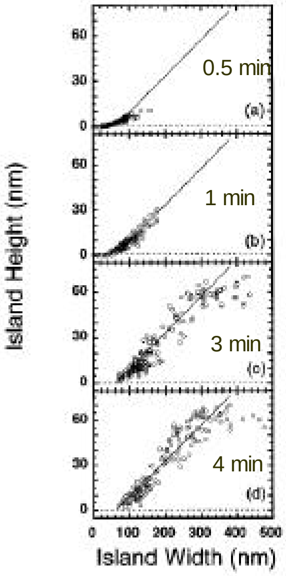
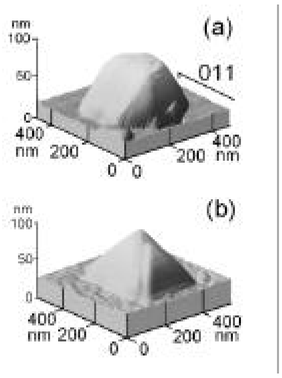
Further results on Ge/Si(100)

G.Capellini et al Appl. Phys. Lett. 70,493 1997

- **Low Pressure CVD**
  - **P=0.5-2 mTorr ; T=400 - 650 °C**
- **Low coverage. Onset of the pyramids formation**
- **Dislocated islands appear after a critical height (50 nm)**



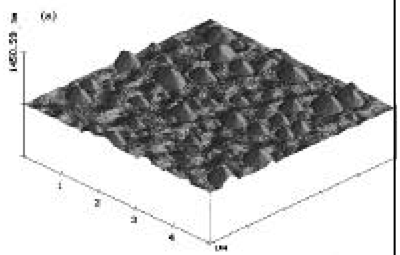


Further results on Ge/Si(100)

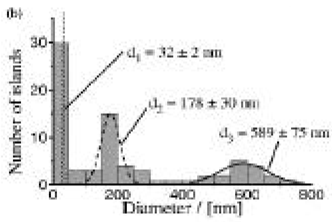
Goryll, Vescan et al Appl. Phys. Lett. 71,410 1997

- **Low Pressure CVD**
  - **P=0.12 Torr ; T=525 - 700 °C**
- **Pyramids are favoured at high T**
- **Dislocated islands appear after a critical height (50 nm)**

AFM image of Ge/Si at 700 °C
Large dots: {111} and {113} faceted
Small dots: rounded shaped



Island size distribution.
Three gaussian fits:
32 nm: small dots: precursors
178 nm: domes: coherently strained
589 nm: dislocated islands



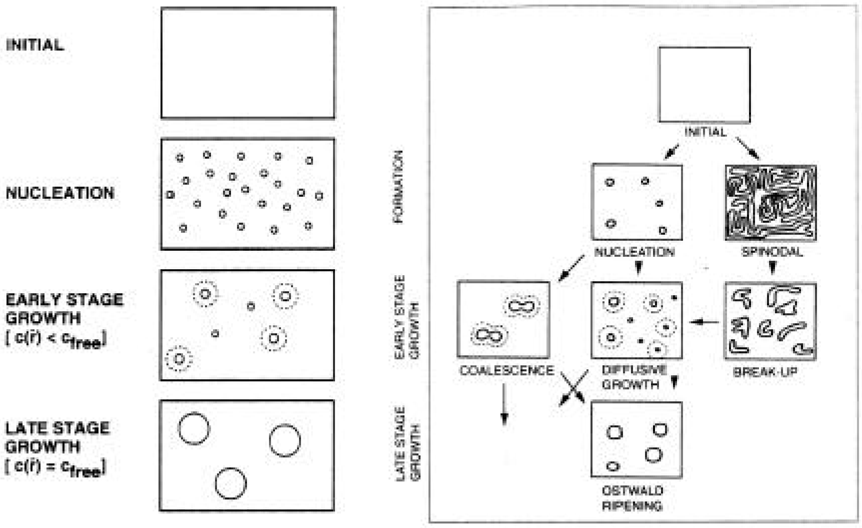
Island evolution
Ge/Si(001)

Kamins, Medeiros-Ribeiro, Ohlberg, Stanley Williams
J. Appl. Phys. 85, 1159 (1999)

- **Ostwald ripening or shape stabilization?**
  - **smaller islands disappear when growth proceeds**
    - **Ross et al. PRL 80, 984 (1998): smaller islands shrink during evaporation**
    - **Medeiros-Ribeiro et al. Science 279, 353 (1998): the distribution of the islands is the equilibrium one, in agreement with Shchukin et al. PRL 75, 2968 (1995)**
  - **Note: the Ostwald ripening (Ostwald, Z.Phys.Chem. 34, 495, (1900)) is the coarsening of a particle size distribution driven by the Gibbs-Thomson effect**

Islands evolution

Zinke-Allmang, Feldman, Grabow, Surf.Sci.Rep.16,377 (1992)



