STM visualization of the growth of Ge nanostructures on Si(111)

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Outline

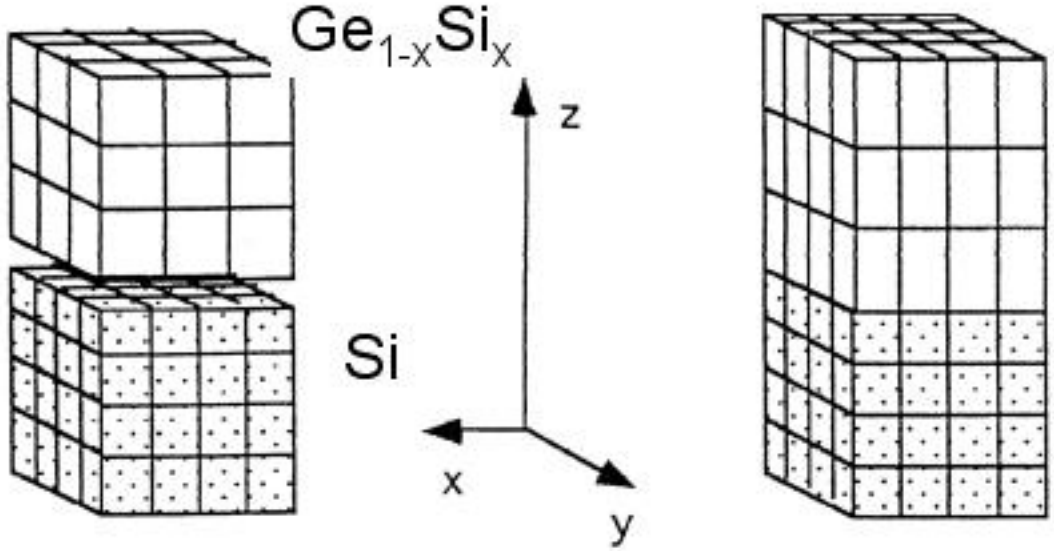
- ✓ Physical topics
- ✓ Experimental Apparatus
- ✓ Results
- ✓ Conclusions

Aim

- ✓ Growth and characterization of self-assembled quantum dots of Ge on Si(111)

- ✓ Determination of the influence of some experimental parameters on the kinetic of the growth

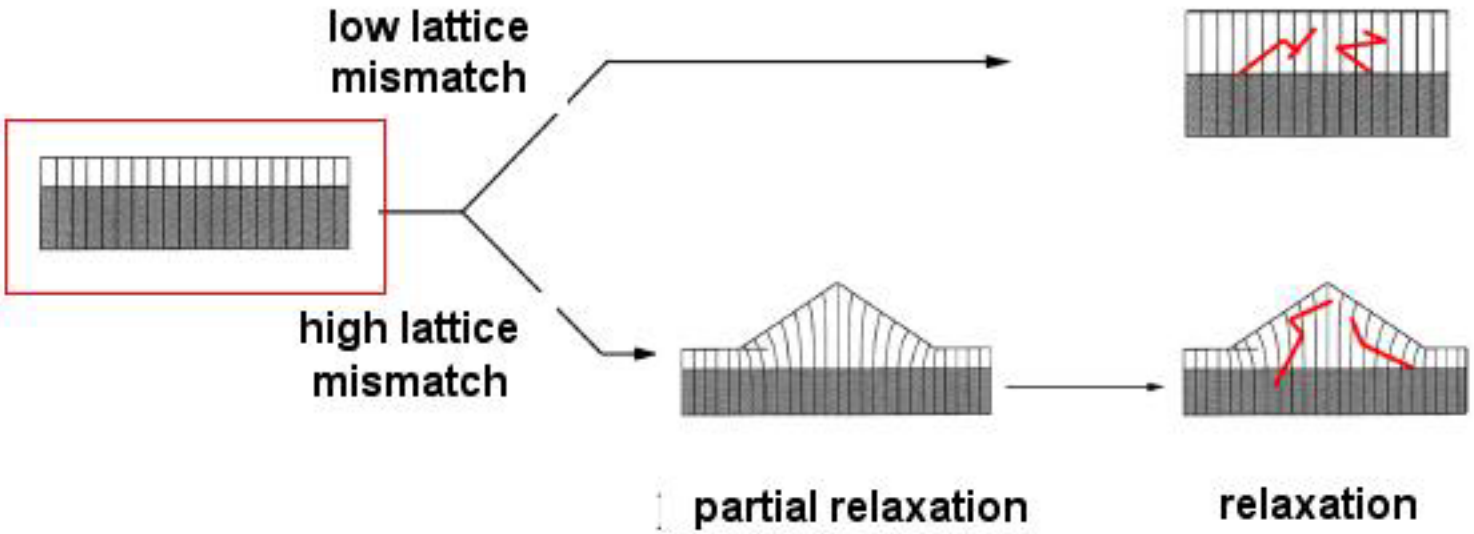
Heteroepitaxy: atomic species are deposited on a substrate with different composition



Lattice parameter { Ge = 5.65 Å ; Si = 5.43 Å

Lattice Mismatch $\varepsilon = \frac{d_{Ge} - d_{Si}}{d_{Ge}} = 4\%$

Evolution of a strained heterostructure



$$\varepsilon = \frac{d_{Ge} - d_{Si}}{d_{Ge}} = 4\%$$

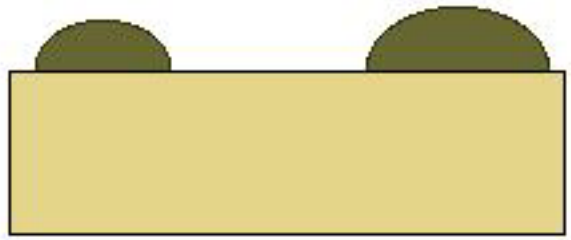
Stranski-Krastanov

- $h < h_o$: Coherent layer-by-layer growth
- $h > h_o$: nucleation of coherent islands

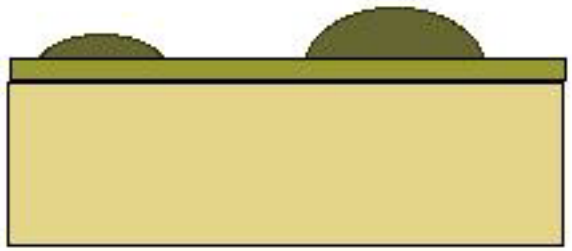
Epitaxial growth modes

- Frank-Van der Merwe

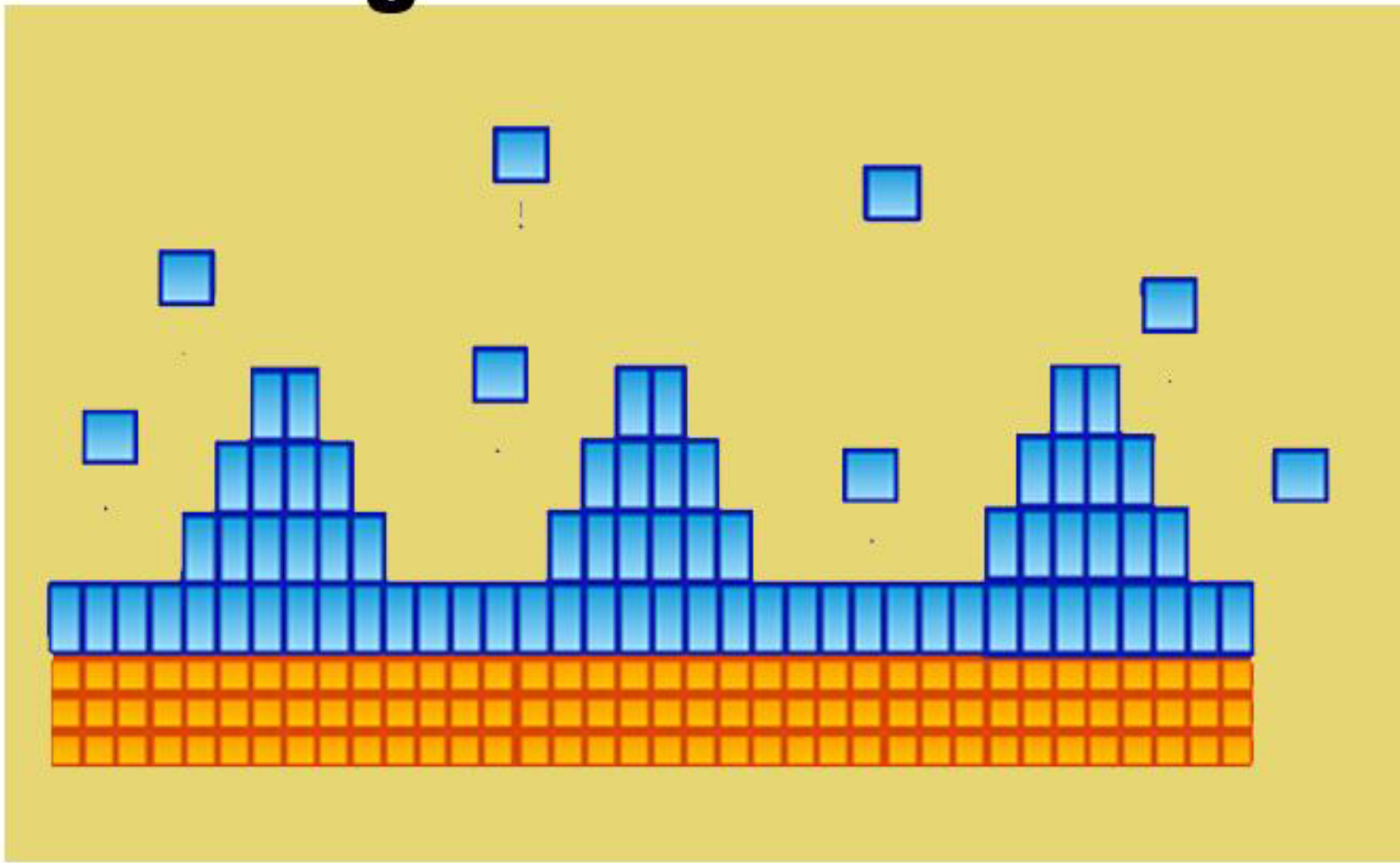
- Volmer-Weber



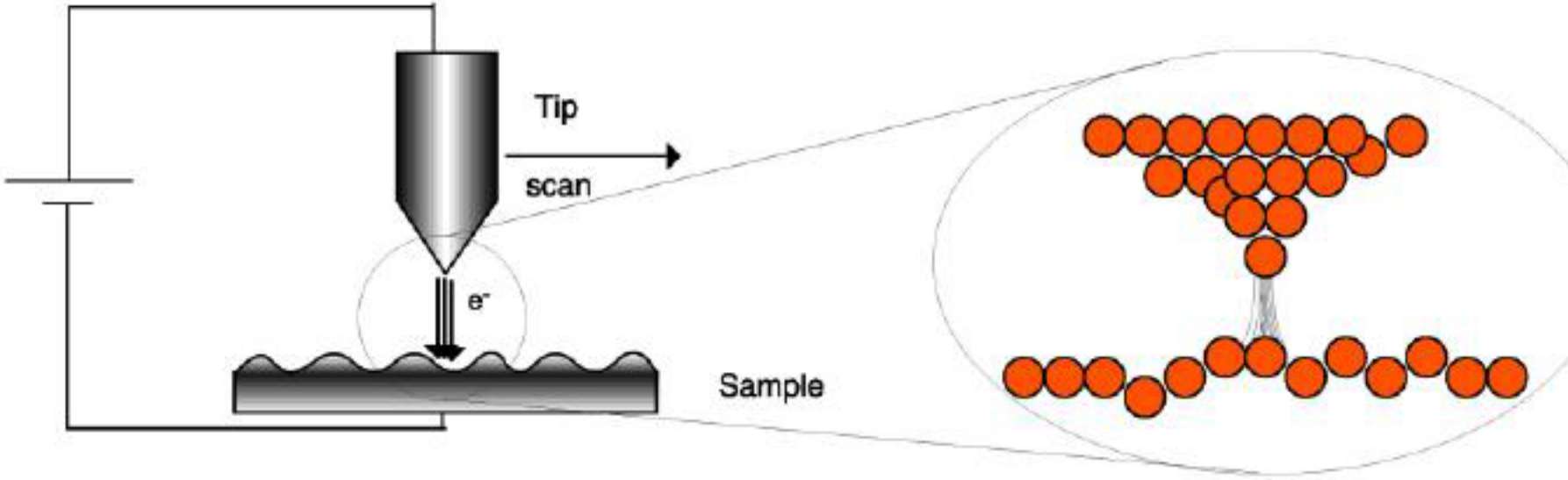
- Stranski-Krastanow



Stranski Krastanov growth mode



Experimental Technique: Scanning Tunneling Microscopy



By putting a metallic tip very close to the surface of a solid, and applying a small bias voltage (0.02-2 V) the electrons can "tunnel" through the vacuum barrier.

This quantum mechanical effect can be exploited to visualize the atoms of a surface because of the exponentialbehavior of the tunneling current as a function of the tip-sample distance.

