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SMR/1758-15

"Workshop on Ion Beam Studies of Nanomaterials: Synthesis, Modification and Characterization"

26 June - 1 July 2006

Nanostructures by Ion Beams

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Nanostructures by Ion Beams

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Outline

1. Introduction
2. Ion beam processing:
   - **I**on **Im**plantation (**IIM**)
   - **I**on **B**eam **S**ynthesis (**IBS**)
   - **I**on **Ir**radiation (**IIR**) of interfaces
3. IBS of nanostructures
4. IIR induced self-organization
5. Applications
6. Outlook

1. Introduction

Why ion beams?

Ion beams in industry:

- widely used in microelectronic technology – doping of semiconductors (ion implantation into silicon)

Ion beams in R&D:

- *Ion implantation for advanced CMOS technologies - < 0.15 µm technologies*
  (low energy ion implantation for shallow junction doping, individual and cluster ion doping, doping profile tailoring, defect annealing etc. in Si)
- *Ion beam synthesis and processing of advanced materials:*
  - Fundamentals & defect kinetics – development of simulation tools
  - Materials with noval electrical, optical and magnetic properties
  - Ion beam induced slicing & Focused Ion Beam applications
  - Surface modification – hardness, texture, corrosion
  - Metastable phases – plastic flow and patterning of surfaces
  - Synthesis of nanostructures and thin layers

Reasons for current effort in ion beam processing of advanced materials:

Highly developed level of ion implantation technique:

- Concentration of implanted ions (impurities) is precisely controlled (electrical current measurement in the fluence range 10^{10} -10^{17} ions/cm^2)
- Penetration depth of ions in the range 1 nm – 100 µm can be precisely adjusted by choosing the ion energy in the range of 10^{-1} – 10^5 keV
- Isotope clean impurity implantation (ion mass seperation)
- Wide variability between ion species and substrates to be implanted

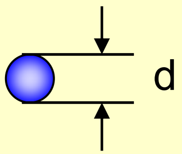
Physical understanding of ion-solid interactions:

- Existing physical models describe ion range and straggling of implanted ions, recoil cascades and sputtering of target atoms, defects & phase separation
- Existing simulation tools:
  - TRIM; CrystalTRIM*; TRIDYN* → depth profiles
  - 3DKLMC* → phase separation
  - classical MD → defects, annealing
  - ab initio calc. → atomistic structure

*) devoloped at FZR

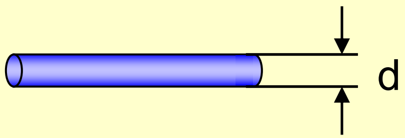
What are nanostructures?

0D-structures:
Nanodots (Q-Dots)



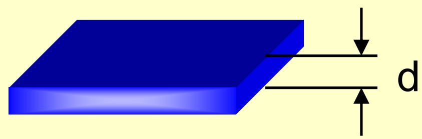
SET,
NC-Memory Circuits

1D-structures:
Nanowires (Q-Wires)



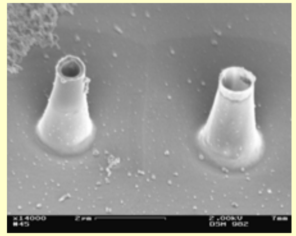
QW-Laser

2D-structures:
Nanolayers (Superlattices)



III-V-Superlattices

3D-structures:
Tools on nm-scale



......

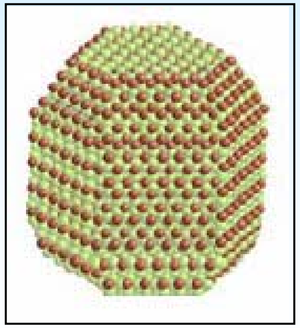
Typical Properties:

d < mean-free-path of electrons → Metals: < 50 nm (Ag)...10 nm (Li)

d < Bohr‘s exiton radius → Semiconductors: <20 nm (Ge), <10 nm (Si)

Confinement:

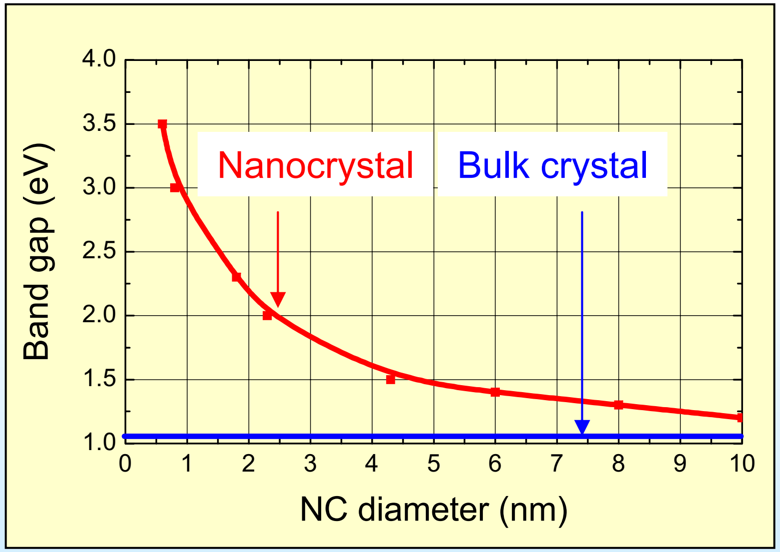
Electrons are spatially localized within a potential well.

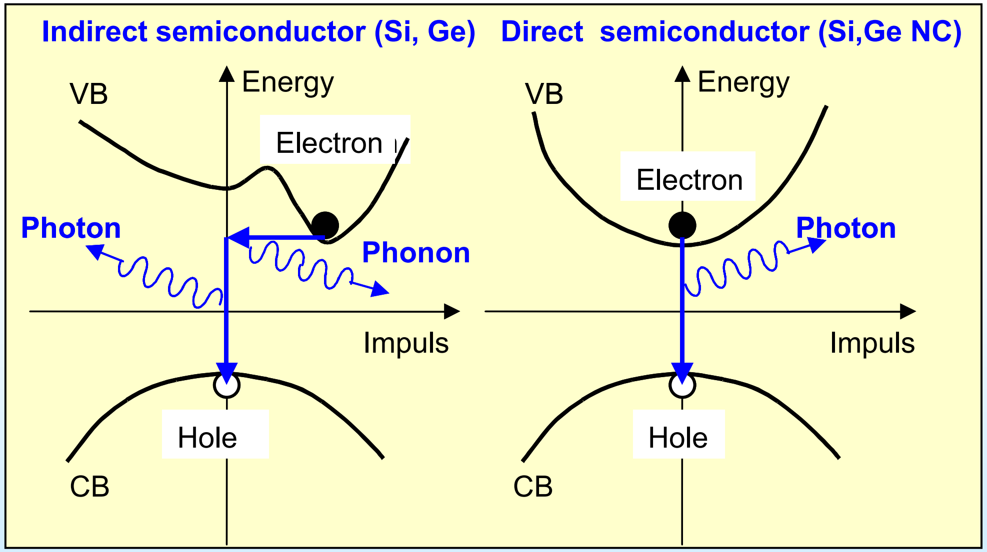


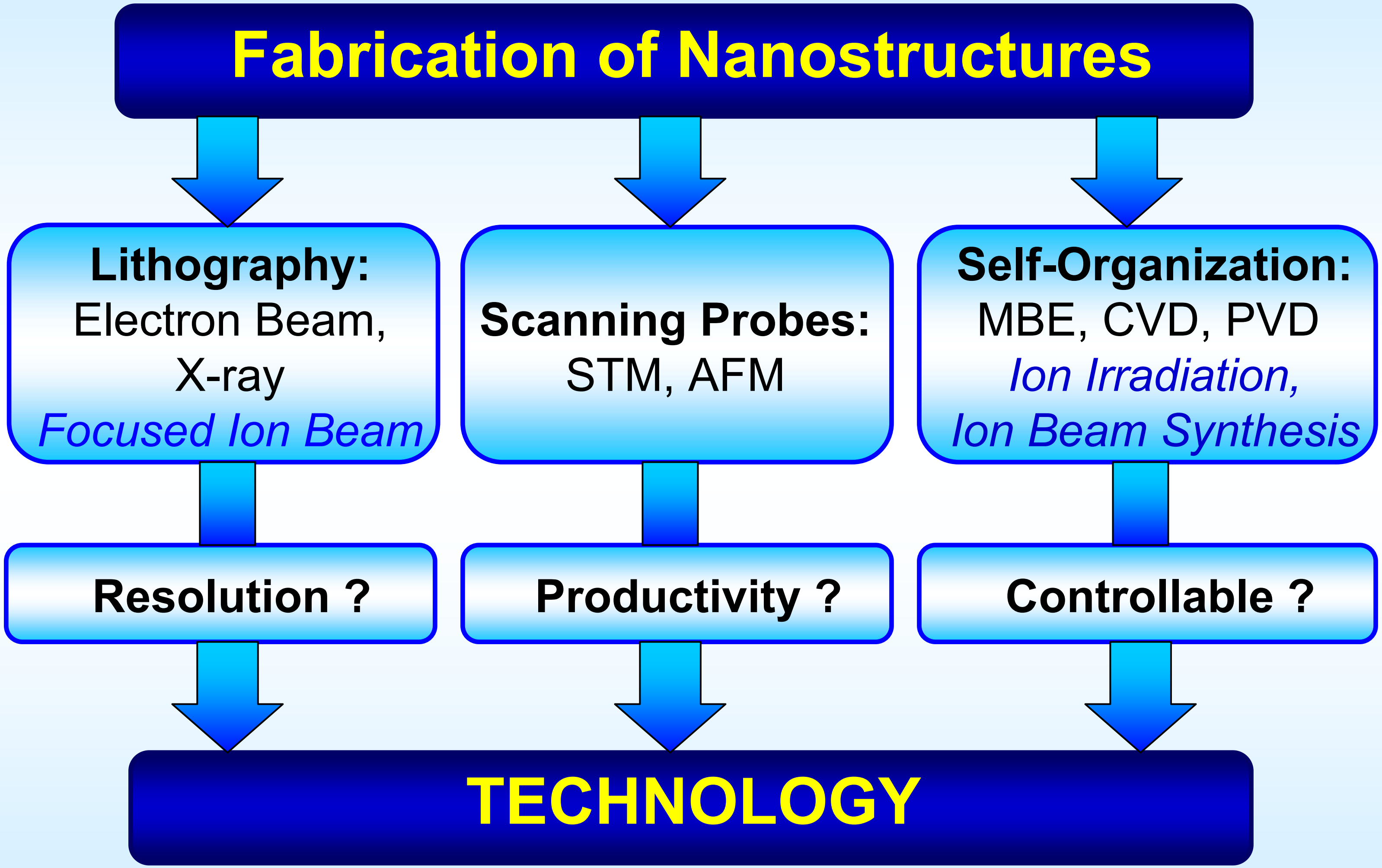
Quantum dot:

(Nanodot, Nanocrystal, Nanocluster, NC)

- Number of atoms: 10...10.000
- Surface/volume-ratio ↑
- Band gap $E_g = f(d_{NC}) \rightarrow d_{NC} \downarrow = E_g \uparrow$
- Indirect semiconductor silicon: at d_{NC} <10 nm
  → direct semiconductor

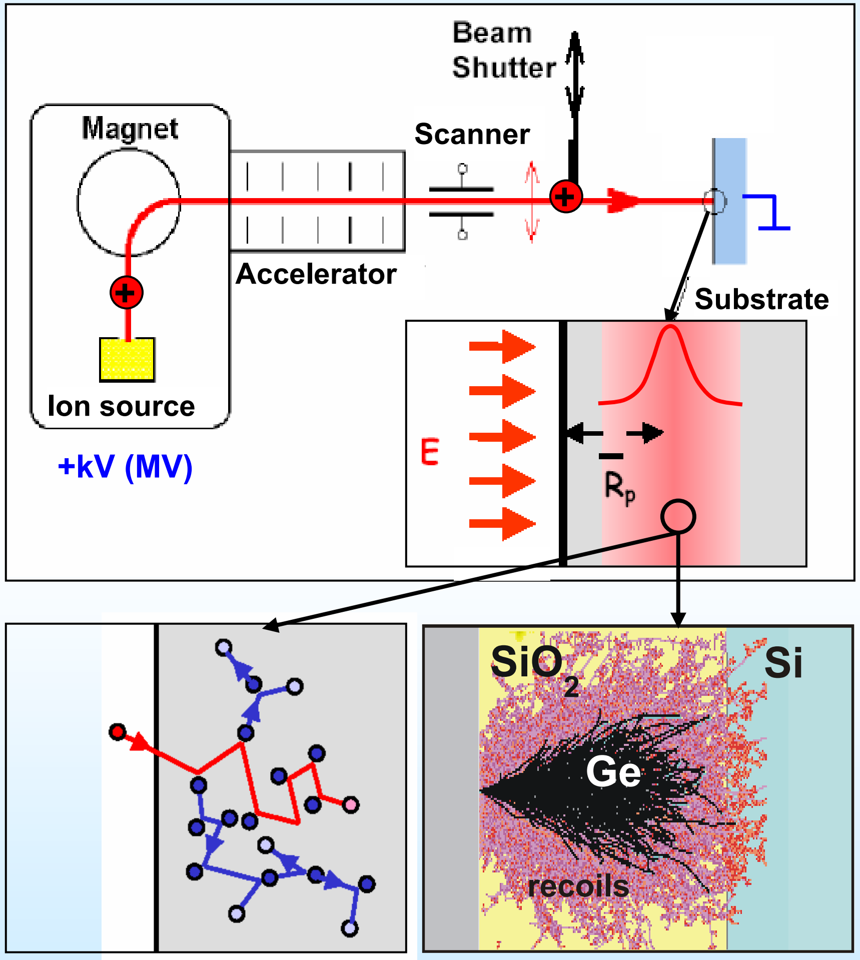






Heinig, Schmidt, Müller, 104th Annual Meeting of The American Ceramic Society, St. Louis, April 2002, invited talk

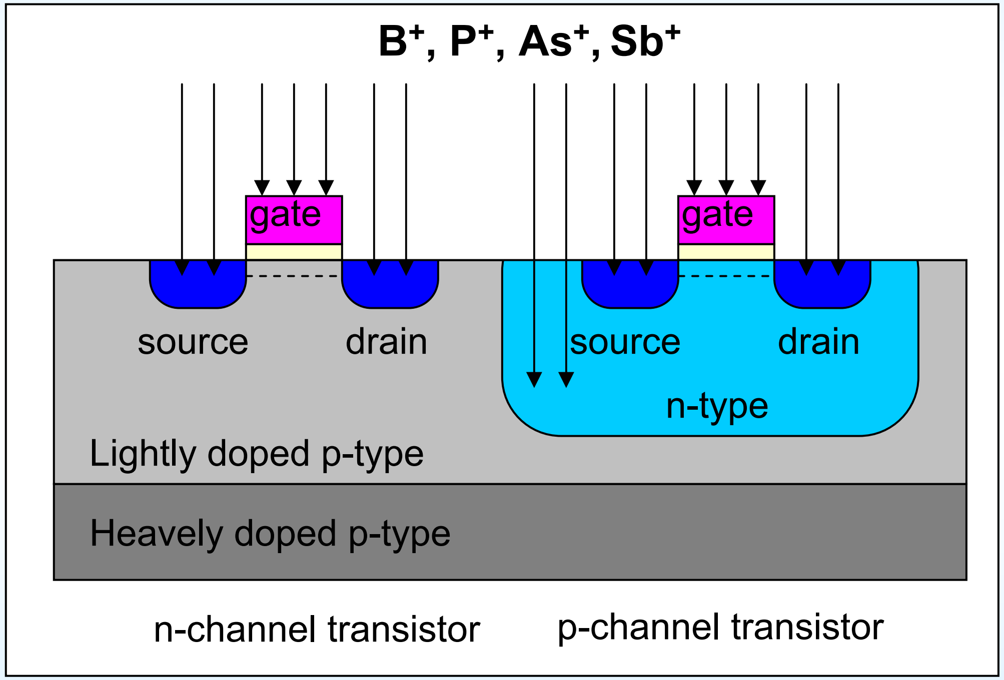
2. Ion Beam Processing



Ion beams create disorder →
radiation damage due to collisions of penetrating ions with atoms of the solid state target
(recoil atoms, collisional cascades)

Recovery of order →
thermal treatment of the irradiated sample for annealing of radiation damage and defined atomic arrangement of introduced ions in in the host matrix (e.g. on crystal lattice places)
→ self-organization

IIM: Ion implantation in microelectronics

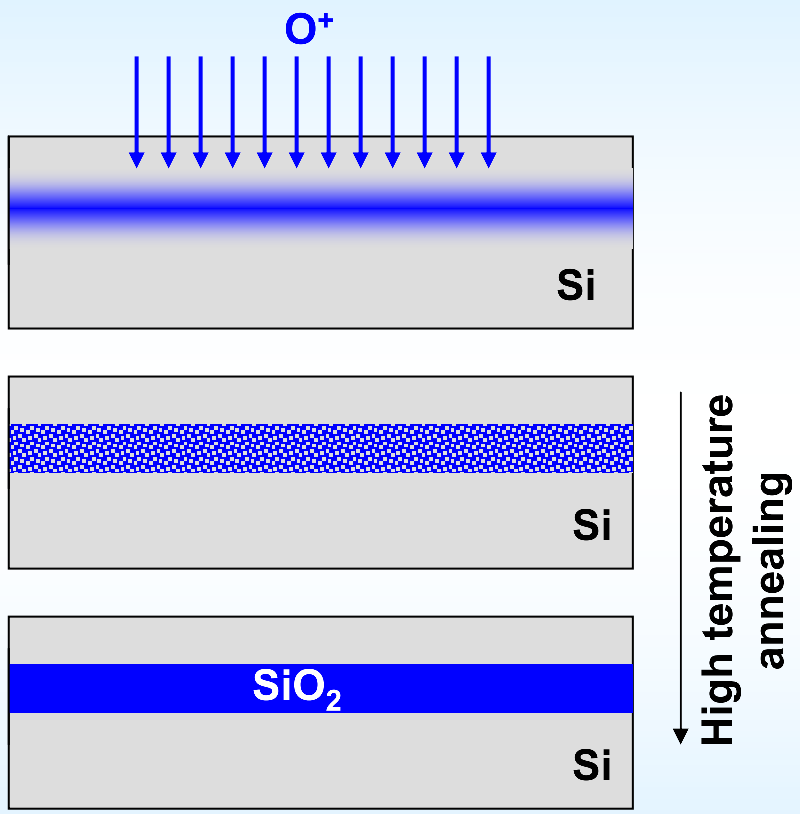


CMOS devices:

- Source/drain doping
- Channel threshold voltage adjust
- p/n-well doping
- poly-Si gate (n^+) doping
- .....

