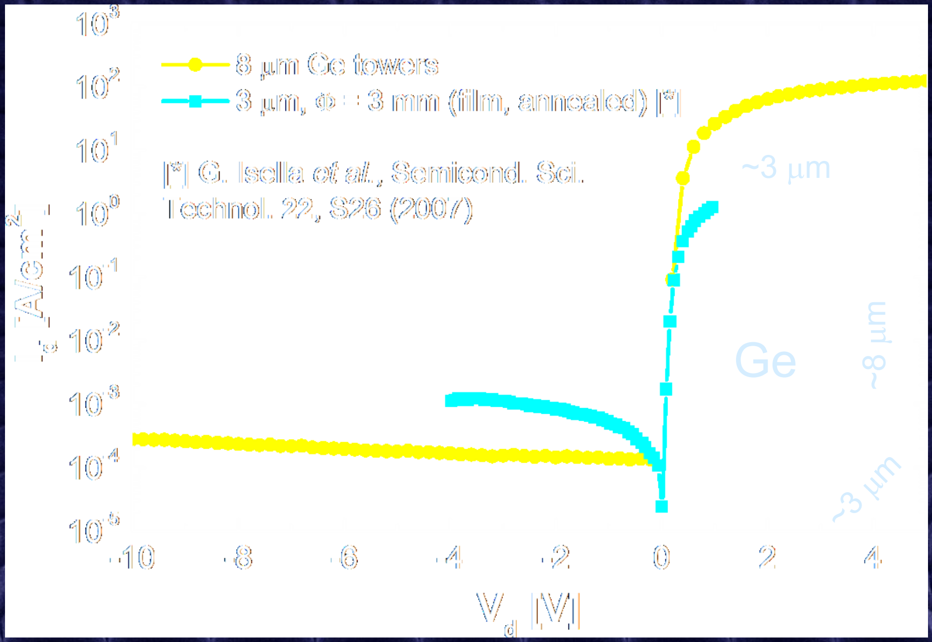
Electrical Measurements



- Rectifying behavior with low DC (1 mA/cm^2)
- Surface leakage doesn't seem to play a role

