Critical issues in Ge/Si nanostructures: intermixing and ripening

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Open problems[†]:

- Alloying: *exact composition of WL and islands*

- Growth Instabilities: *Island evolution and ripening*

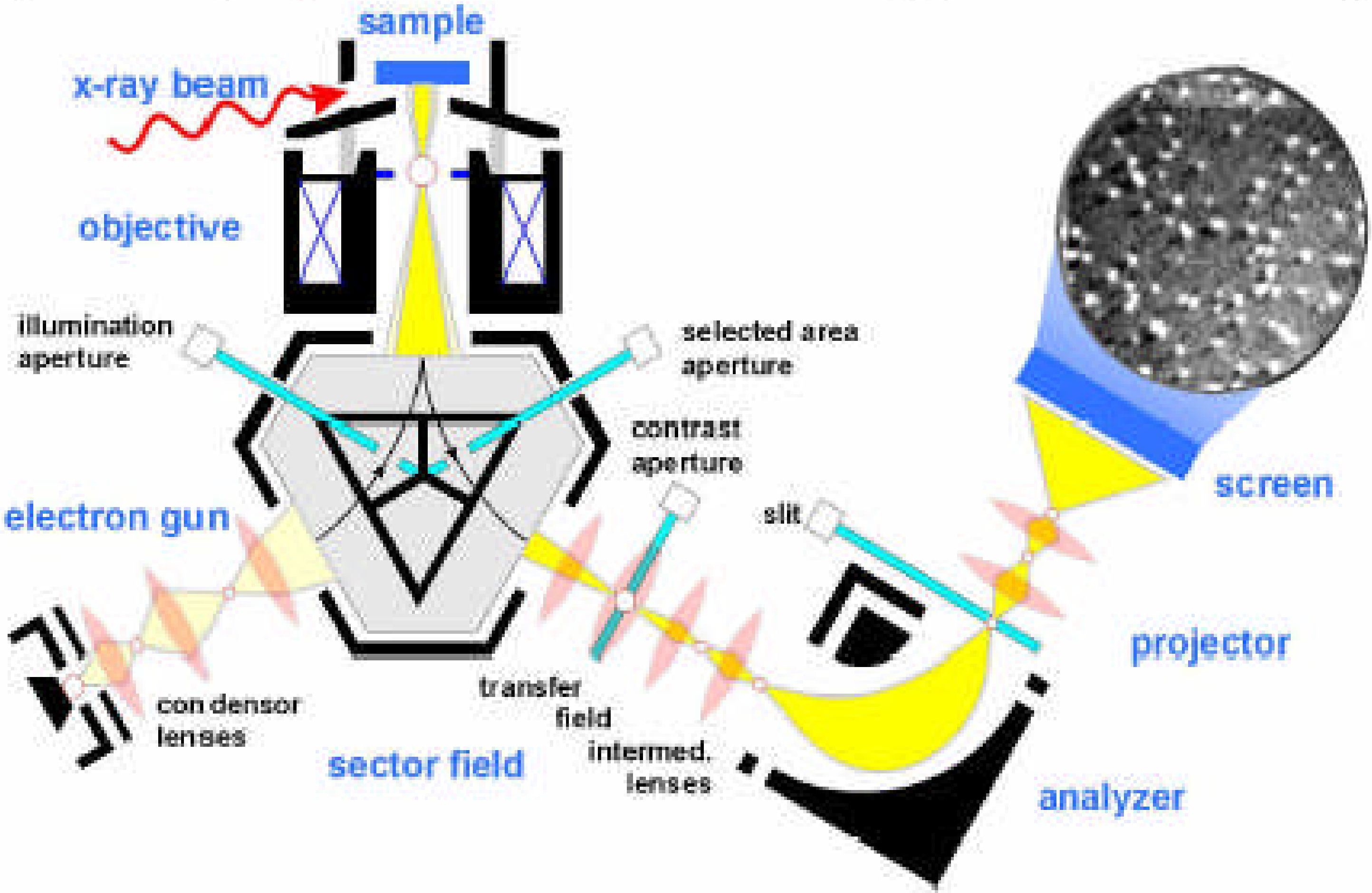
- Substrate–island interactions (depletion–erosion)

- **Island positioning by control of self–assembly**

[†] **Note: several other groups are studying the growth of Ge on Si(001) (IBM, HP, Max Planck, U Wisconsin (Madison), Rome3, NTT, U Virginia, Sandia NL, etc.), which is more promising for applications since the (001) surface of Si is widely used in industry**

