HELLO PV - LAURIE DENTZ

# TOWARD LOW-COST LOCALIZATION OF GaAs HETEROEPITAXY ON Si

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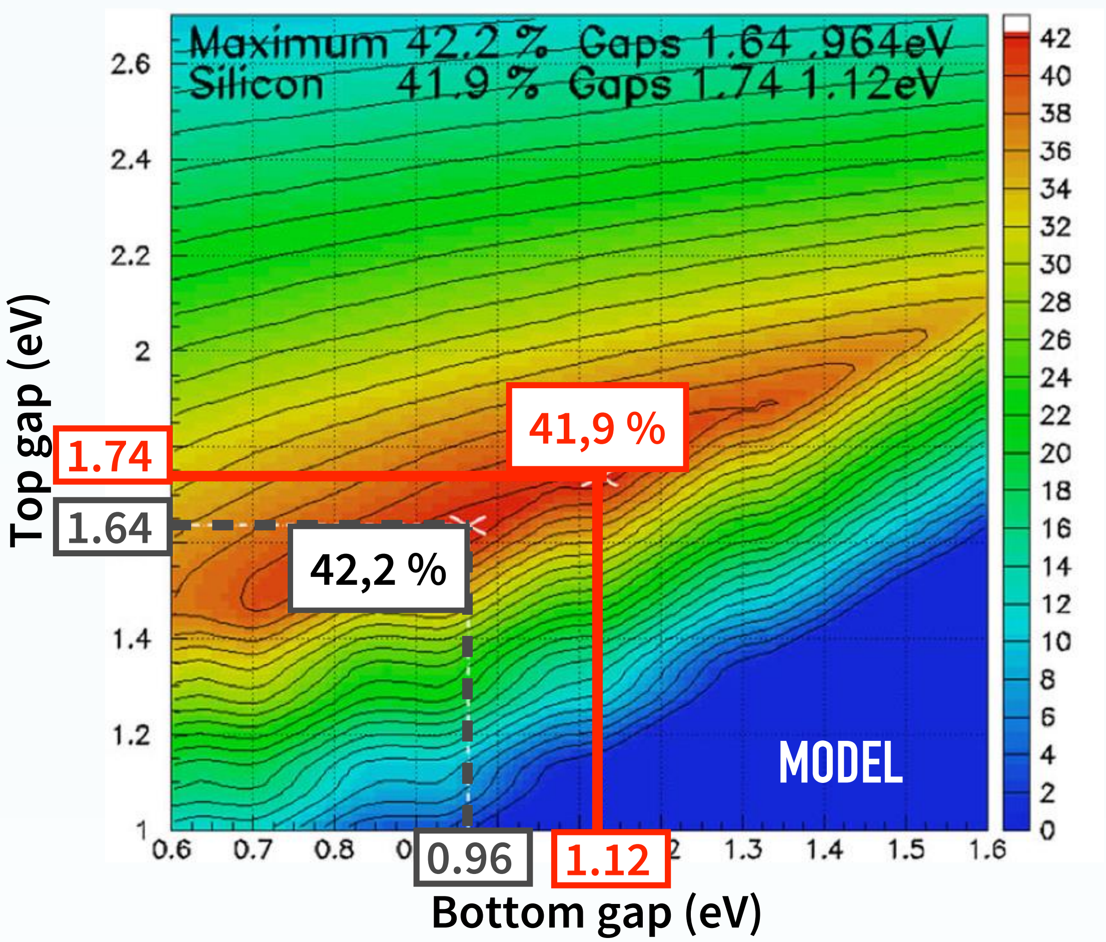
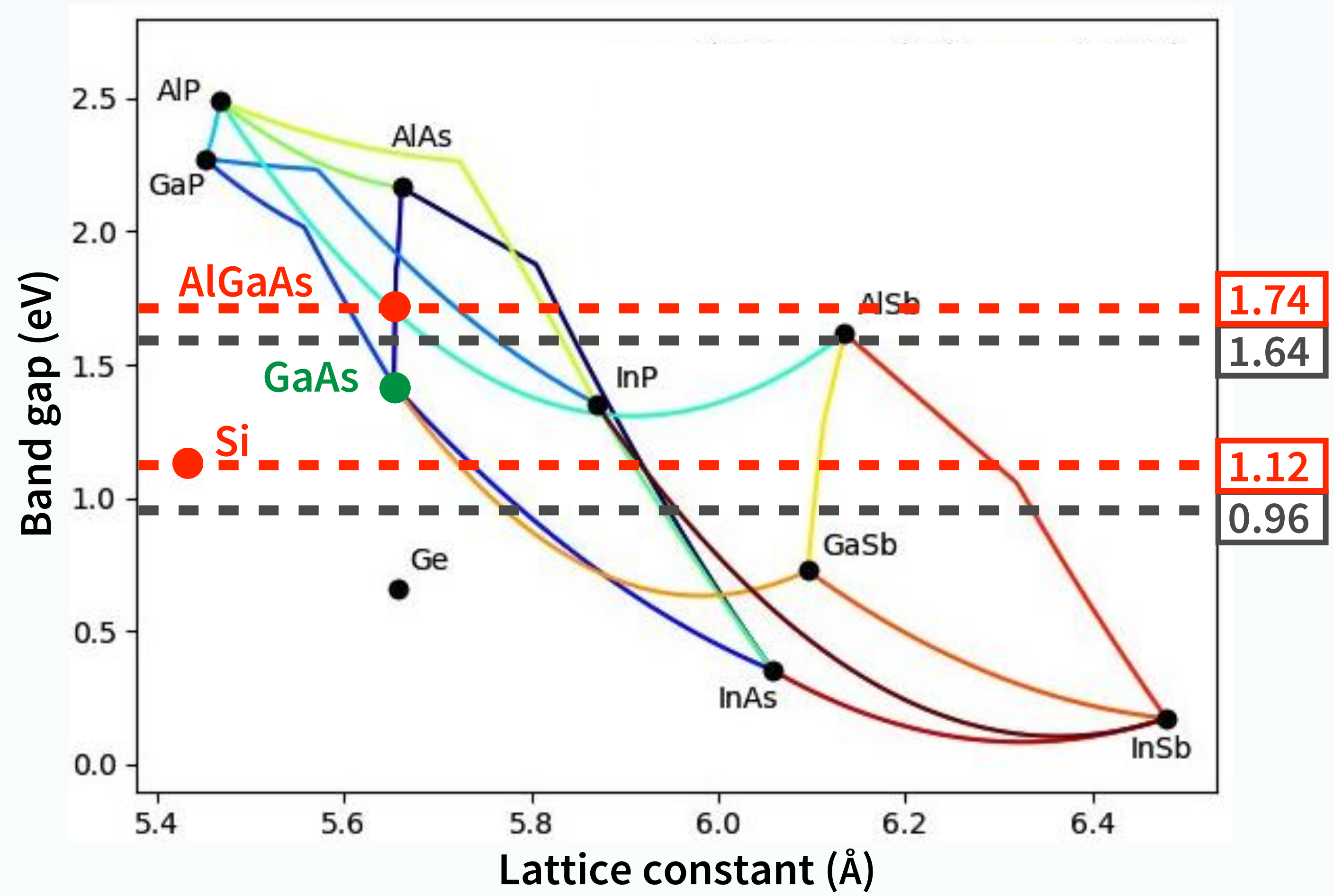
# ANR – HELLO PV : TANDEM CELL DEMONSTRATOR