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VT-STM Lab
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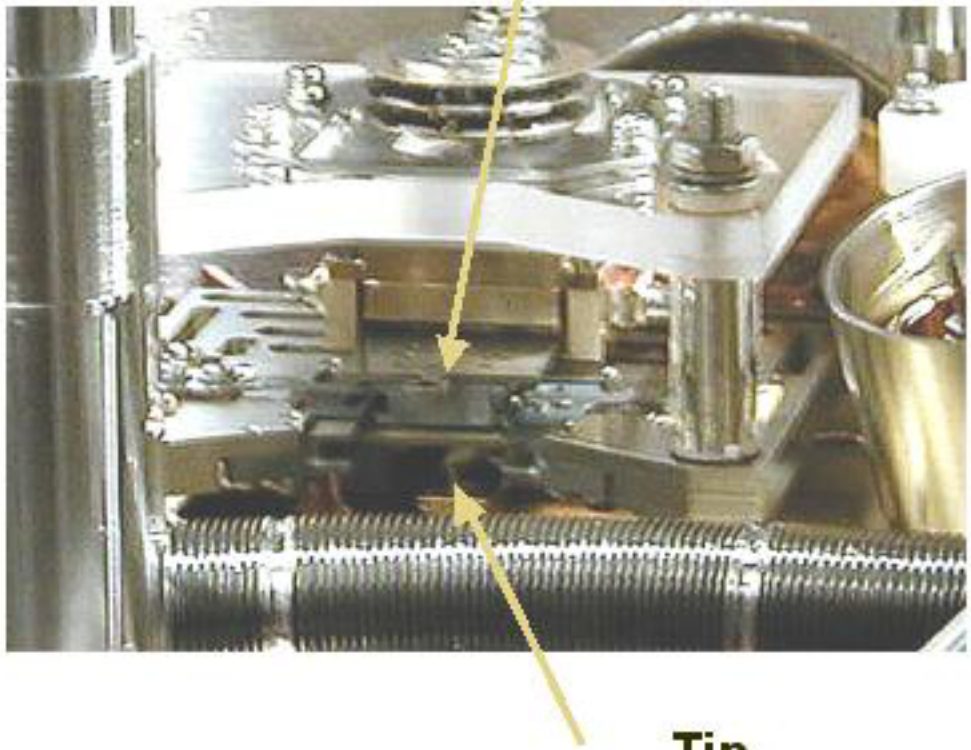
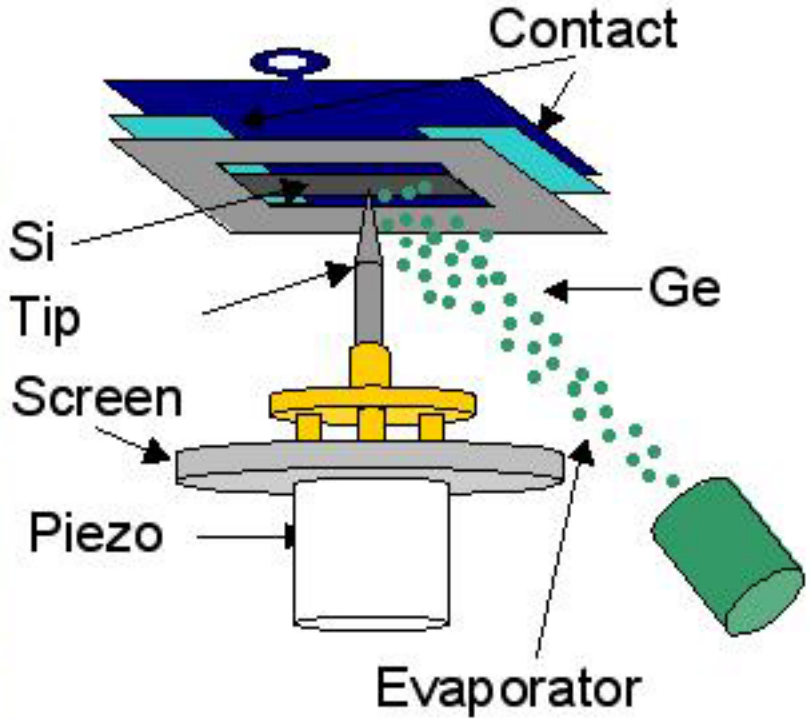
STM with direct current heating (300-1500 K)

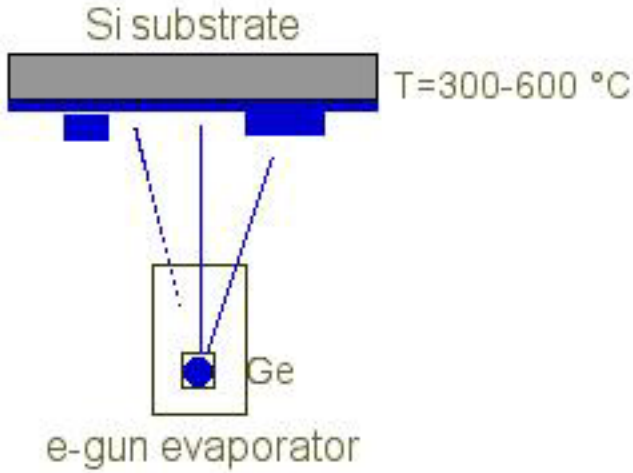


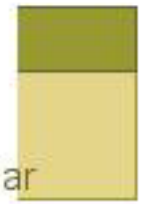


Ge/Si(111) growth

Physical Vapour Deposition

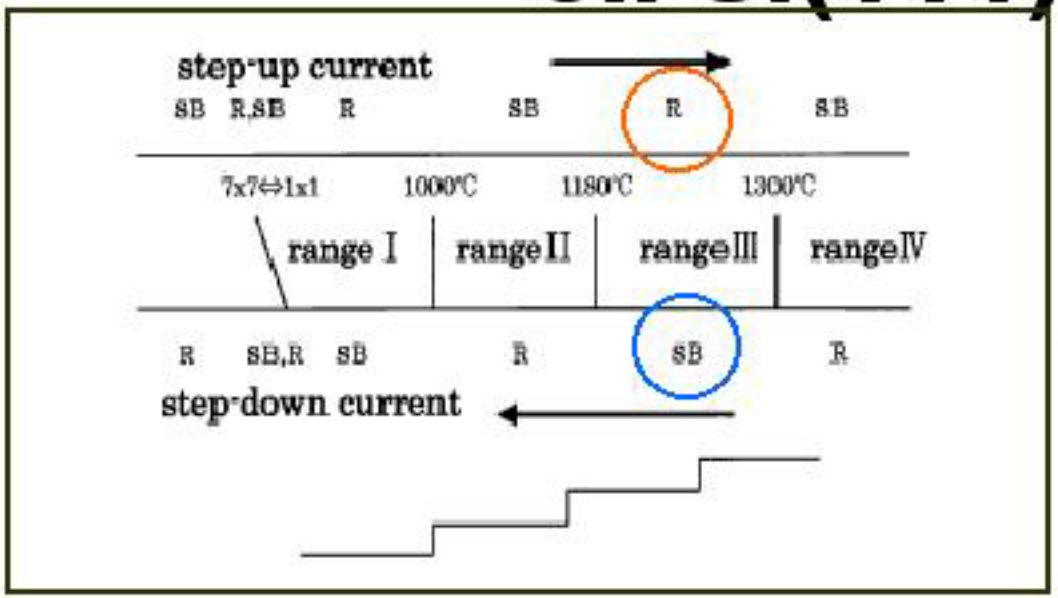
- UHV conditions ($p < 5\ 10^{-11}$ mbar)
  - Si(111) reconstruction: flash at 1250 ° C
- E-gun evaporator for Ge
  - Ge flux: 0.1 nm/min
  - Si substrate: T=450-550 ° C
- $\Theta > 3$ nation
  - (1



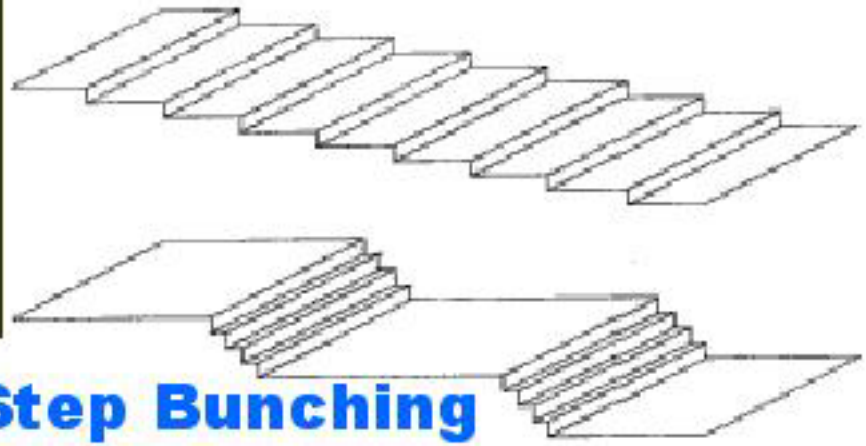


Base Pressure : 5 10^{11}mbar Growth Pressure: 2 10^{10}mbar

Effect of the DC heating on Si(111) surface



R = Regular

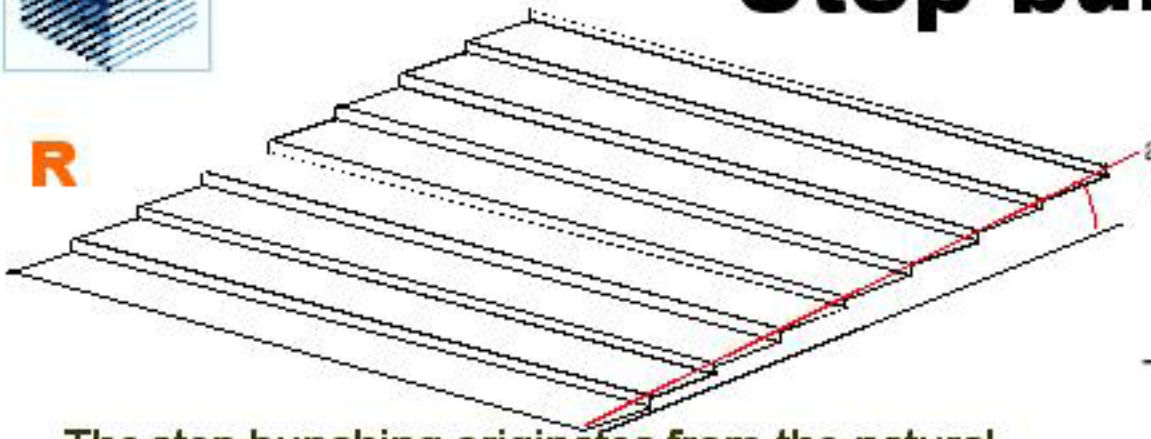


SB = Step Bunching

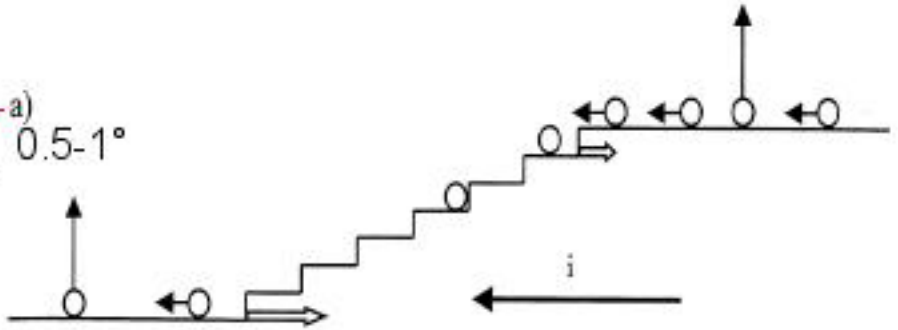
H.C. Jeong et al. Surf Sci Rep 34(1999) 171
K.Yagi et al Surf Sci Rep 43 (2001) 45

Step bunching

R

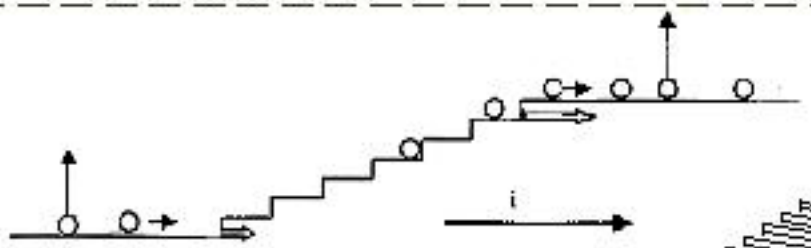


a)
0.5-1°



The step bunching originates from the natural steps which **are on a surface due** to miscut