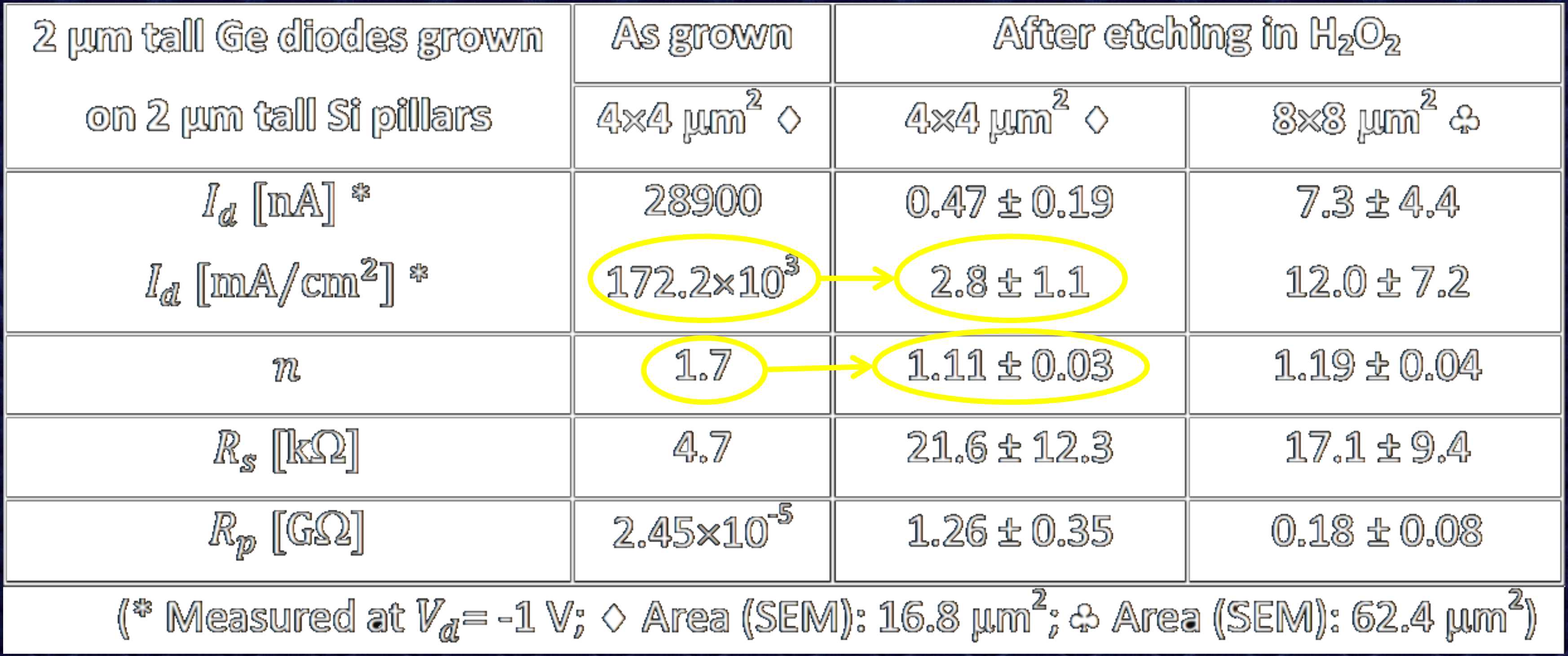






[*] G. Isella *et al.*, Semicond. Sci. Technol. 22, S26 (2007)

Electrical Measurements



2 µm tall Ge diodes grown on 2 µm tall Si pillars	As grown	After etching in H_2O_2	
	4x4 µm^2 ◇	4x4 µm^2 ◇	8x8 µm^2 ♧
I_d [nA] *	28900	0.47 ± 0.19	7.3 ± 4.4
I_d [mA/cm^2] *	172.2×10^3	2.8 ± 1.1	12.0 ± 7.2
n	1.7	1.11 ± 0.03	1.19 ± 0.04
R_s [kΩ]	4.7	21.6 ± 12.3	17.1 ± 9.4
R_p [GΩ]	2.45×10^{-5}	1.26 ± 0.35	0.18 ± 0.08

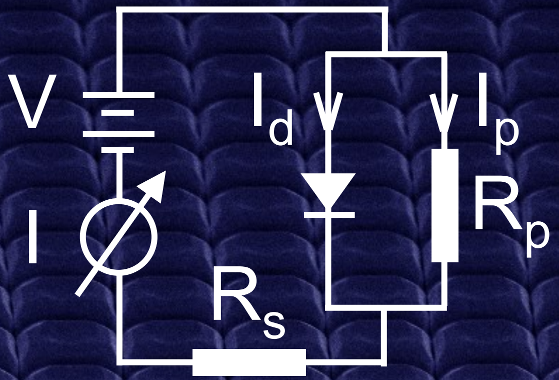
(* Measured at V_d= -1 V; ◇ Area (SEM): 16.8 µm^2; ♧ Area (SEM): 62.4 µm^2)

$$I_d + I_p = I_s\left(exp\left(\frac{\beta}{n}(V - IR_s)\right) - 1\right) + G_p(V - IR_s)$$

I_d , I_s diode and saturation currents; $\beta = e/kT$, R_s series resistance

$R_p = 1/G_p$ (G_p parallel conductance); n – ideality factor

I_p shunt curent, I_s, n, R_s, $G_p \neq$ f(V)



* J.H. Werner, Appl. Phys. A 47, 291 (1988)

From Ge crystals to NEXRAY xensors

DEVICE PROCESSING (in progress)

- 8” CMOS wafer
- Thinned down to 100 μm
- Patterned (DRIE)
- Pillars passivation
- 50 μm Ge towers (backside)
- Sealing of the Ge towers
- Ge etching
- Electrode depositi
- Dicing