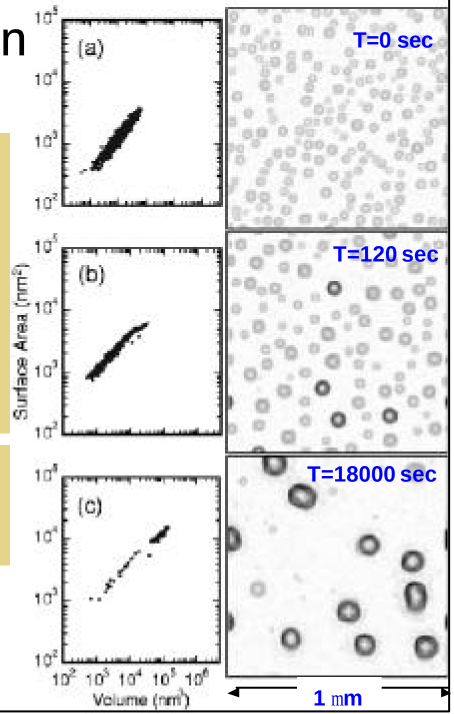
Ostwald ripening (Ostwald, Z.Phys.Chem. 34, 495, (1900)) is the coarsening of a particle size distribution driven by the Gibbs-Thomson effect

Islands evolution AFM

- **Ge/Si(001)**
  - 6 ML Ge grown at 600 °C by CVD
  - Annealing at T= 600 °C for different times
  - The smaller islands are pyramids
  - The larger islands are domes
  - Bimodal distribution after annealing

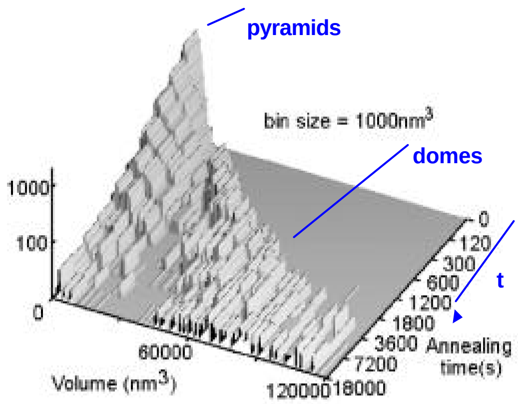
- The coarsening behaviour is not consistent with standard Ostwald ripening models

Kamins , Medeiros -Ribeiro, Ohlberg, Stanley Williams
J. Appl. Phys. 85, 1159 (1999)



Islands evolution AFM

- **Ge/Si(001)**
  - 6 ML Ge grown at 600 °C by CVD
  - Evolution from a large number of pyramids into a bimodal distribution



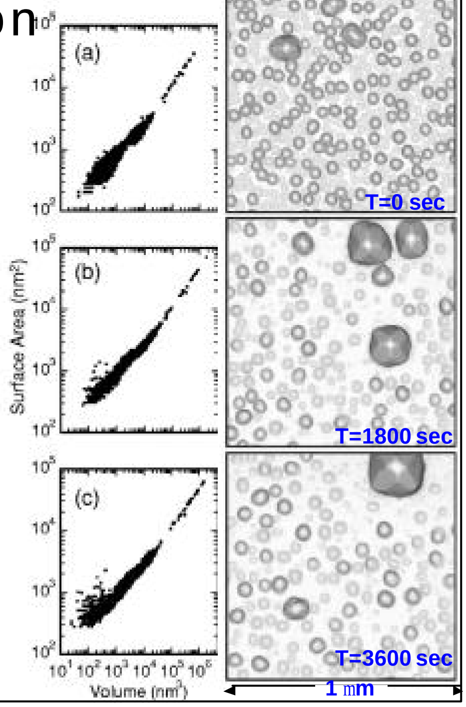
Kamins , Medeiros -Ribeiro, Ohlberg, Stanley Williams
J. Appl. Phys. 85, 1159 (1999)

Islands evolution AFM

- **Ge/Si(001)**
- 13 ML Ge grown at 550 °C by CVD
- Annealing at T= 550 °C for different times
- Growth of very large superdomes at the expenses of pyramids and domes

- At T=650 °C larger islands are stabilised by the Ge-Si intermixing

Kamins , Medeiros -Ribeiro, Ohlberg, Stanley Williams
J. Appl. Phys. 85, 1159 (1999)



Erosion around the islands

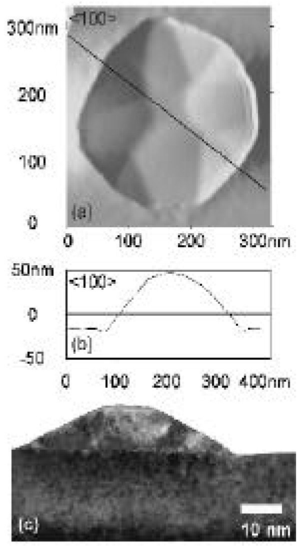
S. A. Chaparro, Y. Zhang, and Jeff Drucker
Appl. Phys. Lett. 76, 24 3534 (2000)