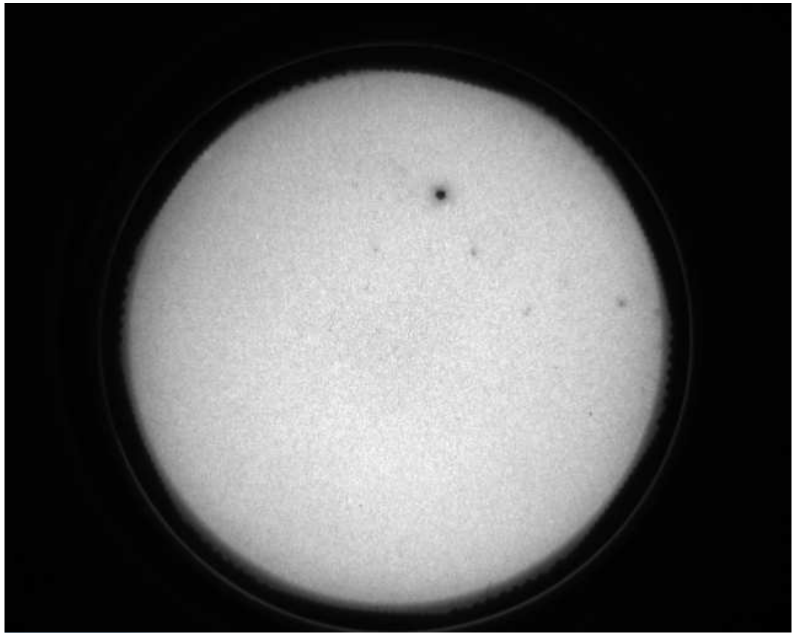
The SPELEEM at ELETTRA

Spectroscopic photoemission and low energy electron microscope



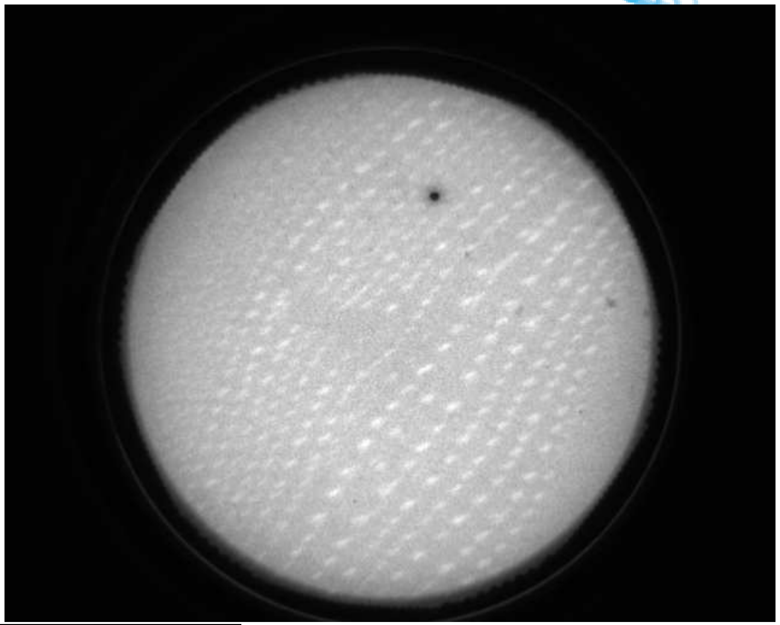
S. Heun, Th. Schmidt, B. Ressel, E. Bauer, and K. C. Prince: Synchrotron Radiation News Vol. 12, No. 5 (1999) 25.

Online crystal growth by LEEM



T = 430 ° C ←

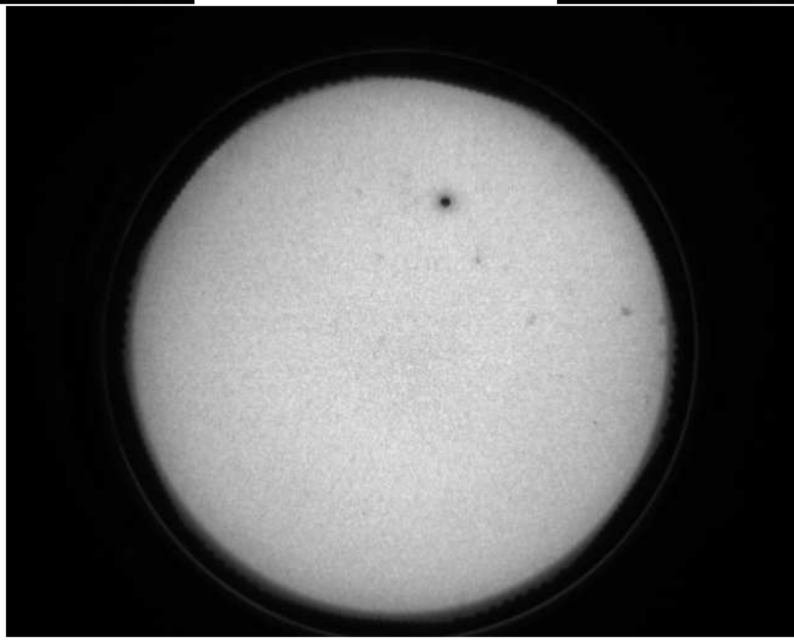
T = 530 ° C →



T = 560 ° C →

8 ML Ge on Si(111)

LEEM Movies:
Fov 10 µm



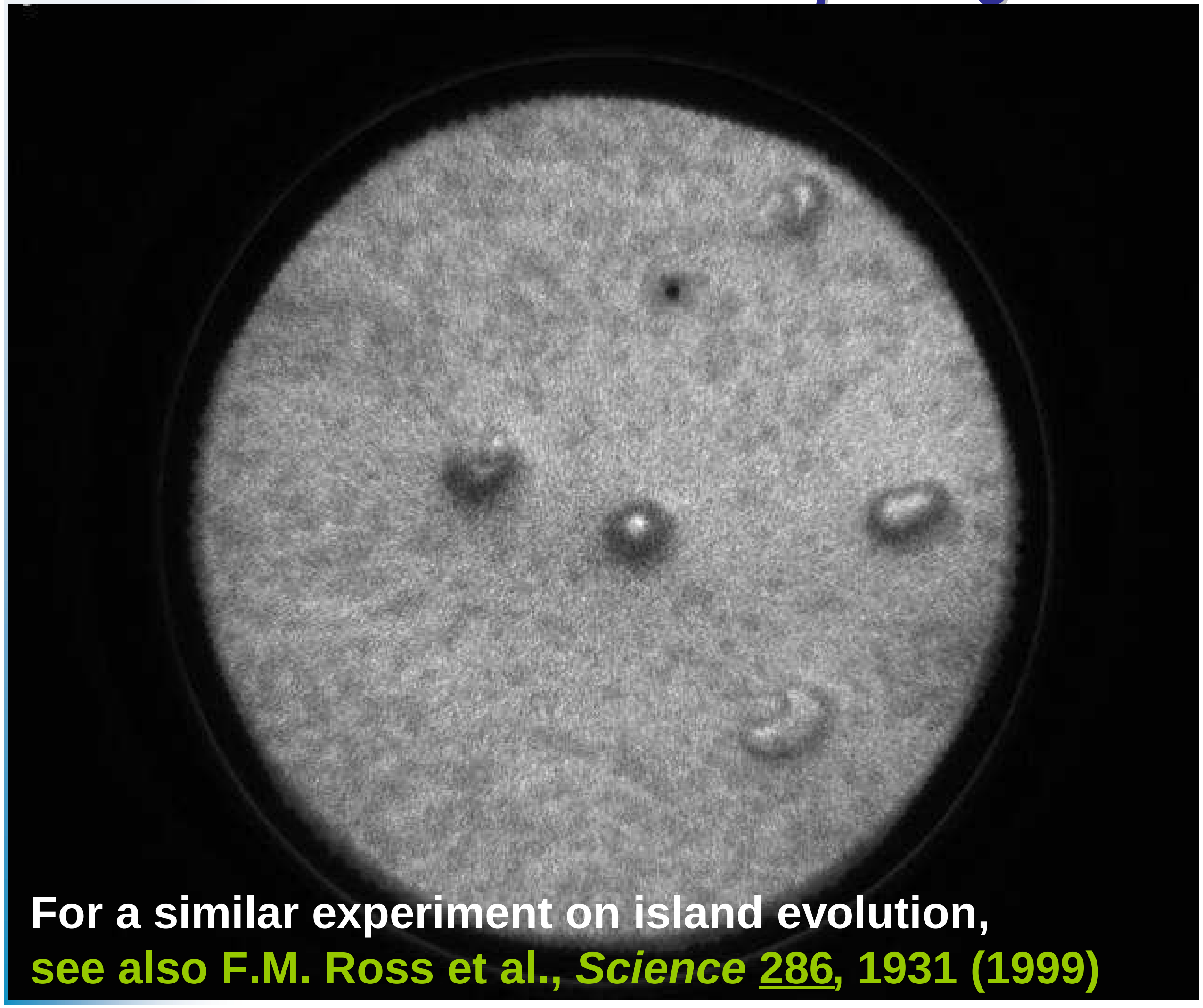
- As Ge is deposited, the reflectivity changes