Current: step down



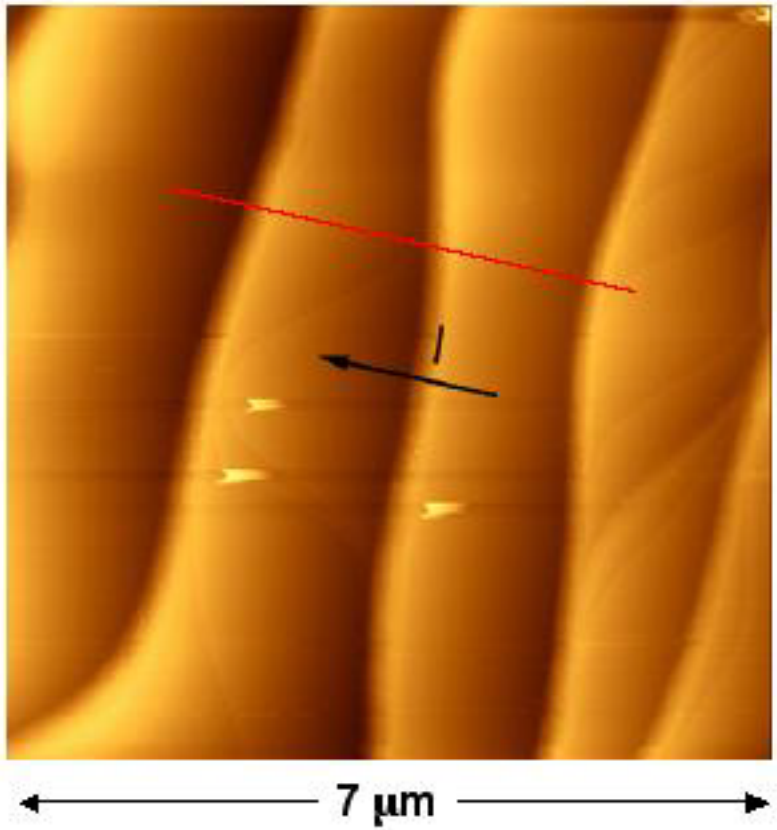
Current: step up

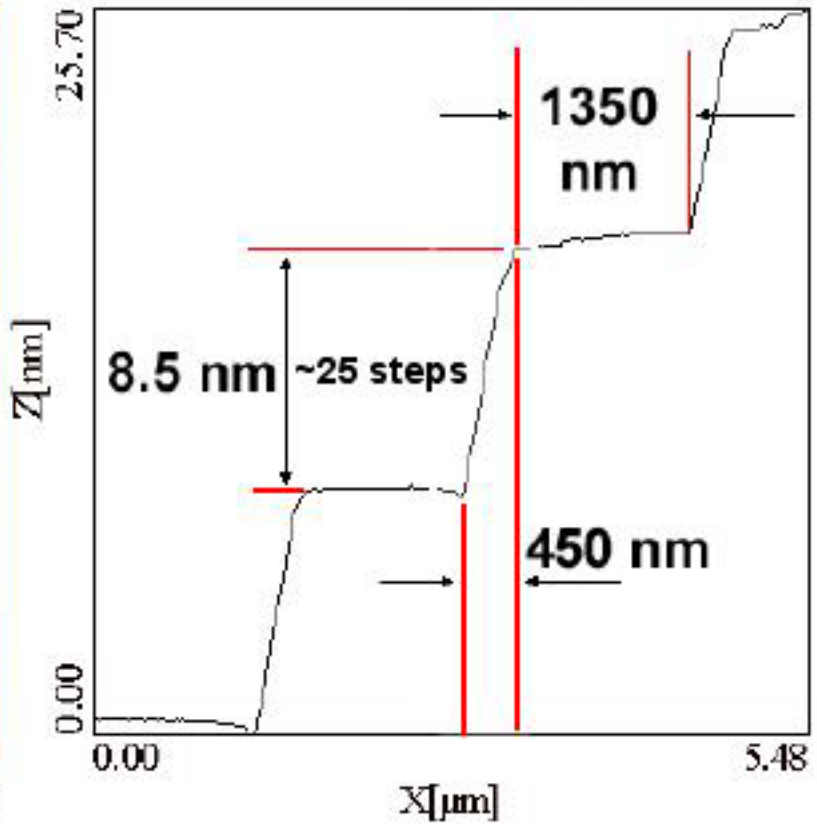
SB

On Si(111) surfaces, during growth or sublimation, the direct current heating can favour the enlargement of some terraces at the expenses of the others

Step bunching: large steps

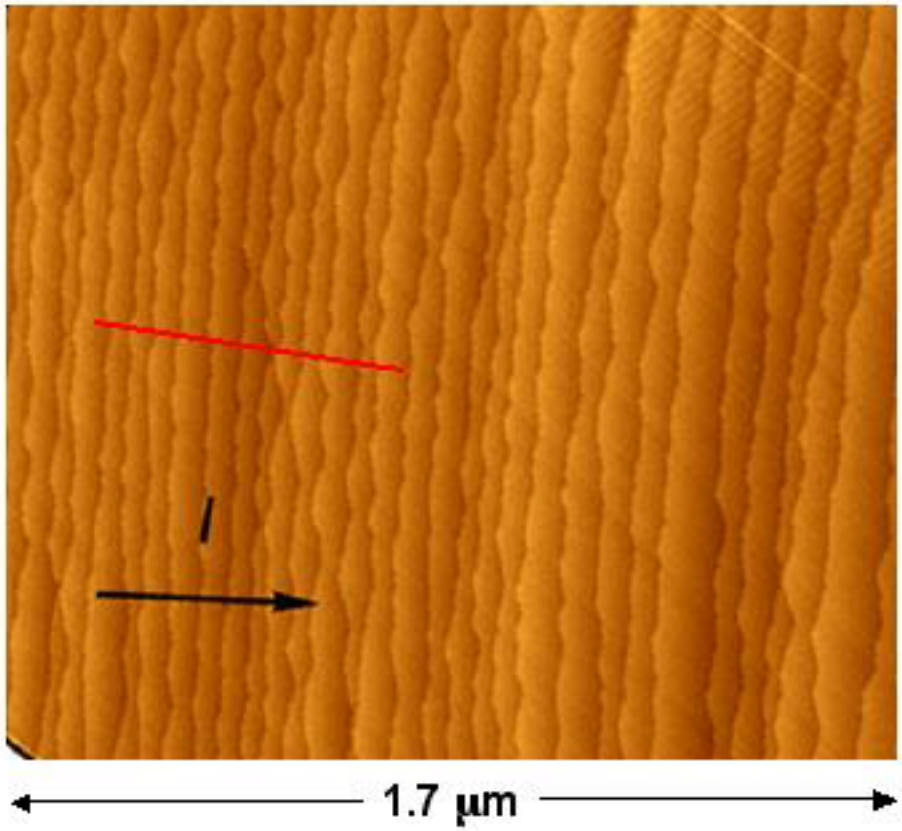
Flash T=1250 °C – Current direction: step down

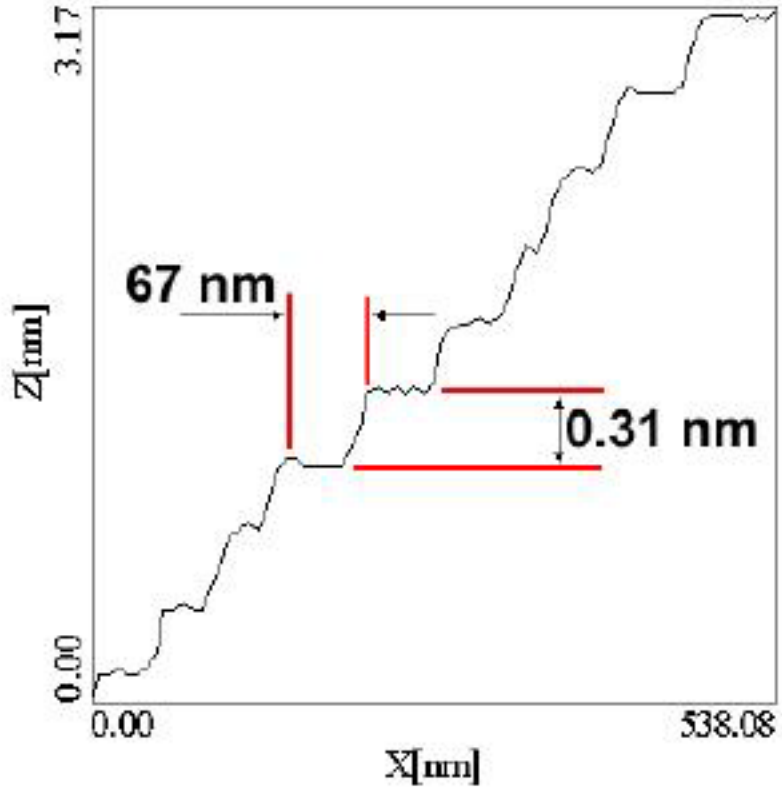




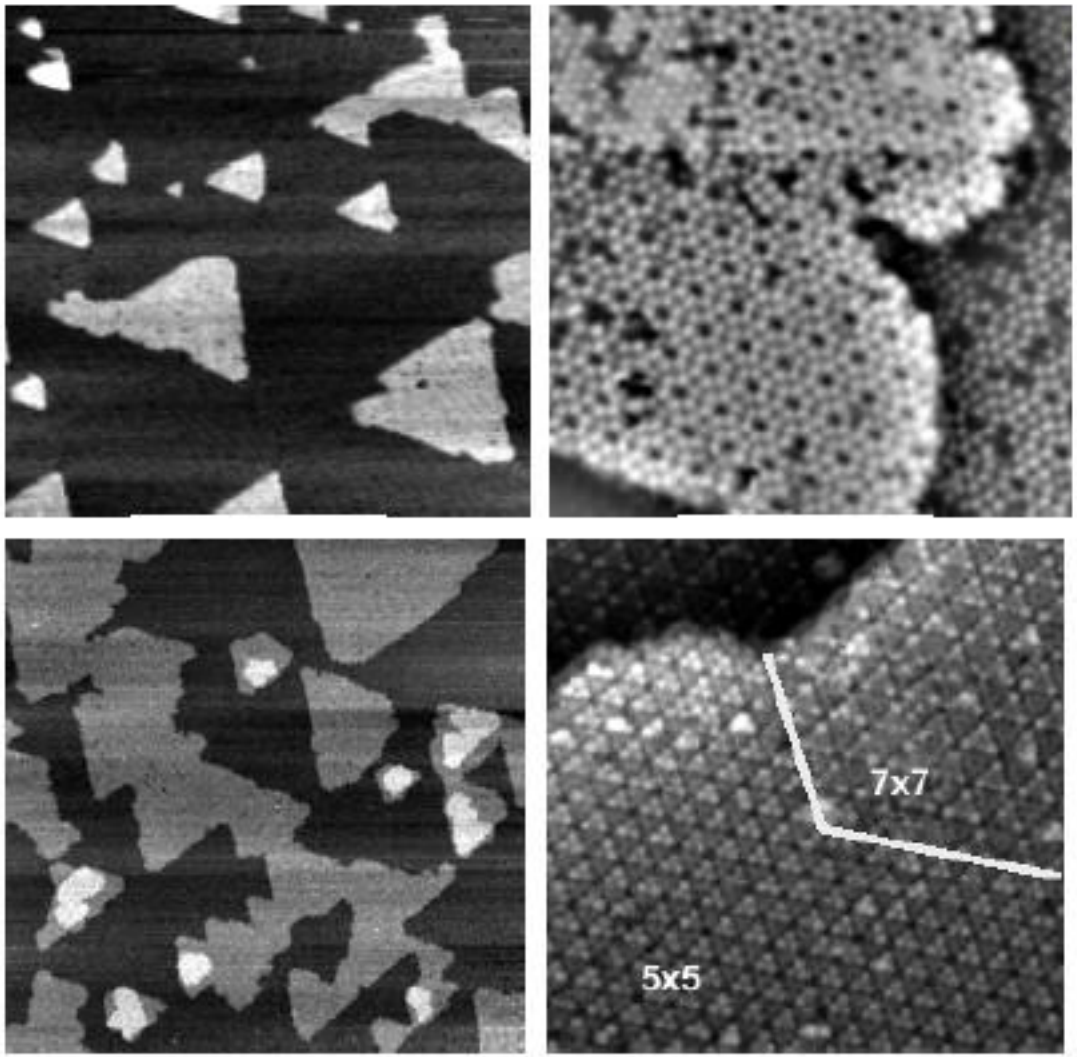
Step debunching: small steps

Flash T=1250 °C – Current direction: step up





Growth of the wetting layer



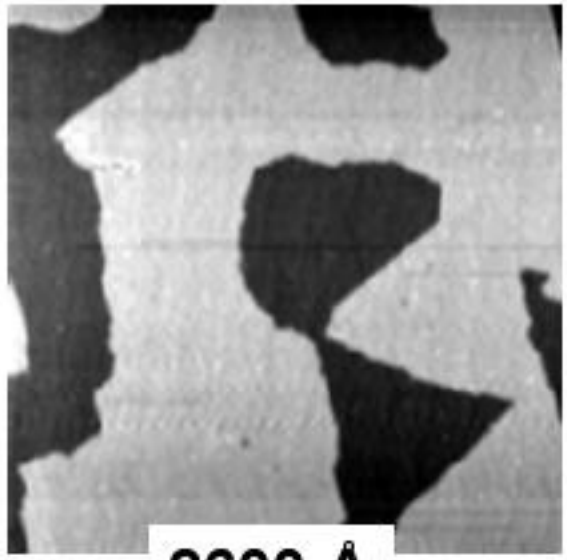
Ge/Si(111) T= 500 °C

0.65 ML

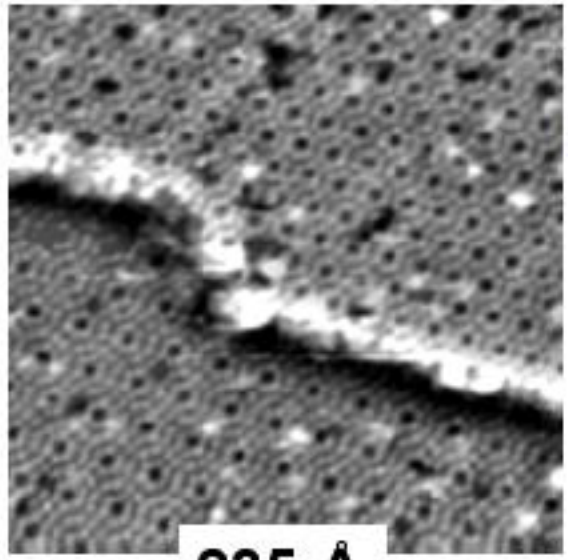
1.35 ML

N.Motta et al.
Surf.Sci 406, 254 (1998)