- **Ge/Si(001)**
- Ge grown at 550 °C by CVD

- AFM image

- (100) cross section of a dome grown at 550 °C

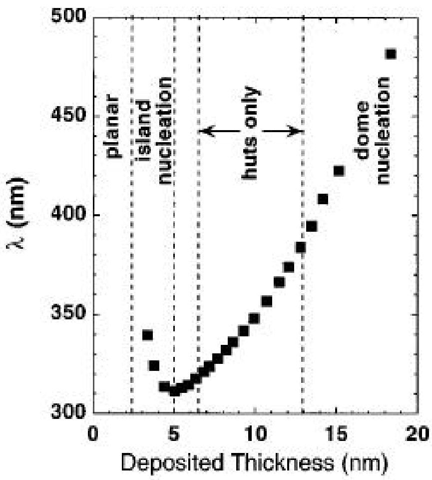
- TEM cross section



Dense array of islands

- **self ordering**
  - **Springholtz et al**
    - **Science 282, 734 (1998)**
  - **J.A.Floro et al**
    - **APL 73, 951 (1998)**
- At high coverage, repulsive elastic interactions between islands will become important.

Evolution of the mean island spacing during $Si_{0.8}Ge_{0.2}$ /Si(001) growth by MBE at 755 °C

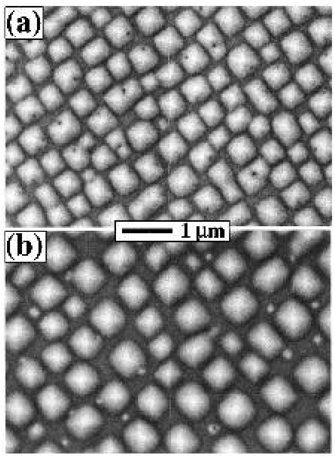


Dense array of islands

Floro, Sinclair et al. PRL 84, 701 (2000)

- **coarsening.**
  - **Ostwald ripening is enhanced by elastic repulsion**

$Si_{0.8}Ge_{0.2}$ /Si(001) hut cluster arrays grown by MBE at 755 °C
a) as deposited (10 nm)
b) annealed at 755 °C



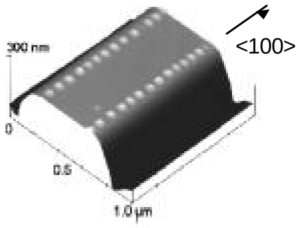
SEM Images

Lithographic positioning

Kamins and Stanley Williams APL 71, 1201 (1997)

- **Self assembly of Ge islands on Si(001)**
- **patterned substrates.**
  - **SiO_2 grown on Si(001)**
  - **Local oxidation defines Si lines surrounded by oxide**
  - **Epitaxial Si(001) grown at T=850 °C by SiH_2Cl_2 and HCl**
  - **Ge deposition from GeH_4 at T=600 °C**

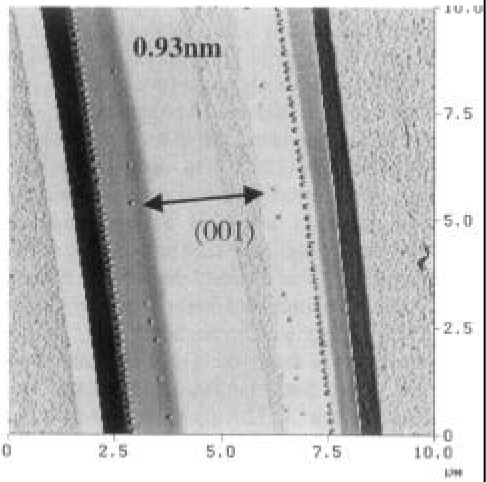
AFM Image



Lithographic positioning

Vescan, Grimm, et al. Mat.Sci. and Engin. B69, 324 (2000)

- **Growth on patterned substrates.**
  - **Pattern by optical lithography**
  - **Si buffer layer (500 nm) at T=800 °C**
  - **Ge deposition at T=700 °C, 0.3 nm min^{-1}**

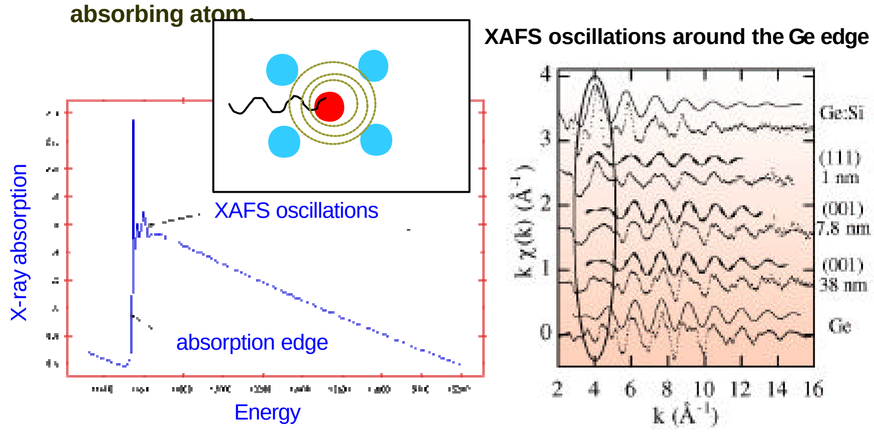


AFM Image

Intermixing measured by XAFS

F.Boscherini et al. APL 76, 682 (2000).