- When the Wetting Layer is Complete, 3 D islands nucleate randomly

ICNT 2005

Growth instability

- *Metastability of Ge/Si islands upon annealing: island evolution and ripening*



For a similar experiment on island evolution,
see also F.M. Ross et al., *Science* 286, 1931 (1999)

8 ML Ge on Si(111)

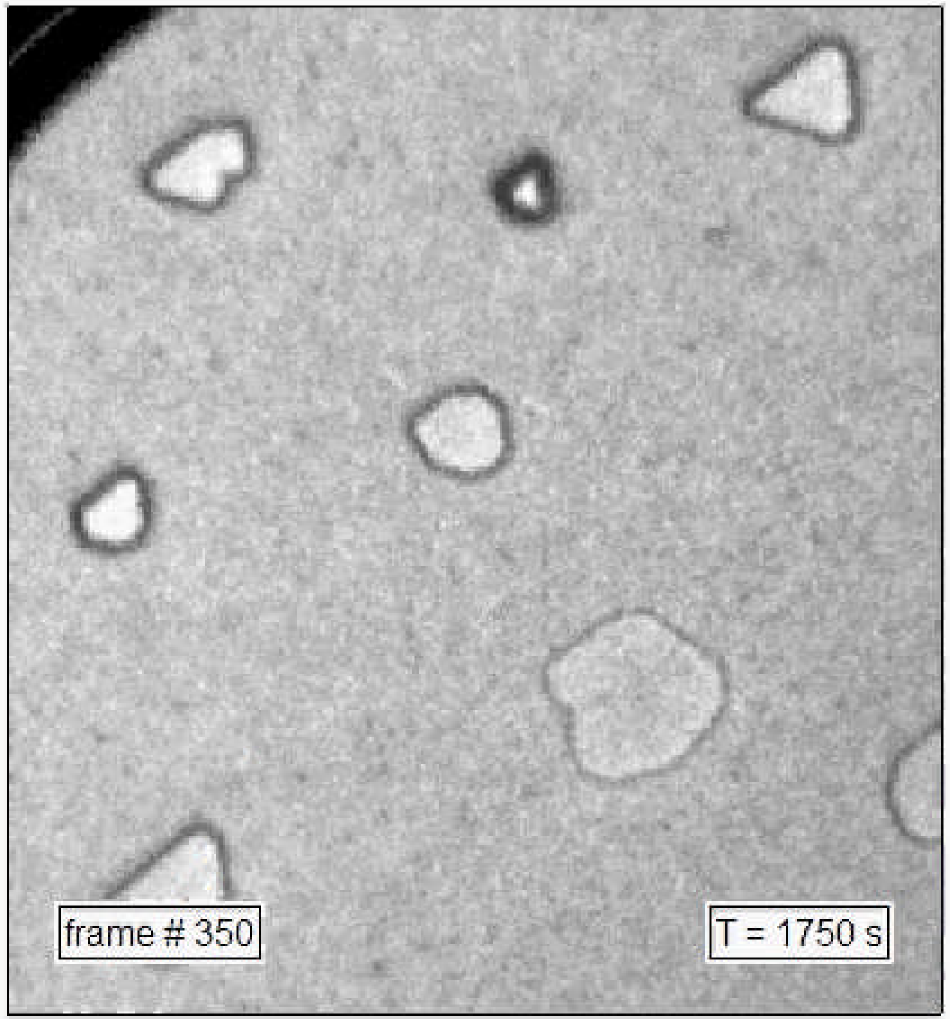
LEEM Movie: post–deposition annealing to 550 °C

Bottom right: an unstable island "melts"