## (Al)GaAs/Si: 41,9% EFFICIENCY




*Radiative efficiencies of tandem junctions for an AM1.5G solar spectrum*, J. P. Connolly and al, Prog. Photovolt: Res. Appl., 2014

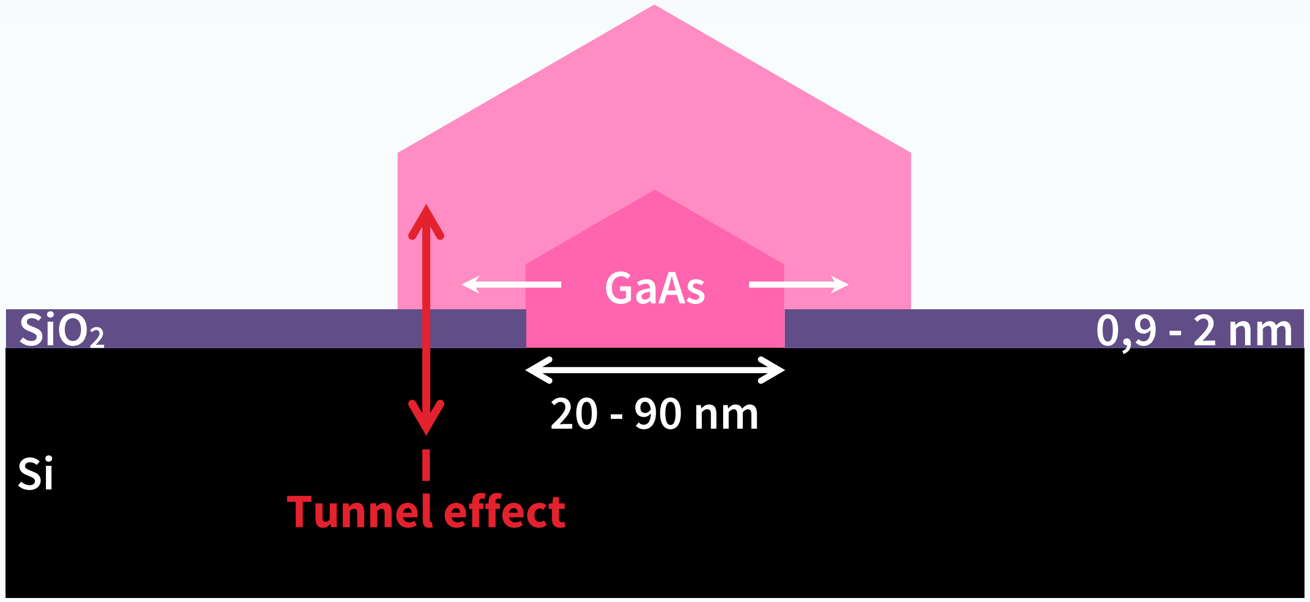
- AlGaAs/Si : **41,9 % radiative efficiency**
- Si substrate are **cheaper** than Ge substrate
- Main epitaxy challenge: **lattice mismatched**

# ANR – HELLO PV : TANDEM CELL DEMONSTRATOR

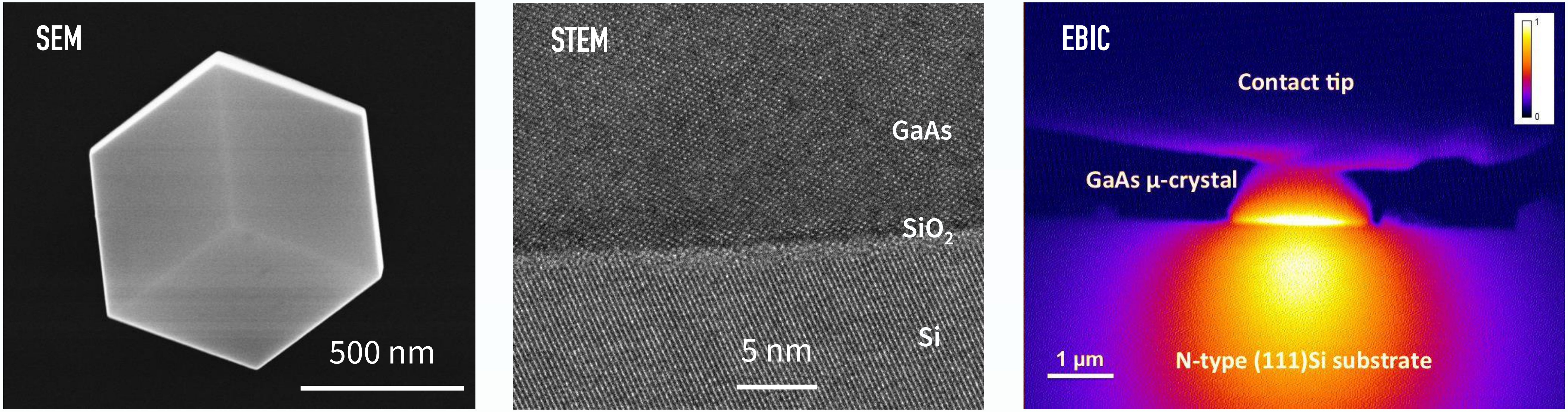


## ELTOn METHOD: Epitaxial Lateral overgrowth on Tunnel Oxide from nano-seed

GaAs micro-cristal growth in nano-openings in an ultra-thin silica layer:




- **Relaxed and non-deficient GaAs cristal:** openings < 90 nm in diameter in the $SiO_2$ layer
- **Tunnel-effect conductive interface:** $SiO_2$ layer < 2 nm thick