→ Concentration of implanted ions usually below the solubility limit of impurities in Si

IBS: Ion Beam Synthesis of new phases



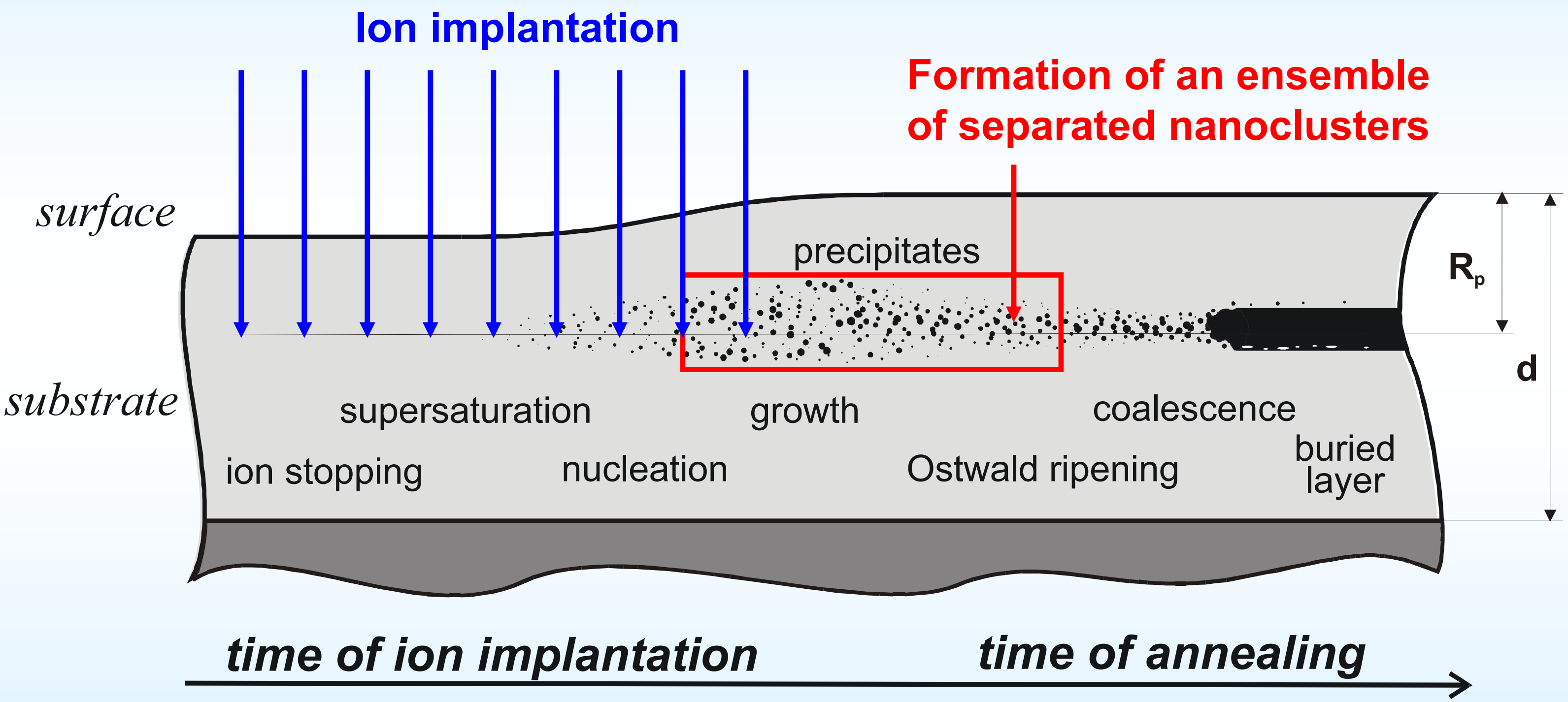
SOI-Technology (SIMOX):
IBS of buried SiO_2-layers by high-dose O^+ implantation

(established in device fabrication !)

- **Introduced oxygen above the solubility limit of oxygen in Si**
- **Phase separation: SiO_2 precipitation, Ostwald ripening, coalesence**

IBS: Ion Beam Synthesis of new phases

Phase Separation in Supersaturated Solid Solutions



Ions: Si^+, Ge^+, Sb^+ for IBS of semiconductor NCs → microelectronics
Ag^+, Au^+, Co ... for IBS of metallic NCs → photonics

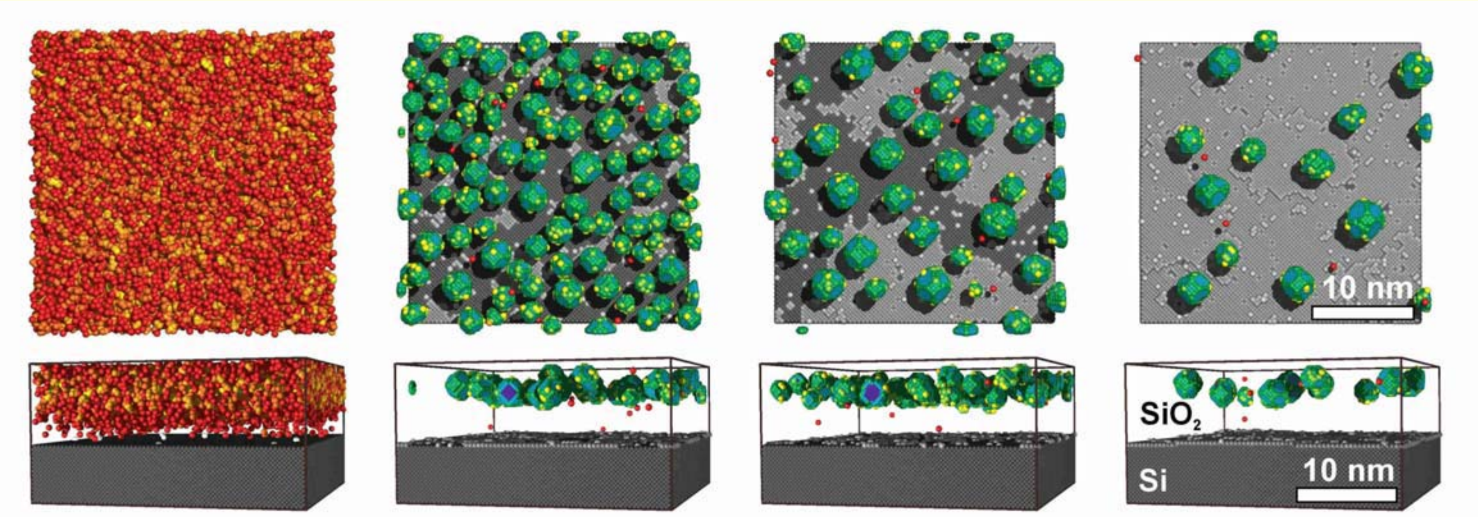
S.Reiss, K.H.Heinig, Nucl. Instr. & Methods **B102** (1995) 256

IBS of Si-NCs - computer simulation

Conditions: d_{SiO2} = 8 nm, Si^+, E = 1 keV, D = $2x10^{15}$ cm^{-2}

Atomistic MC simulation of phase separation (nucleation and ripening of Si NCs)

Müller, Heinig



0 MCS | 100 kMCS | 1000 kMCS | 4000 kMCS

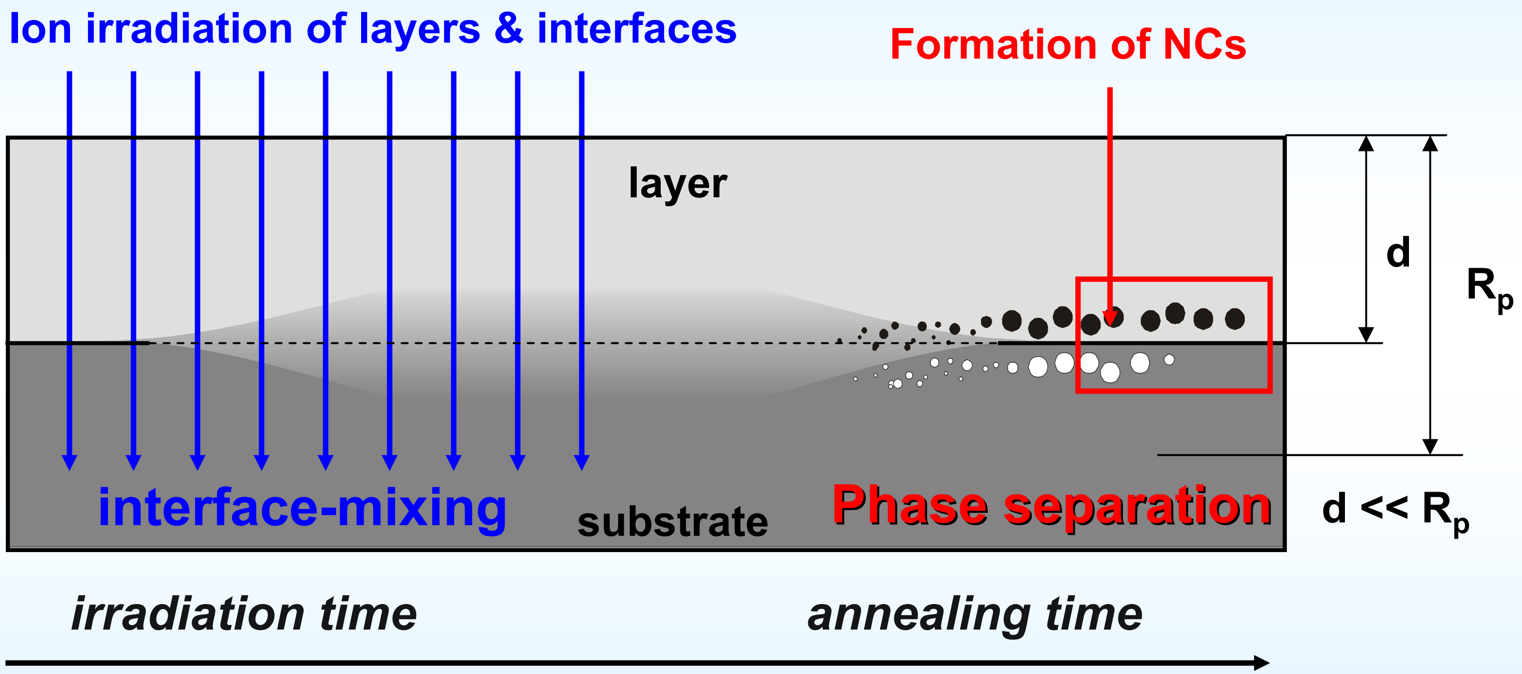
Ion implantation ***Annealing time***

NC dimensions ↑, NC density ↓ with increasing annealing temperature and time

T. Müller, K.H. Heinig, W. Möller, Appl. Phys. Lett. **81** (2002) 3049

IIR: Ion Irradiation through Interfaces -

A non-conventional ion assisted synthesis of NCs

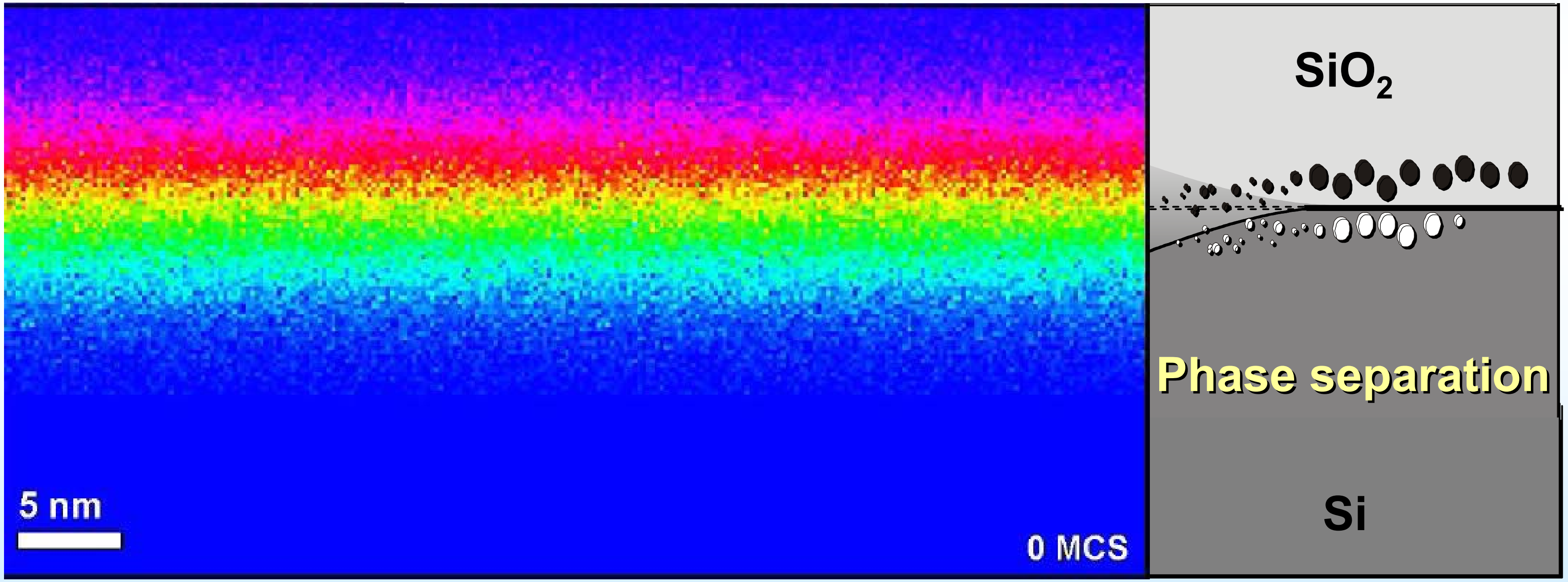


Separation of nonstoichiometric phases near interfaces:
Precipitation, Ostwald ripening, NC formation

B. Schmidt, K.H. Heinig, Patent DE 199 33 632 C2, 1999
B. Schmidt, K.H. Heinig, Patent EP 1 070 768 A1, 2000

IIR: Ion Irradiation through Interfaces – computer simulation

Separation of non-stoechiometric phases at SiO_2/Si interfaces: Precipitation, Ostwald-ripening, NC formation



(Kinetic Monte-Carlo simulation)

T. Müller, K.H. Heinig, FZR

Annealing

Ion Beams for Nanostructure Processing

Ion implantation

Far-from-equilibrium state
(high supersaturation,
high interface energy)

Relaxation
(self-organization)

Ion irradiation

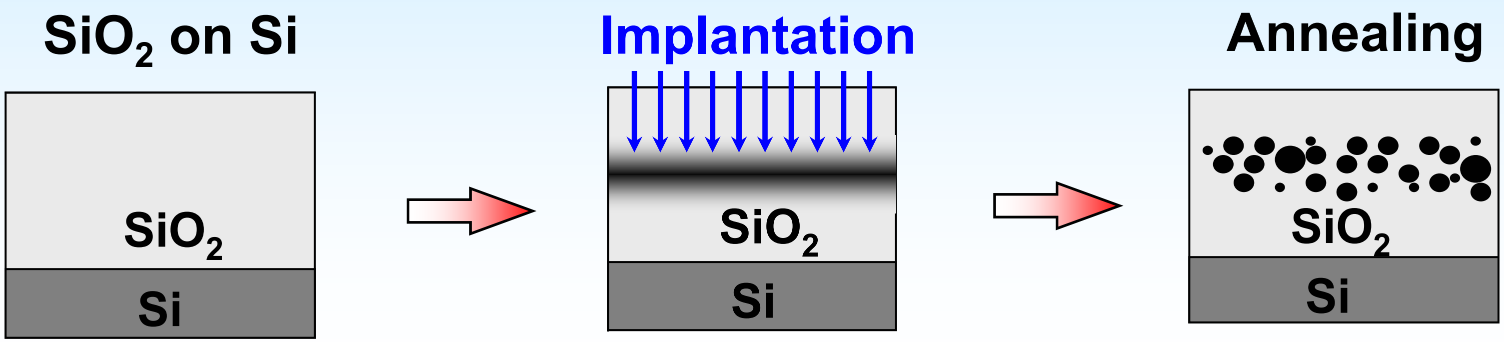
„Driven system“
(non-equilibrium
processes)

Steady-state
(pattern formation)