Upper left: an island nucleates, then is divided in 2

FoV: ~5 μm

Island instability: super–islands



8 ML Ge on Si(111) at 550° C

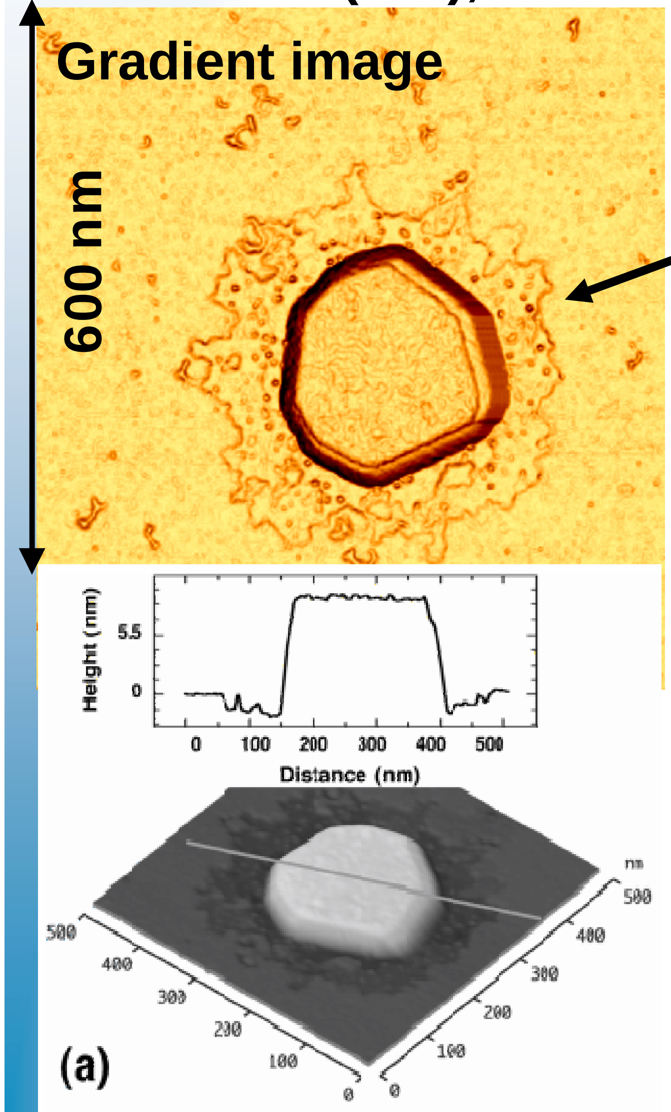
LEEM Movie: post–deposition annealing to 700° C

Several islands "melt"
Upper right: formation of a super–island

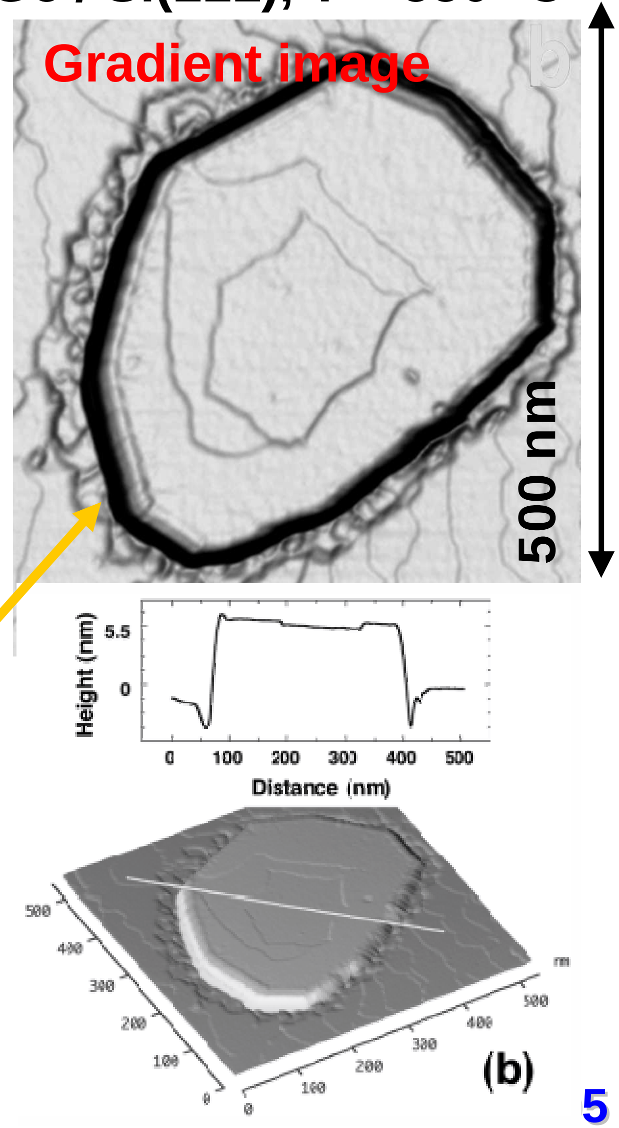
FoV: ~1×1 μm²

Ge/Si(111): island ripening

30 Å Ge / Si(111), T = 500 °C



20 Å Ge / Si(111), T = 550 °C



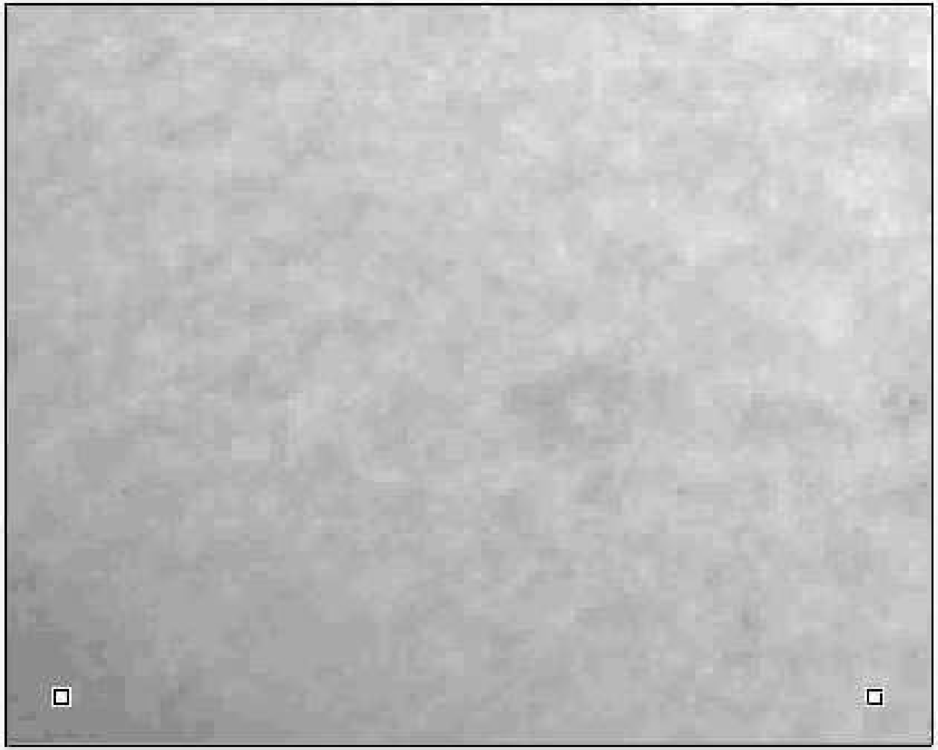
- Main features:

- **Ripening effect: island is rounded**
- **Substrate erosion: formation of a trench around the island.**

- Full Ripening:

- **Atoll–like shape: formation of a central hole**
- **Substrate erosion**

Ge/Si(111): island evolution



FoV: ~2.2×2.2 μm^2

from 3 to 10 ML

Ge on Si(111)

LEEM Movie: post–deposition annealing to 550 °C (0.2 ML/min)

At the beginning the island is triangular-shaped, then looses simmetry and become atoll-like

Ge/Si(111):

composition of a single 3D island

- **Substrate + Island morphology: STM**
- **Dynamics of the islands morphology: LEEM**
- **Open question: what is the composition of a single 3 D island?**
- **Answer: combine spatial resolution with chemical contrast**

=> X–Ray Microscopy using Synchrotron Radiation (XPEEM)

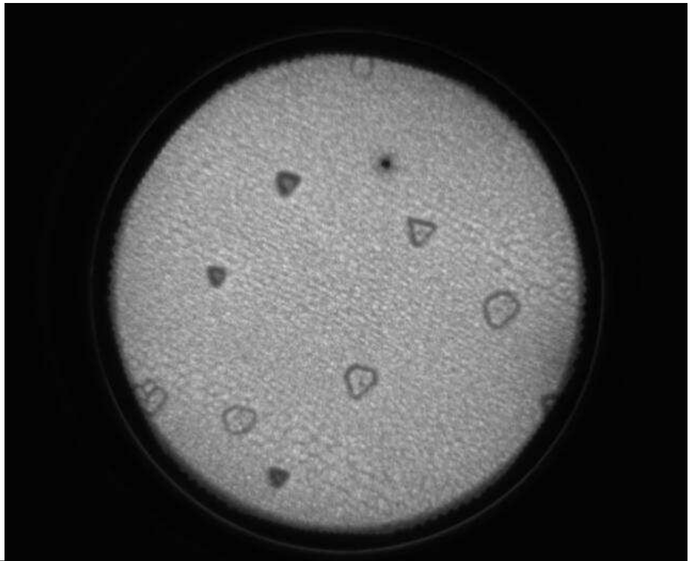
Nanospectroscopy:

a microscopy technique with chemical contrast

5 ML Ge on Si(111), T = 450 ° C

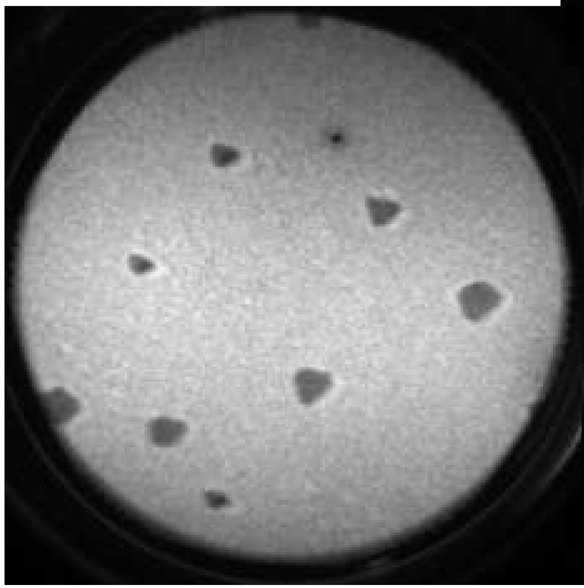
XPEEM:
X–Ray Photoemission Electron Microscopy

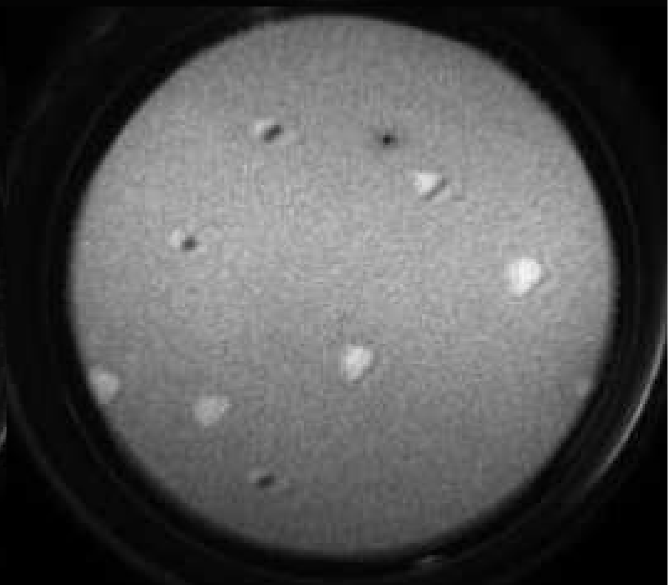
– in essence, it means photoelectron spectroscopy with 40–50 nm spatial resolution