LFoundry

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

L-NESS

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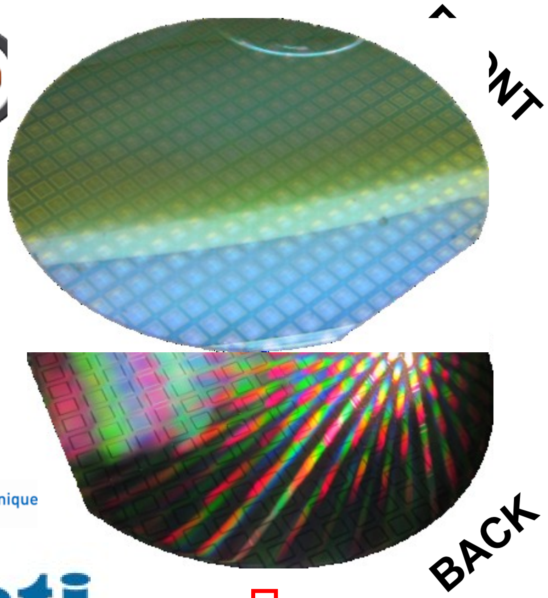
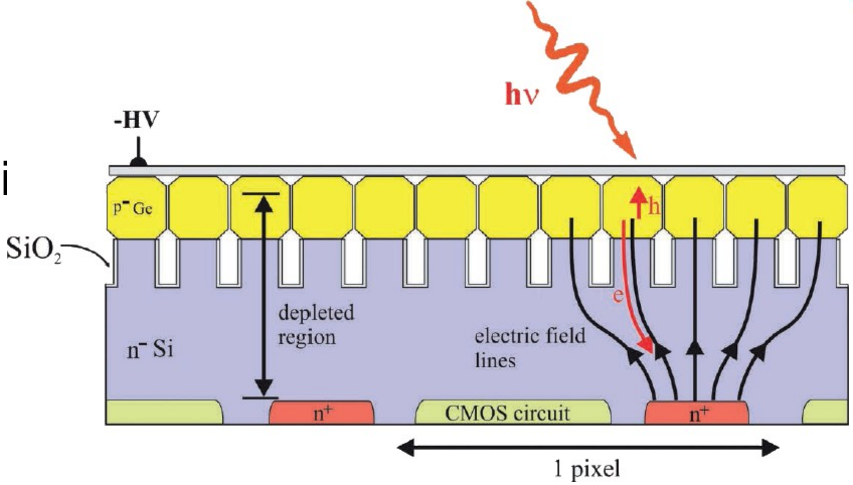
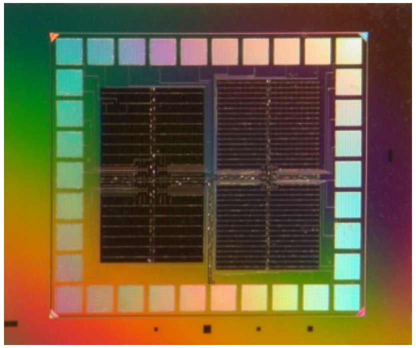
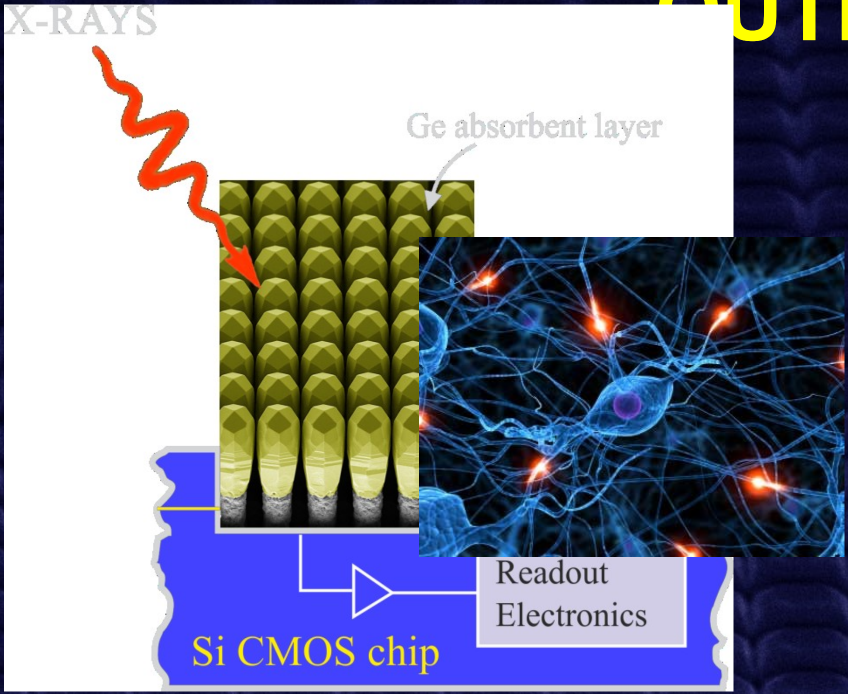
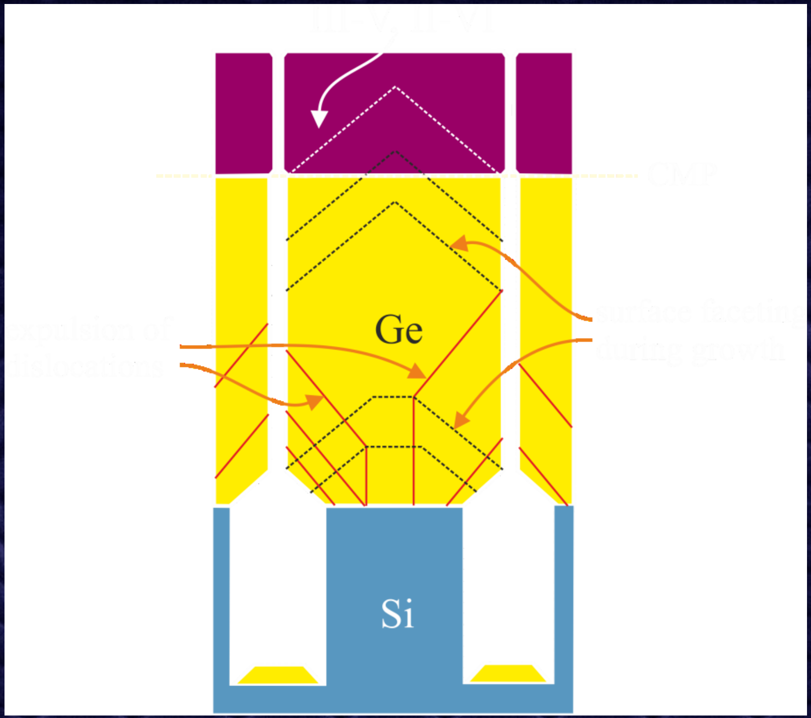