*C. Renard et al., Scientific Reports 6, 25328 (2016)*

# ANR – HELLO PV : TANDEM CELL DEMONSTRATOR



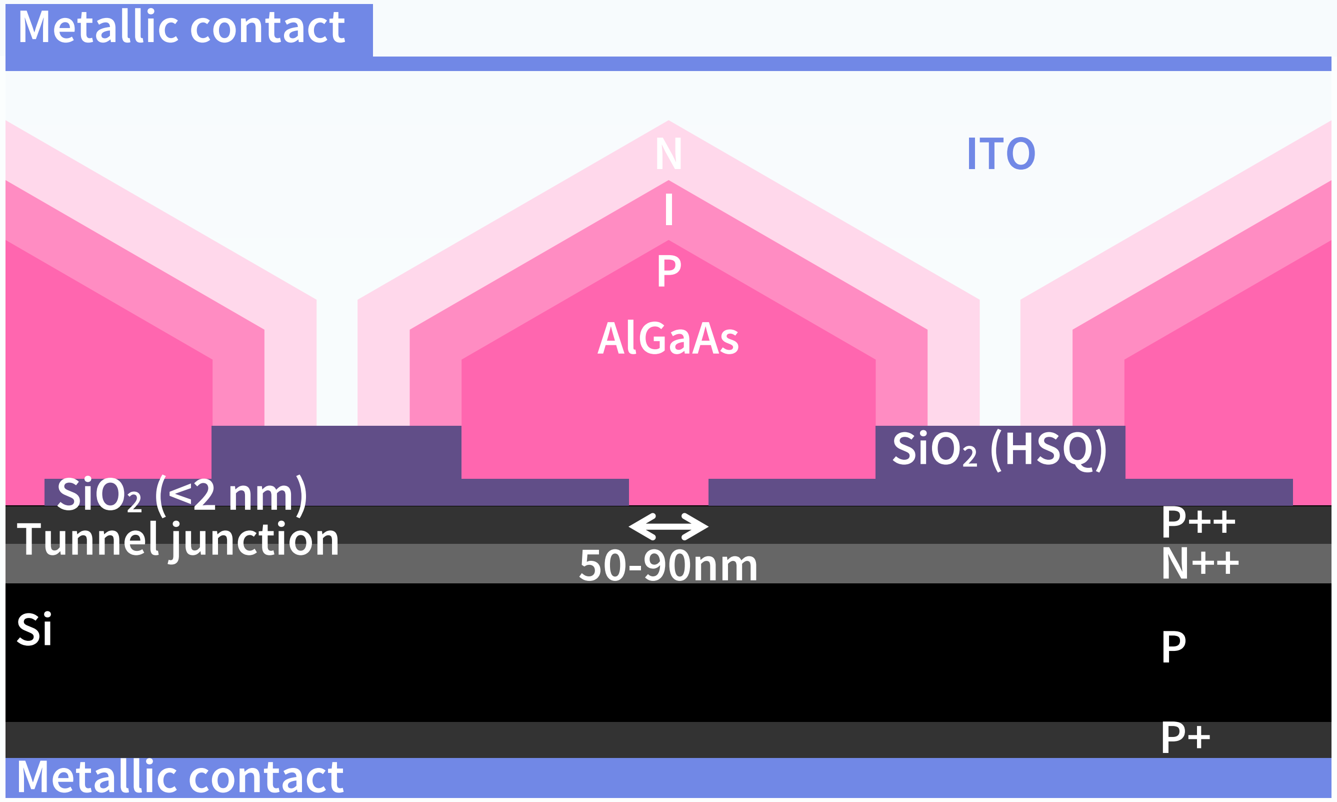
## CHALLENGE TO ACHIEVE THE MOST EFFICIENT CELL

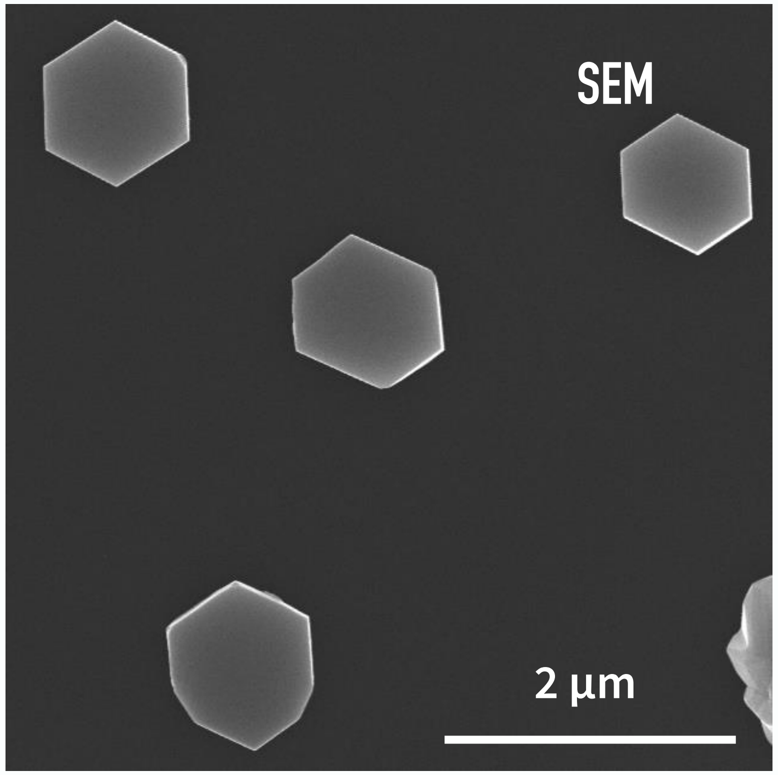
**To maximize the radiative efficiency:**