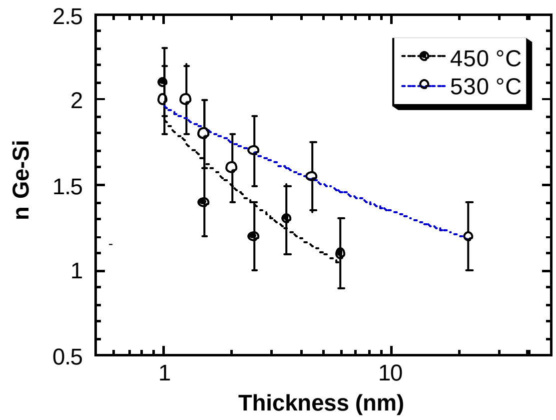
- X-ray Absorption Fine Structure
  - The oscillations of the absorption coefficient after an absorption edge are connected to the distance and to the number of neighbours of the absorbing atom.



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.



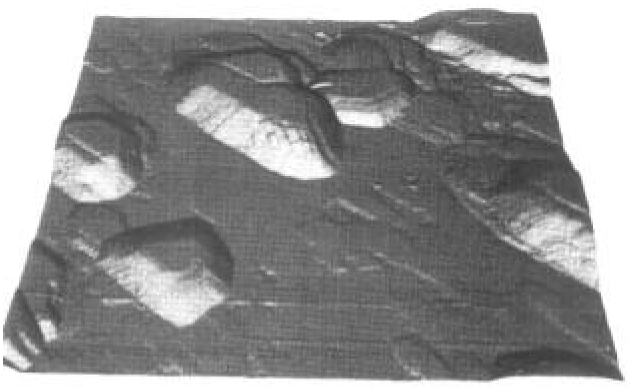
The intermixing increases with T, but is limited in the 3D islands

Intermixing measured by XAFS

F.Boscherini et al. APL 76, 682 (2000).
N.Motta et al. Mat. Res. Eng. (2001)

- **XAFS results:**
  - **Average Si atoms around Ge = 1**
  - **Average Ge atoms around Ge = 3**
  - **Ge content in the islands for Ge/Si(001) ~ 70%**
  - **Ge content in the WL for Ge/Si(111) ~ 50%**
  - **Intermixing depends on the thickness**
  - **Si is randomly distributed**
  - **Local lattice distortion:**
    - **Ge-Si distance ~ 2.41 Å (2.398 Ge-Si average)**
    - **Ge-Ge distance ~ 2.44 Å (2.446 in pure Ge)**

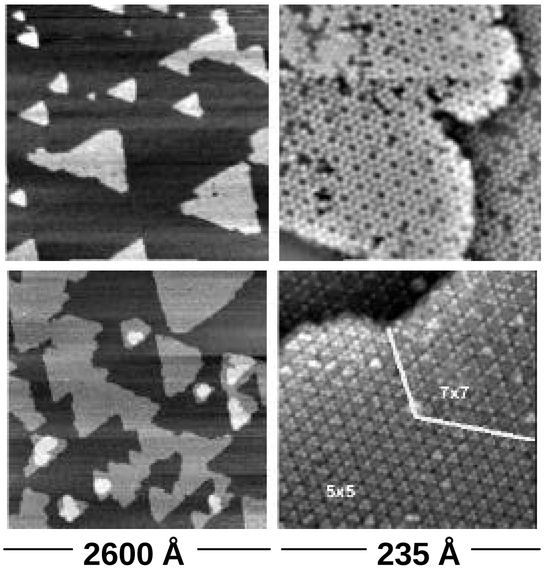
Ge/Si(111): the first images



STM image of a 3000x2000 Å area
9 ML Ge deposition at 420 °C

Köhler et al Surf.Sci 248 (1991)