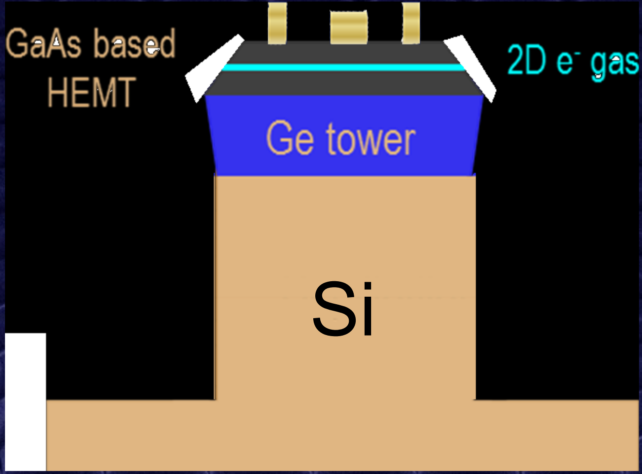




OUTLOOK







- **III-V, II-VI integration with CMOS**
- **High-efficiency solar cells**
- **<u>Power electronic devices (SiC on Si)</u>**
- **Emitters, resonators, etc.**

OUTLOOK

Integration of III-V optoelectronic devices on Si substrates

Si

- Small mass
- Good thermal conductivity
- Large wafer diameter
- Mainstream Technology

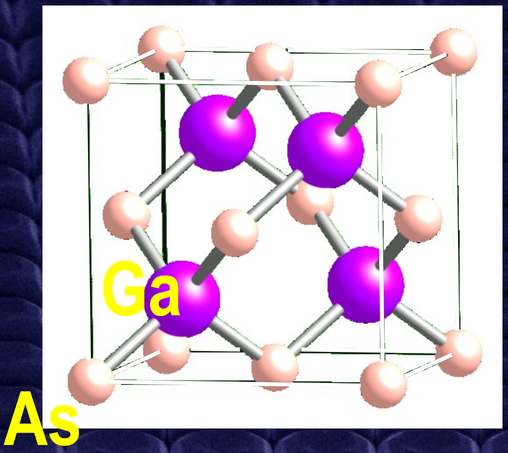
GaAs

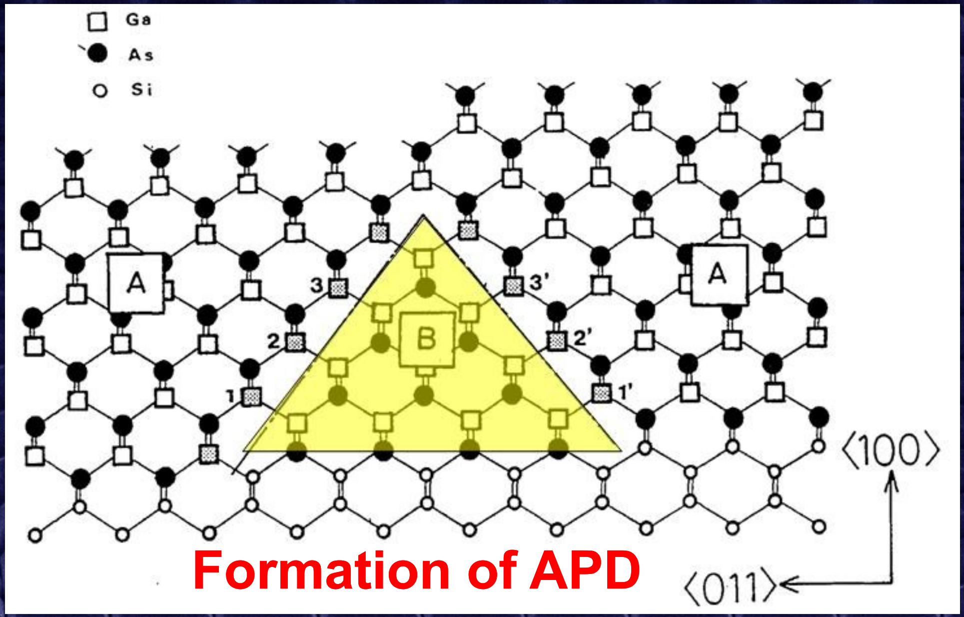
- direct band gap alignment
- high carrier mobility
- Optimum for the development of optoelectronic devices