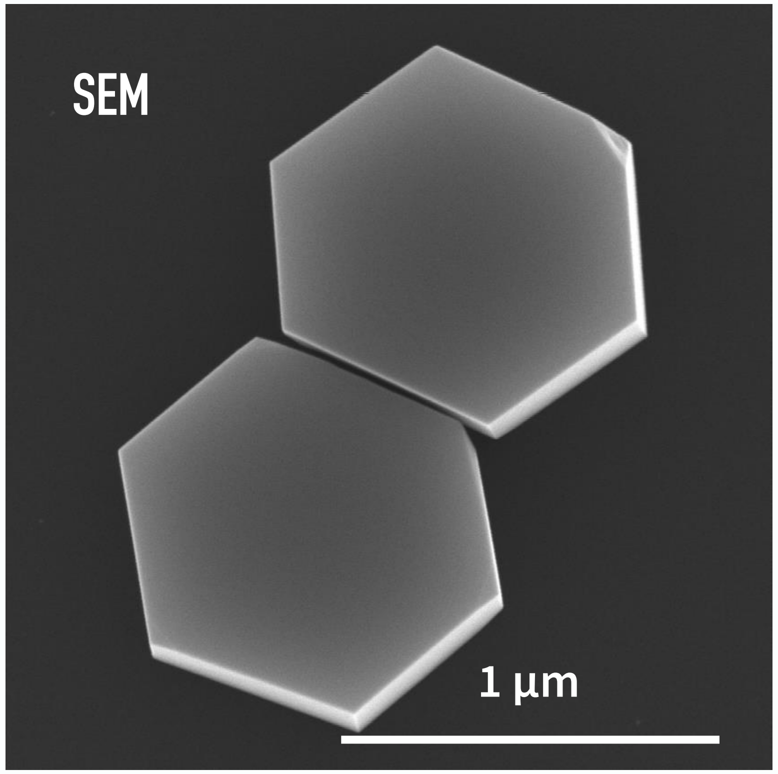
- Largest possible active surface area

**Objectives:**

- Hexagonal lattice



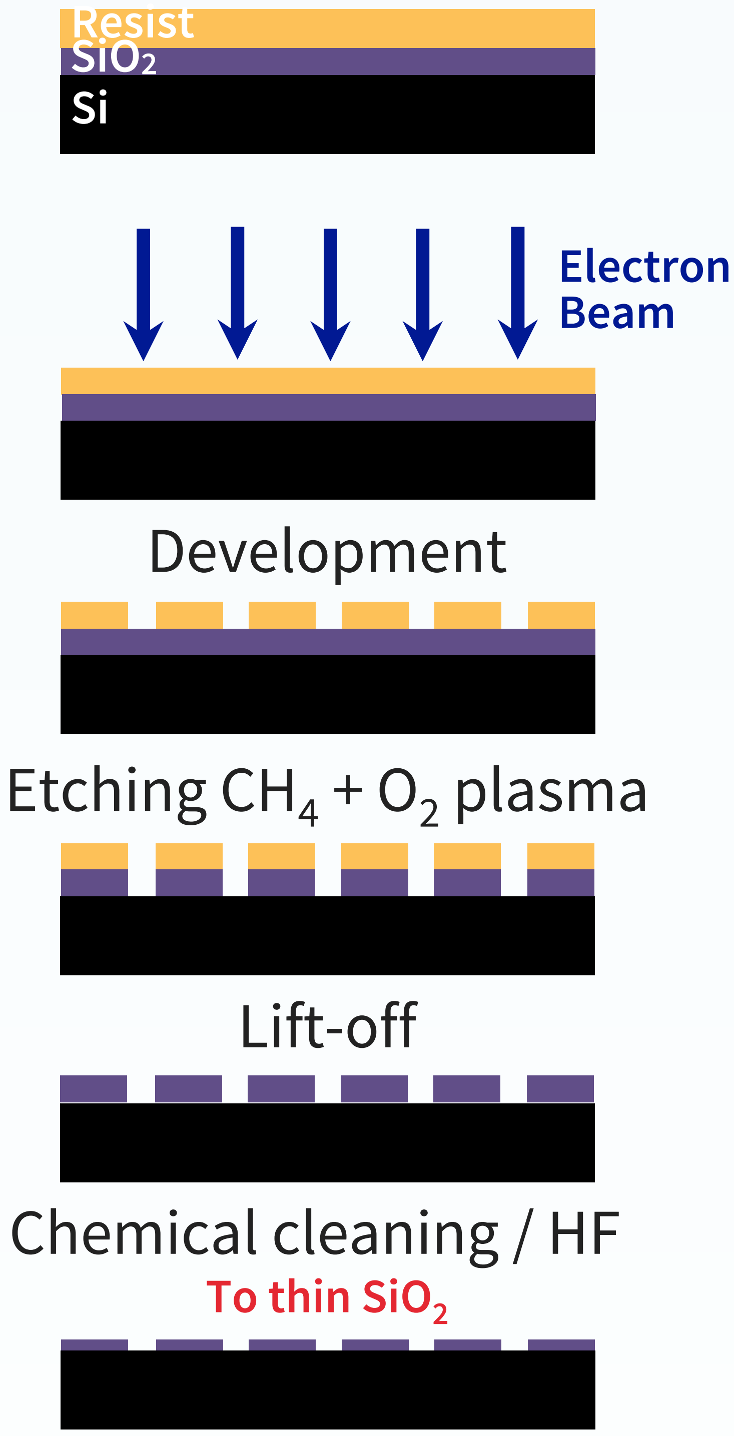



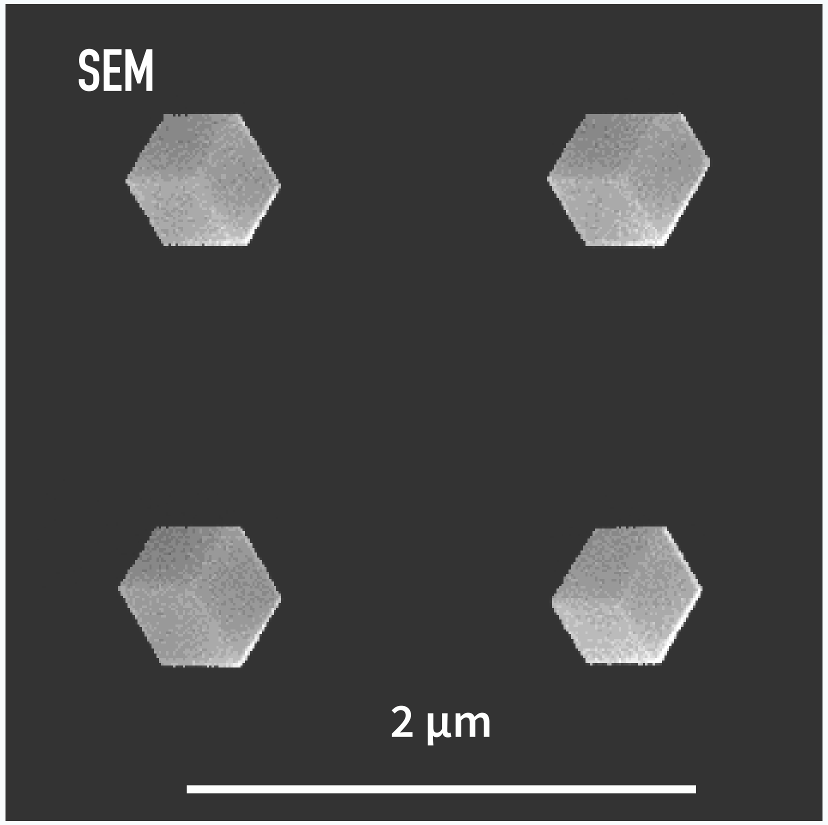

# LITHOGRAPHY TO GROWTH – PROCESSES

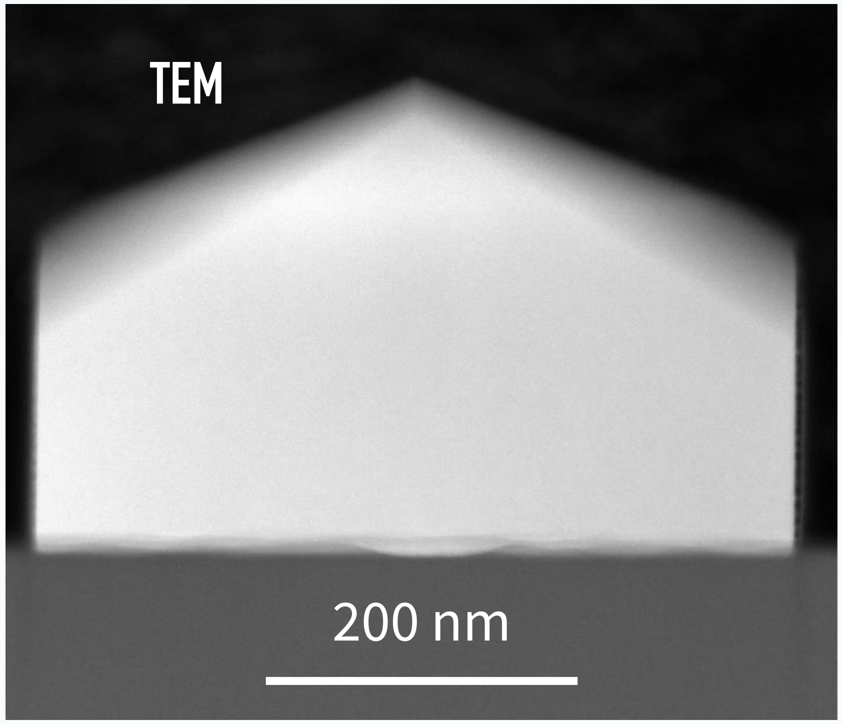


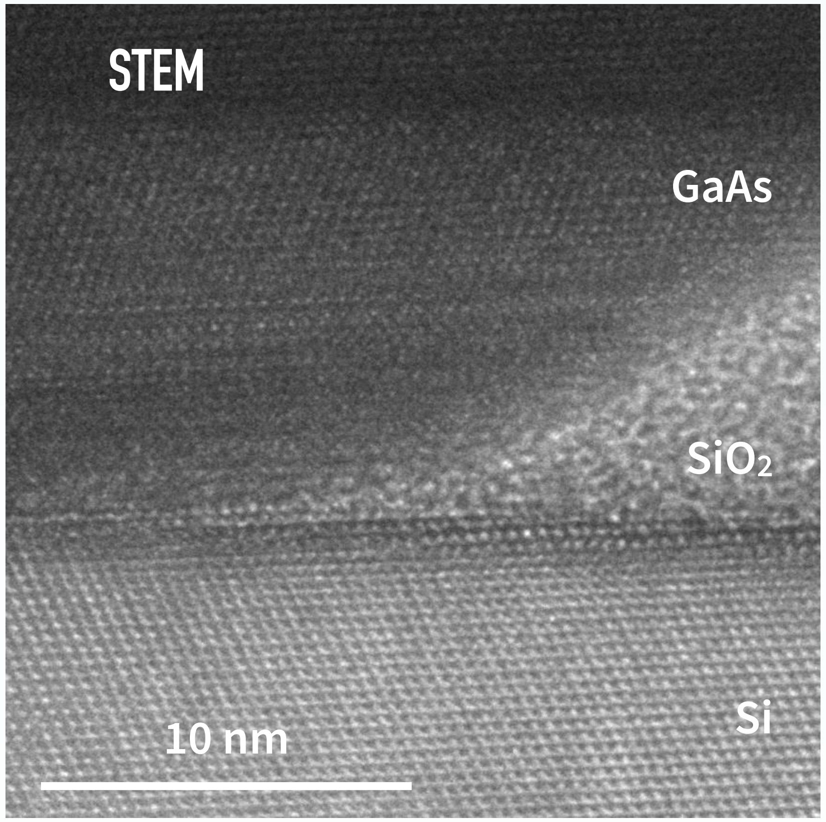
## E-BEAM

With thick $SiO_2$




$SiO_2$
10 nm