LEEM:
2.5 µm FoV

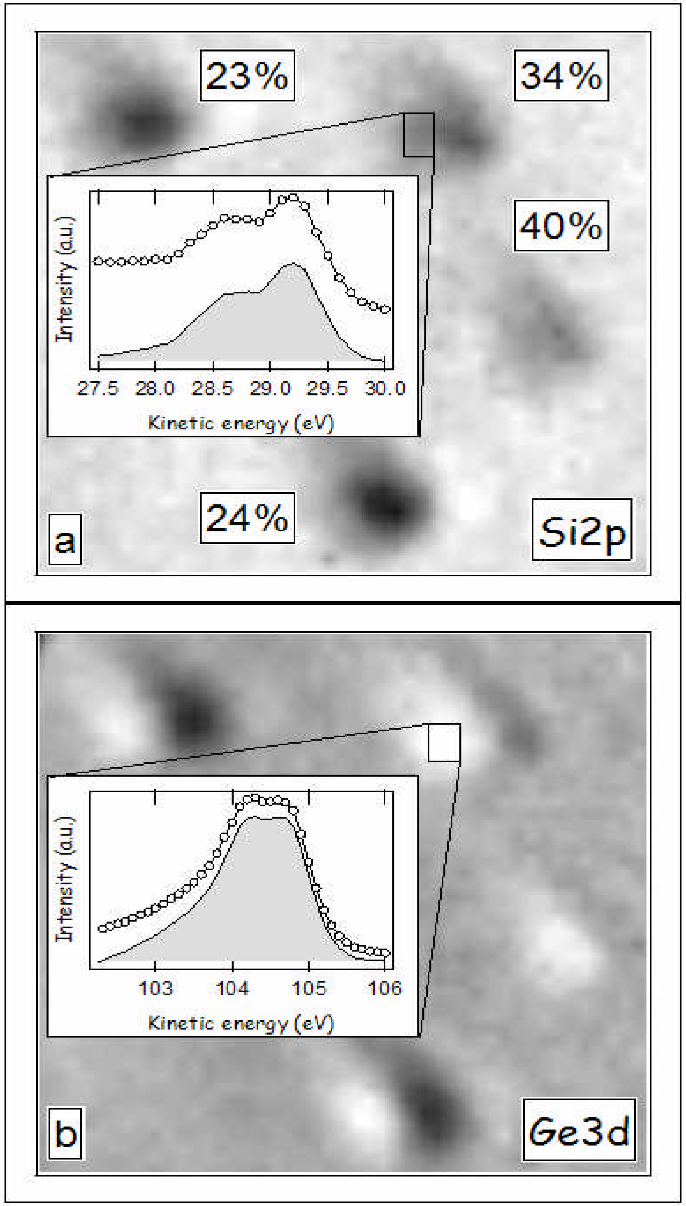
XPEEM:
Si 2p





XPEEM:
Ge 3d

Composition of single 3 D islands



4×4 μm^2 integrated XPEEM images taken at:

a) the Si2p core level peak and

b) the Ge3d core level. Spectra are shown in the insets.

The micrographs are obtained by integrating the spectra with ~25 nm lateral resolution.