FABRICATION of NANOSTRUCTURES

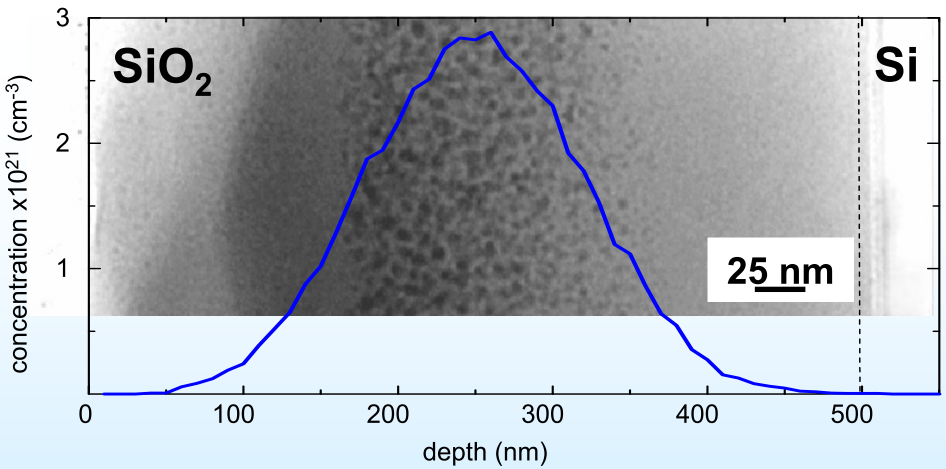
K.H.Heinig, T.Müller, B.Schmidt, M.Strobel, W.Möller, Appl. Phys. **A 77**, 17-25 (2003)

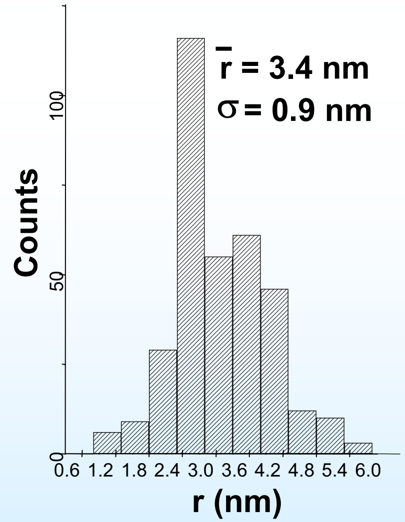
3. IBS of Nanostructures - Fundamentals



Ge^+ implantation:
E = 350 keV
D = 5×10^{16} cm^{-2}

Annealing:
1100 °C, 1 h





Layer of Ge NCs centered at R_p

LSW-distribution

A.E. White et al., Appl.Phys.Lett. **50** (1987) 95; M.Strobel, S.Reiss, K.H.Heinig, Nucl. Instr. Meth. **B120** (1996) 216

- Ion Beam Synthesis (IBS) of nanoclusters (NC) requires thermal treatment for damage annealing and phase separation of the supersaturated solid solution.
- Solute concentration at curved interfaces is given by a Gibbs-Thomson relation:

$$C_{GT} = C_s \cdot \exp(R_c/R_0) \approx C_s \cdot (1 + R_c/R_0)$$

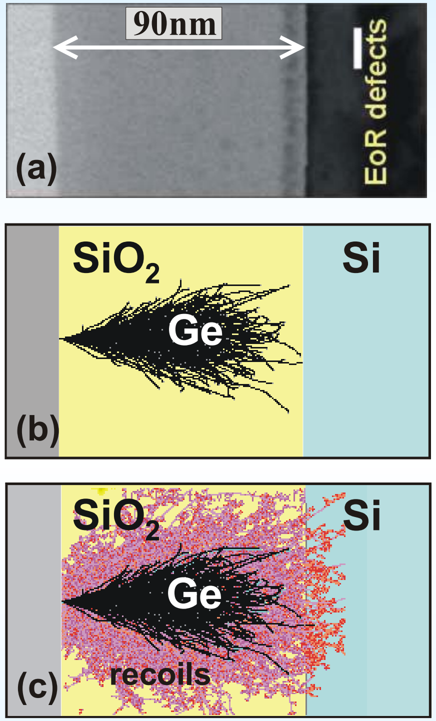
C_s – saturation solubility
R_c – capillarity lenght
R_0 – NC radius

- Broad NC size distributions of the Lifshitz-Slyozov-Wagner (LSW) type are typical for Ostwald Ripening (OR).

⇒ **Large NC's grow at the expense of smaller ones !**

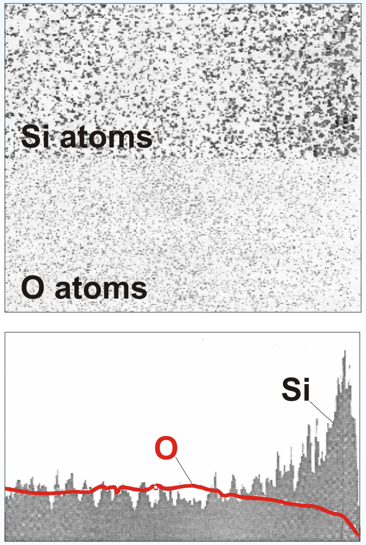
Lifshitz, Slyozov, J.Phys. Chem. Solids **19** (1961) 35
Wagner, Z. Elektrochem. **65** (1961) 581

4. IIR induced self-organization



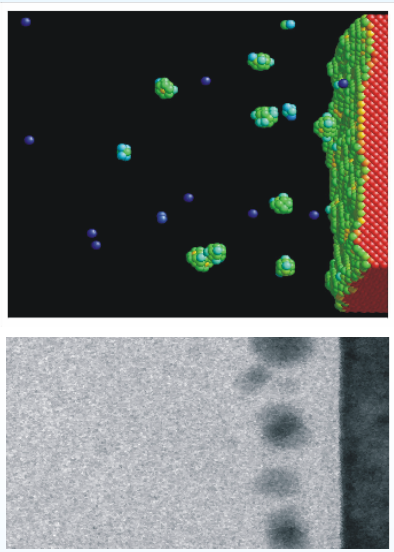
Despite the absence of Ge^+ ions at the SiO_2/Si-interface, O and Si recoils cause ion beam mixing there of a few dpa´s

Kin. MC simulation of SiO_2 dissociation & Si and O diffusion



Unbonded O and Si migrate and recombine to SiO_2, but the interface can act as a sink for O and therfore $C_{Si} > C_O$ at the interface

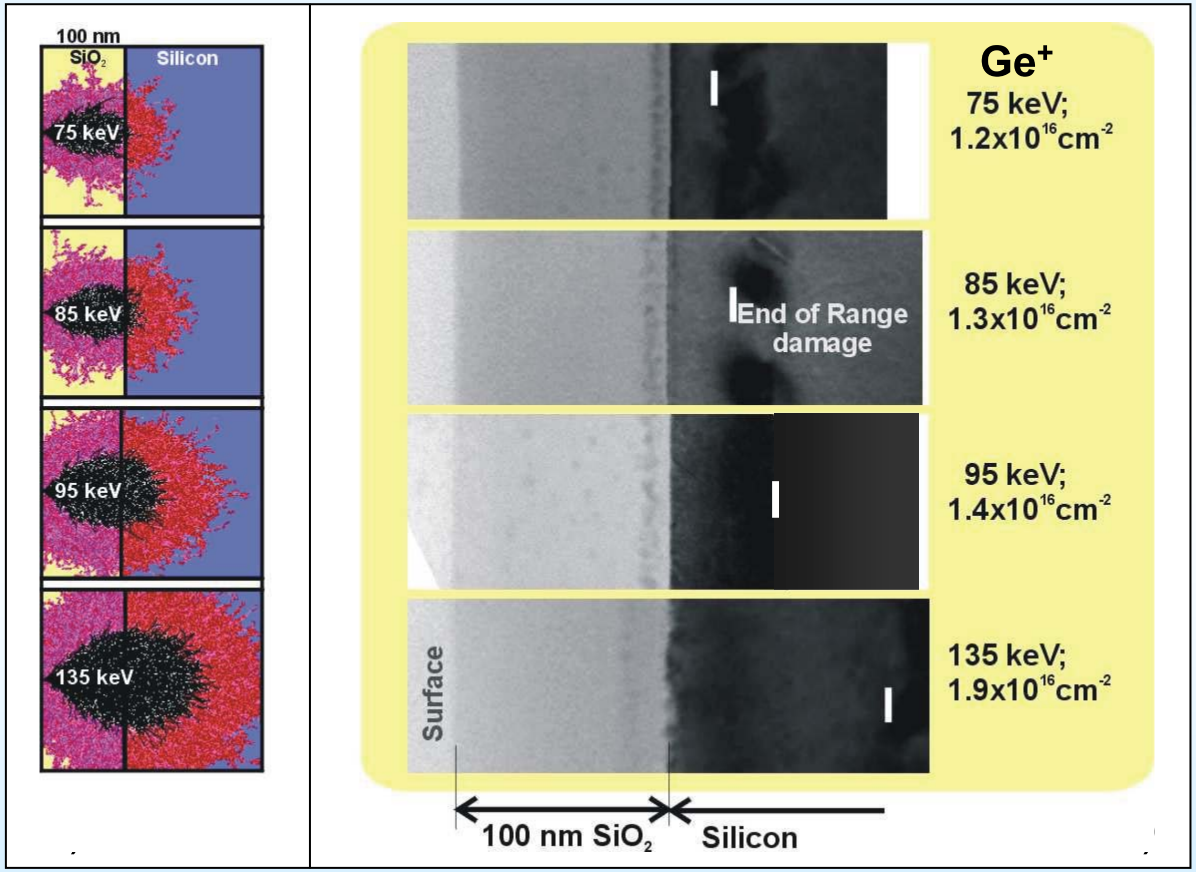
Kin. MC simulation of ion beam mixing and diffusion



O and Si recoils cause ion-induced detachment of Si atoms into the SiO_2, higher steady state Si-concentration in SiO_2 can lead to nucleation of tiny Si-NC´s

S.Reiss, K.H.Heinig, Nucl. Instr.&Meth. **B84** (1994) 229, ibid. **B112** (1996) 223
V.Borodin, K.H.Heinig, S.Reiss, Phys. Rev. **B56** (1997) 5332

IIR: Ion Irradiation through Interfaces

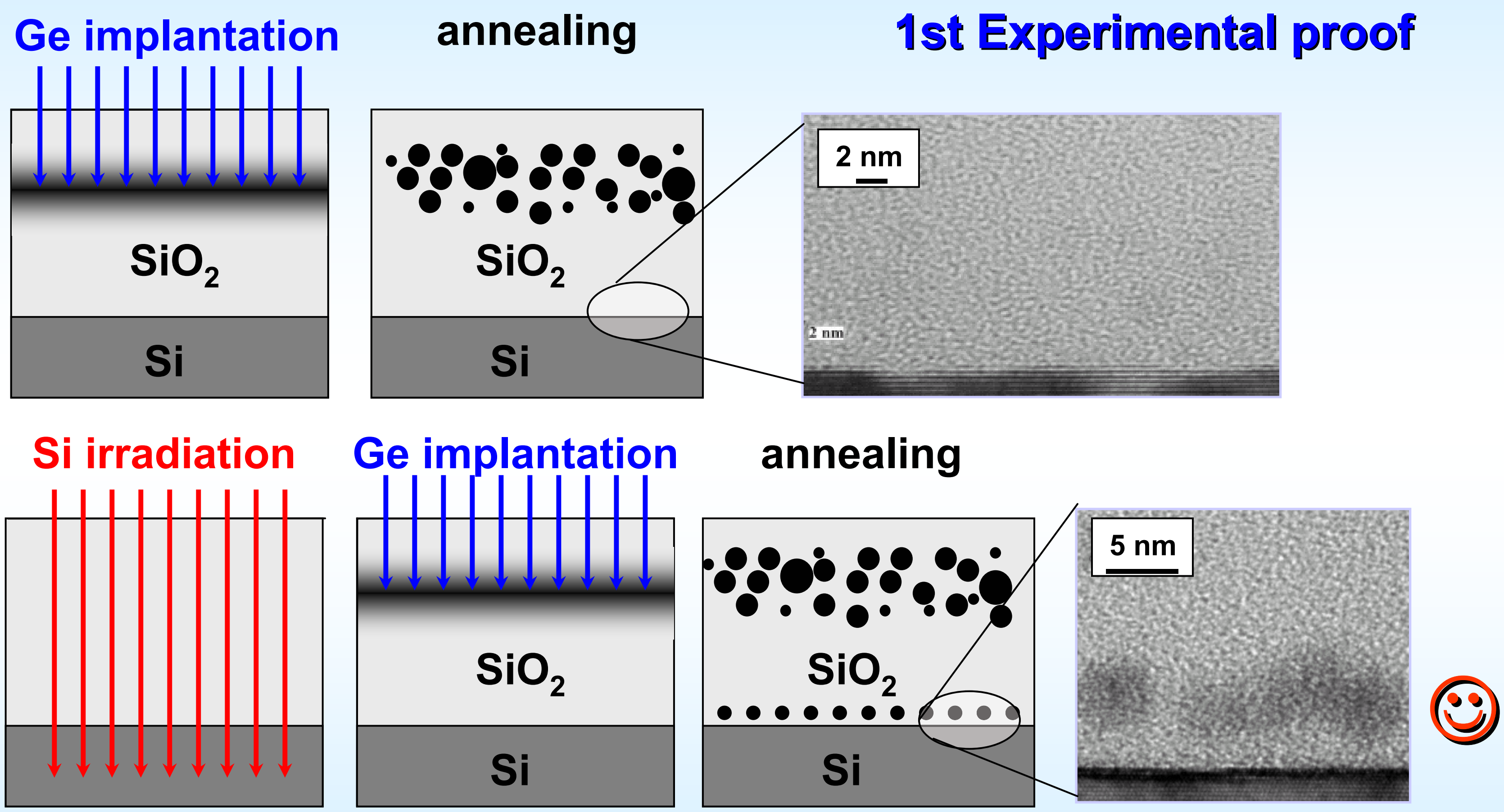


Tuning of NC-interface distance by changing of ion energy !

Prediction:

Positioning of „δ-layers“ of NCs without ion implantation into the layer is possible.

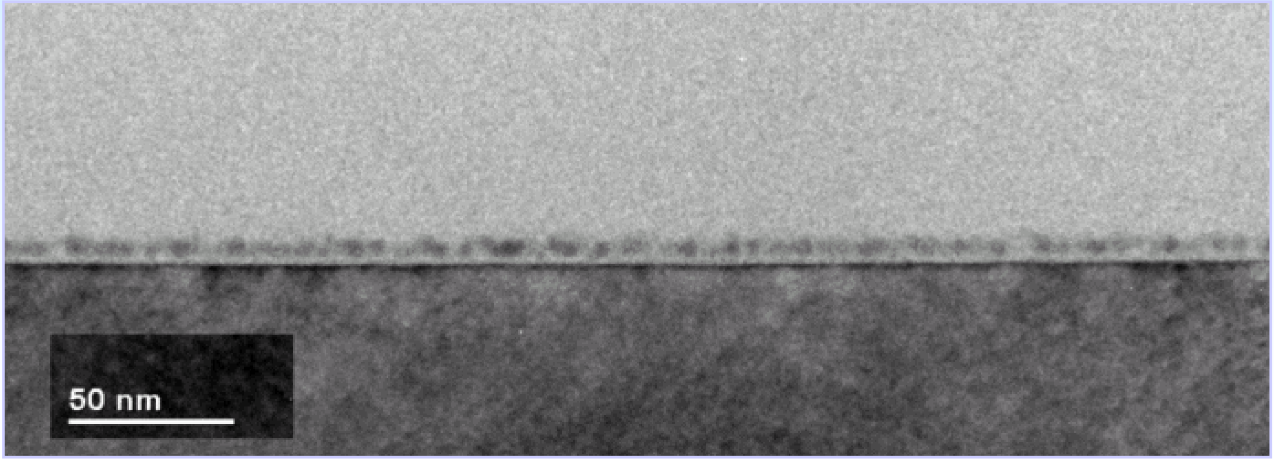
K.H. Heinig, B. Schmidt, M. Strobel, H. Bernas, MRS2000 Fall Meeting, Boston, 2000, inv. talk