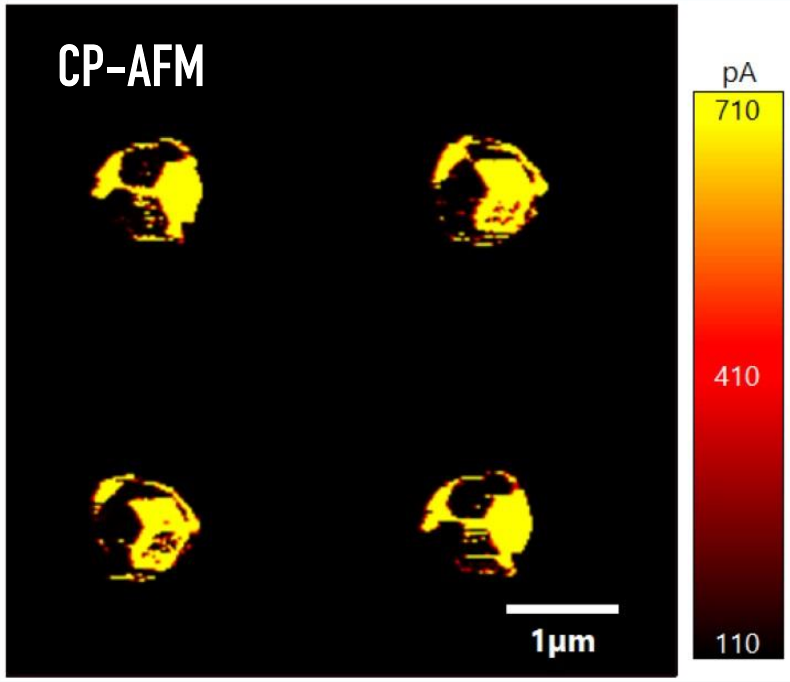
**GaAs / Si :**

Good integration

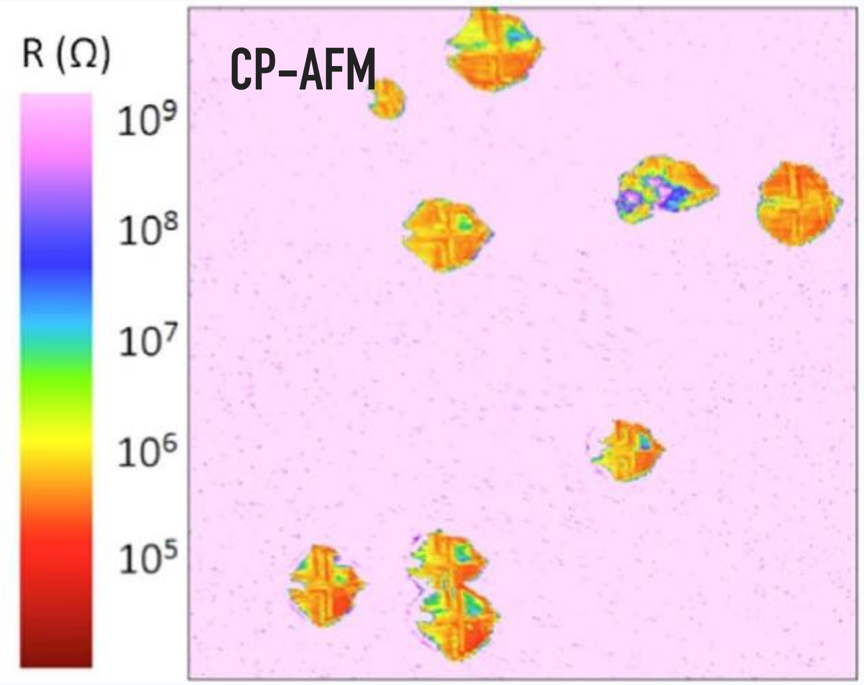
Good cristalinity

# LITHOGRAPHY TO GROWTH

## E-BEAM




## RANDOM OPENINGS




*C. Renard et al. Sci. Rep. 6 (2016)*

Direct polarisation 4V:

$7.10^{-7}$ A ⟶ $4{,}2.10^{-5}$ A

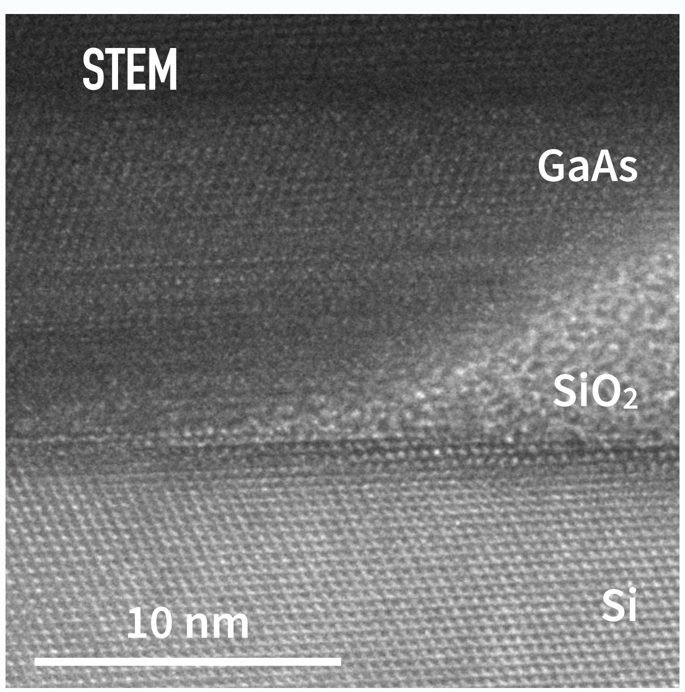
**200 times lower**

Through the openings:

**7 kA.cm$^{-2}$**

Through the entire crystal:

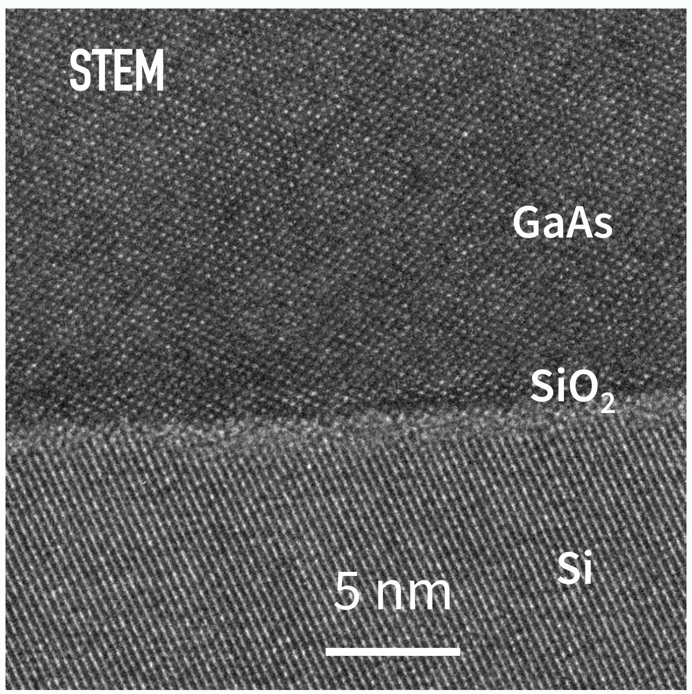
**10 kA.cm$^{-2}$**




$SiO_2$
10 nm
No tunnel effect

✳ **10nm $SiO_2$ thickness: current is limited through the oxide**

$SiO_2$
< 2 nm
Tunnel effect

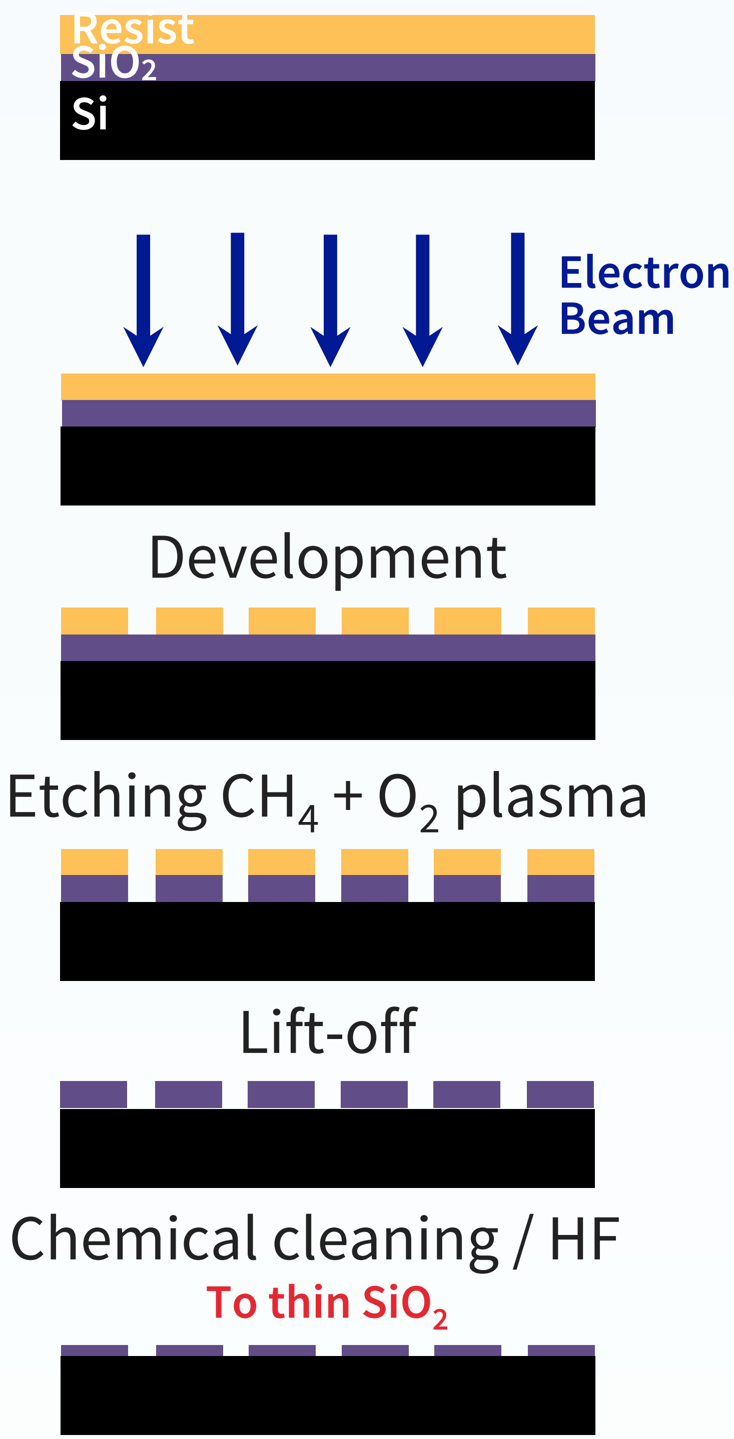



*CP- AFM: Conducting Probe Atomic Force Microscope*

# LITHOGRAPHY – PROCESSES

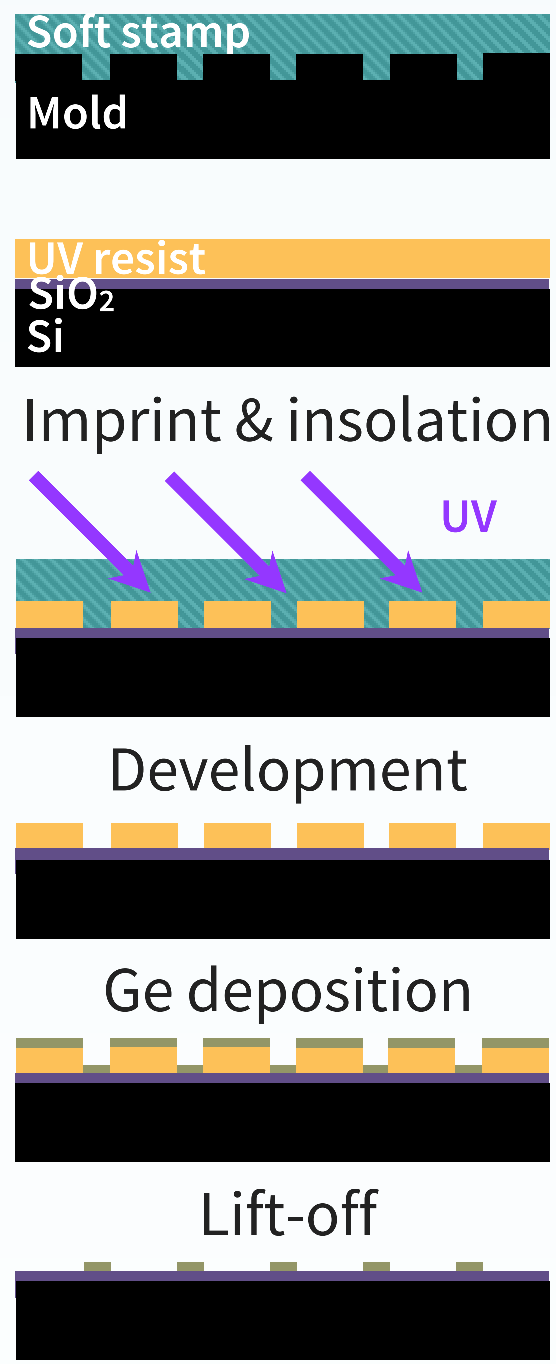
## E-BEAM

With thick $SiO_2$



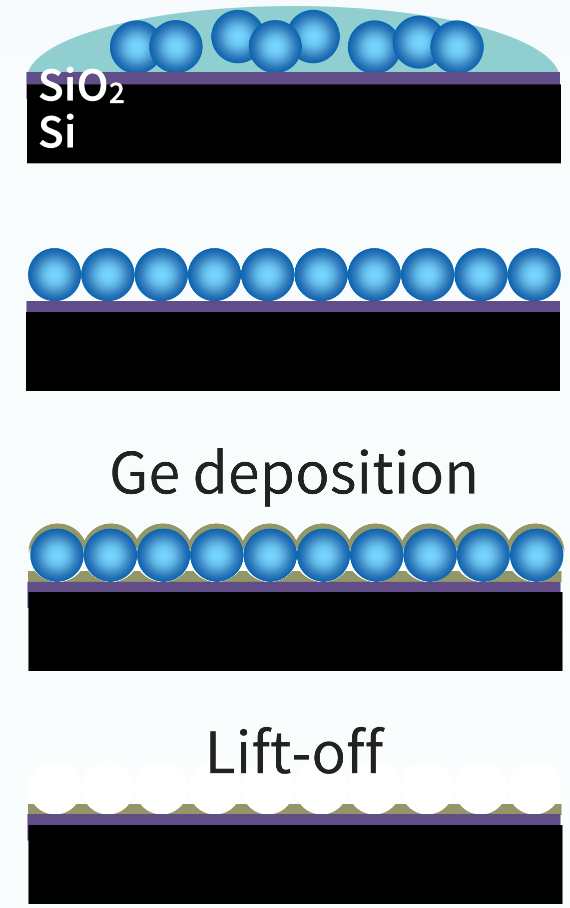