CHALLENGES

- 4% lattice mismatch
- 60% thermal mismatch
- Anti Phase Domains (APD)

GaAs unit cell



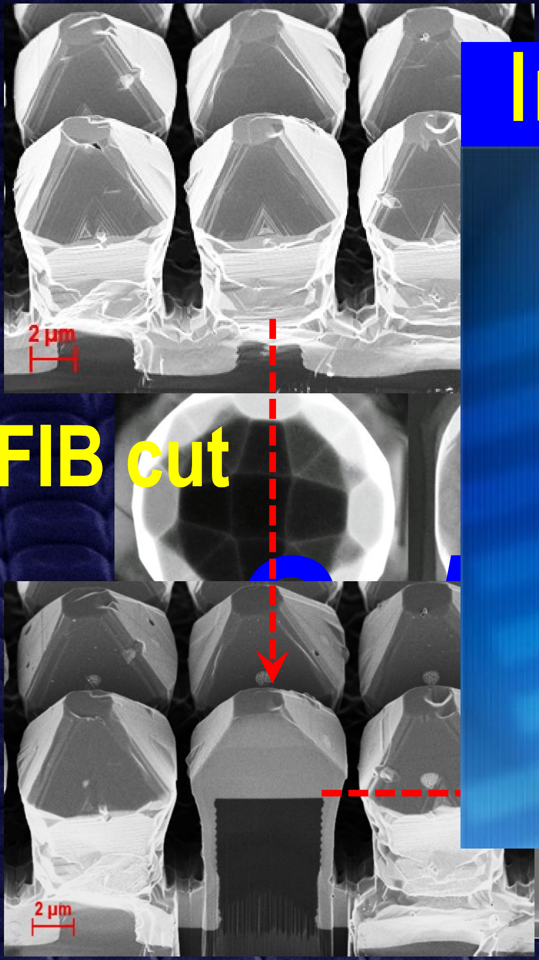


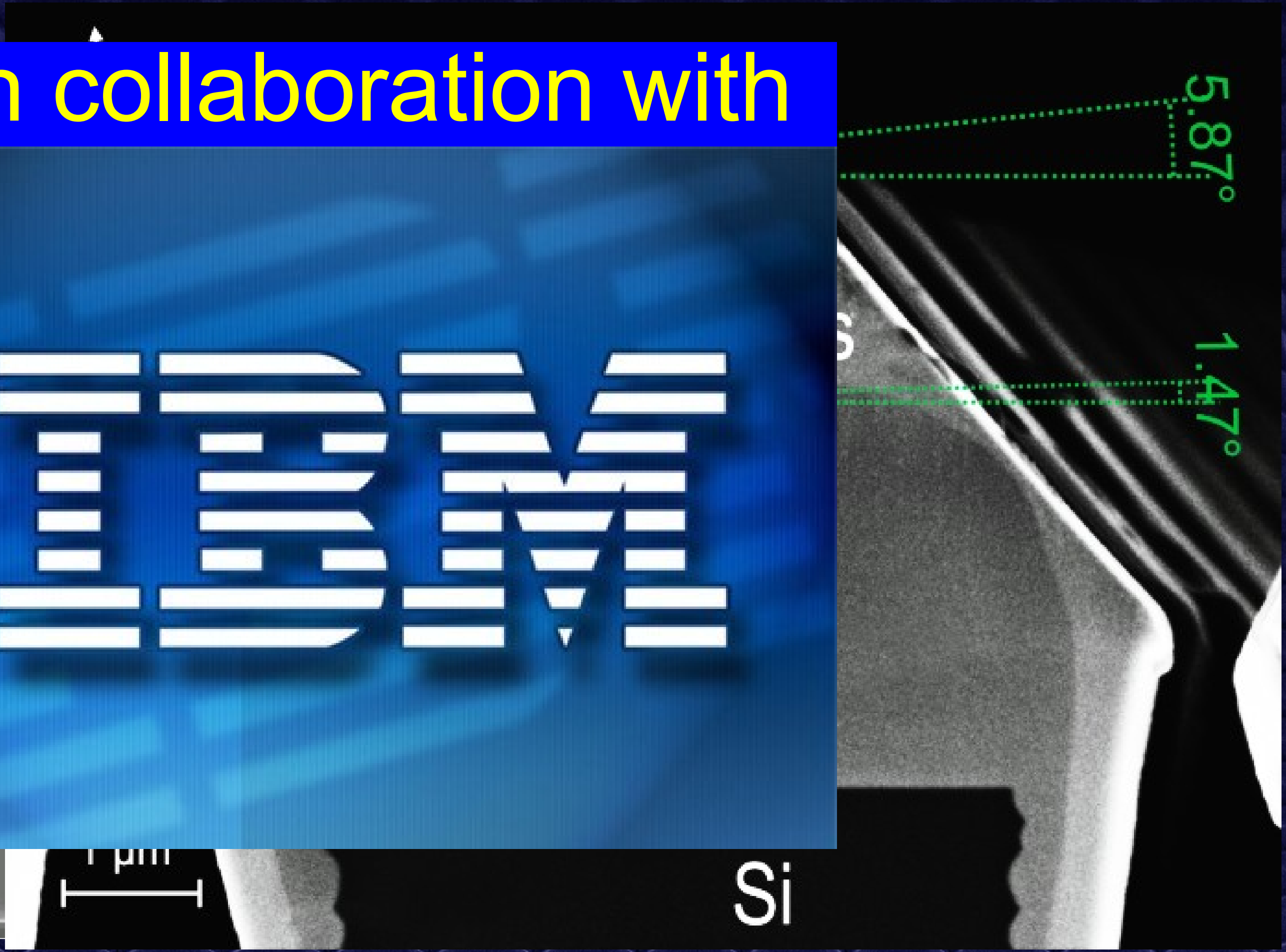
Formation of APD

OUTLOOK

Integration of III-V optoelectronic devices on Si substrates

Si **GaAs** **CHALLENGES**



