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

Online crystal growth by LEEM

8 ML Ge on Si(111)

LEEM Movies: Fov 10 µm

- As Ge is deposited, the reflectivity changes
- When the Wetting Layer is Complete, 3D islands nucleate randomly

T = 430 °C
T = 530 °C
T = 560 °C
Growth instability

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

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

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

- 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

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 symmetry and become atoll-like

FoV: $\sim 2.2 \times 2.2 \ \mu m^2$

from 3 to 10 ML
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 3D 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 3D islands

4×4 μm² 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

Intensity contour maps of 3D islands

- 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 3D islands, due to the 16° X–Ray incidence angle.
- The WL is highly inhomogeneous.

2×2 μm² Si2p core level integrated XPEEM image

Growth at \( T = 530 \degree \text{C} \)

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 (1\textsuperscript{st} step) and the 3D islands were grown afterwards at relatively high temperature ~450 °C (2\textsuperscript{nd} 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 \text{um}^2 \text{ LEEM image of a surface prepared by depositing 10 ML Ge on Si}(111) \text{ at } 450 \degree \text{C}

5 x 5 \text{um}^2 \text{ LEEM micrograph of a surface resulting from the two-steps growth procedure: 3 ML Ge at 300 \degree \text{C} followed by 7 ML Ge at 450 \degree \text{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 3D Ge islands on a Si substrate

• => by controlling Ge/Si alloying, it will be possible to control island size and other properties