## SOFT-UV NIL

With thin $SiO_2$



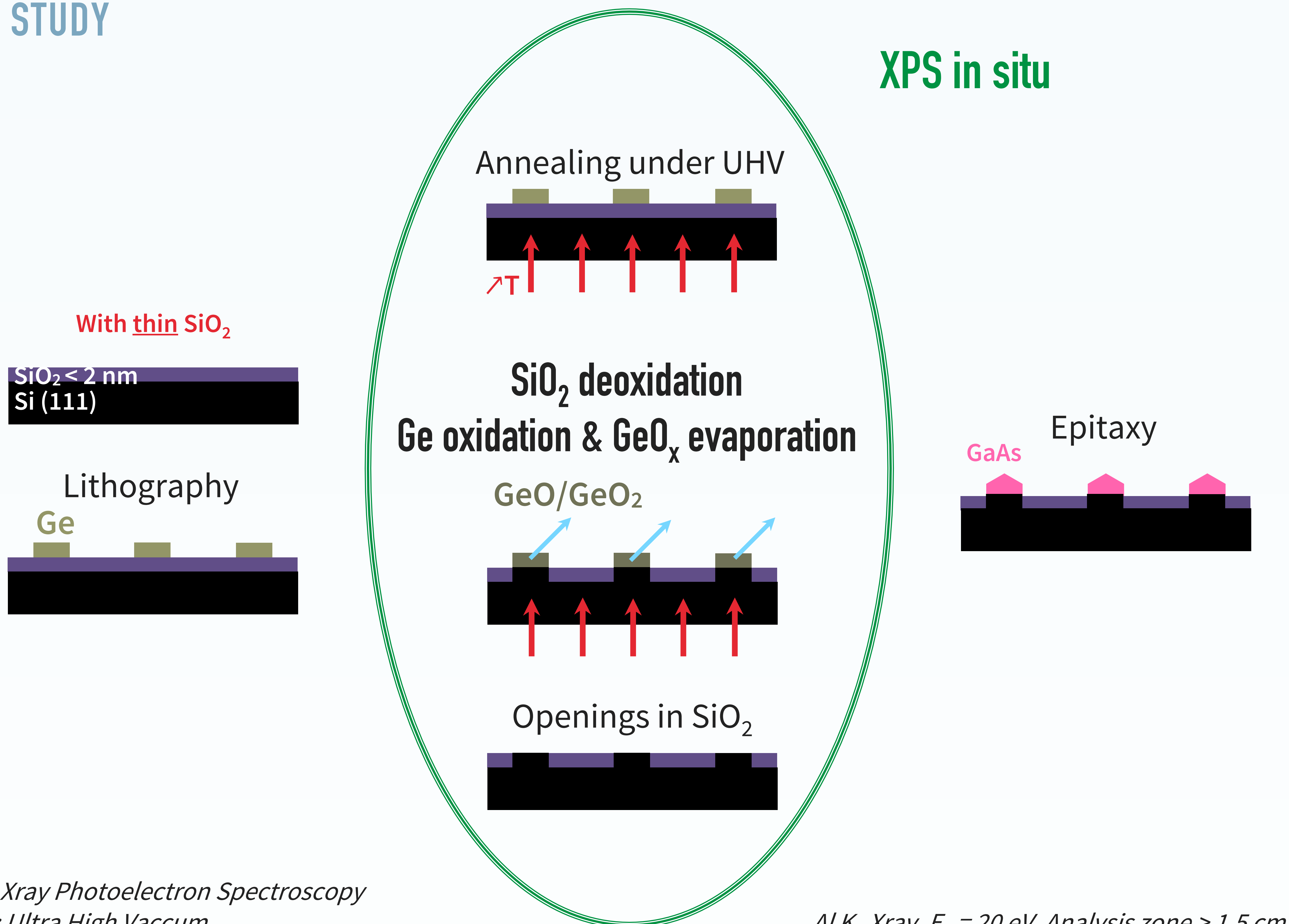

## NANOSPHERE

With thin $SiO_2$



# LITHOGRAPHY TO GROWTH – GERMANIUM EVAPORATION

## XPS STUDY




*XPS: Xray Photoelectron Spectroscopy*
*UHV: Ultra High Vaccum*

*Al $K_\alpha$ Xray, $E_p$ = 20 eV, Analysis zone > 1,5 cm*

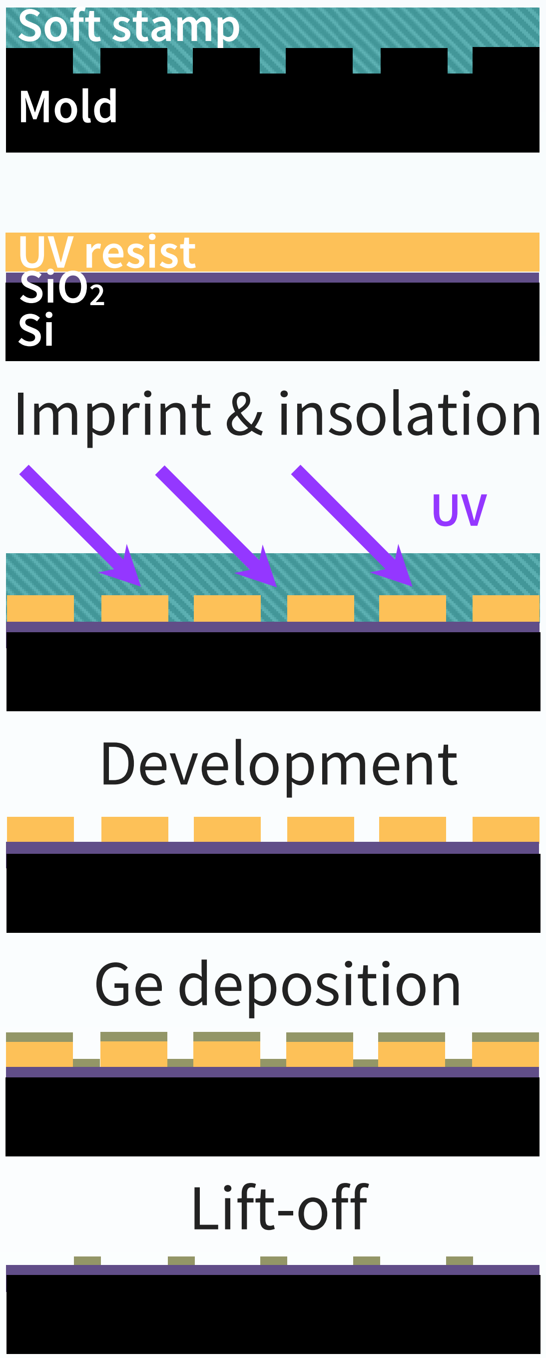
HELLO PV – LAURIE DENTZ

# ALTERNATIVE LITHOGRAPHY

# Soft-UV NIL : NANO-IMPRINT LITHOGRAPHY

## SOFT-UV NIL

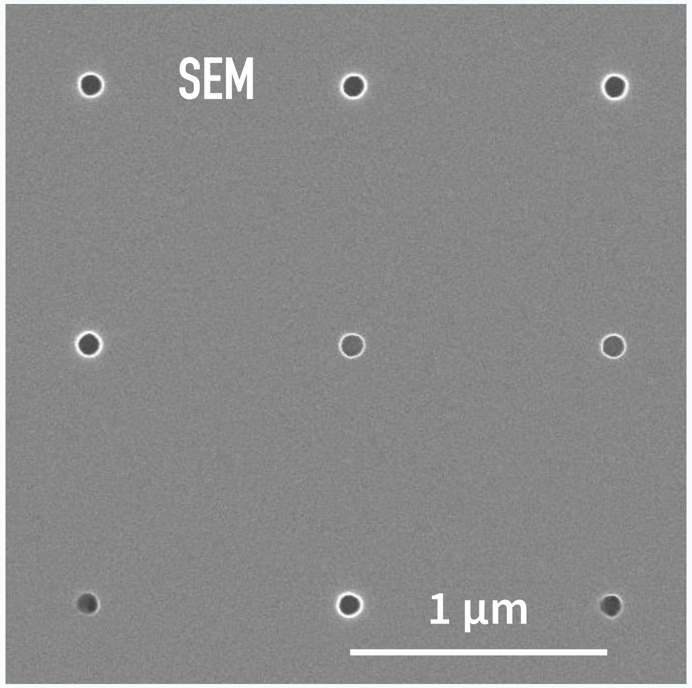