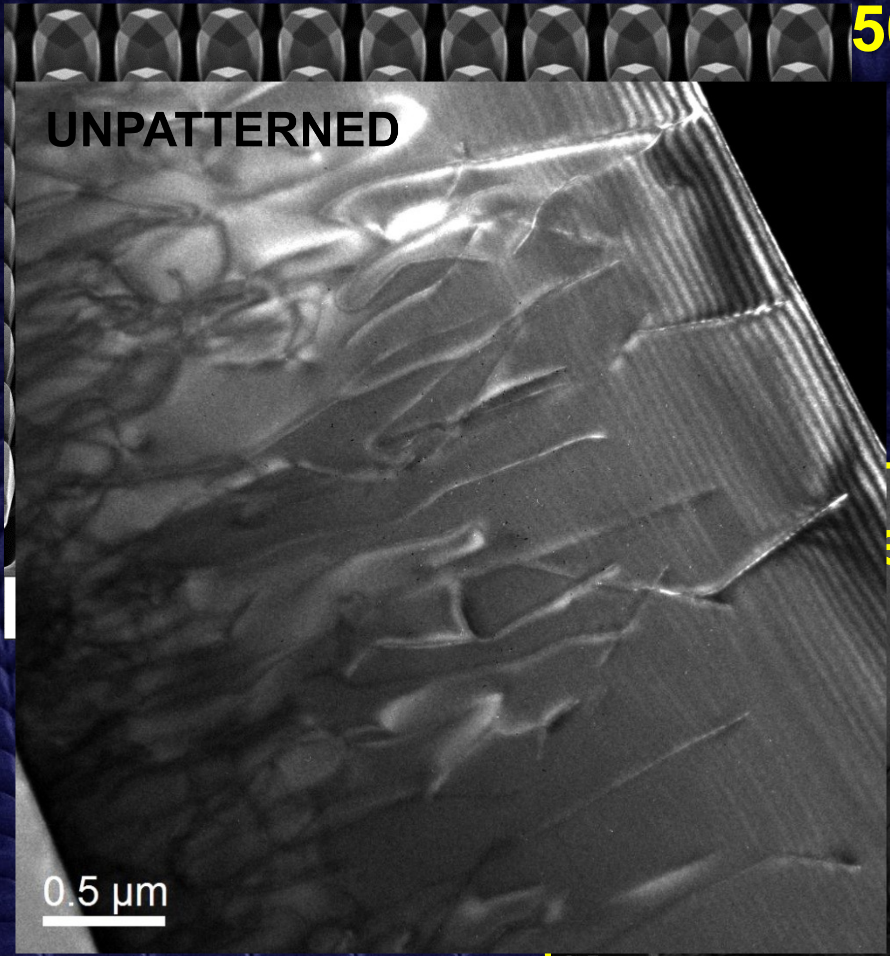


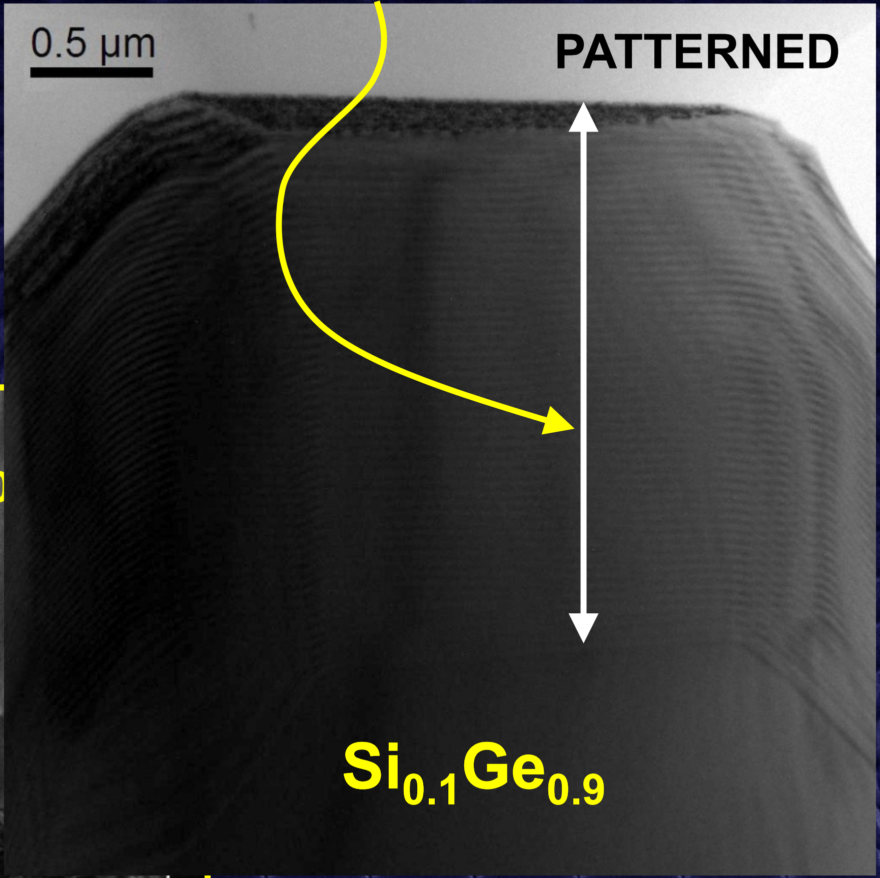
In collaboration with

OUTLOOK

Integration of SiGe MQW

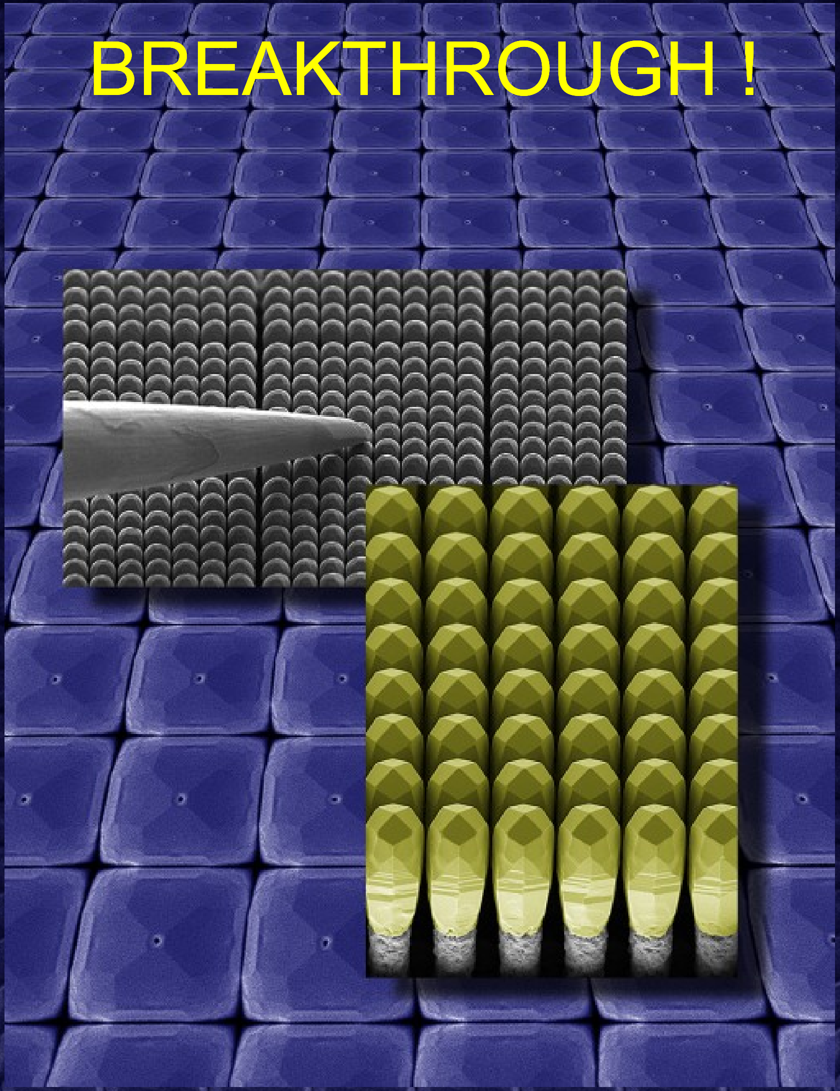
50× (21 nm $Si_{0.1}Ge_{0.9}$ + 10 nm Ge)





SUMMARY

- 3D Heteroepitaxial growth of lattice and thermally mismatched semiconductor systems on clean, patterned substrate surfaces:
  - allows dislocation management;
  - avoids wafer bending;
  - avoids layer cracks.
- Applicable to wide range of layer thicknesses.
- Diode characteristics (i.e. low DC).
  - Monolithically integrated X-ray detector (high resolution & sensitivity).
- Applicable to other systems (III-V, etc).
- Allows novel applications & devices (e.g. emitters, resonators, etc.)

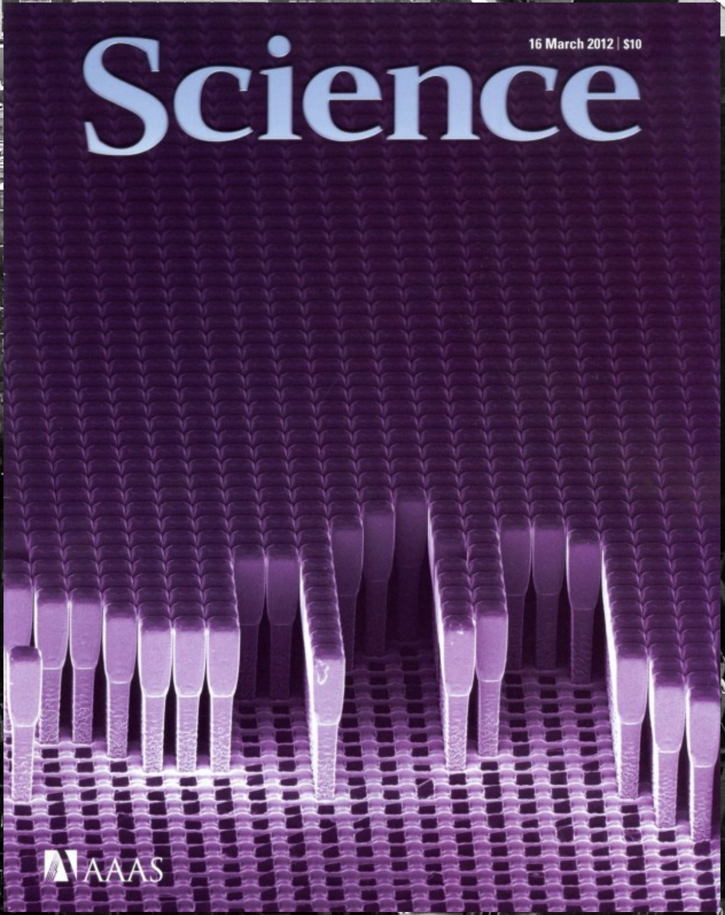

BREAKTHROUGH !

ACKNOWLEDGMENTS

nano-tera.ch

ESRF

FIRST
Center for Micro- and Nanoscience



16 March 2012 | $10

Science

AAAS

Thank you for your attention !

Khumjung, Himalaya, Nepal, November 2003