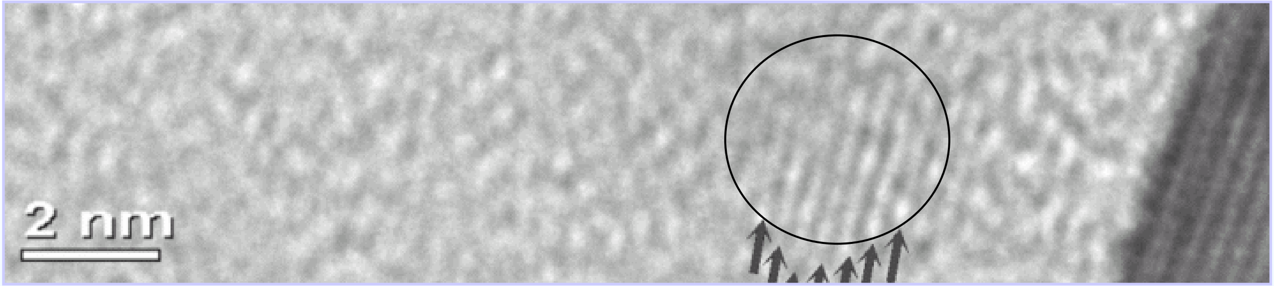


Si irradiation:
E = 450 keV, D = 5*10^{15} cm^{-2}

Ge implantation:
E = 350 keV, D = 5*10^{16} cm^{-2}

Annealing:
T_A = 1100 °C, t = 1h



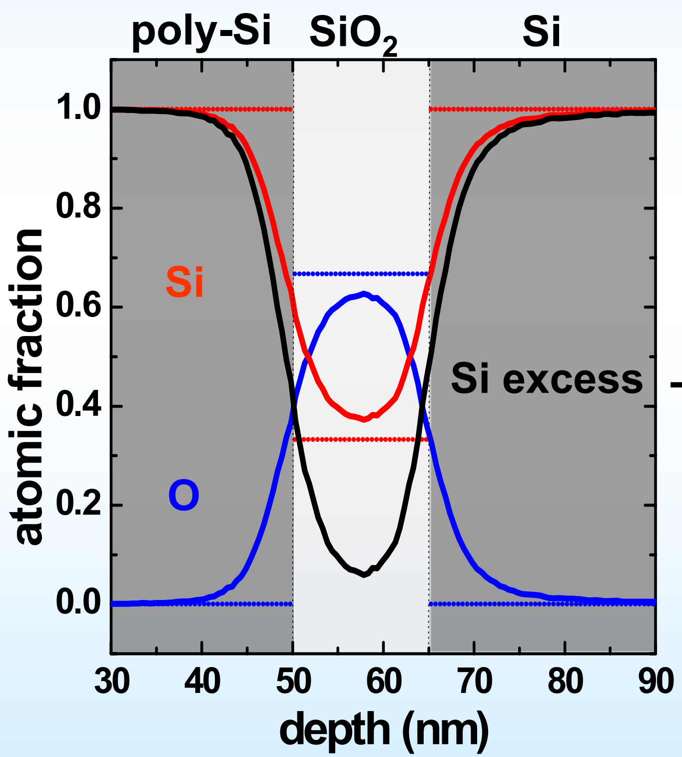


- Si precipitates next to the interface <u>must</u> exist to which Ge atoms attach
  → formation of NCs during annealing
- Ge decoration improves mass contrast in TEM
- a denuded zone (~3nm) exists in-between NC layer and substrate

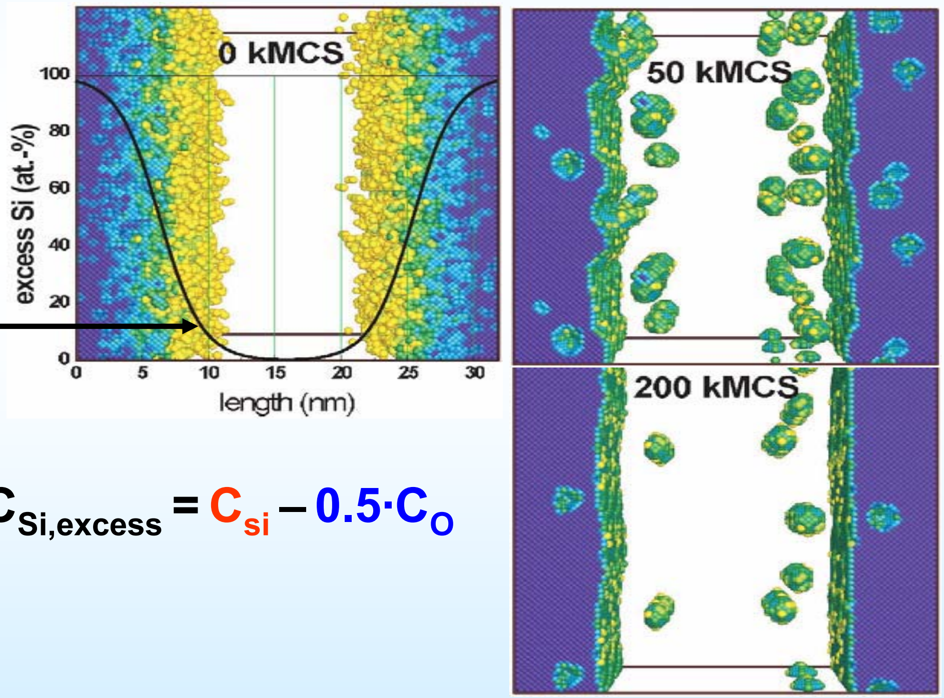
PREDICTIONS for Si NCs in buried SiO_2 layers after ion irradiation

TRIDYN (here: $D=1x10^{16}cm^{-2}$)
→ mixing profiles

Kinetic Monte-Carlo
→ phase separation



Röntzsch

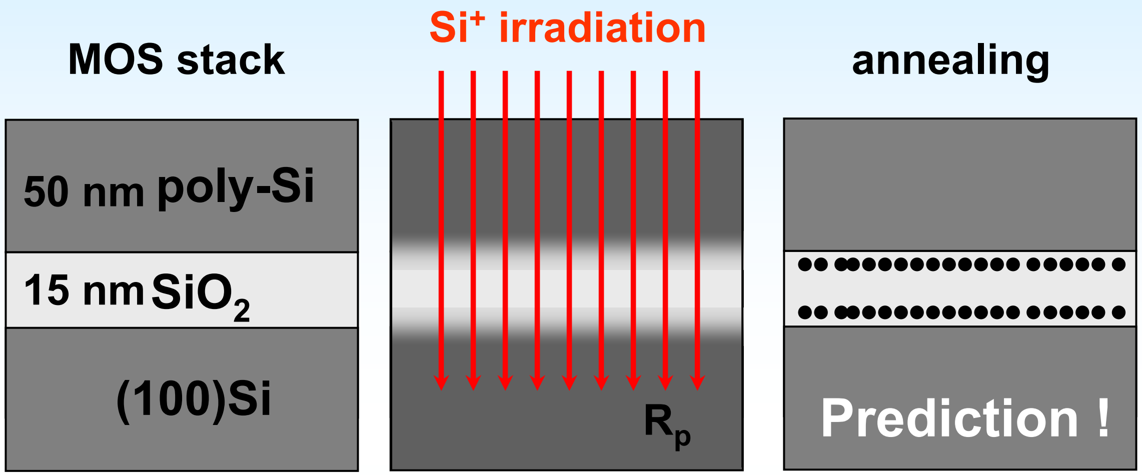


$$C_{Si,excess} = C_{si} - 0.5 \cdot C_O$$

Heinig

L. Röntzsch, et al., phys. Stat. Sol (a) 2002 (2005) R170

Structural Investigations (ToFSIMS)

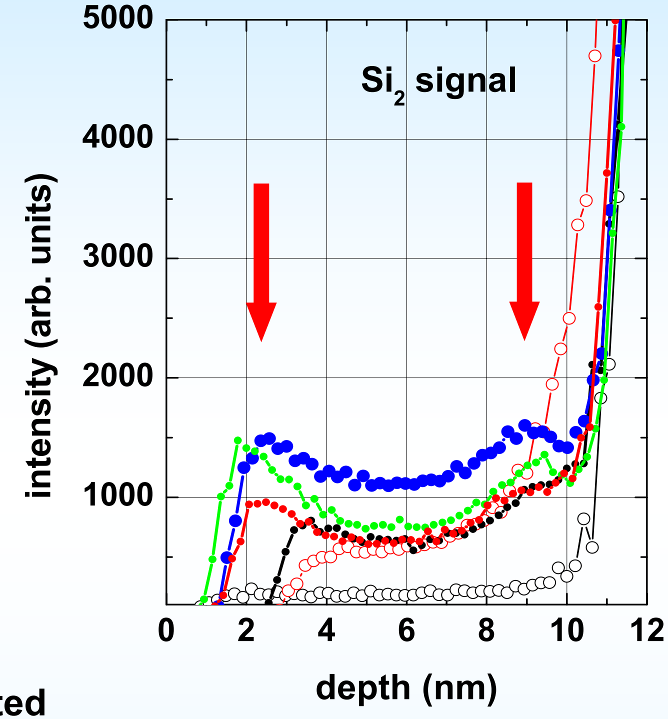


E = 50 keV,
D = $1x10^{16}$ cm^{-2}

R_p = 70 nm
(Si deposition at SiO_2/c-Si interface < 1 at%)
EoR defects 70 nm below the interface

isothermal annealing
@ T = 1000 °C

- reference
- as-implanted
- 30 s
- 60 s
- 120 s
- 240 s

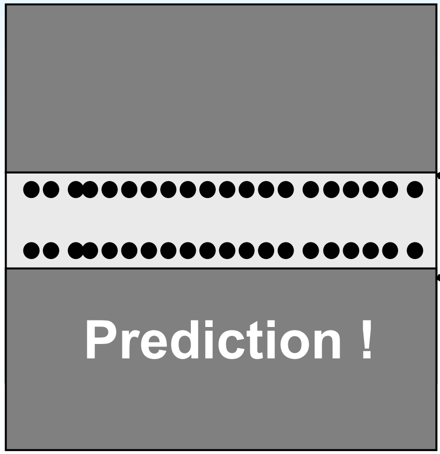


ToF-SIMS

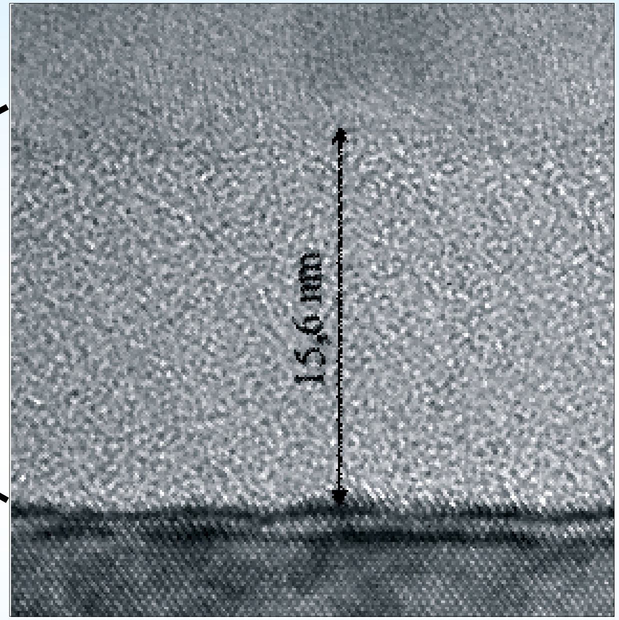
1. Si_n conglomerates (seeds) occur in regions expected to contain NCs.
2. Oxide stoichiometry at the interface is largely restored.

ToF-SIMS measurements performed by M. Perego, S. Ferrari and M. Franciulli, INFM/MDM, Milano, Italy

Si NCs near irradiated interfaces – „just“ predictions or real?



?



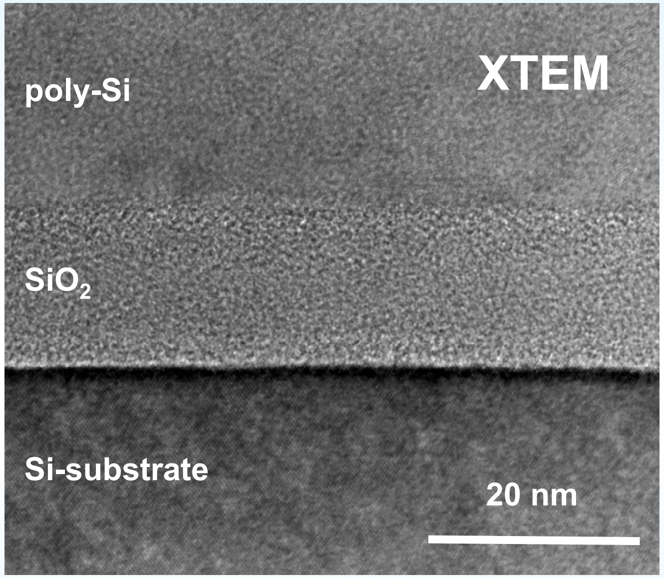
C. Bonafos et al., NanoMat group, CEMES/CNRS, Toulouse, France

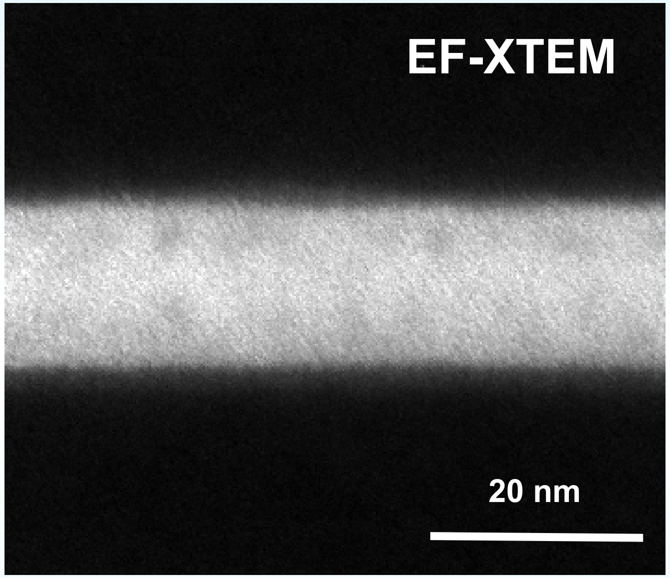
😐 Si NCs are not observed in **HR-XTEM** images!

potential reasons:
- **below visibility limit**
- **amorphous**
- **low contrast**

⇒ **Further structural investigation by EF-XTEM using Gatan Imaging Filter GIF 200 for Elelectron Energy Loss Spectroscopy (EELS)**

Energy Filtered Transmission Electron Microscopy





← Si NC δ-layer

← Si NC δ-layer

☺ !

(EFTEM by M. Klimenkov, Research Center Jülich)

no clusters visible

clusters faintly visible

50 nm poly-Si/14,5 nm SiO_2
Si^+, E = 50 keV
D = 7.0×10^{15} cm^{-2}
T_A = 1100°C, 160 s

NC diameter below 3 nm !

L. Röntzsch, et al., phys. Stat. Sol (a) 2002 (2005) R170

IIR: Ion Irradiation through curved interfaces - Inverse Ostwald ripening of NCs

- NCs have curved interfaces – how do they respond to ion irradiation?
- Narrow size distributions are required for many applications !

→ It is desirable to control
- the size
- the size distribution
of ion beam synthesized nanocluster ensembles.

→ Examples:
- size dependent optical absorption and luminescence
- size dependent Coulomb blockade effect

- A new method for re-ensembling of NC size distributions using irradiation induced Inverse Ostwald Ripening (IOR) was predicted, which should allow even the formation of monodispersive NC size distribution !

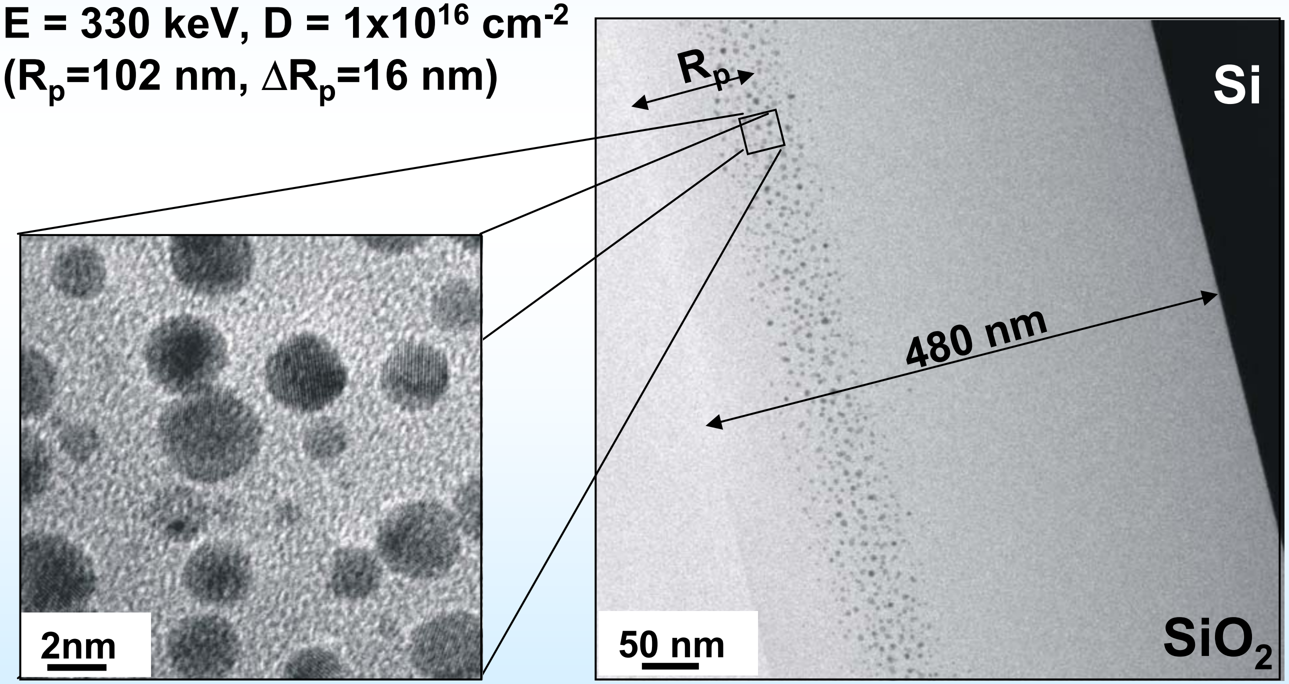
K.H. Heinig, B. Schmidt, M. Strobel, H. Bernas, Mat. Res. Soc. Proc. **650** (2001) R9.6.1
K.H. Heinig, T.Müller, B.Schmidt, M.Strobel, W.Möller, Appl. Phys. **A 77** (2003) 17