Growth of the wetting layer



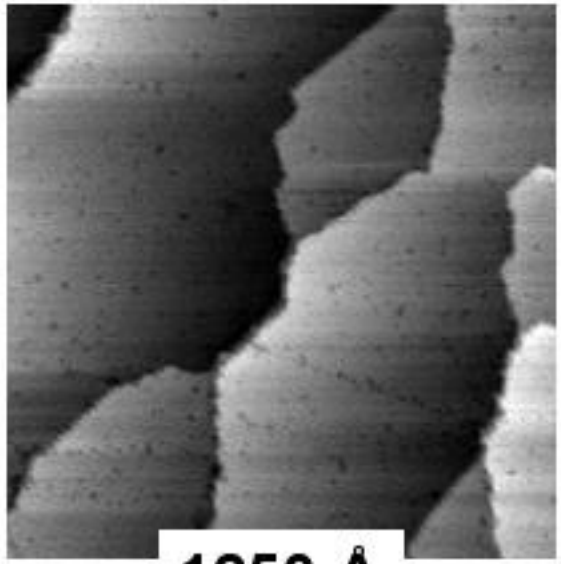
2600 Å



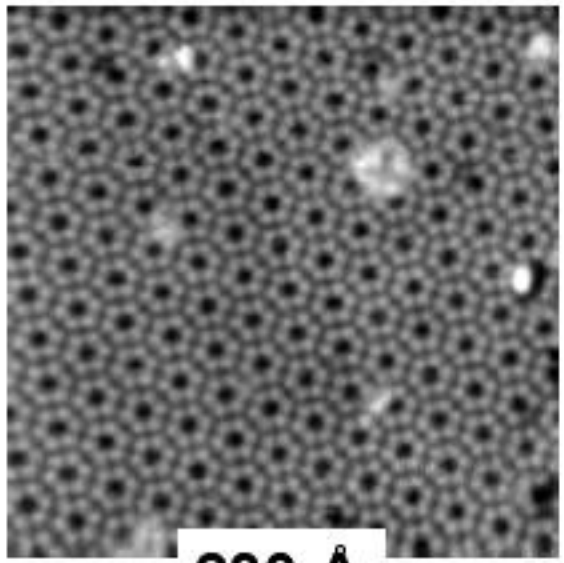
235 Å

Ge/Si(111) T= 500 °C

2.0 ML



1250 Å

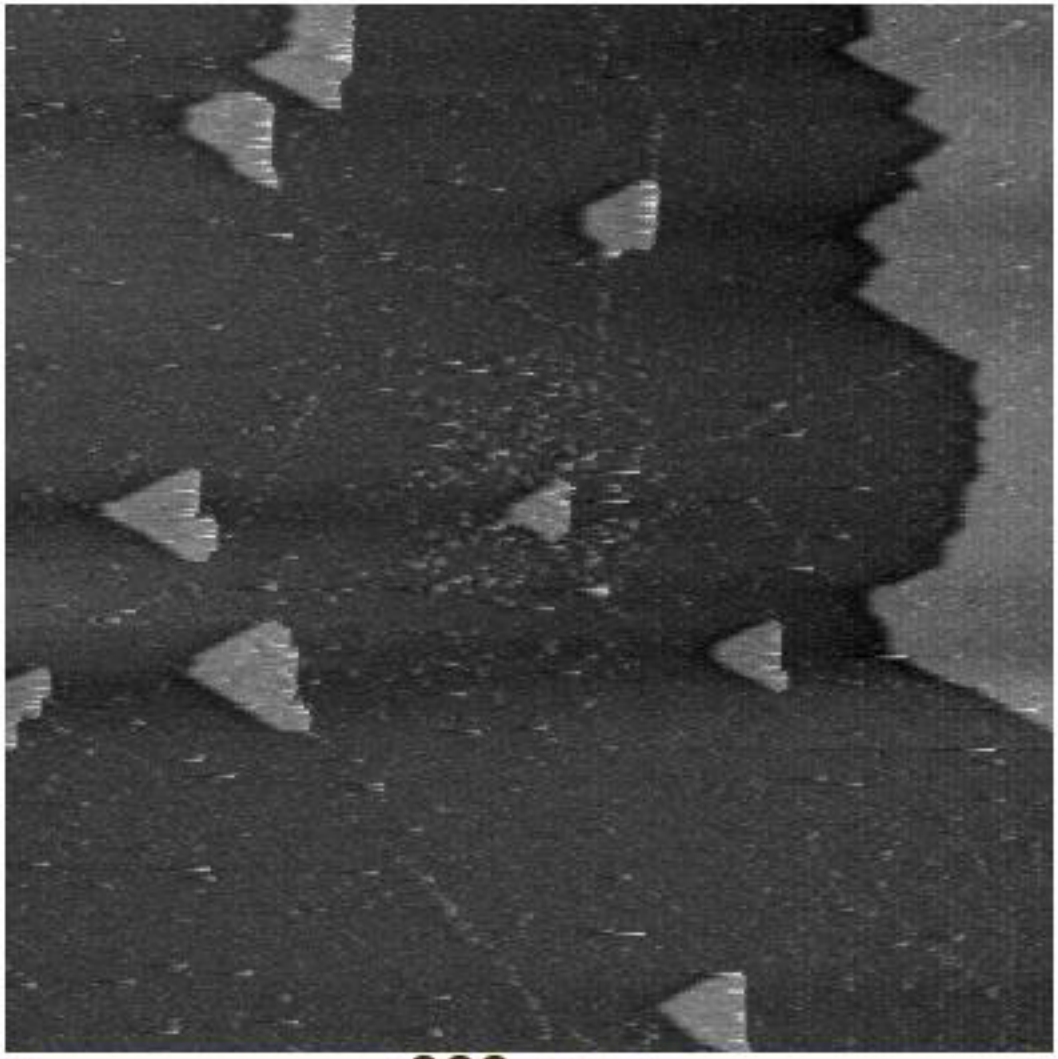


230 Å

3.0 ML

N.Motta et al.
Surf.Sci 406, 254 (1998)

Growth of the wetting layer



Ge/Si(111)

Flat substrate

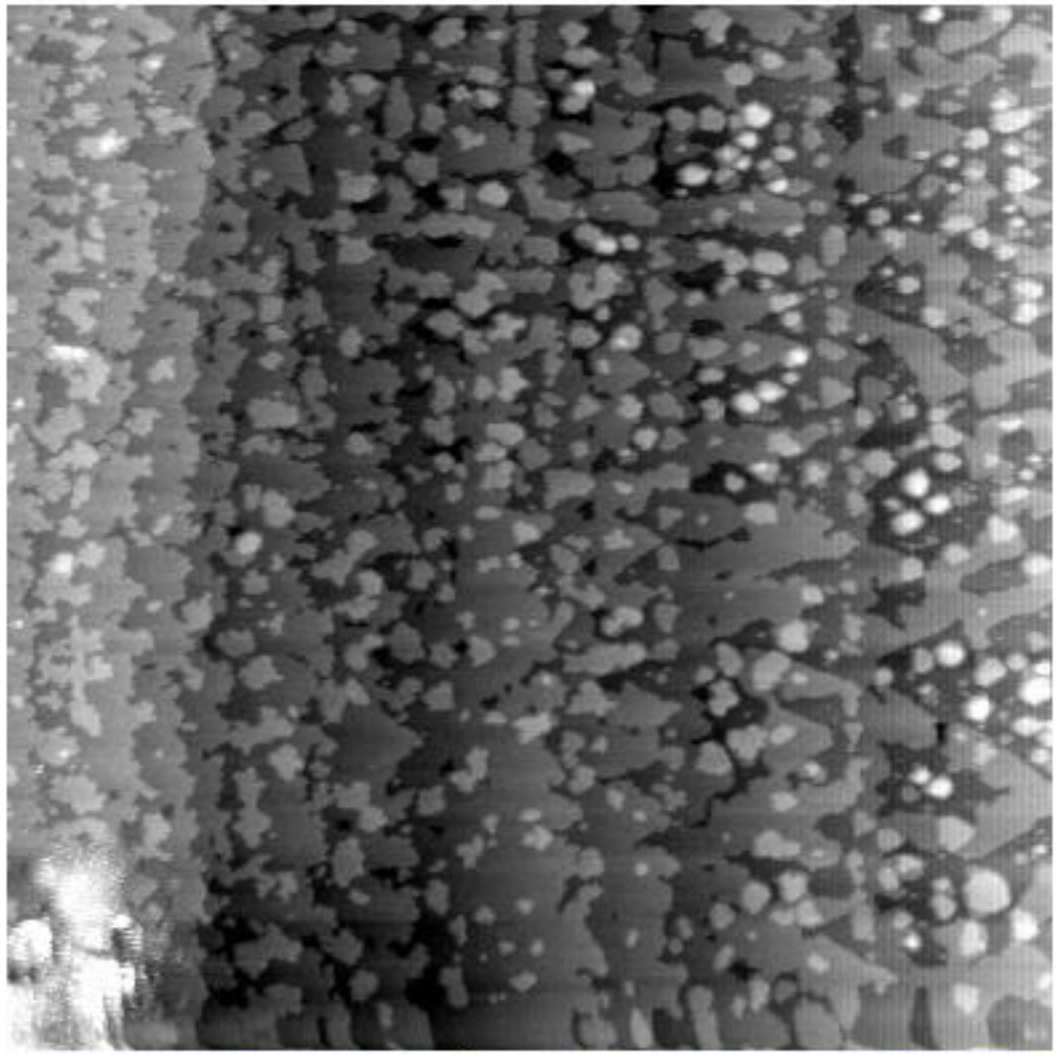
T=400°C

Ge flux = 0.02 ML/min
Final coverage: 2 ML

Total time: 2h
~1 image/min

A.Sgarlata et al: to be published

Growth of the wetting layer



Ge/Si(111)

Stepped substrate

T=400°C

Ge flux = 0.15 ML/min
Final coverage: 20 ML

Total time: 1h 30min
~1 image/min

A.Sgarlata et al: to be published

Ge/Si(111) 3D growth

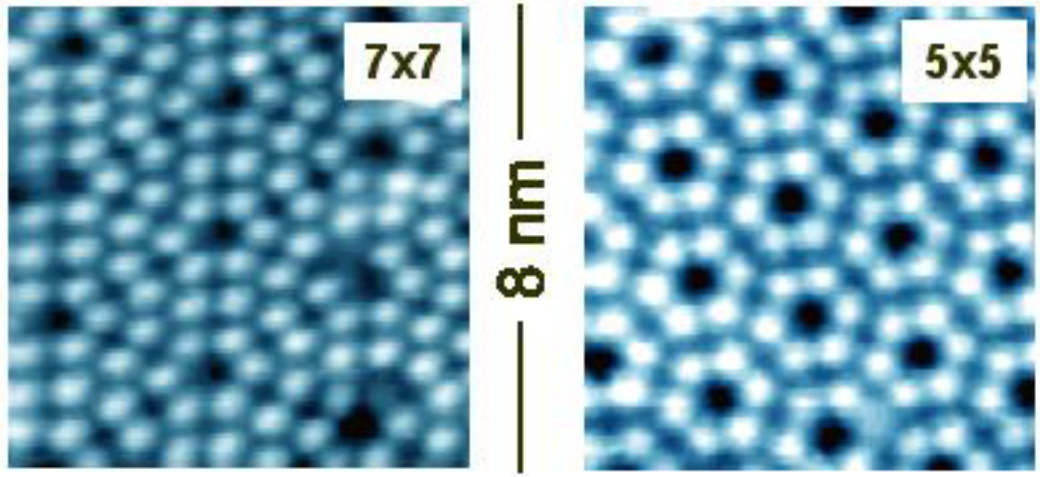
2000 nm

9 ML Ge deposition
0.1 nm/min T=500°C
+ 10' annealing T=500°C

Islands:

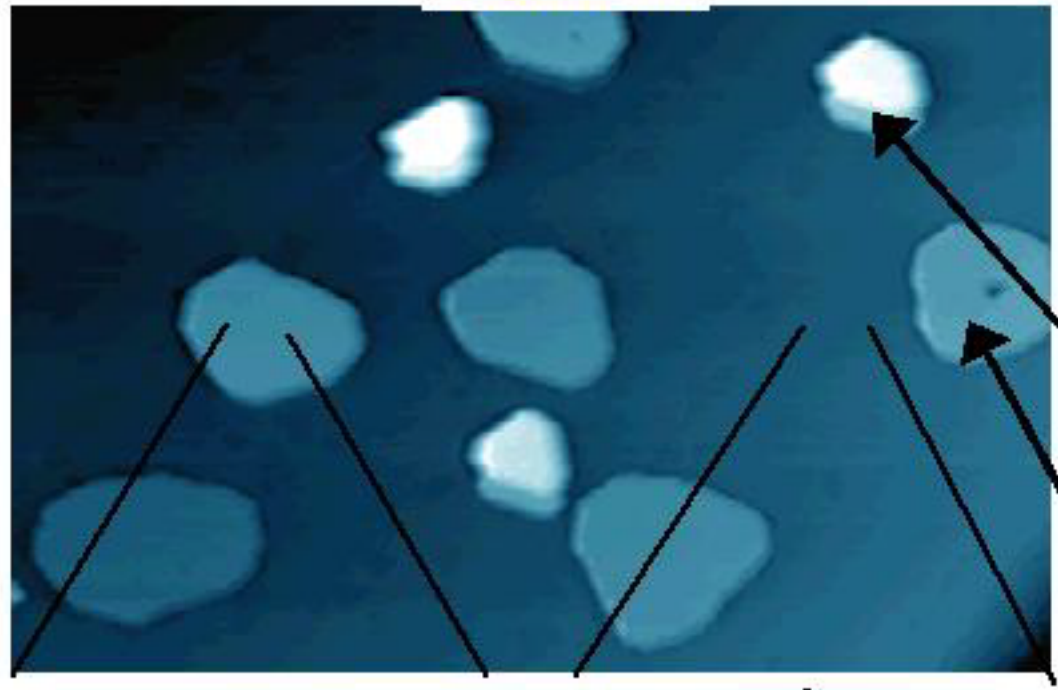
tall – triangular (strained)
(180 nm wide x 40 nm high)

low – rounded (ripened)
(350 nm wide x 2 nm high)



N.Motta et al.
Surf.Sci 406, 254 (1998)