Growth of the wetting layer



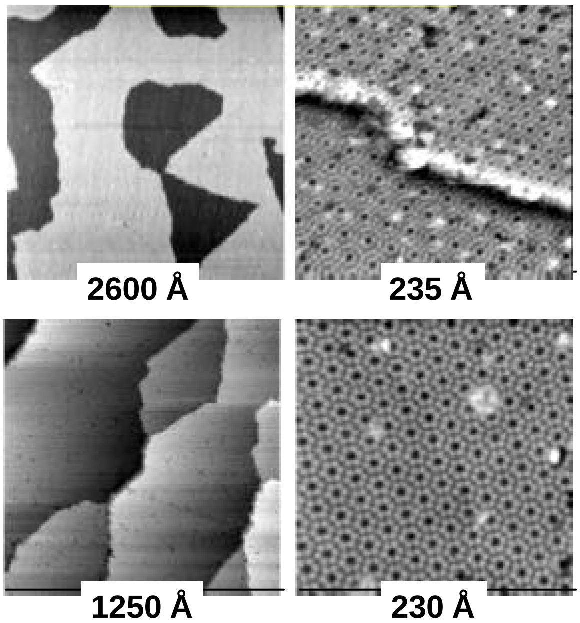
Ge/Si(111) T= 500 °C

0.65 ML

1.35 ML

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

Growth of the wetting layer



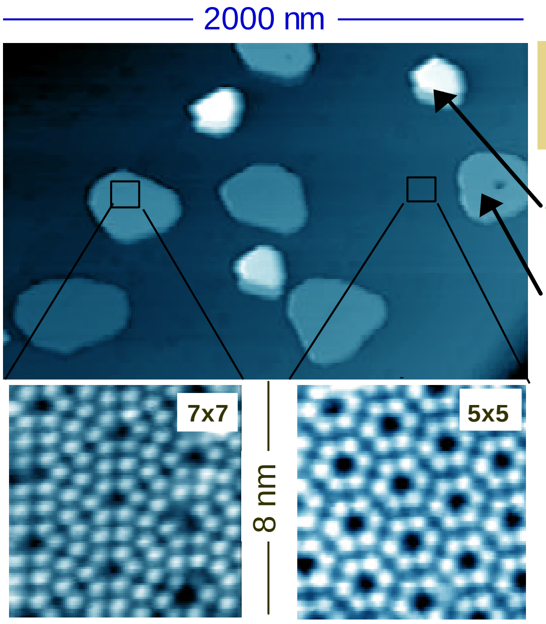
Ge/Si(111) T= 500 °C

2.0 ML

3.0 ML

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

Ge/Si(111) growth: STM results



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

Islands:

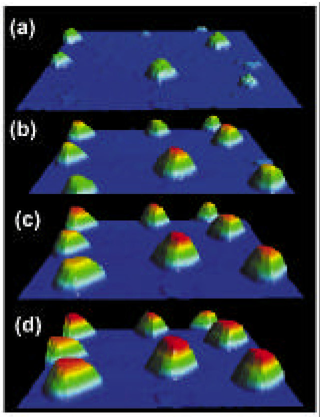
tall – triangular (strained) (180 nm wide x 10 nm high)

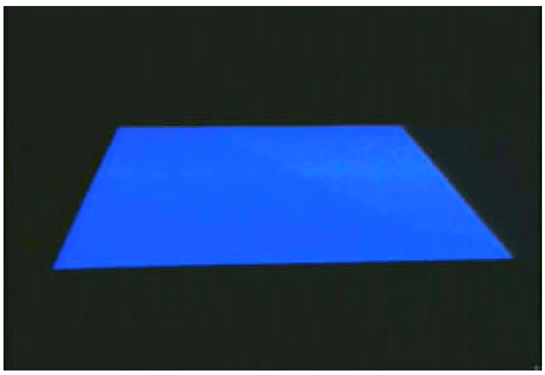
low – rounded (ripened) (350 nm wide x 2,5 nm high)

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

Ge/Si(111) growth: STM results

B.Voigtlaender, Surf.Sci. Rep. 43 (2001) 127



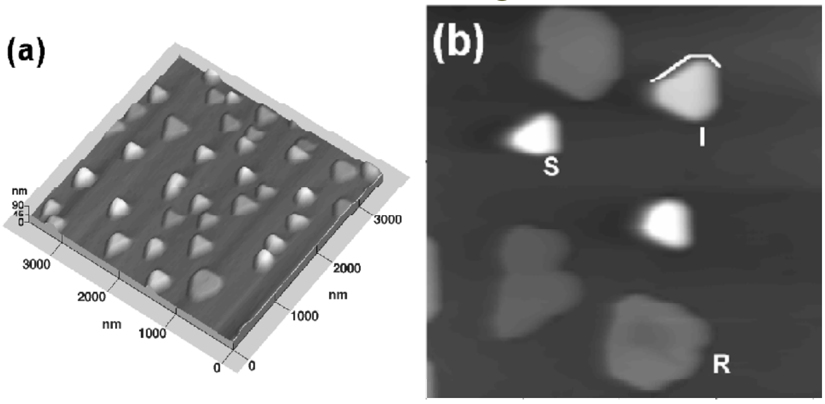


Video: 3D Ge islands grown on Si(111) at T=300°C
Voigtlaender and Zinner, APL 63 (1993) 3055

Ge/Si(111) AFM results

Capellini et al. S.S.Comm. 112, 145 (1999)