IIR: Ion Irradiation through curved interfaces - Inverse Ostwald ripening of NCs

Ion beam processing far-from-equilibrium for controlled tailoring of ion beam synthesized Au NC ensembles in SiO_2:

Au^+ implantation:
E = 330 keV, D = 1×10^{16} cm^{-2}
(R_p=102 nm, ΔR_p=16 nm)

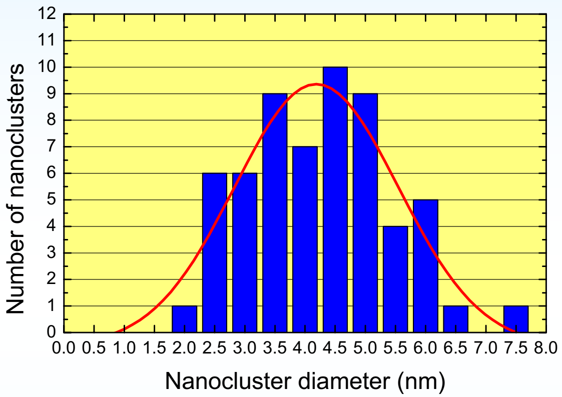
Annealing: T = 1000°C for 1h, O_2



B.Schmidt, K.H.Heinig, A.Mücklich, Mat. Res. Soc. Proc. **647** (2001) O11.20.1

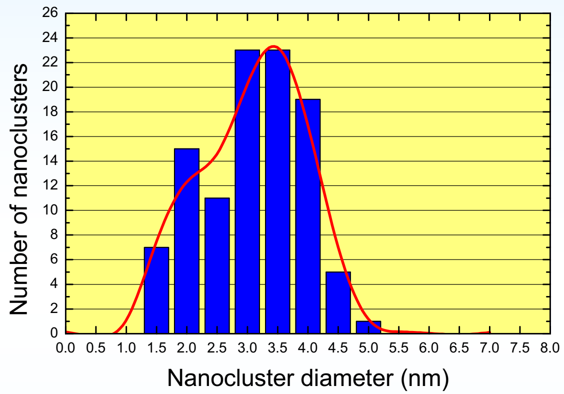
IIR: Ion Irradiation through curved interfaces - Inverse Ostwald ripening of NCs

Initial Au-NC distribution

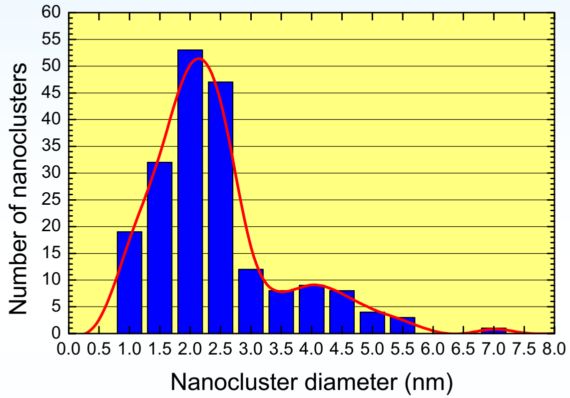


$d_{NC} = (4.2 \pm 2.7)$ nm at $(R_p \pm 15$ nm)

Re-ensembling of NC size distribution



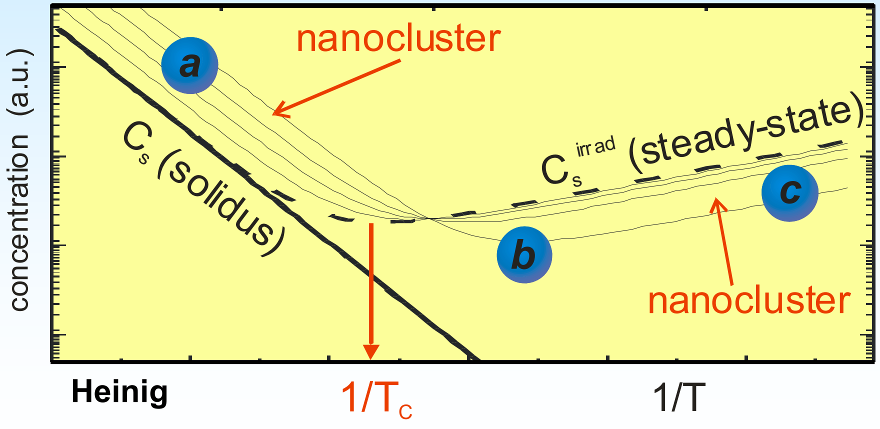
Au⁺ irradiation:
E = 4.5 MeV, D = 5×10^{15} cm^{-2}
T_i = 190 °C



Au⁺ irradiation:
E = 4.5 MeV, D = 1×10^{16} cm^{-2}
T_i = 210 °C

- Ion beam processing far-from-equilibrium allowes controlled tailoring of ion beam synthesized NC ensembles in SiO_2.
- Small NC's grow at the expense of larger ones, and, consequently, the NC size distribution becomes narrower.

K.H. Heinig, B. Schmidt, M. Strobel, H. Bernas, Mat. Res. Soc. Proc. **650** (2001) R9.6.1
K.H. Heinig, T.Müller, B.Schmidt, M.Strobel, W.Möller, Appl. Phys. **A 77** (2003) 17



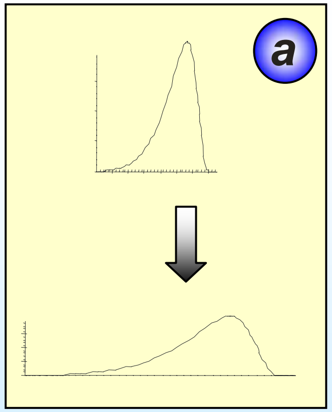
OR $C_{GT} = C_s\,(1 + R_c/R_0)$

IOR $C_{GT}^{IIR} = \tilde{C}_s\,(1 + \tilde{R}_c/R_0)$

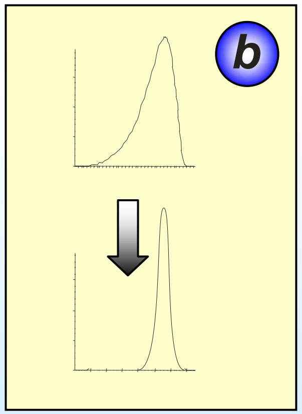
$\tilde{C}_s = C_s \cdot (1 + \Delta)$
$\tilde{R}_c = (R_c - 5 \cdot \lambda \cdot \Delta/4)/(1 + \Delta)$
$\Delta = q \cdot \lambda^2 / D \cdot C_s$

Q proportional to displacements per atom (dpa)
λ mean distance of displaced atoms
D thermal diffusion coefficient
C_s thermal solubility (solidus)

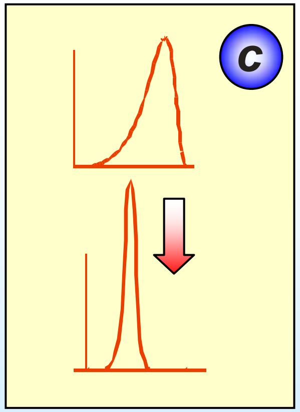
Above T_c : Ostwald Ripening (OR)



Below T_c : Inverse Ostwald ripening (IOR)



Far below T_c : Nucleation + Inverse Ostwald Ripening (IOR)



- **Only parameters $\tilde{C}_s$, $\tilde{R}_c$ modified!**
- **$\tilde{R}_c$ can becomes negative for intense irradiation or low temperatures !**

K.H. Heinig, B. Schmidt, M. Strobel, H. Bernas, Mat. Res. Soc. Proc. **650** (2001) R9.6.1
K.H. Heinig, T.Müller, B.Schmidt, M.Strobel, W.Möller, Appl. Phys. **A 77** (2003) 17

5. Applications

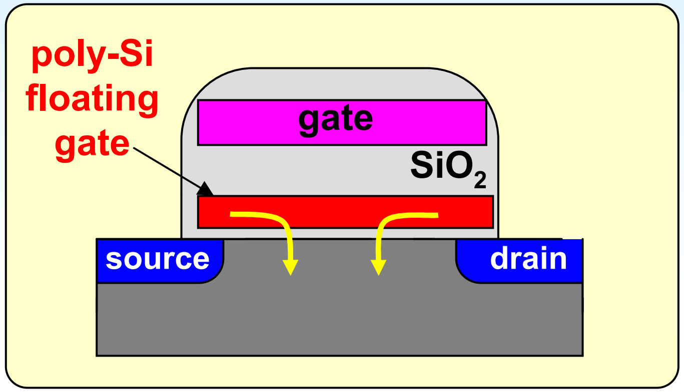
Synthesis of Si NC-δ-layers in SiO_2
a few nm above the SiO_2-Si interface:

A) Si ion implantation – phase separation (IBS)
Low energy ion implantation, E < 10 keV

B) Self-organization by Si ion irradiation (IIR)
Medium energy ion irradiation, E > 10 keV

→ for non-volatile Nano-Crystal Memory devices (nv-NCM)

Conventional Floating Gate NVM



Charge storage in contineous layer

Disadvantages

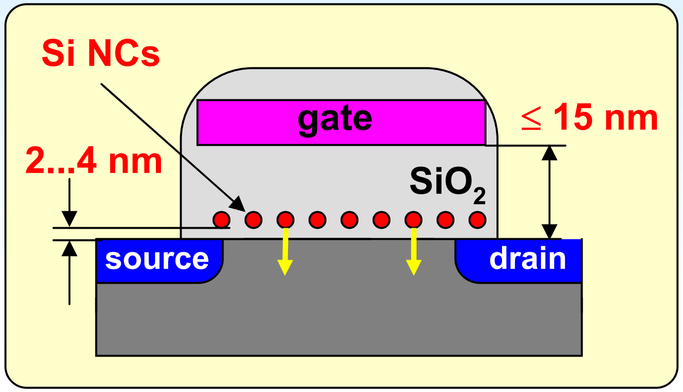
No Scalability (<65 nm)

Low Endurance (<10^6 W/E cycles)

High P/E voltages (>12 V)

Slow operation (>10 ms)

Nanocrystal Memory



Discrete charge storage nodes

Advantages/Demands

Scalable to <65 nm

Good Endurance (≥10^6 W/E cycles)

Low P/E voltages (<7 V)

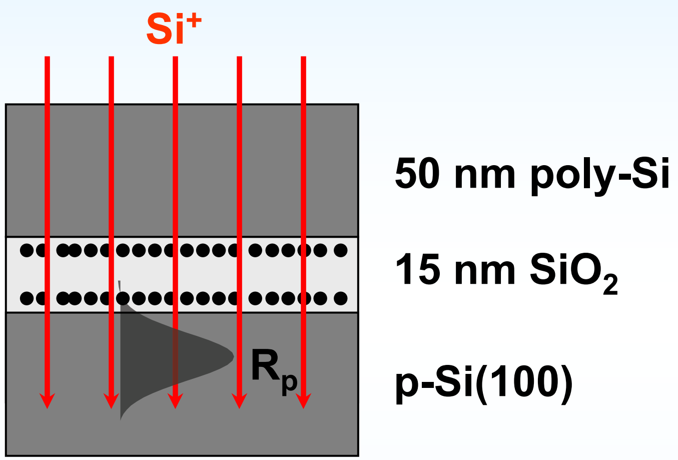
Fast operation (<1 ms)

Electron Tunneling vs. Data Retention: Strongly determined by the location NCs

Can we fabricate and control δ -layers of Si NC by Ion Beam Processing?

Applications in NC nv-memories

Layer stack:



Selected process parameters:

- **Si^+ irradiation:**
  E = 50 keV
  D = (3-10)x10^{15} cm^{-2}

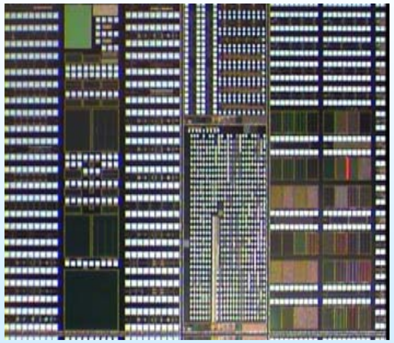
↓

- **Annealing:**
  RTA,
  T = 950-1100 °C
  T = 5-180 s

  { Annealing after 2^{nd} poly-Si deposition and poly-gate doping by P^+ implantation }

↓

- **nMOSFET processing**
  in standard 0.6 µm CMOS line at ZMD
  (http://zmd.de)

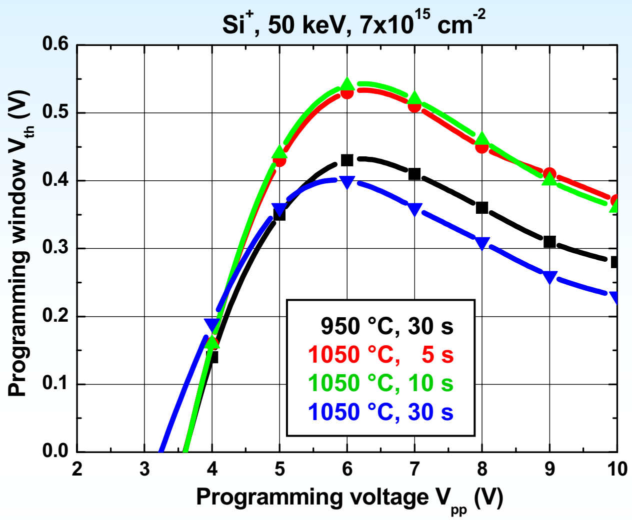


Single cell characterization:

- gate width/length
  W/L = 20/20 and 20/0.6 µm
- programming voltage
  V_{pp} = +6/-6…+9/-9 V
- Programming time t_{pp} = 10 µs…20 ms
- Endurance test: 10^7 write/erase cycles
- Retention test: at T = 20, 55, 70, and 85 °C

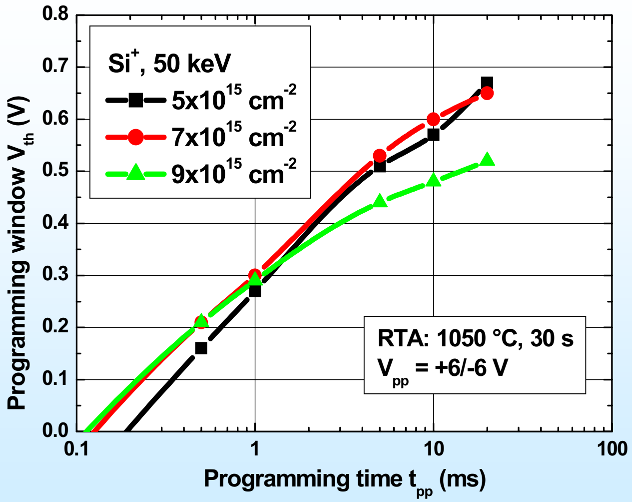
nMOSFET characteristics (low thermal budget) :

f(V_{pp})



Programming window

f(t_{pp})

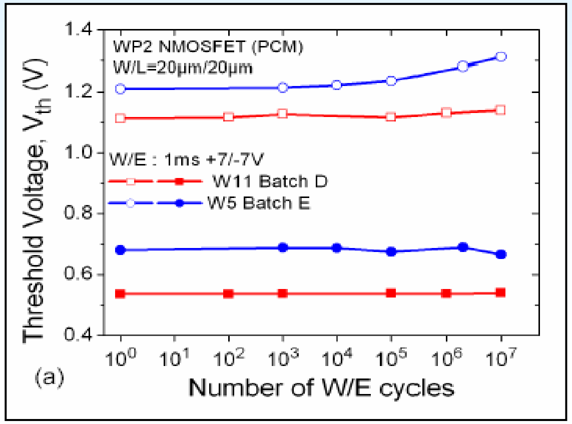


- program & erase by quantum mechanical direct electron tunneling
- low voltages are sufficient
- fast program + low current consumption during write/erase
- higher programming voltages lead to trap assisted tunneling through the dielectric (leakage)

B.Schmidt, et al. Nucl. Instr. Meth., B242 (2006), 146

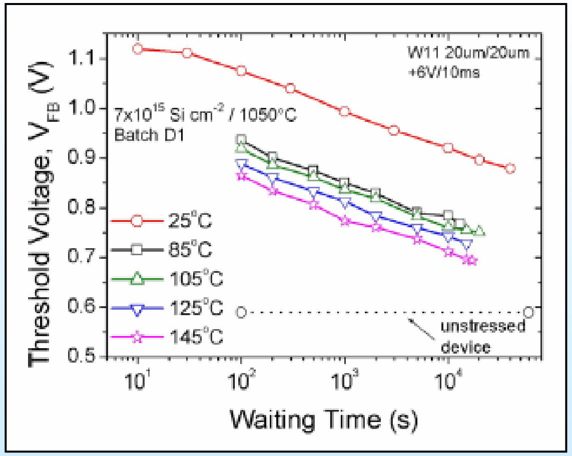
nMOSFET characteristics (low thermal budget) :