Ge/Si(111) 3D growth



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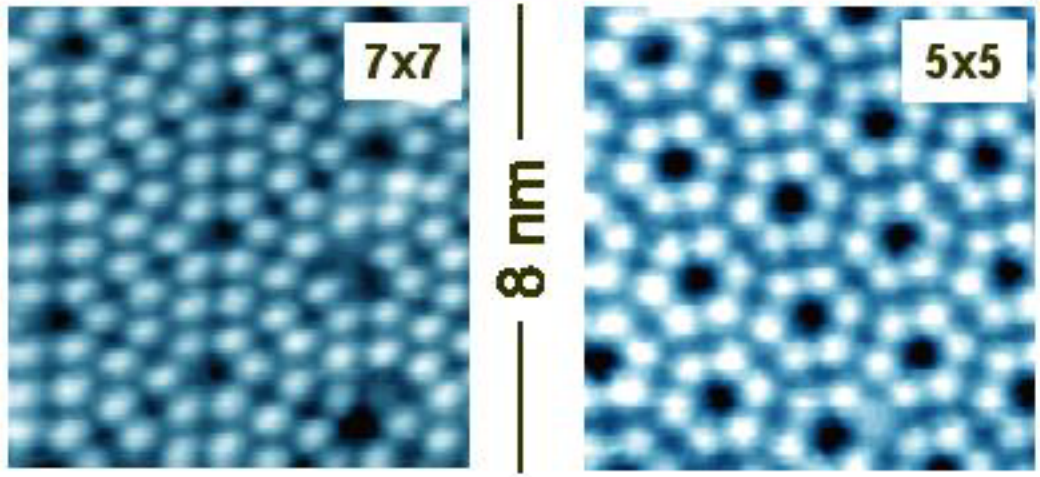
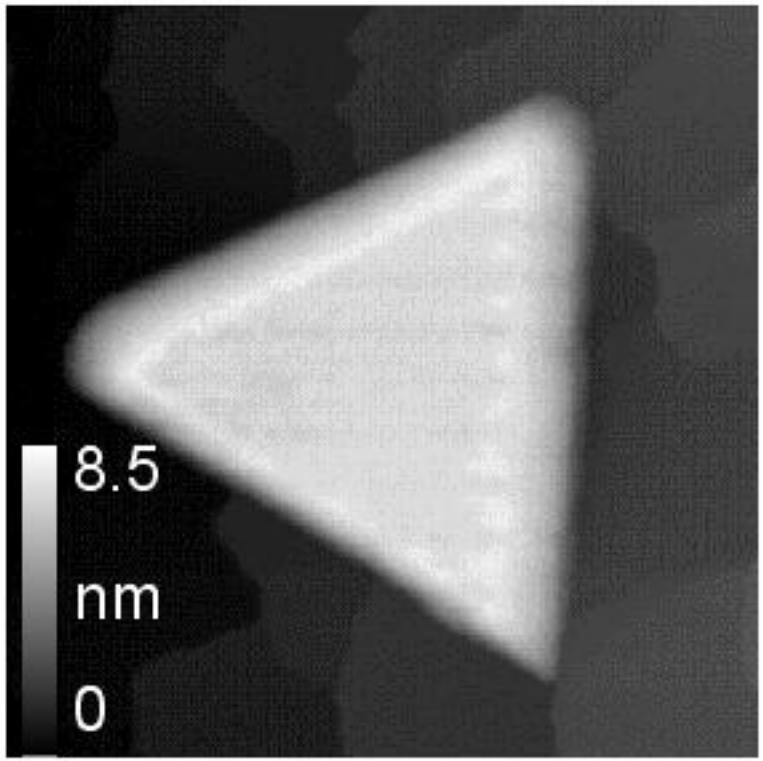
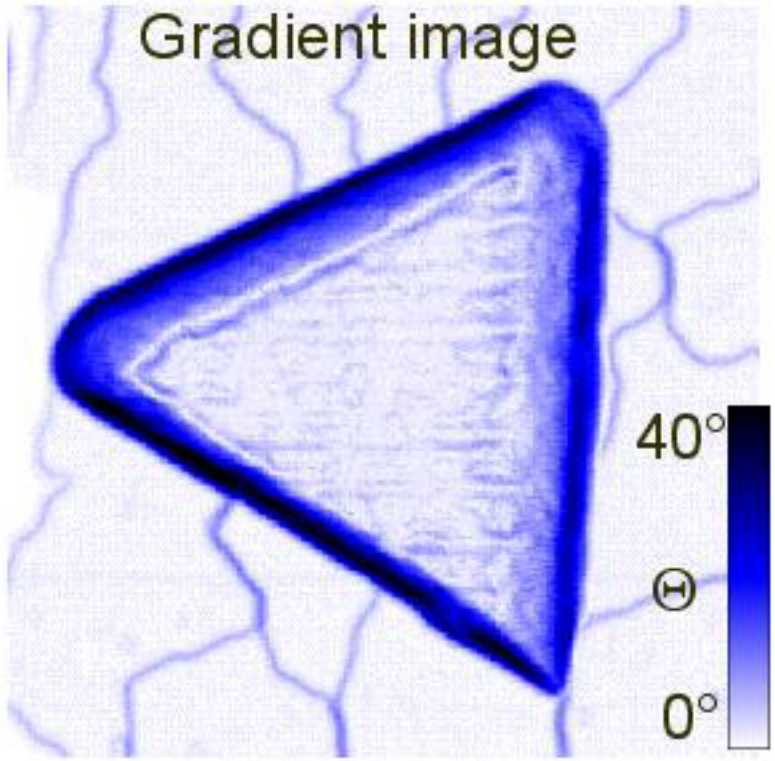


N.Motta et al.
Surf.Sci 406, 254 (1998)

Ge/Si(111) island evolution
I stage: tetrahedra like islands

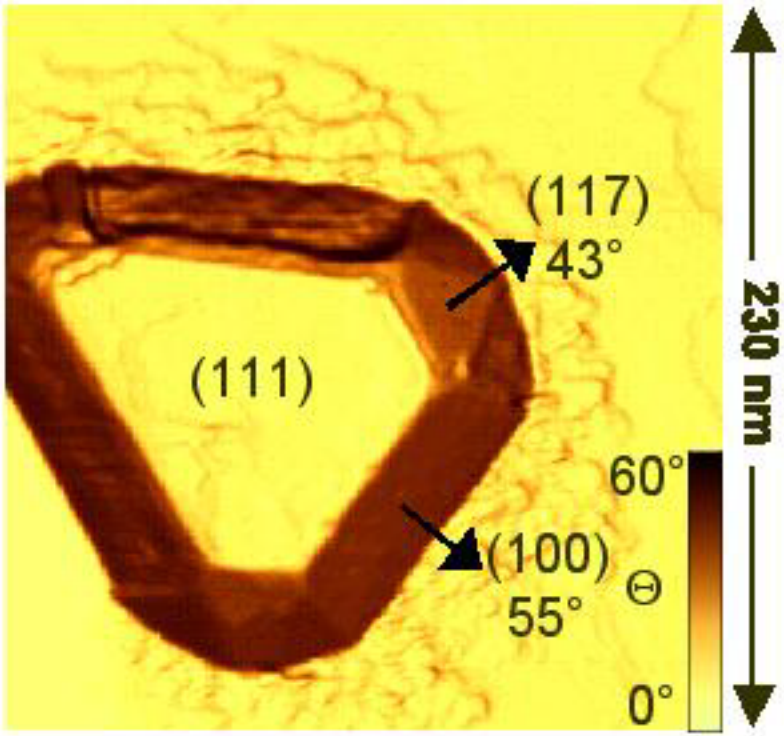
20 Å Ge/Si(111) T=530°C





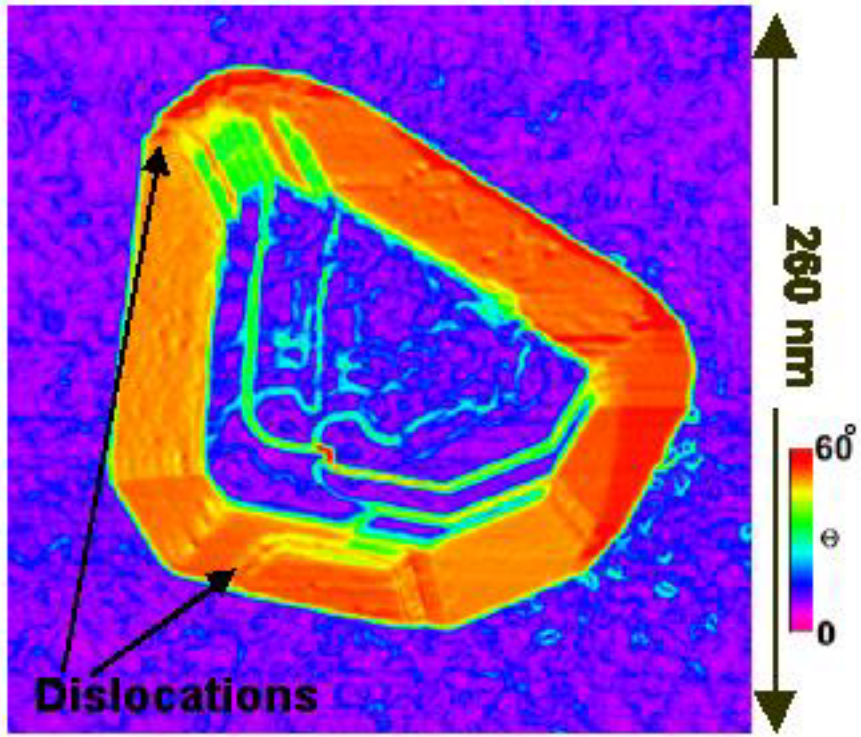
Ge/Si(111): islands evolution
II stage: dislocated islands

25 Å T=450°C



- Island height: 40 nm
- Insertion of new faces: [100] [117]

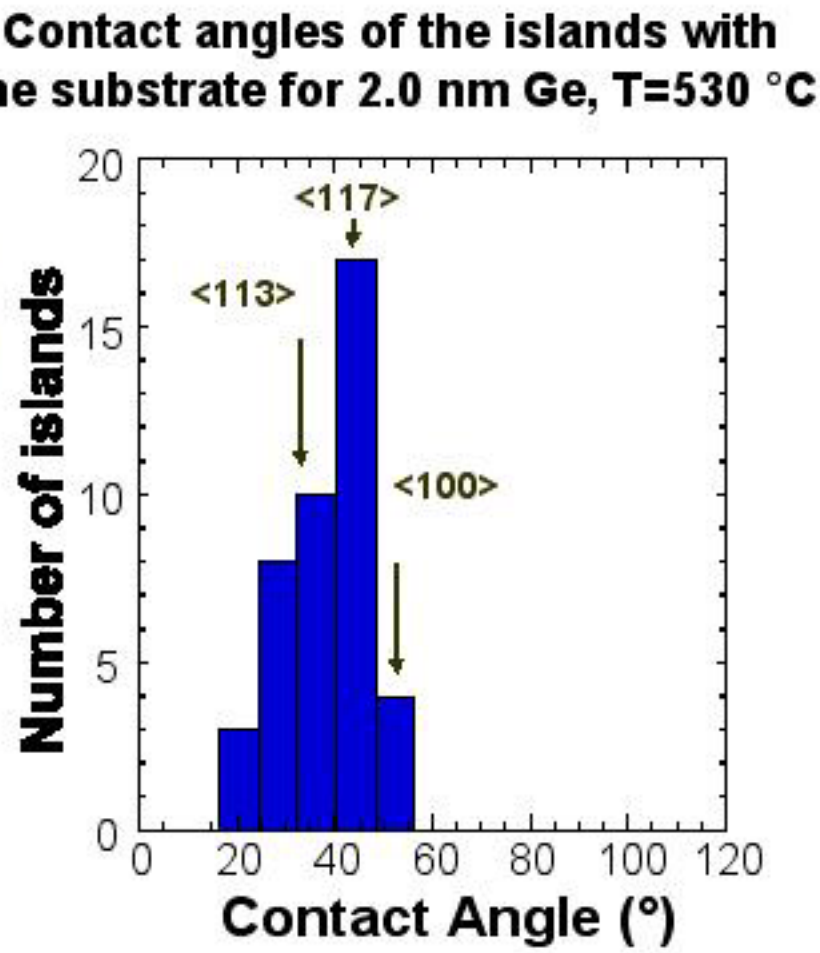
45 Å T=450°C



- Island height: 63 nm
- Insertion of dislocations

Distribution of the contact angles of the islands with the substrate.

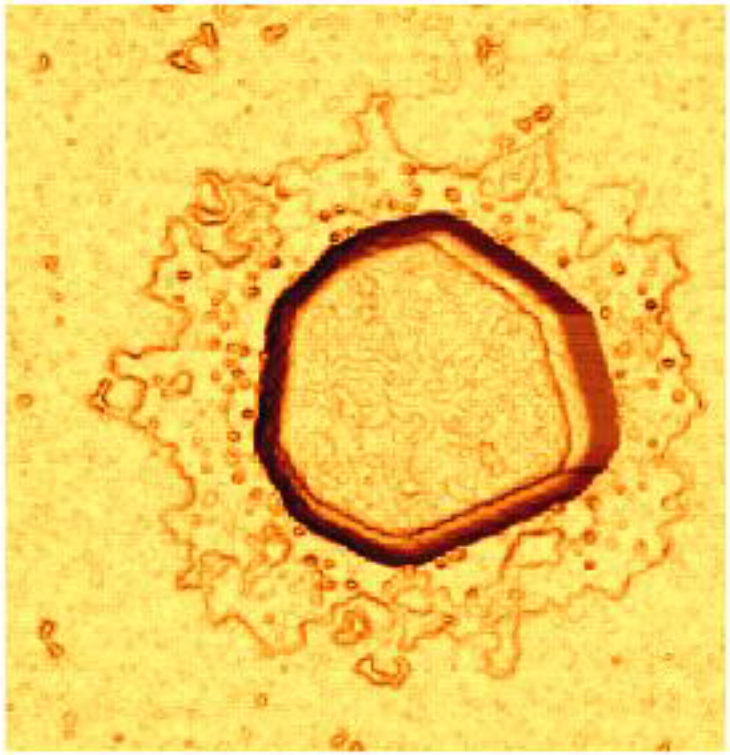
- The histogram shows the insertion of new crystallographic facets.