- 4 nm Ge/Si
- T=500 C + 10' annealing

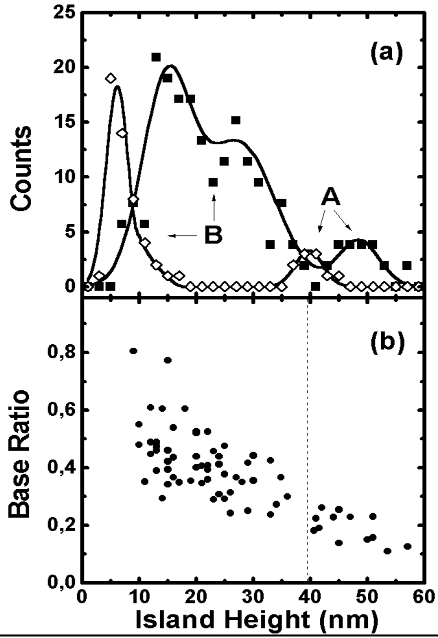


Ge/Si(111) AFM results

Capellini et al.
S.S.Comm. 112, 145 1999

- ■ Unannealed sample
- ◇ Annealed sample

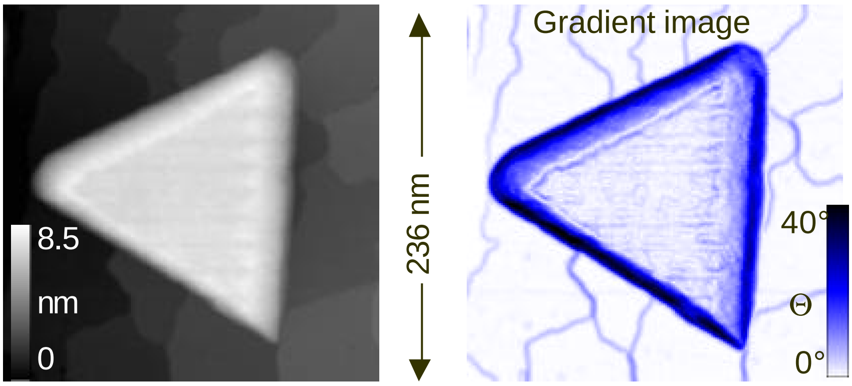
- Base ratio:
  - Top base / bottom base



Ge/Si(111) island evolution

20 Å Ge/Si(111) T=530°C

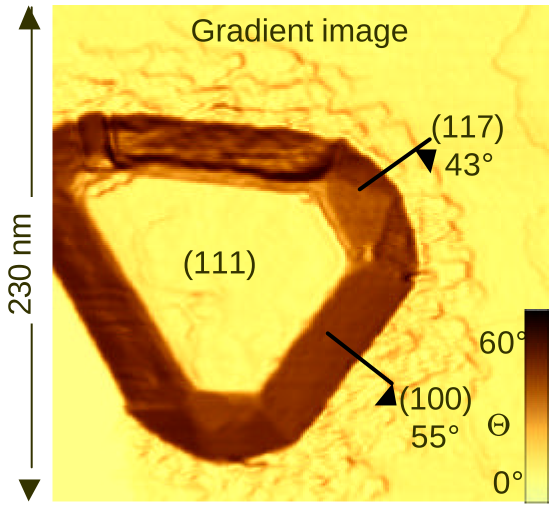
- **Nucleation:**
  - **Precursors (platelets)**
  - **Transition of the WL?**



Ge/Si(111) island evolution

25 Å Ge/Si(111) T=450°C

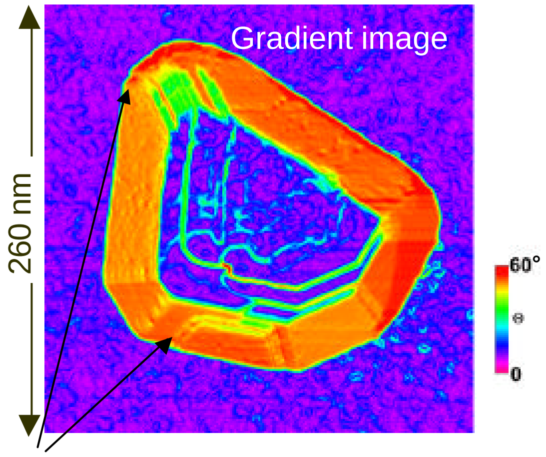
- **Island height: 40 nm**
- **Insertion of new faces:**
  - **[100]**
  - **[117]**



Ge/Si(111) island evolution

45 Å Ge/Si(111) T=450°C

- **Island height: 63 nm**
- **Insertion of dislocations**

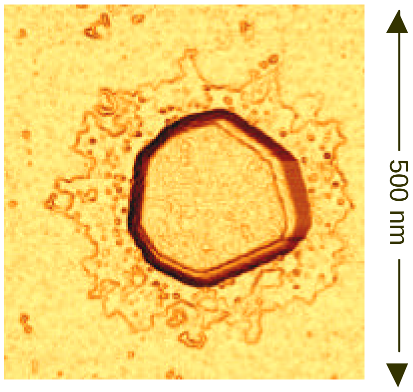


Dislocations

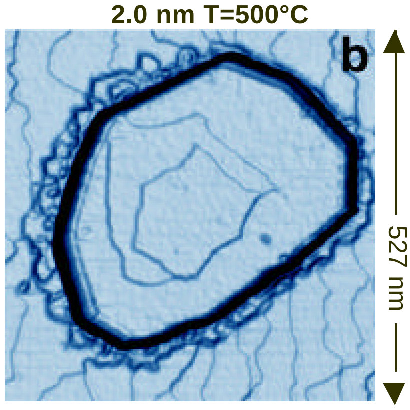
Ge/Si(111): islands evolution

“ripening”