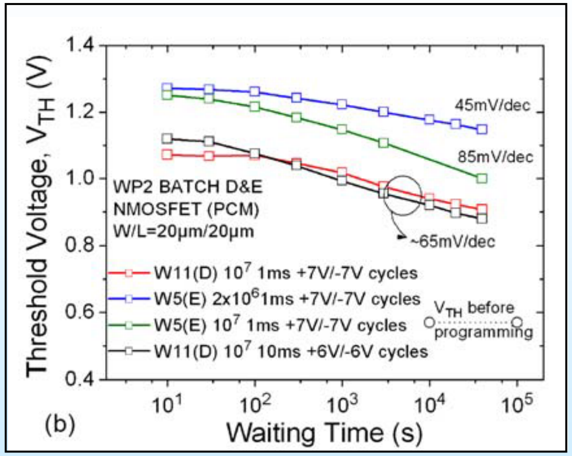
Endurance



- superior endurance (very limited degradation up to 10^7 cycles)
- limited data retention only (pre-cycling of 10^7)
- improved RT retention for reduced pre-cycling

data retention (after pre-cycling)





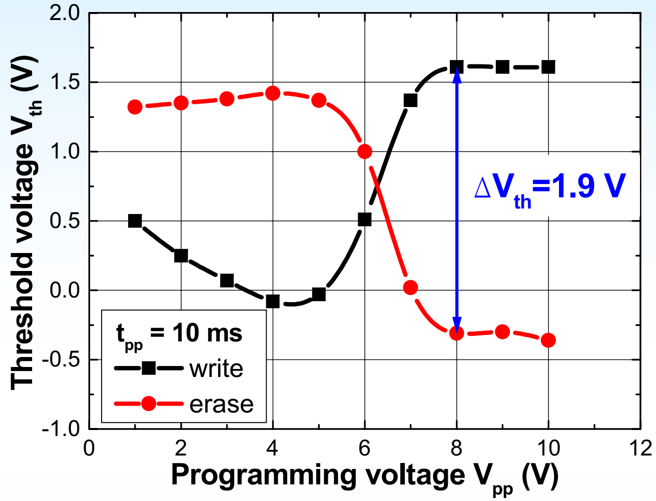
P. Dimitrakis,
P. Normand,
IMEL,
DEMOKRITO
S, Athens,
Greece

nMOSFET characteristics (higher thermal budget) :

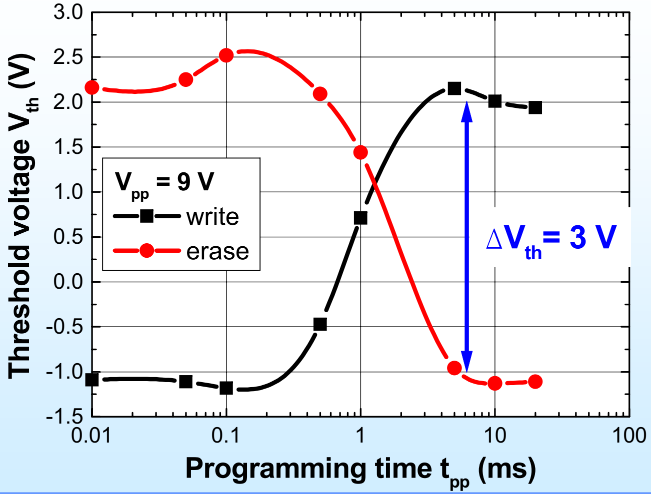
→phase separation (NC formation) could proceed further

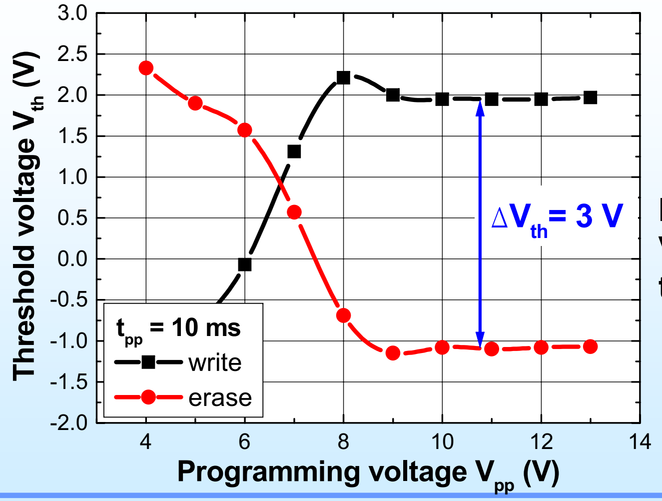
- large and stable memory window (ΔV_{th} ~ 3V)
- retention remain low

50 nm poly-Si/14.5 nm SiO_2
Si^+, E = 50 keV, D = 7.0×10^{15} cm^{-2}
T_A = 1100°C, 160 s



Initialization:
V_{pp}=6 V/-6 V
t_{pp}=10 ms





Initialization:
V_{pp}=9 V/-9 V
t_{pp}=10 ms

Ion Beam Synthesis – Direct Implantation vs. Ion Beam Mixing

conventional: Ion implantation

Unprotected gate oxide →
serious impact of the ambient during processing

Low Energy, High dose implantation →
strong sputtering & swelling of SiO_2

NC location due to implantation →
difficulty to place NCs close to channel

Ions and recoils come to rest in the interface region →
degradation of the channel

here: Ion beam mixing

Gate oxide potected during processing by poly-Si →
***no contamination** by impurities and/or humidity**

Irradiation with low fluences →
no sputtering & no swelling of SiO_2

NCs due to ion beam mixing →
*Self-alignment of NC layer close to the channel (ion energy is **not** critical)*

Ions come to rest deep within Si →
defects do not deteriorate the channel

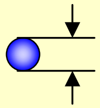
* B. Schmidt et al., NIM B **191**, (2002) 482

→ ion beam mixing delivers the more stable process of Si NC synthesis

6. Outlook

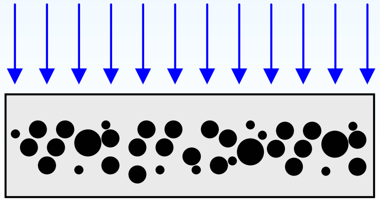
Broad (x,y-scanned) ion beam:

0D-Structures:
Nanodots
(Quantum-dots)



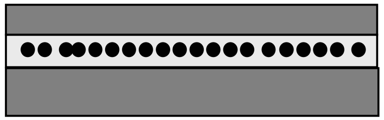
SET,
NC-memory

✓



Homogeneous target
& ion implantation (IBS)

✓



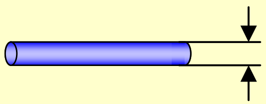
Interfaces between
different thin layers
& ion irradiation (IIR)

Emerging technologies:

**IBS &
IIR induced
self-assembly
of nanostructures**

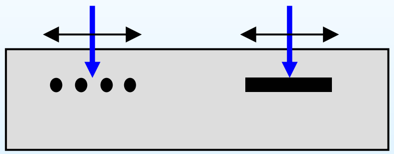
Focused ion beam (FIB):

1D-Structures:
Nano-wires
(Quantum-wires)



Nanowire-laser

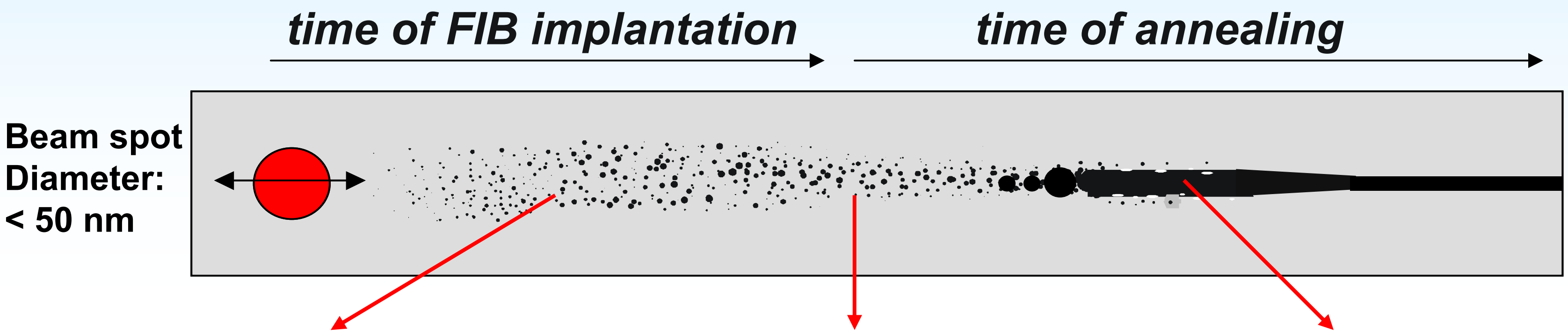
?



Local ion irradiation:
point-like, writing

**FIB-IBS &
FIB induced
self-assembly
of nanostructures**

Focused ion beam synthesis of nanostructures



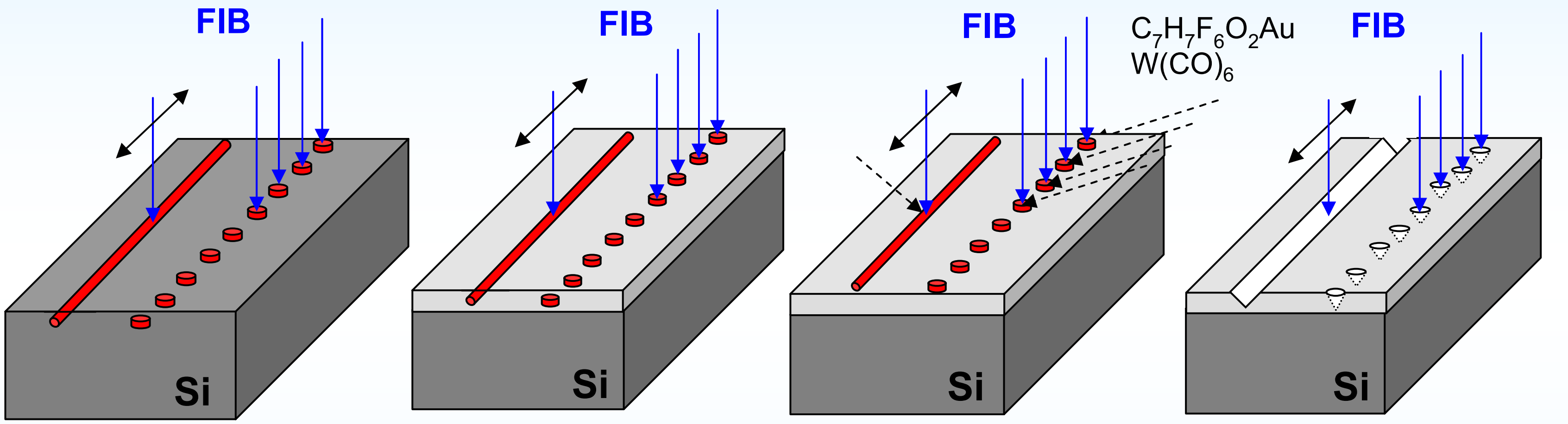
Ion implantation by FIB:
Ion energy **E**
Ion fluence ϕ
Substrate temperature $\mathbf{T_S}$
Pixel dwell & relax. time $\mathbf{t_{d,r}}$

Phase separation & coarsening (wire growth):
Annealing temperature $\mathbf{T_A}$
Annealing time $\mathbf{t_A}$
Orientation of FIB trace relative to crystal orientations

Prediction:

Narrowing during phase separation and coarsening by a factor ~ 5 !!!

Promising fabrication of nanostructures by FIB



FIB-IBS:
Phase separation of $CoSi_2$ from Si

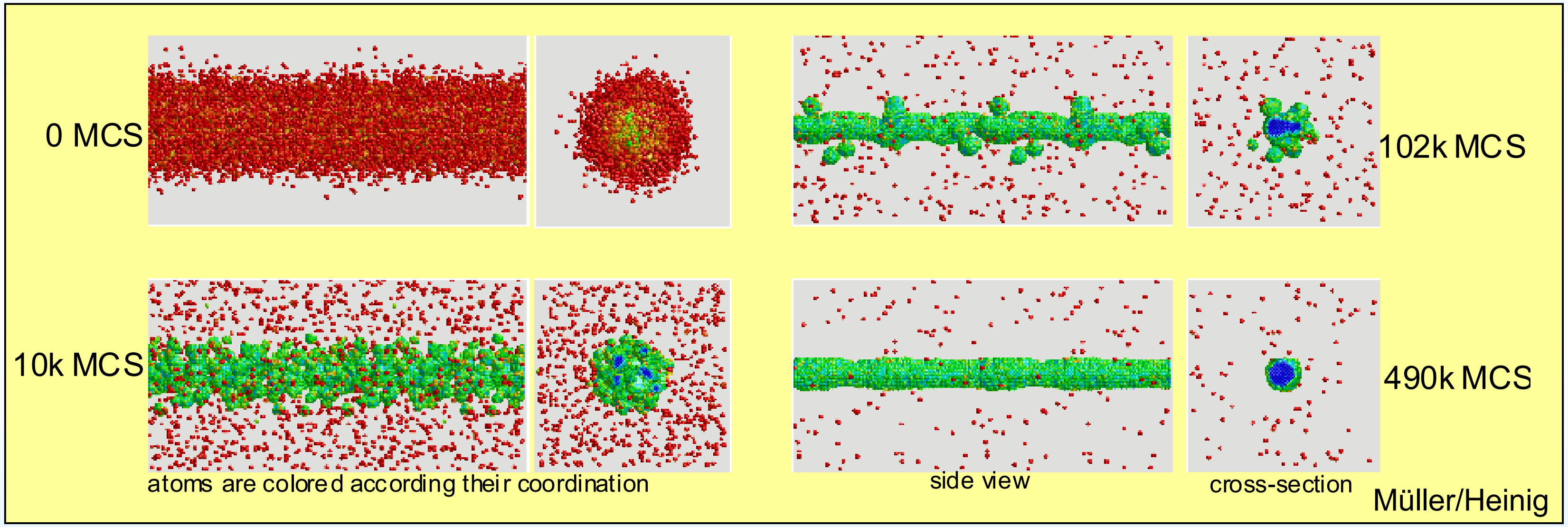
FIB-IBS:
Phase separation of Ge, Au,... from SiO_2

FIB-assisted MOCVD:
Deposition of Au, W,... onto SiO_2

FIB-assisted templating (sputtering):
Wettening & nucleation seeds

Kinetic 3D Lattice Monte-Carlo Simulation of phase separation of Ge from SiO_2

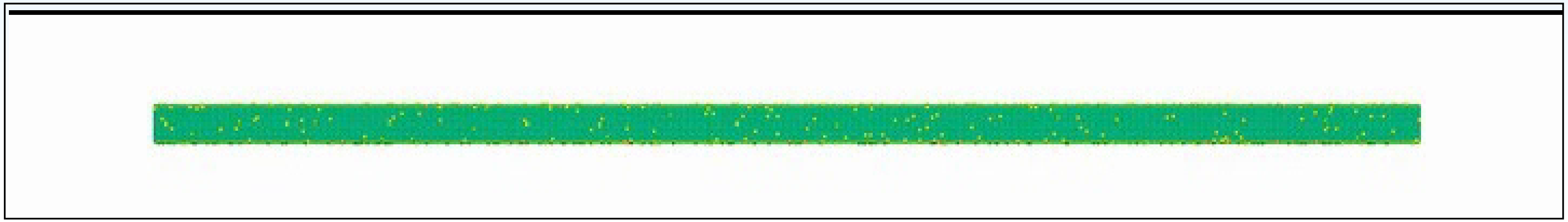
Cylindrical Gaussian profile as initial distribution of implanted impurities with a peak concentration of 31% and diameter of 16 nm (95% of the atoms lay within this range)



A continuous Ge nanowire forms under thermal treatment (diameter 5nm) !