Ge/Si(111): islands evolution

"ripening"

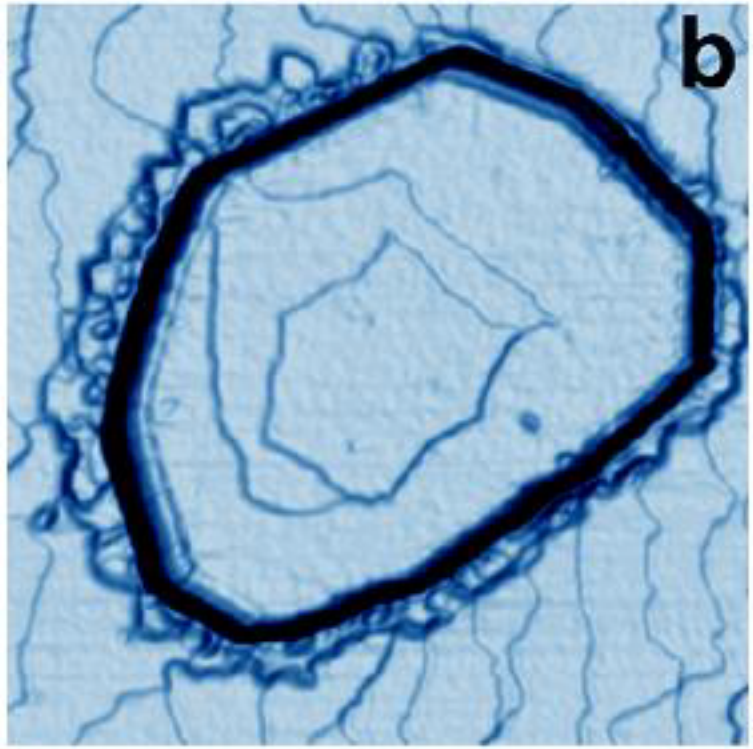
3.5 nm T=500°C



500 nm

- Island height: 10 nm
- Substrate erosion: 1 nm

2.0 nm T=500°C



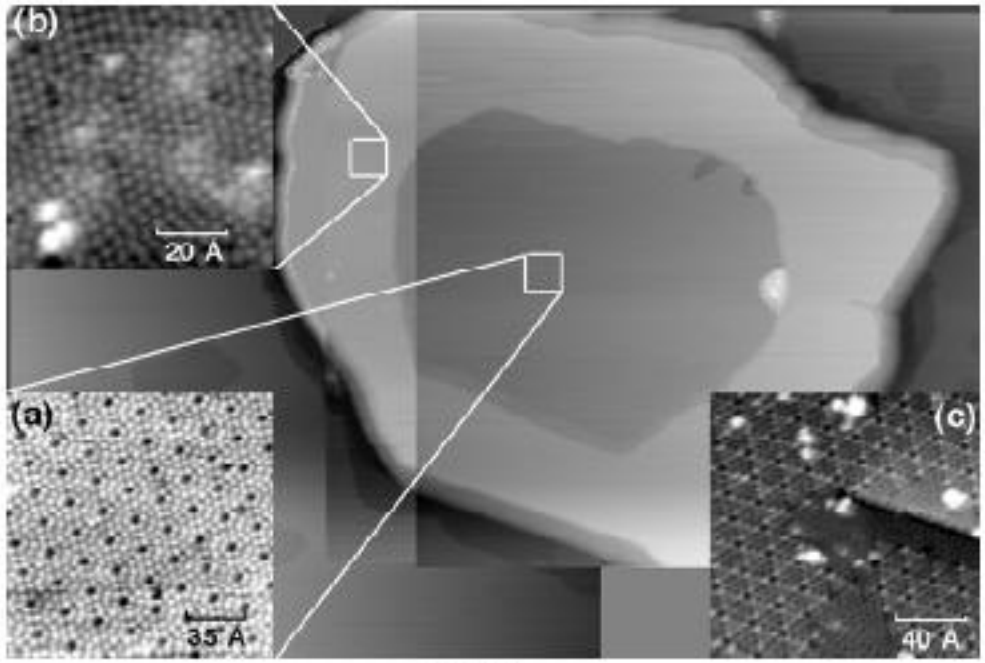
527 nm

- Island height: 5 nm
- "Atoll" formation

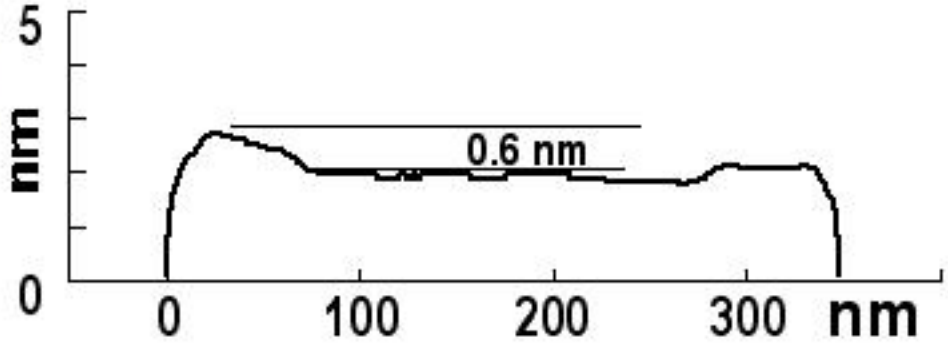
N.Motta et al. S. S. Comm. (1999). F.Boscherini et al. APL (2000)

Ge/Si(111) island evolution

- After the nucleation:
  - the islands grow vertically up to a critical value
  - the strain energy introduces dislocations
  - morphological transition
  - lateral growth
  - material flow from the top - central hole formation



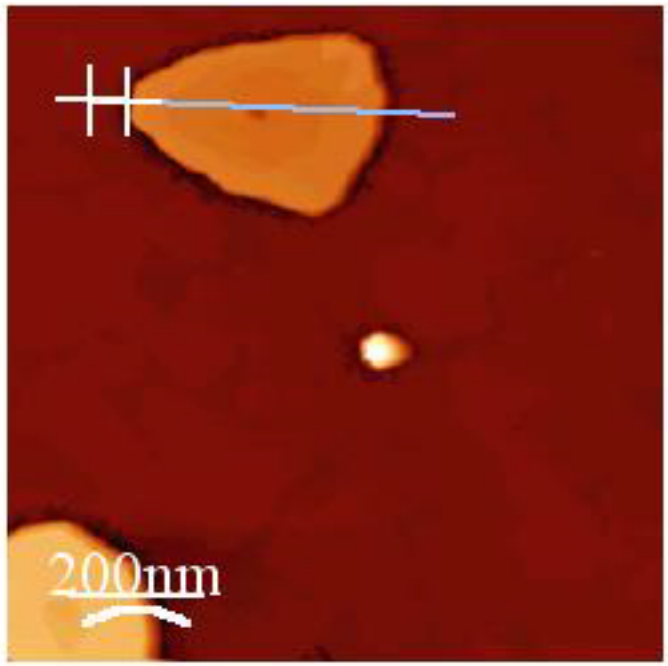
800 nm

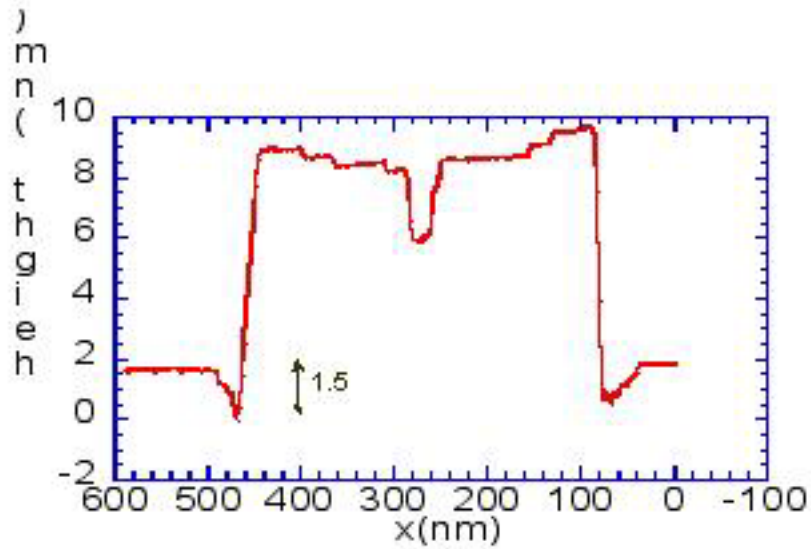


Ge/Si(111): islands evolution

analysis of the trench

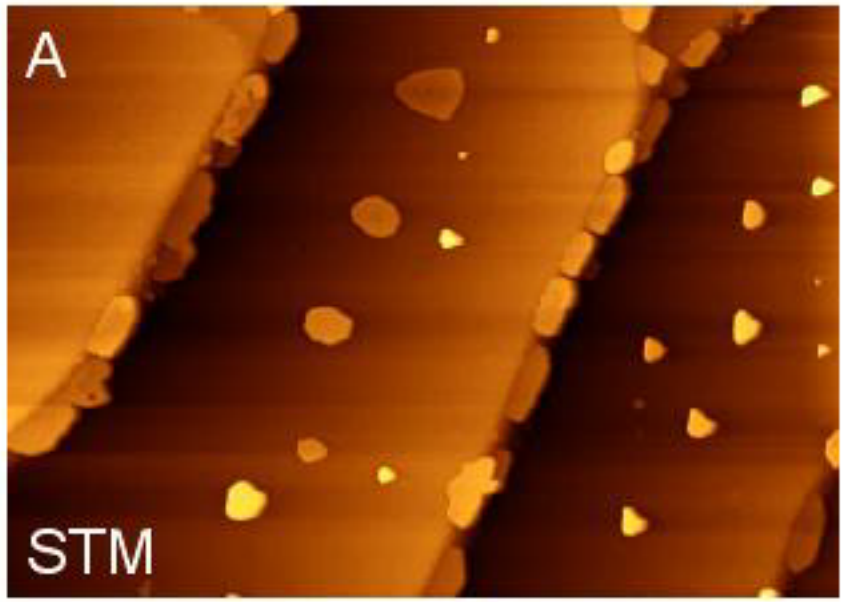
2.5 nm Ge T=450°C





Ge/Si(111) island distribution

25 Å Ge/Si(111) T=450°C

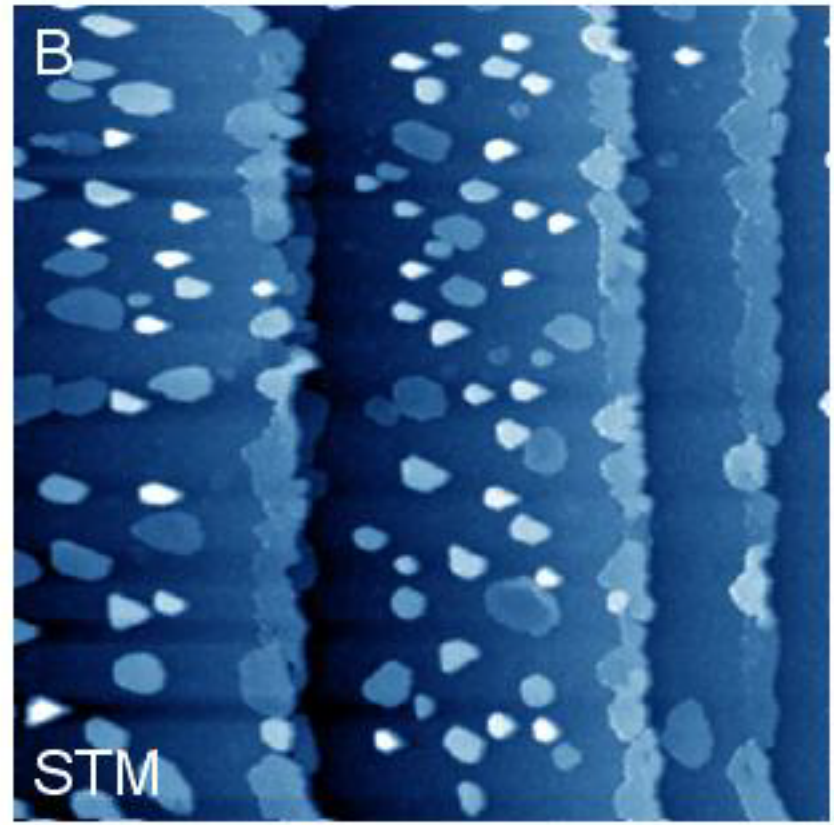


3.7 μm

A) First - second generation of islands: spacing controlled by diffusion coefficient

B) Third - fourth generation of islands.