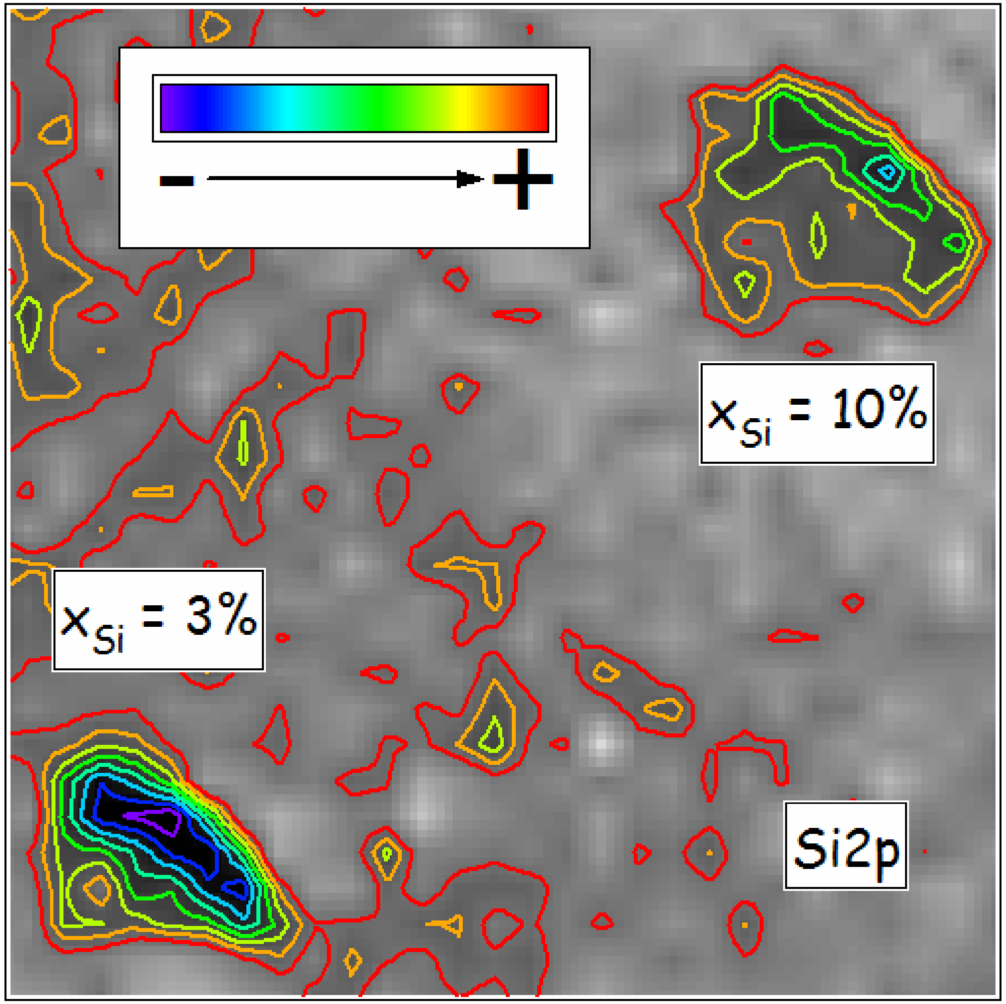
X–Ray photon energy: 130.5 eV

Growth at T = 560 °C

F. Ratto, F. Rosei et al., *Appl. Phys. Lett.* 84, 4526 (2004)

Intensity contour maps of 3 D islands

2×2 μm² Si2p core level integrated XPEEM image

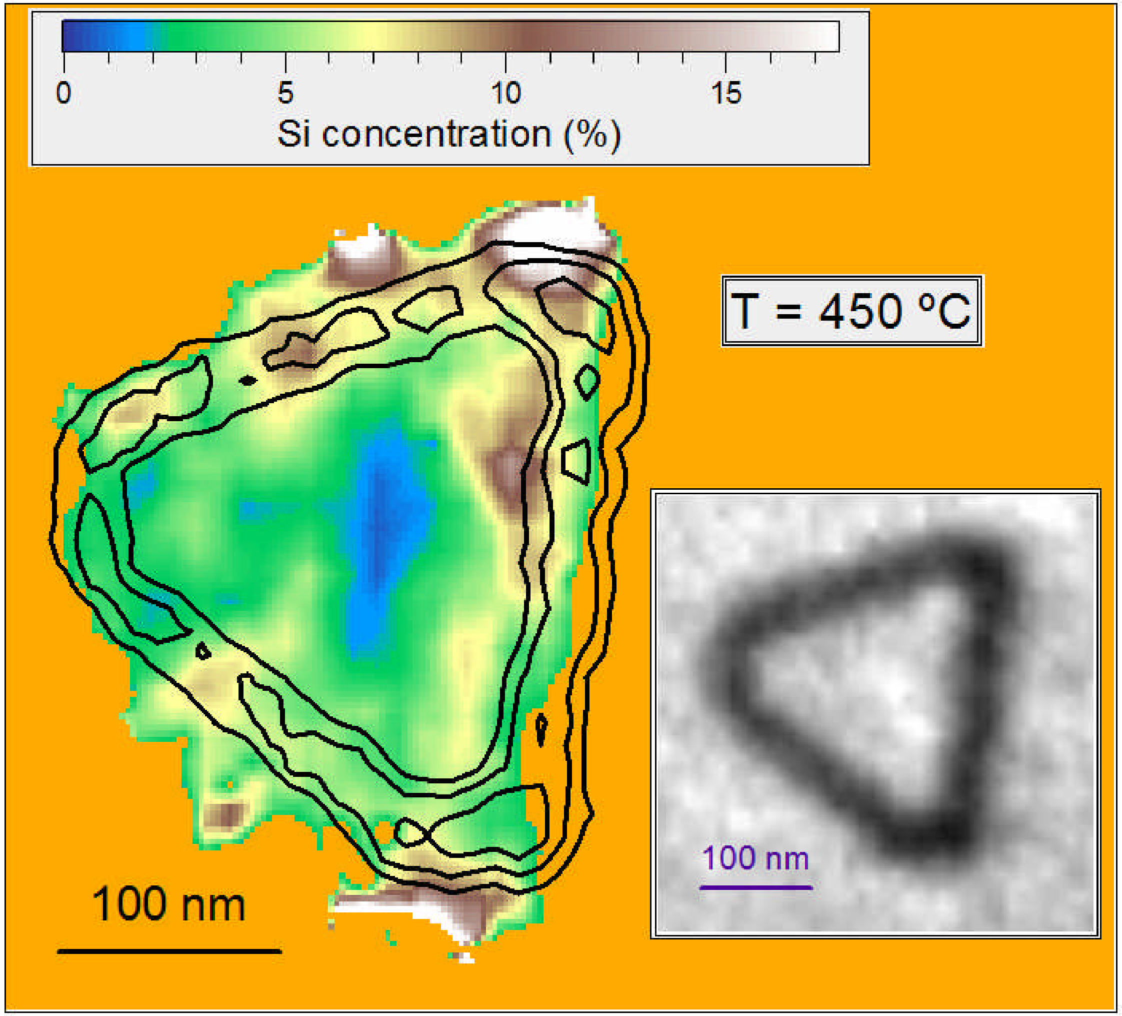


- Intensity contour maps of a more (top) and a less (bottom) ripened island.
- Photoelectron yields are increasing from blue (lowest) to red (highest).
- Darkest regions: shadows of the 3 D islands, due to the 16° X–Ray incidence angle.
- The WL is highly inhomogeneous.

Growth at T = 530 °C

F. Ratto, F. Rosei et al., *Appl. Phys. Lett.* 84, 4526 (2004)

Composition mapping of *individual* Ge/Si islands



Relative Si surface concentration in a Ge(Si) island on Si(111).

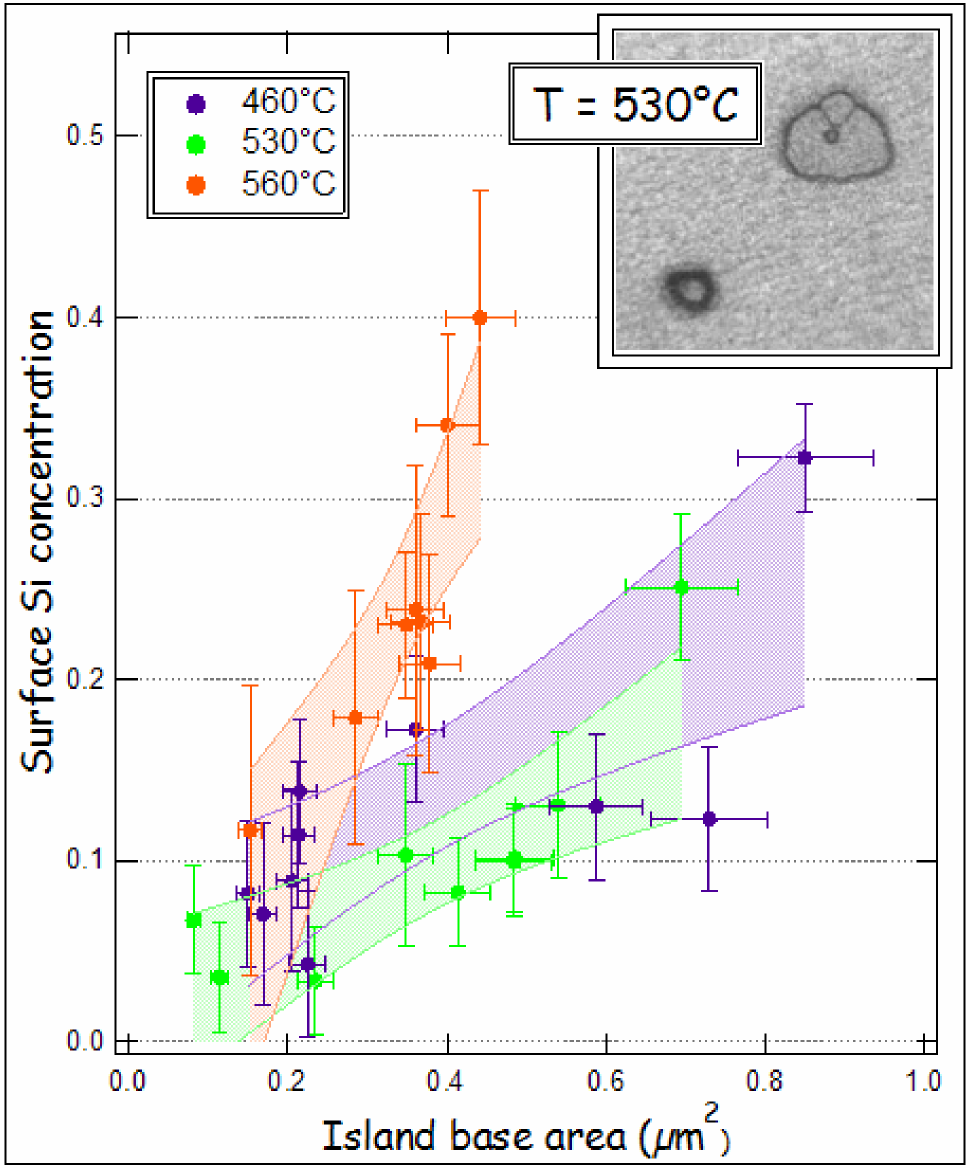
The composition mapping is obtained by combining sequences of Si2p and Ge3d XPEEM micrographs with a lateral resolution of ~30 nm.