T.Müller, K.H.Heinig, B. Schmidt, Mat. Sci. Eng. **C19** (2002) 209

Long lasting thermal treatment (atomistic simulation): Decay of a semi-infinite wire under surface diffusion



(FZR, MC simulation, T. Müller, K.H. Heinig, L. Röntzsch)

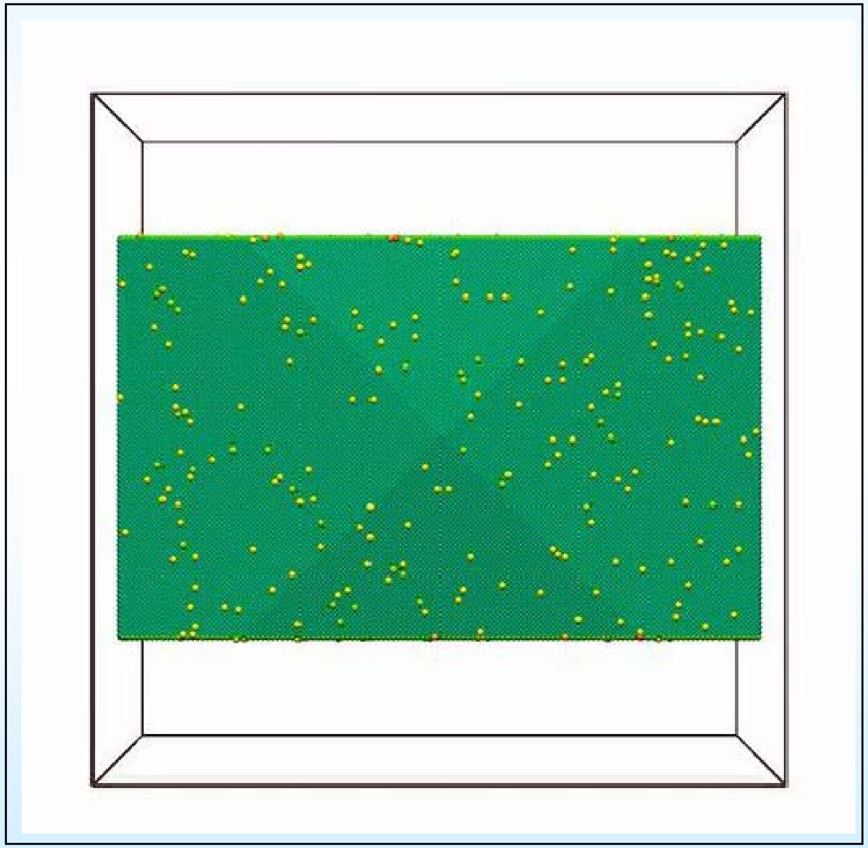
Wire diameter: 6.2 nm → **Mean droplet diameter: 11.9 nm**

Droplet diameter prediction from lin. stability analysis: 11.7 nm (Rayleigh-Instabilität)

$$d_{cluster} = \sqrt[3]{6\lambda_m R_0} = 1.89 d_{wire}$$

T.Müller, K.H.Heinig, B. Schmidt, Mat.Sci.Eng. **C19** (2002) 209

Kinetic Monte-Carlo Simulation of phase separation in quasi-2D structures

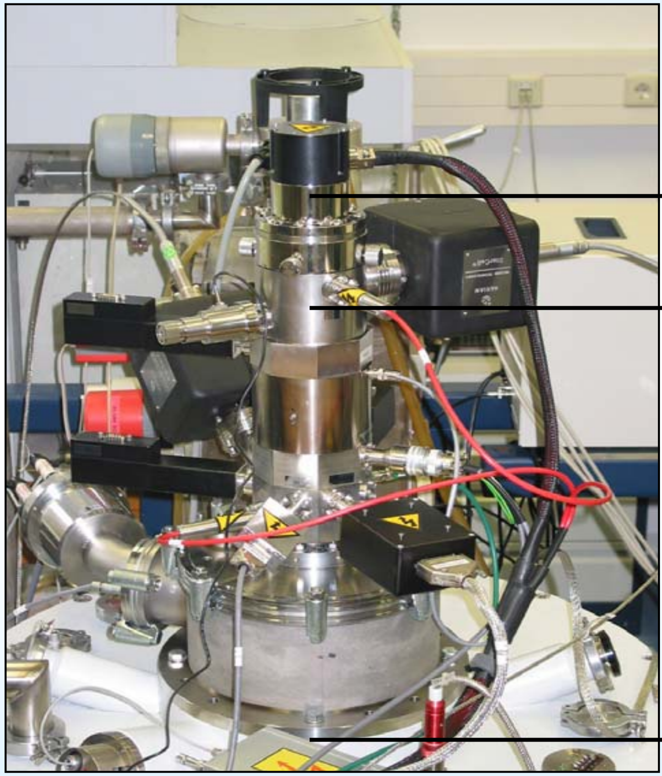


(FZR, MC simulation, T. Müller, K.H. Heinig)

Phase separation through:

- spinodal decompositition,
- wire formation at prolonged boundaries
- droplet formation

Experiments of FIB-IBS



IMSA - Canion 31 Mplus FZR - Orsay Physics

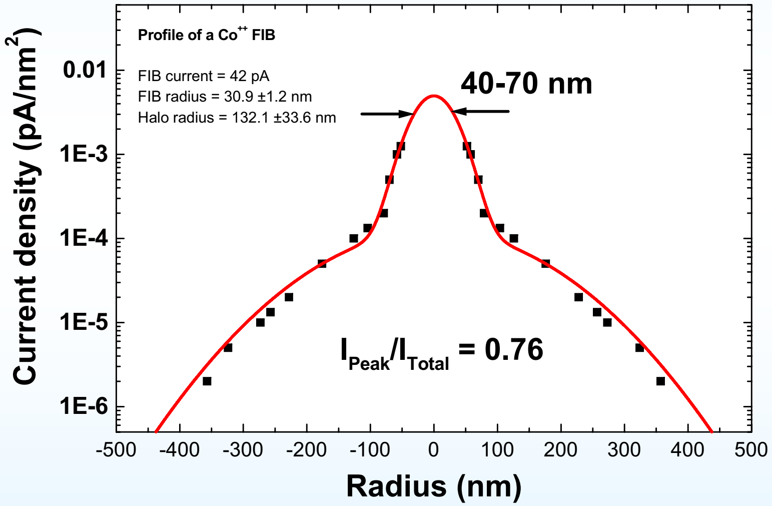
LMAIS
$Co_{36}Nd_{64}$,
T_M = 566 °C

Ion optics, mass separator, scan system

x,y-stage with sample holder

Co^{++} ions
E = 60 keV
Φ = 2x10^16...1x10^17 cm^-2

FIB profile

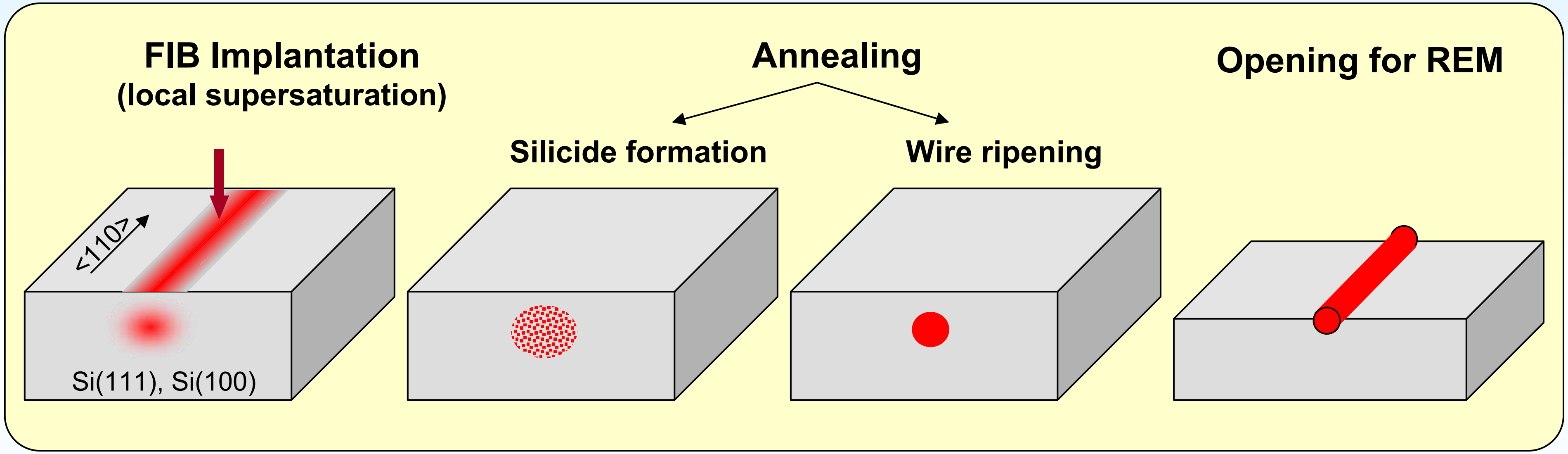


T_S = 420...430 °C
Samples:
(100)Si and (111)Si

C. Akhmadaliev, L. Bischoff, B. Schmidt
Mat. Sci. Engn. C26 (2006), 818

L. Bischoff, B. Schmidt, C. Akhmadaliev, A. Mücklich
Microelectronics Engineering 83 (2006), 800

Experiments – $CoSi_2$- Nanowires



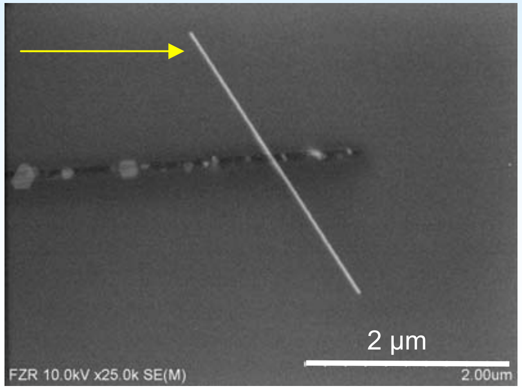
Co^{++} FIB:
E = 60 keV
D = 2...10x10^{16} cm^{-2}
T_i =420°C .. 430°C !

Annealing in N_2:
TA = 600 °C, 60 min + TA = 1000 °C, 30 min

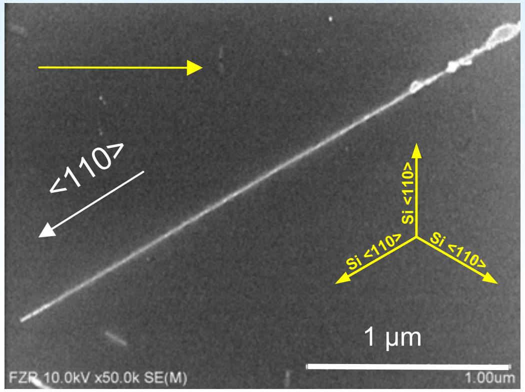
Reactive Ion Etching (RIE):
CF_4, 30 – 45 s
(20 –30 nm Si removal)

SEM Inspection:
Imaging in SE-mode and EDX-Analysis

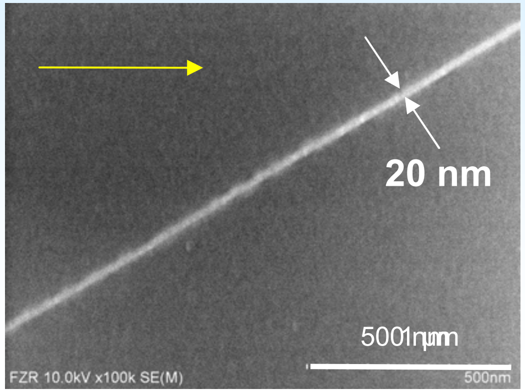
Results: $CoSi_2$- nanowire growth & decay



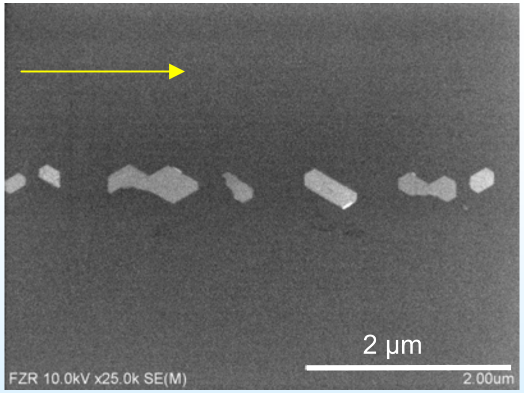
2.5·10^{16} cm^{-2}



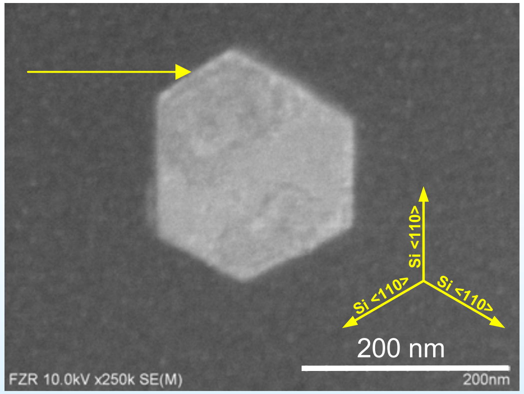
2.5·10^{16} cm^{-2}



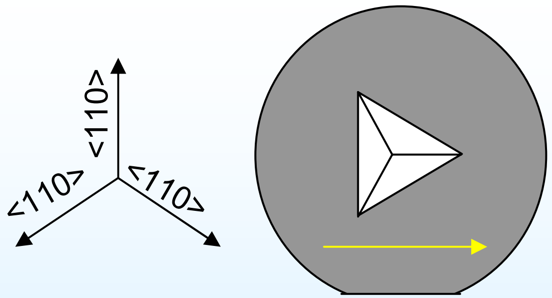
2.5·10^{16} cm^{-2}



4·10^{16} cm^{-2}



4·10^{16} cm^{-2}

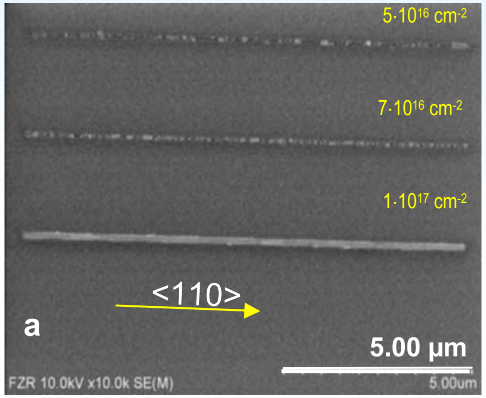


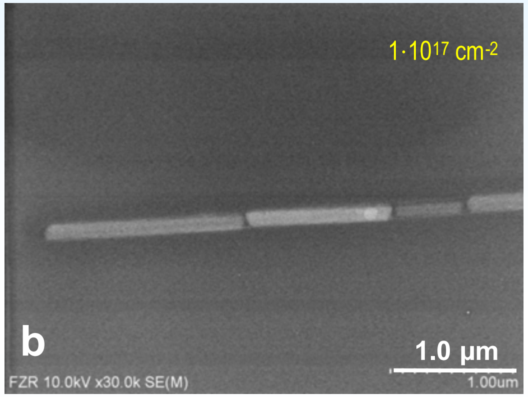
Si (111)

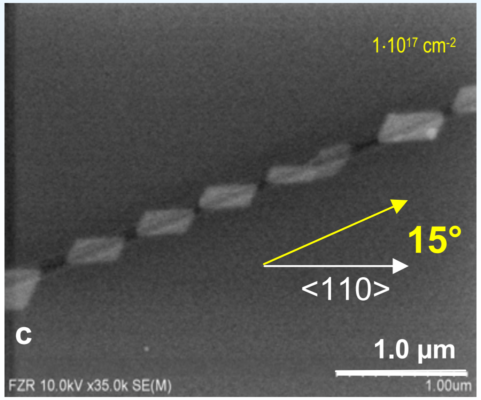
Scan direction (unsuitable !)

→ spontaneous nanowire growth ?

Results: $CoSi_2$- nanowire growth & decay



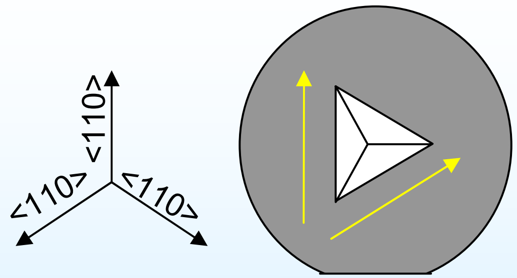




(a) wire growth in dependence on the implanted cobalt dose (FIB trace along <110> direction !)

(b) small misalignment of about 1° leads to the decay of the nanowire

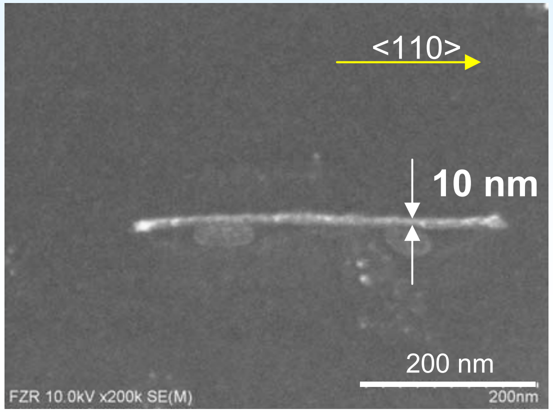
(c) at a misalignment of about 15° the nanowire transforms into a chain of crystalline nanoparticles. (sample temperature during implantation 450°C)



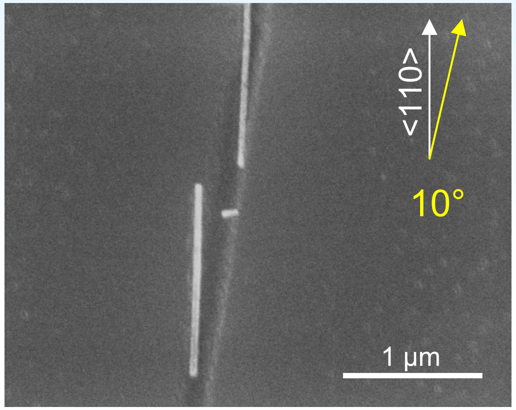
Si (111)

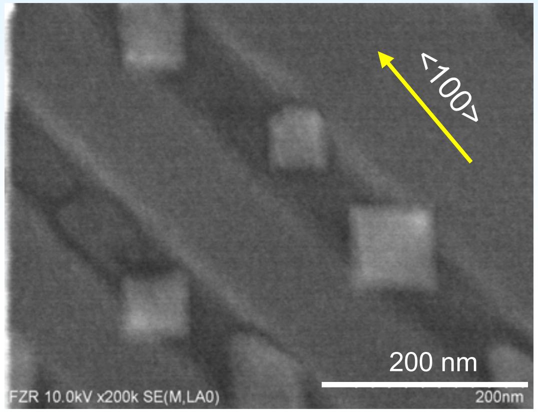
Scan direction (correct)

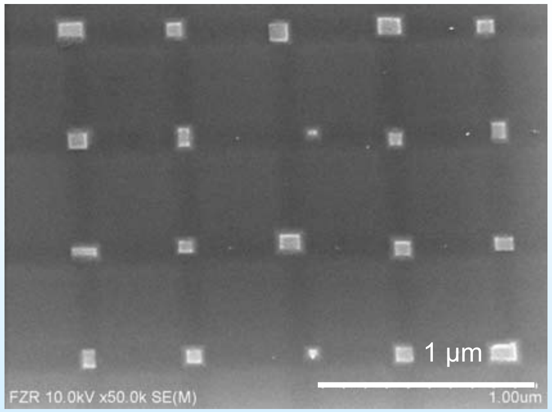
Results: $CoSi_2$- nanowire growth & decay