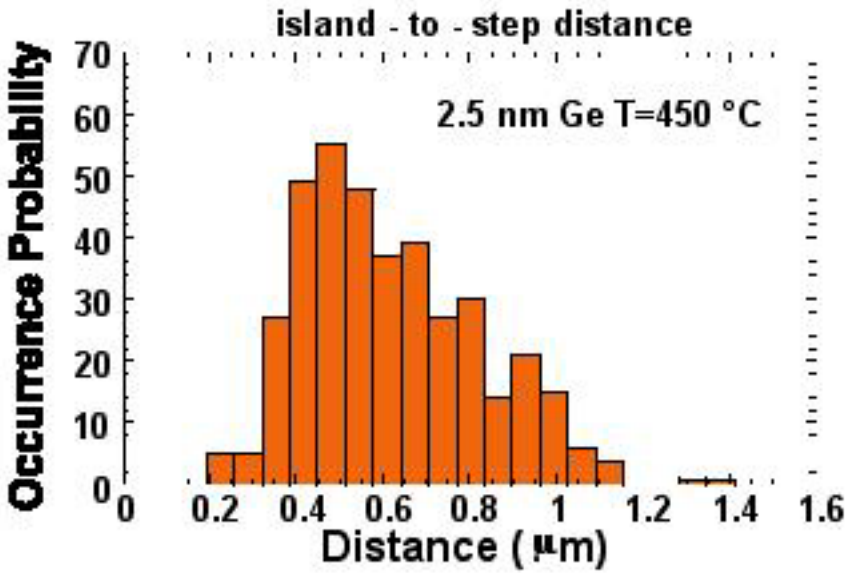
60 Å Ge/Si(111) T=450°C

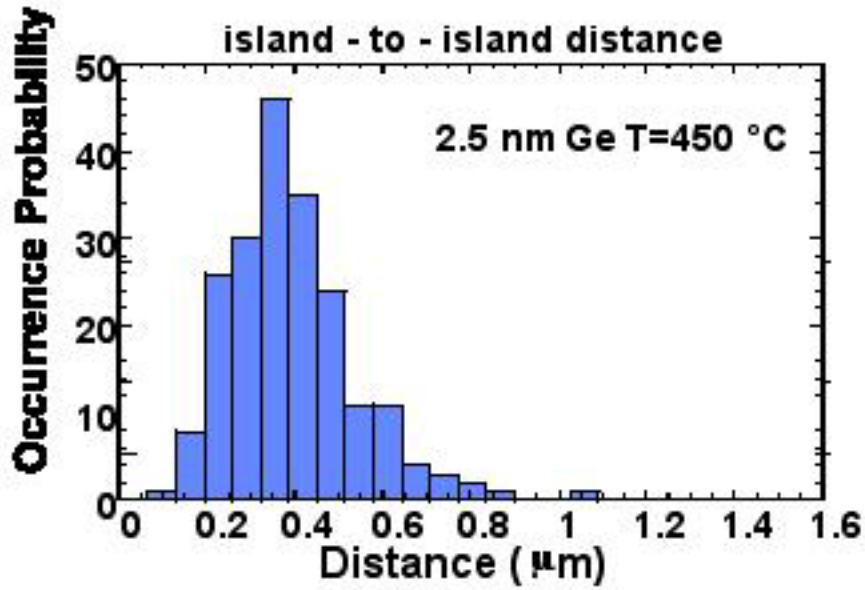


10 μm

Distribution of island distances on terraces

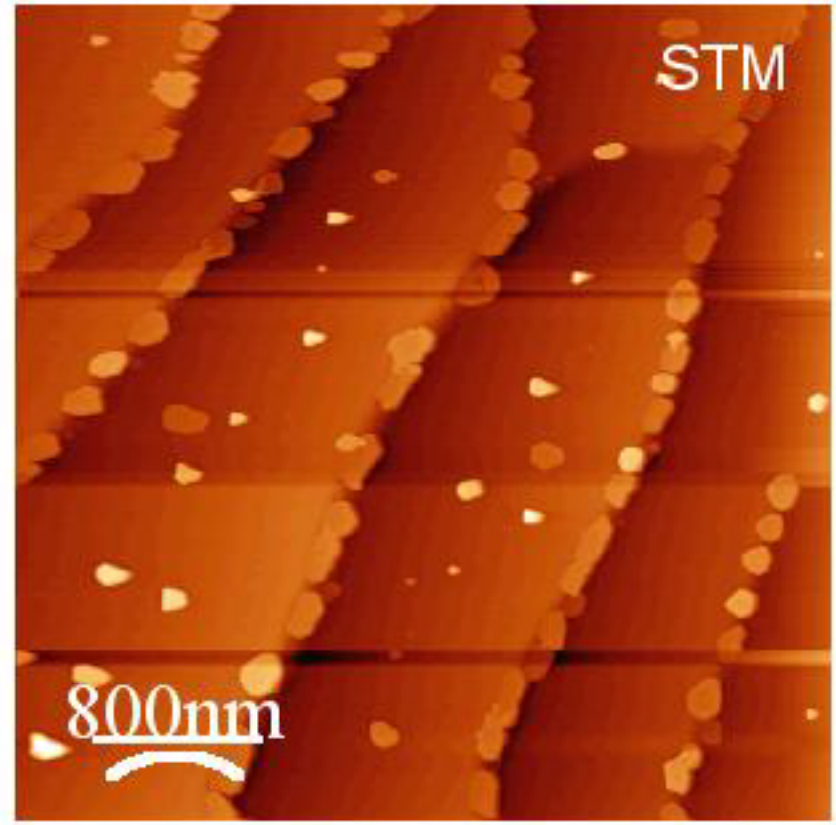
- 25 Å Ge - T = 450 °C
- Terrace width: 1.0 ÷ 1.2 μm
- Island-to-step distance :
  - D_{i-s} = 0.62 μm
    - σ = 0.21 μm
- Island-to-island distance:
  - D_{i-i} 0.39μm
    - σ = 0.14 μm