3.5 nm T=500°C



2.0 nm T=500°C



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

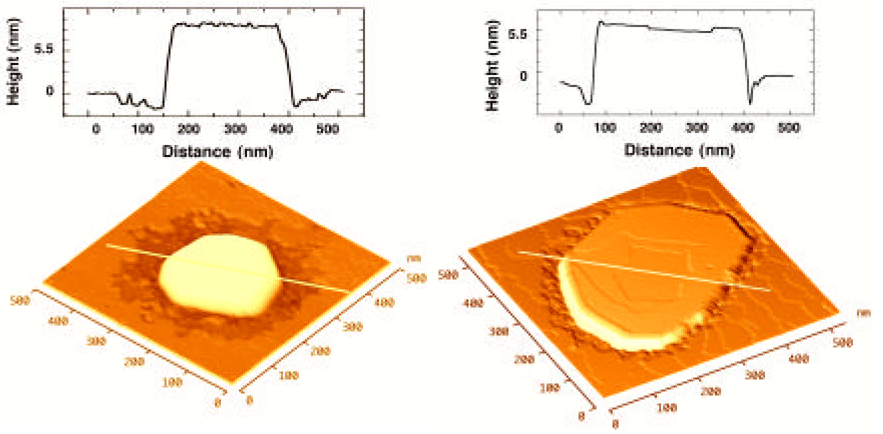
- **Island height: 5 nm**
- **“Atoll” formation**

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

Ge/Si(111): islands evolution

The final stage (ripening and erosion)

3.5 nm T=500°C **2 nm T=500°C**



Measured erosion of the substrate around the islands reaches 5 nm!

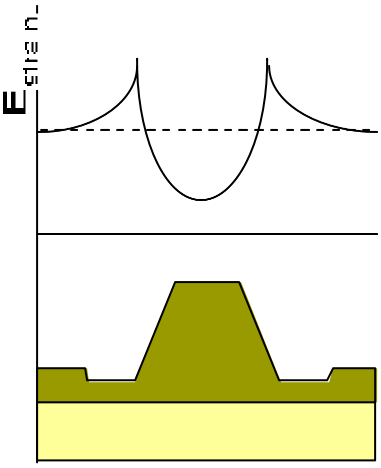
Erosion of the substrate

- **Kamins et al. - Ge/Si(100):**
  - J.Appl.Phys 81 (1997): AFM measurements.
    - Not understood in terms of erosion.
    - Not clear due to the oxydation of the surface.
- **N.Motta et al. - Ge/Si(111):**
  - Surface Science (1998). STM measurements.
  - Solid State Comm. (1999). STM and AFM measurements.
    - Erosion of the central part of the island.
    - Not very clear the erosion of the surrounding wetting layer.
- **Actual results:**
  - Evidence of the depletion of the islands top.
  - Evidence of the erosion of the substrate.
  - Strain + Ostwald ripening.

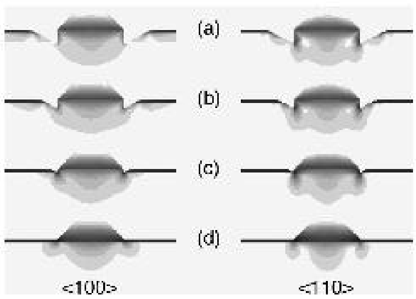
Erosion of the substrate

Seifert et al., J.Cryst.Growth 170 (1997) 39

- Model calculation:
- Local strain energy profile:
  - Increase of strain at the island edge.
- Strain accelerated decomposition of the surrounding layer.



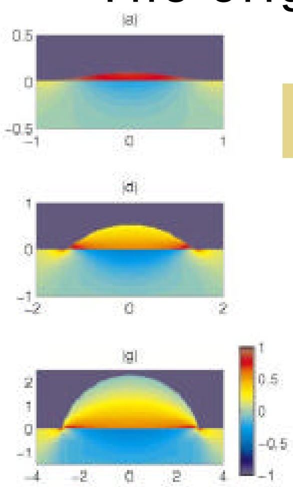
Erosion around the islands



- Calculation of the elastic energy for trenches of different depths

S. A. Chaparro, Y. Zhang, and Jeff Drucker
Appl. Phys. Lett. 76, 24 3534 (2000)

The origin of the erosion



- **Calculation of the stresses and strain of equilibrium islands**

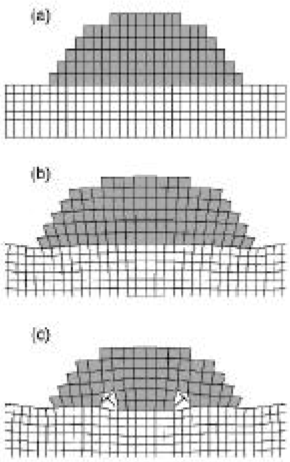
Stresses and strains of equilibrium islands. All stresses and strains are scaled relative to the misfit stress and strain for a planar film.