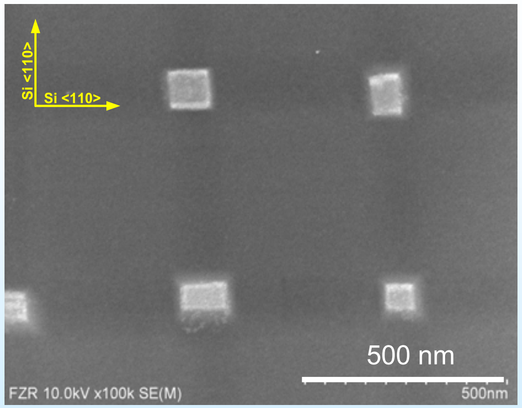
$2x10^{16}$ cm^{-2}

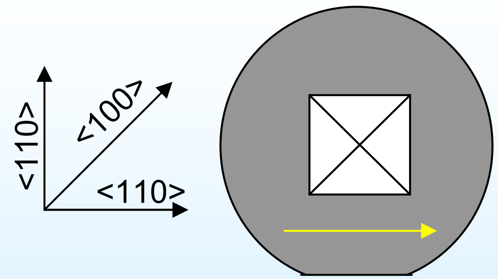






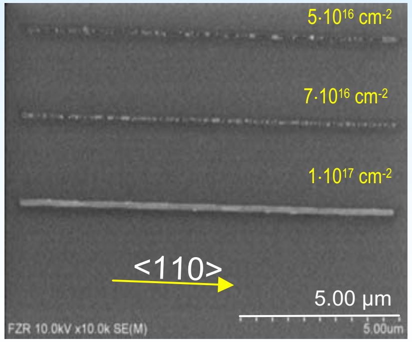
$4x10^{16}$ cm^{-2}

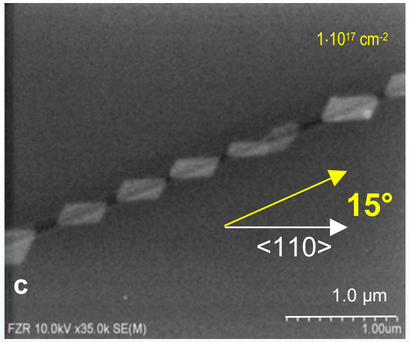


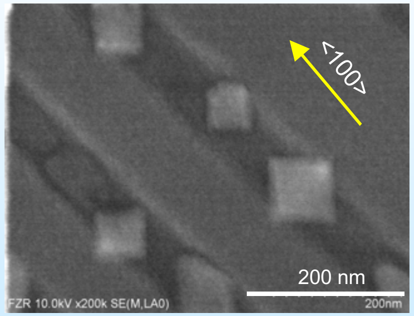


Si (100) **Scan direction**

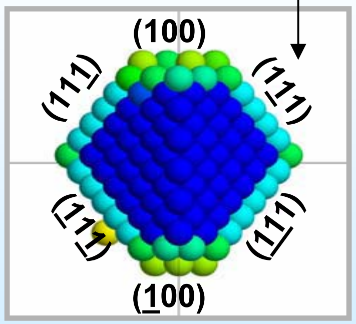
Comparison with computer simulations

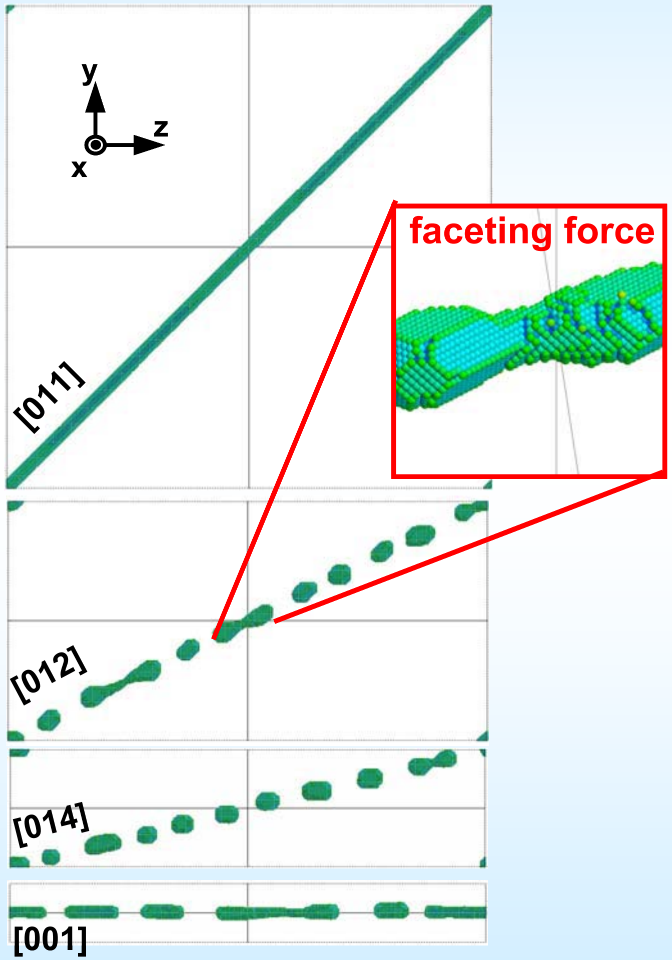






Stable interfaces

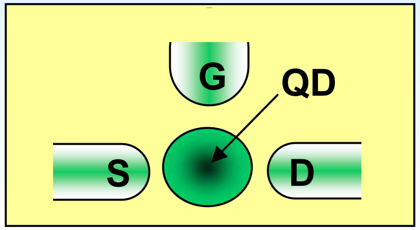




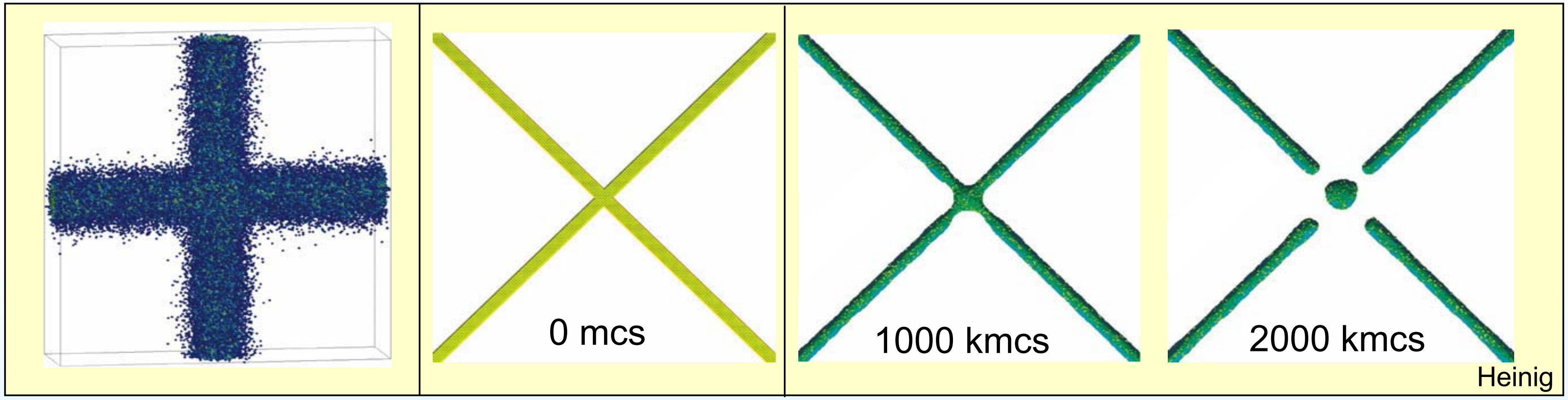
3DKLMC simulation, L. Röntzsch, K.H. Heinig, SPP1165, Hei 2137/2-1

Vision: nanowires as well as NC chains & single quantum dots for optics and electronics

1st example: Single Electron Transistor (SET)



Prediction of SET fabrication using FIB-IBS (atomistic simulation):



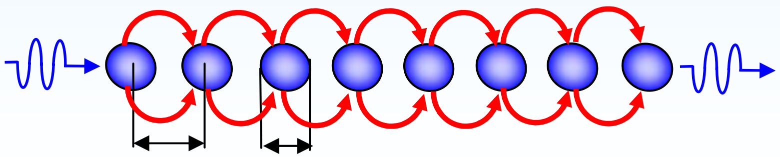
1st step:
Implantation of crossing traces with FIB (d < 50 nm)

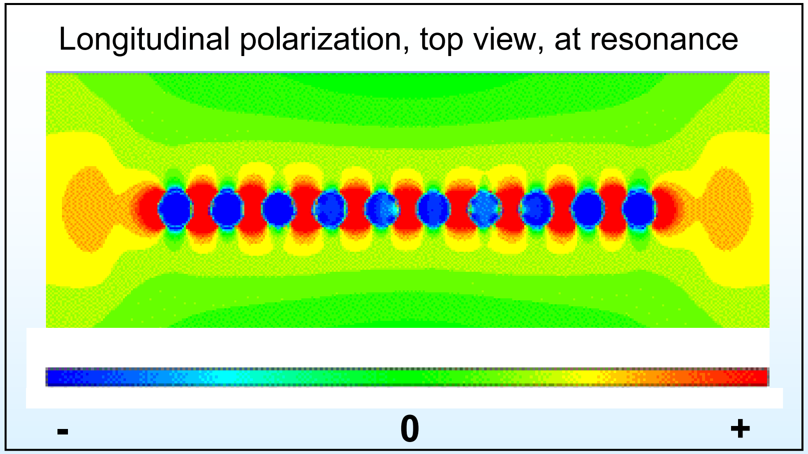
2nd step:
Phase separation by annealing → narrowing of the FIB implanted structure

Third step:
Further annealing & interface energy minimization → droplet separates from wires !

2nd example: Plasmonics - highly integrated optical devices

Plasmon waveguides for electromagnetic energy below the diffraction limit using ordered arrays of metal nanoparticles:





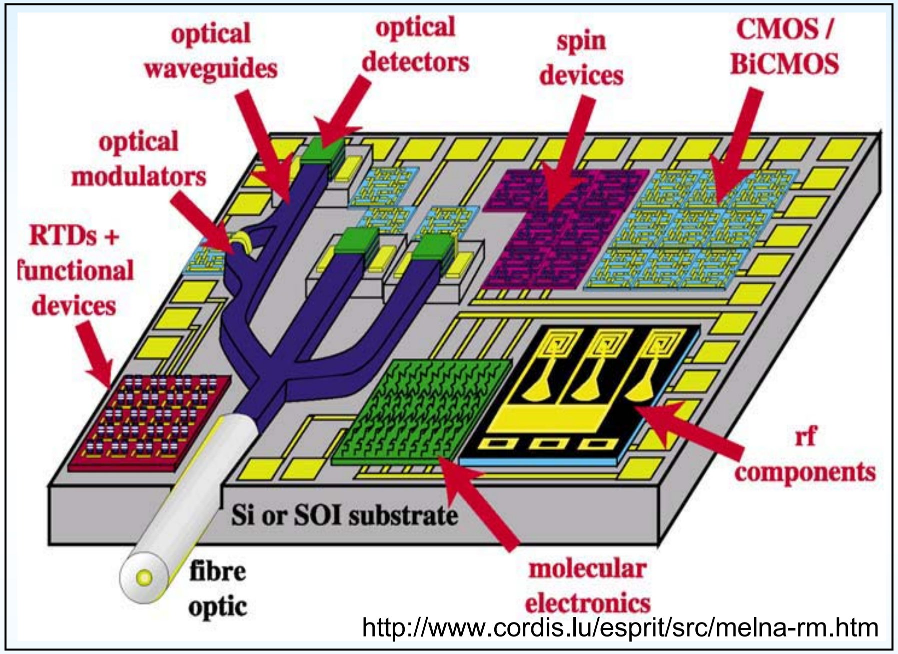
Atwater, Brongersma et al.,
California Institute of Technology, Pasadena, CA

How to synthesize?

Possibly by FIB–IBS through:

- **Line-shape implantation:**
  Au into SiO_2, Co into c-Si
- **Point-like implantation:**
  Au into SiO_2 Co into c-Si
- **Subsequent annealing to form:**
  Au-nanowires and chains of Au-NC´s
  $CoSi_2$-nanowires and chains of $CoSi_2$-NC´s

Finally a look to the „Nanoelectronics Roadmap“:



„System-on-a-chip“ for the future

Some fabrication problems of the „System-on-a chip“ can be solved by emerging technologies like ion beam induced self-assembling of nanostructures:

- **Nonvolatile memories (nvRAMs)**
- **Single Electron Transistors (SETs)**
- **Optical (plasmon) waveguide**
- **Optical pumped light amplification**
- **.....**

➔ **In the last decades ion implantation has been established itselfs as an basic technology in microelectronics.**

➔ **This lecture showed you that ion beam assisted processing has the potential as a basic technology for nanoelectronics & nanooptics !**

IBS of Nanocrystals

Project support

SMWK-Project (1998-2002)

DFG-Project (2000-2003)

BMBF-Project "Konsul"+"Isotop" (2001-2003)

EU-Project "Neon" (2001-2004)

Collaboration

IBS by FIB

Project support

DFG-Project I (2004-2006)

DFG-Project II (2004-2006) (Theory)

Collaboration

FIB patterning

Project support

EU-Project TUD (2004-2006)

Collaboration

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FIB
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Clean room
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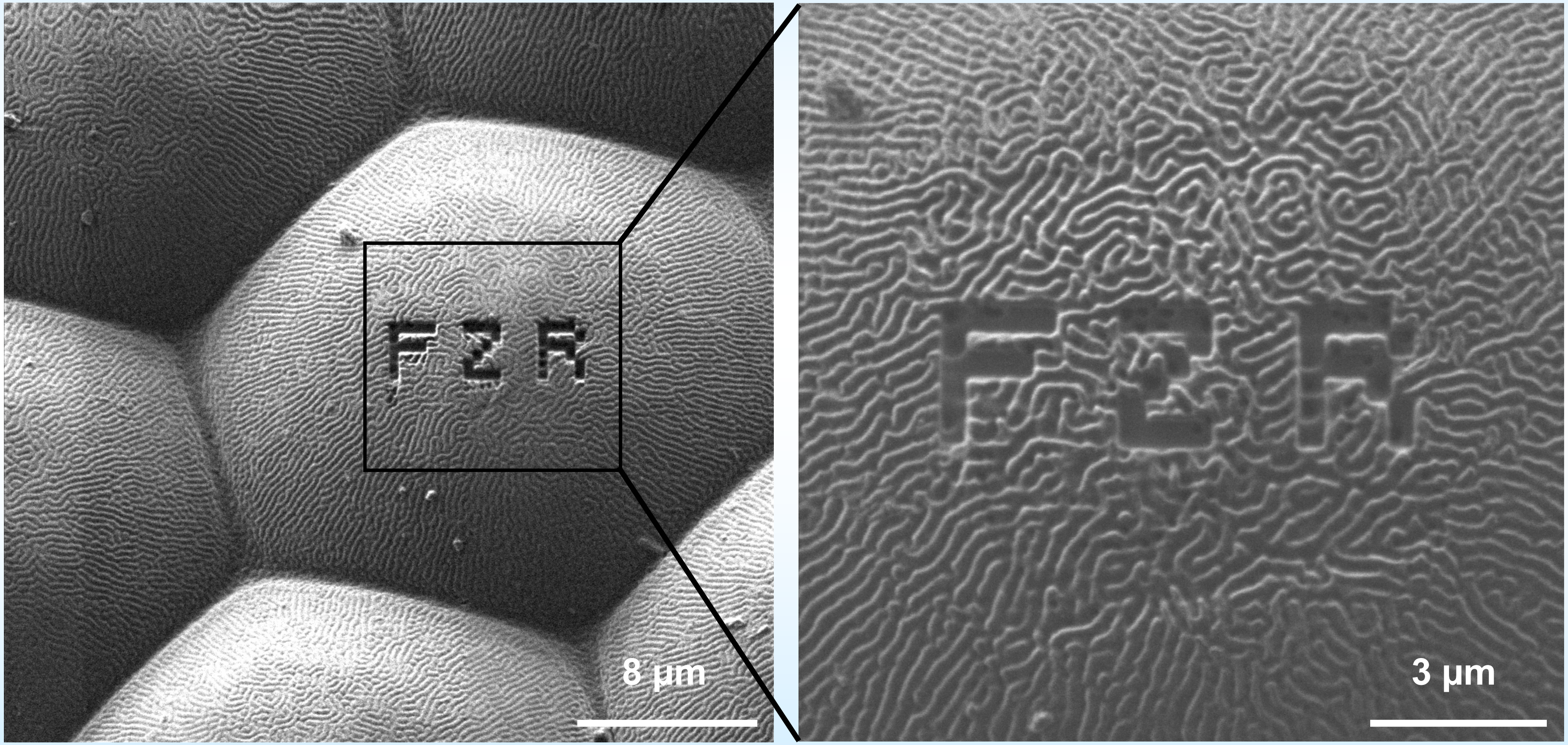
C. Neisser
B. Scheumann
G. Schnabel

ZMD®

S. Buschbeck
K.-H. Stegemann
H.-J. Thees [1)]
E. Votintseva
M. Wittmack

[1)] now with Infineon

FIB – ART: FZR-Logo in the eye of a fly



IMSA-Orsay Physics FIB (FZR, L. Bischoff, C. Akhmadaliev, 2003)