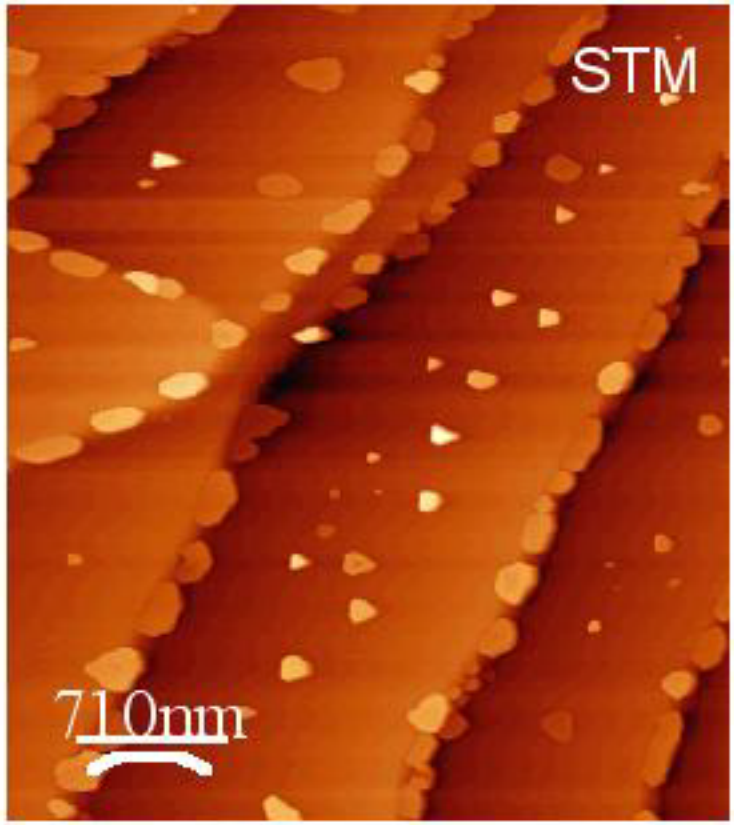


Ge/Si(111) island distribution

25 Å Ge/Si(111) T=450°C



4 μm



3 μm

Ge/Si(111) island distribution

25 Å Ge/Si(111) T=450°C

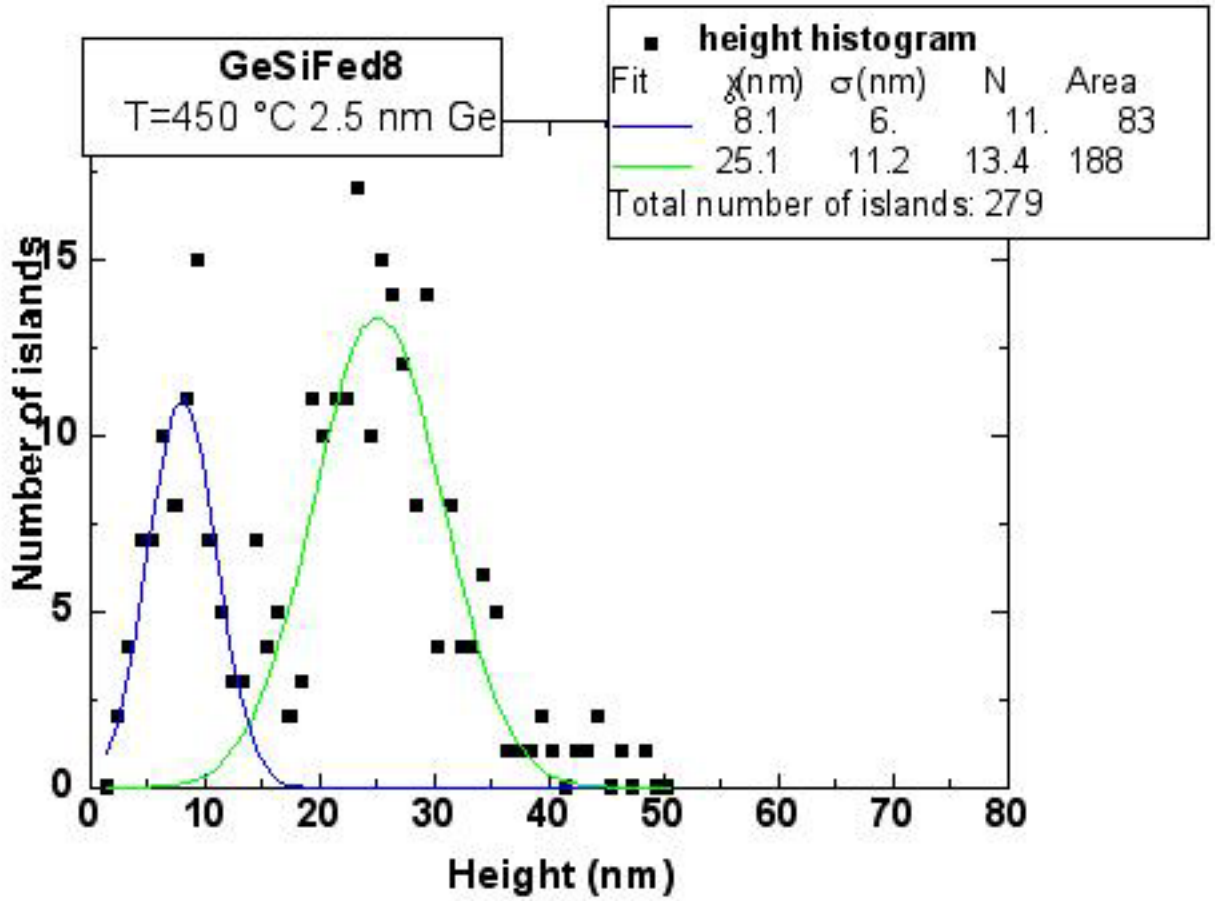
Two main peaks

Dislocated

Relaxed

Small peak

coherents

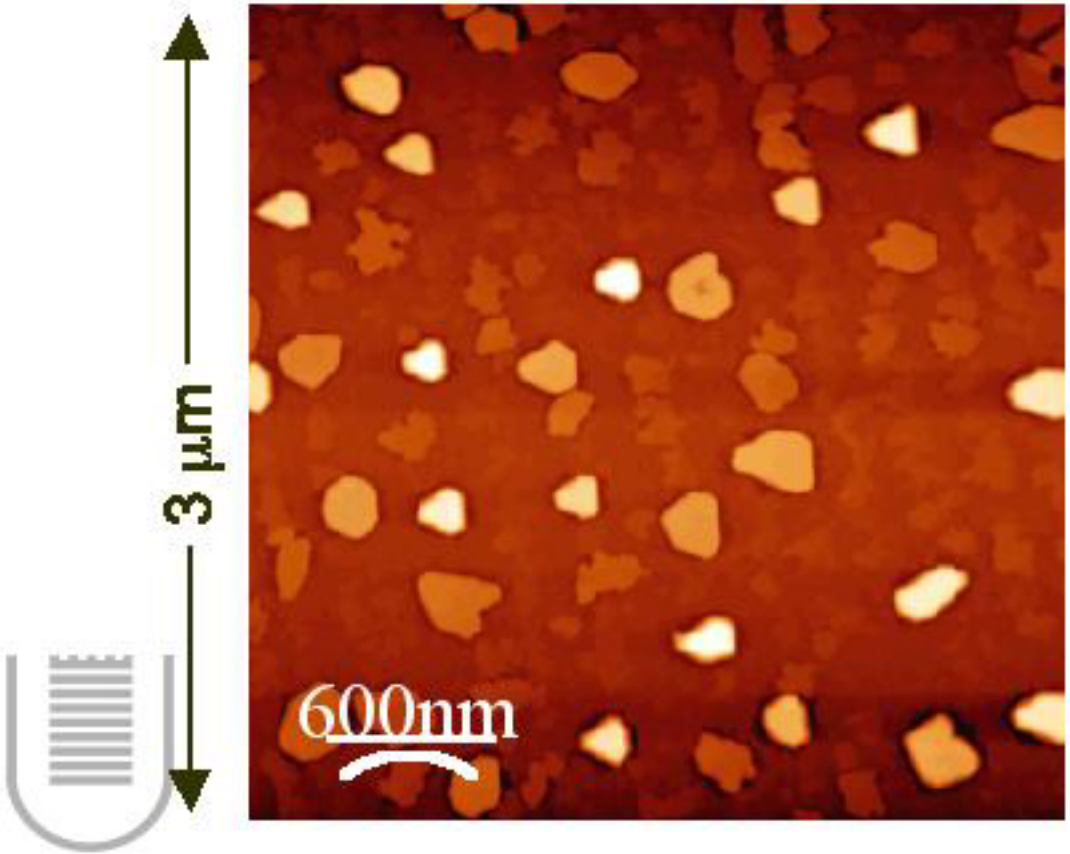


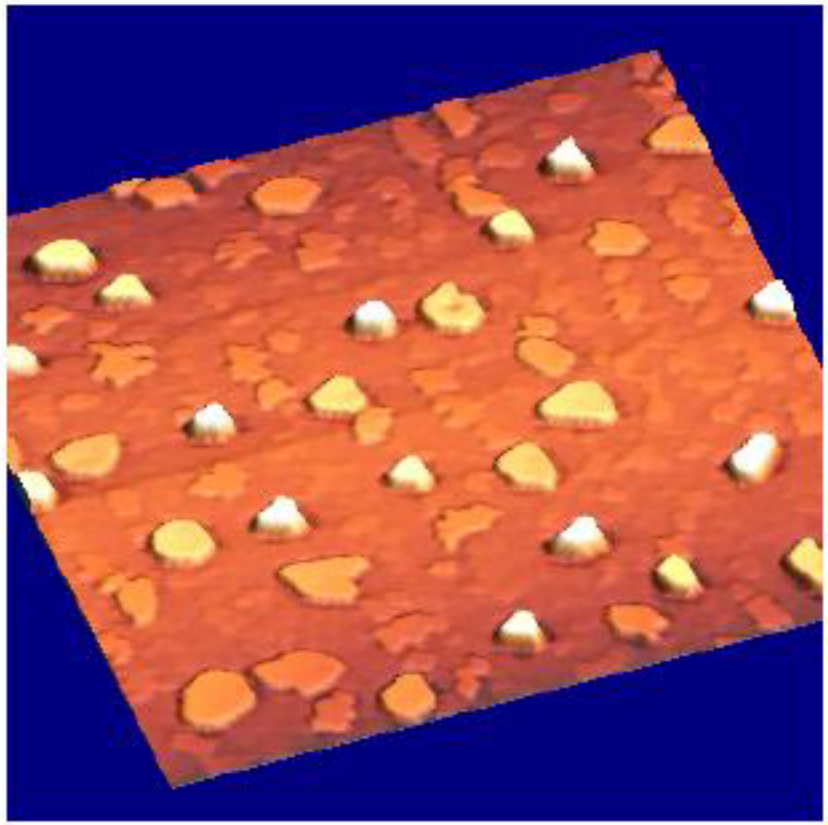
Ge/Si(111) island distribution

70 Å Ge/Si(111) T=500°C

- **Distribution of the islands on a substrate with small steps**

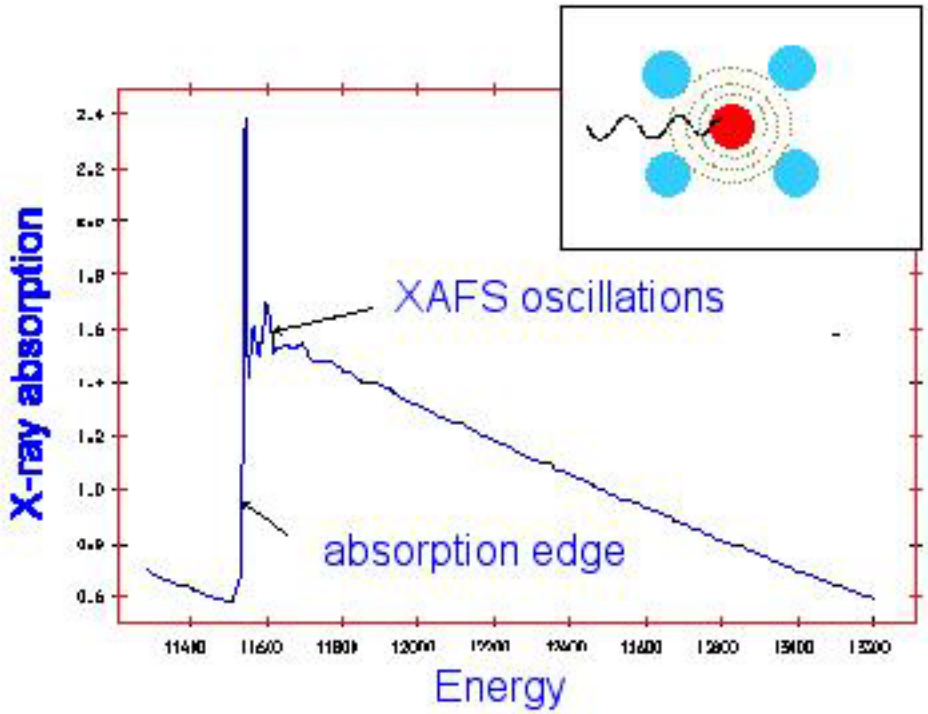
Δz: 29 nm



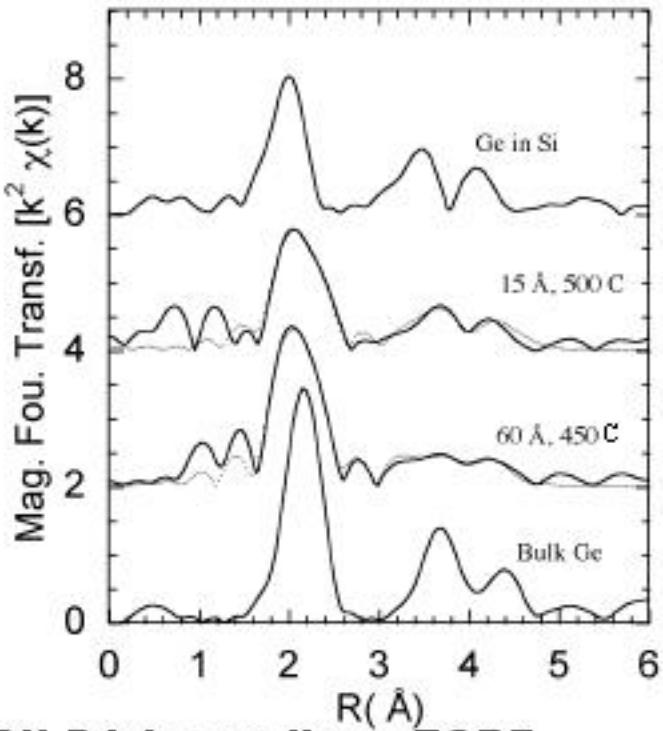


Intermixing measured by XAFS

- X-ray Absorption Fine Structure
  - The oscillations of the absorption coefficient after an absorption edge are connected to the distance and to the number of neighbours of the absorbing atom.
  - By measuring the number of Si atoms around the Ge site we are able to evaluate the intermixing



Radial Distribution Function around the Ge atoms

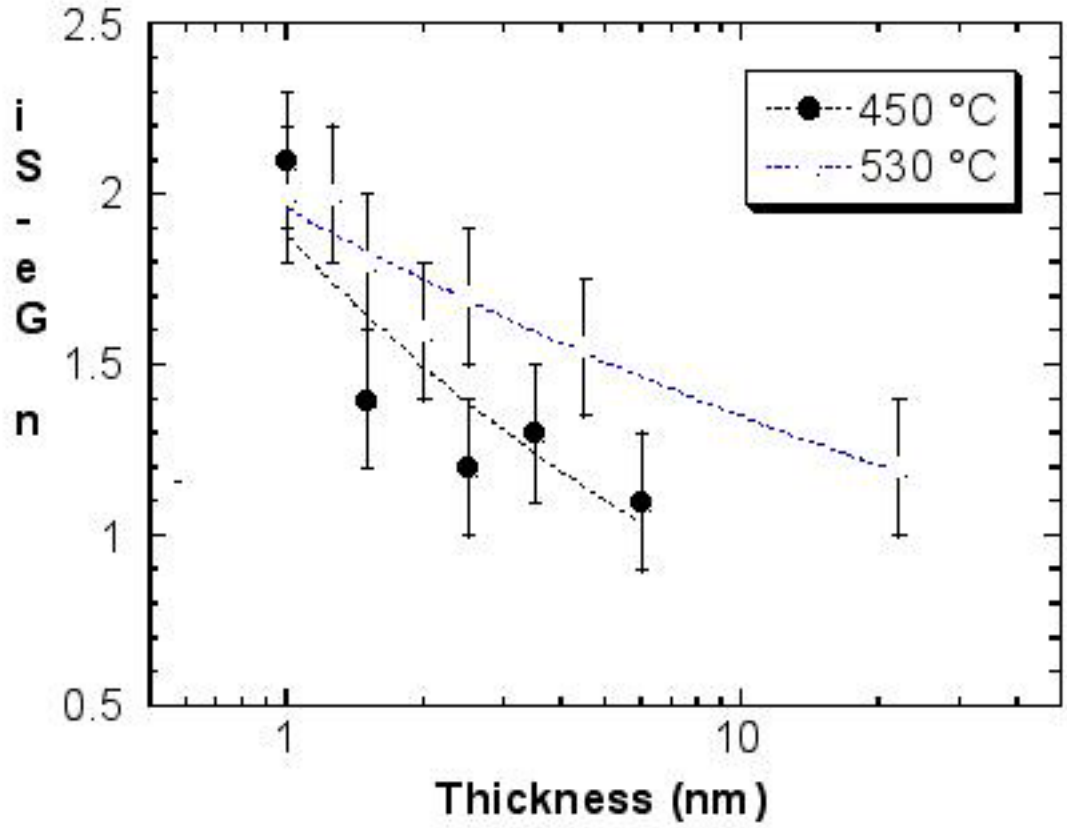


Measurements performed at the GILDA beam line - ESRF

Intermixing measured by XAFS

- Formation of a random alloy in the wetting layer and in the islands of Ge/Si(111)

- Decrease of the number of Si around a Ge (n_Ge-Si) as a function of thickness
- Increase of n_Ge-Si as a function of substrate Temperature.



The intermixing increases with T, but is limited in the 3D islands

The future...

Projet FORUM-FIB (CEE 2001-2004)

CRMC2-Juelich-INSA-Demokritos-Philips-ST-Uniroma2

- - "Patterning" of the substrate through new techniques
  - Lithography
  - Ion gun focalized

⇩

– Nucleation and growth of ordered array of QD

⇩

– New Single Electron devices

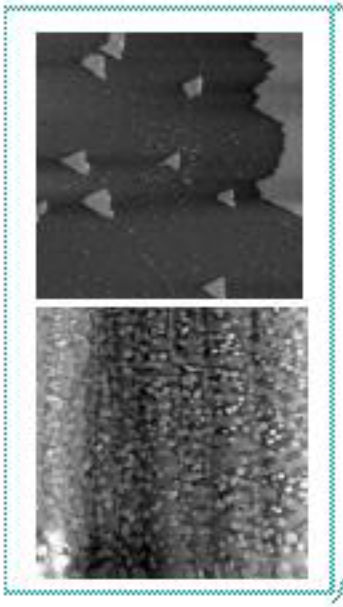
⇩

– And…

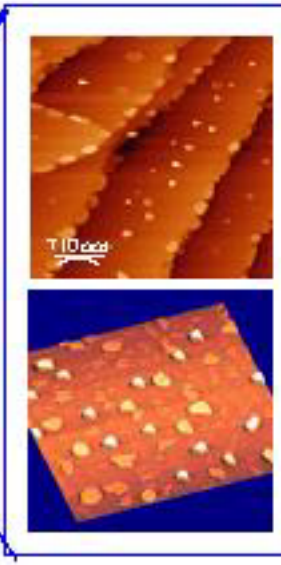
Results

– Step bunching on Si(111): preparation of the substrate with different morphologies

- Visualization on-line of the growth of the Wetting Layer

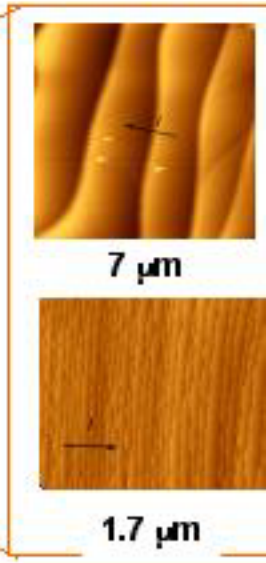


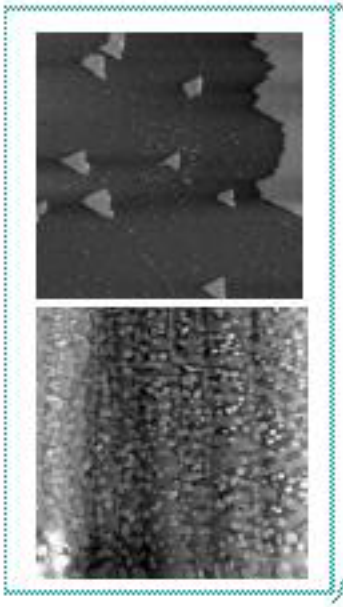
– Evolution and distribution of the 3D islands



Results

– Step bunching on Si(111): preparation of the substrate with different morphologies

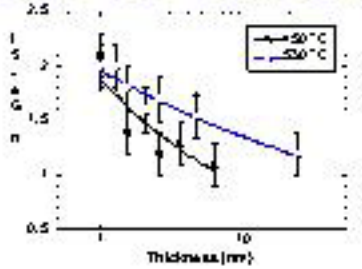




- Visualization on-line of the growth of the Wetting Layer

– Evolution and distribution of the 3D islands

– Evaluation of the intermixing by XAFS



Conclusions

- **Determination of the contribution of the substrate morphology on the heteroepitaxial growth during the formation both of the wetting layer and of the 3D islands**

- **Evaluation of the degree of ripening of the 3D islands in different experimental conditions**

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