Inset: LEEM image of the same 3D structure (~10 nm lateral resolution).

10 MLs Ge
Rate: 0.2 MLs/s
T = 450 ° C.

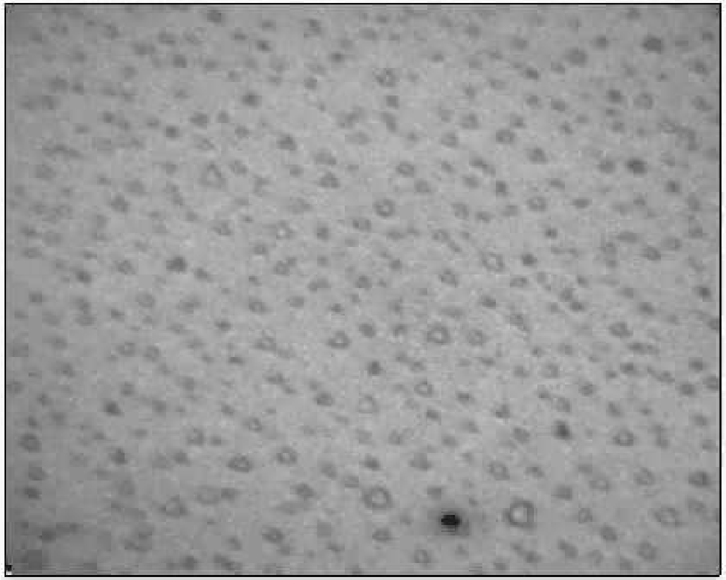
Island height: about 25 nm

Si concentration vs. island morphology

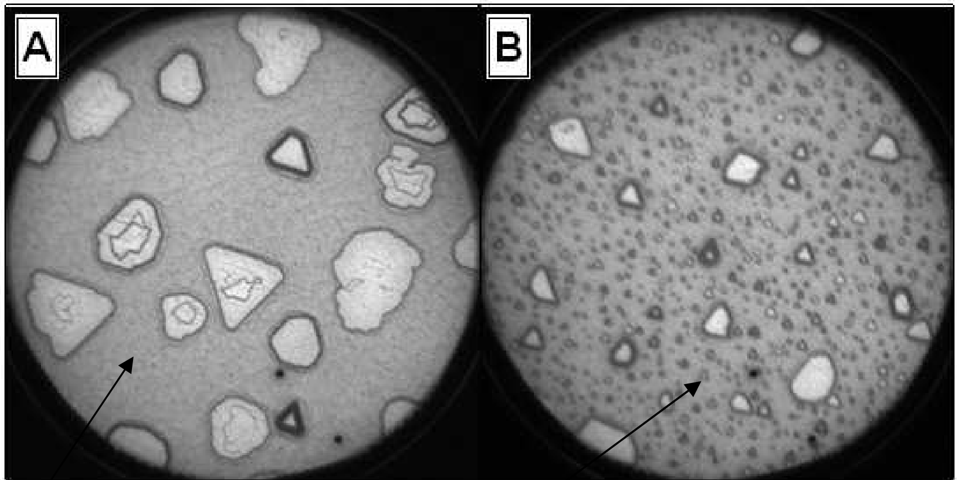


- Si surface concentration as a function of island base area.
- At each deposition temperature, the stoichiometry is uniquely determined by the island's lateral dimensions.

Two-steps growth



Two-steps growth: the WL was deposited at low temperature ~300 ° C (1st step) and the 3D islands were grown afterwards at relatively high temperature ~450 ° C (2nd step).



the 3D islands grown by the two-steps process are morphologically remarkably different from those observed after the one-step growth 0.2 ML per minute

5 x 5 um^2 LEEM image of a surface prepared by depositing 10 ML Ge on Si(111) at 450 ^{o}C

5 x 5 um^2 LEEM micrograph of a surface resulting from the two-steps growth procedure: 3 ML Ge at 300 ^{o}C followed by 7 ML Ge at 450 ^{o}C.

Conclusions and Perspectives

- **Using naturally patterned substrates, we observed island positioning on step–bunched Si(111) surfaces**
- **We have observed – by acquiring LEEM “movies” – growth instabilities that appear during post–deposition annealing of Ge nanostructures on Si(111)**
- **By means of Nanospectroscopy, or XPEEM, we can determine the *composition mapping* of *individual* 3 D Ge islands on a Si substrate**
- **=> by controlling Ge/Si alloying, it will be possible to control island size and other properties**