Stresses *sxx*:

(a) in a small island
(d) in a medium sized island
(g) in a large sized island *(g)*

B.J.Spencer and J.Tersoff
Phys. Rev. B. 63, 205424 (2001)

The origin of the deformation



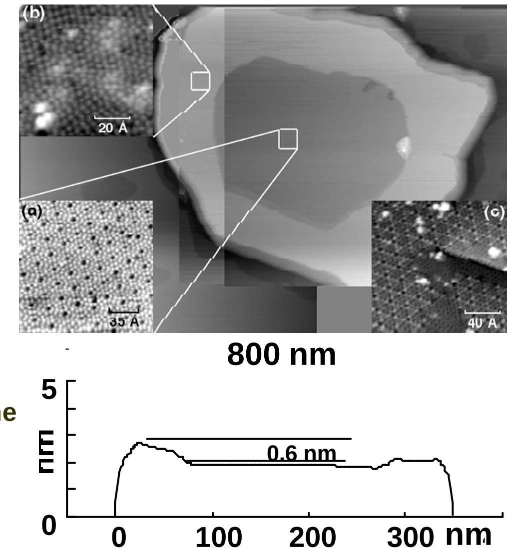
- **Deformation and strain relief in equilibrium islands**

(a) Unrelaxed configuration
(b) Deformation due to strain relaxation in the coherent island
(c) Deformation in island with mixed-type dislocations at "optimal locations"

B.J.Spencer and J.Tersoff
Phys. Rev. B. 63, 205424 (2001)

Ge/Si(111) island evolution

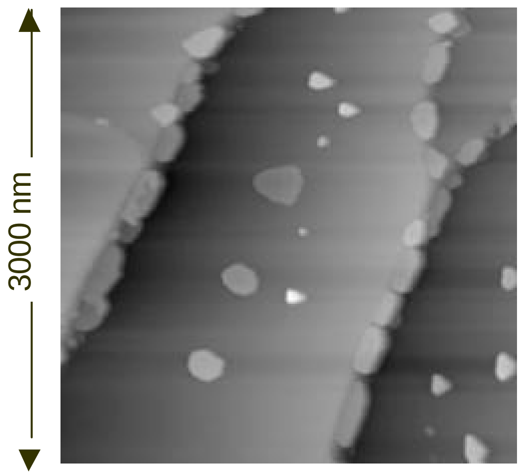
- **After the nucleation:**
  - the islands grow vertically up to a critical value
  - the strain energy introduces dislocations
  - morphological transition
  - lateral growth
  - material flow from the top - central hole formation



Ge/Si(111) island distribution

25 Å Ge/Si(111) T=450°C

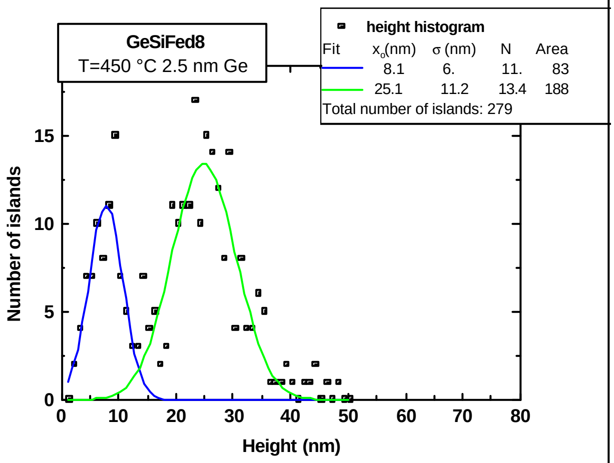
- **Image total height: 55nm**
- **Step decoration**
- **Growth of islands at the center of the steps**
- **Regular spacing**



Ge/Si(111) island distribution

25 Å Ge/Si(111) T=450°C

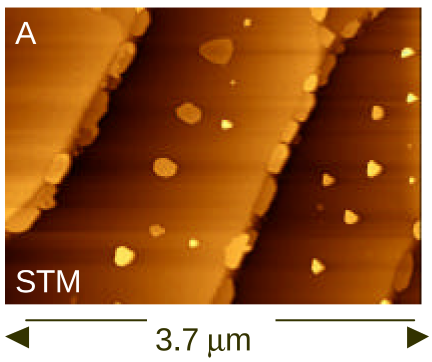
- **Two main peaks**
  - **Dislocated**
  - **Relaxed**
- **Small peak**
  - **coherents**

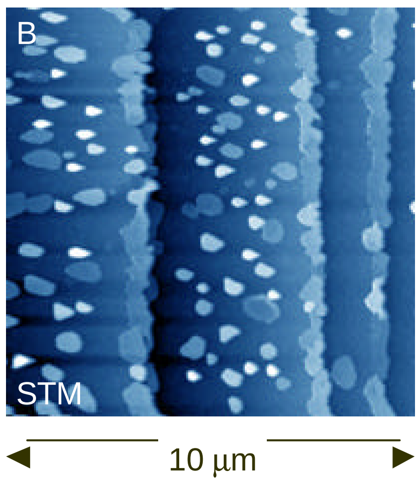


Ge/Si(111) island distribution

25 Å Ge/Si(111) T=450°C

60 Å Ge/Si(111) T=450°C





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

B) Third - fourth generation of islands .

Conclusions

- **Heteroepitaxy of Ge-Si**
  - **Strain and interface energy**
  - **Wetting layer + 3D coherent strained islands**
  - **Dependence of island size on the lattice mismatch**
  - **Quantum dots**
  - **Self assembling and ordering**
- **STM and AFM results**
  - **Auto-organization due to strain + kinetics**
  - **Evolution and ripening of the islands**
  - **Intermixing and substrate erosion**
  - **Distribution of the island sizes**