- Molds produced with e-beam lithography
- Stamps are produced in PDMS from those molds
- Nano-imprint:
  Si substrate covered with a UV-sensitive resist (sacrificial PMMA + AMONIL), then apply the stamp, expose it to UV light, and remove the stamp.
- Etch to remove the sacrificial and residual resist.
- Germanium deposition.
- Lift-off with solvents: acetone (ultrasound) + IPA

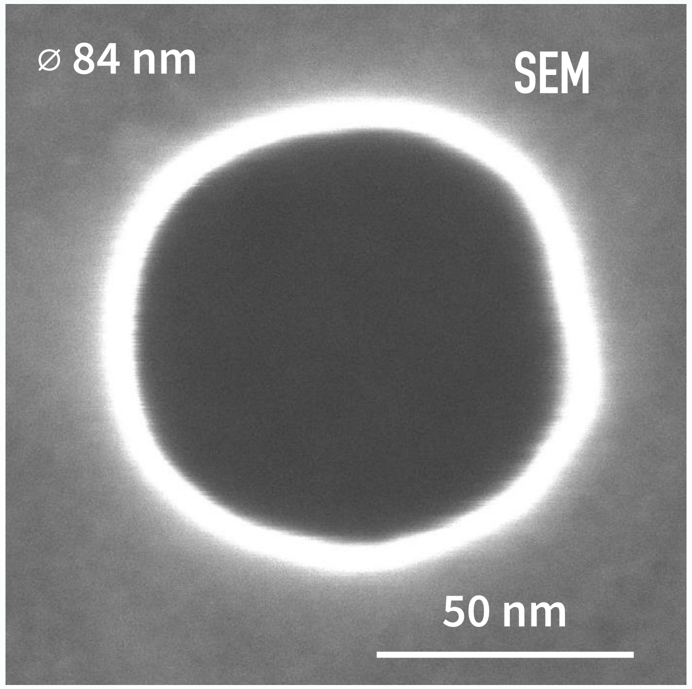


# Soft-UV NIL : NANO-IMPRINT LITHOGRAPHY



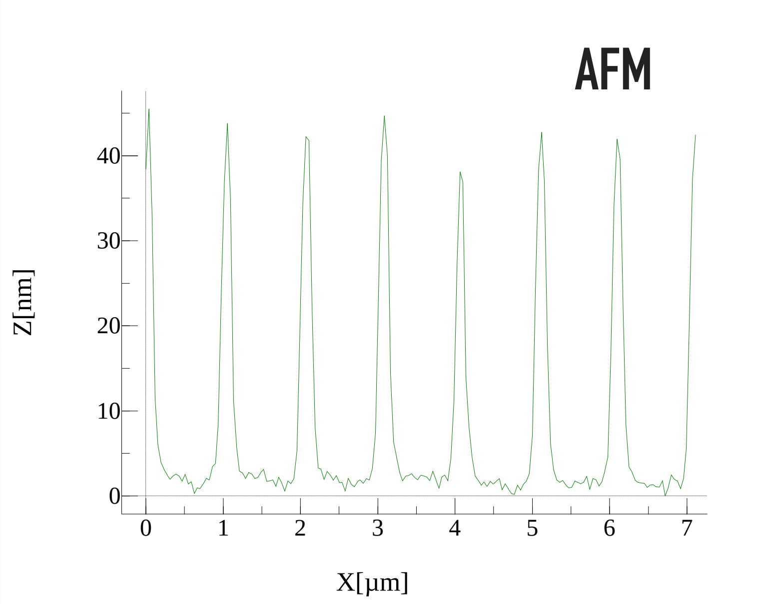
## MOLD

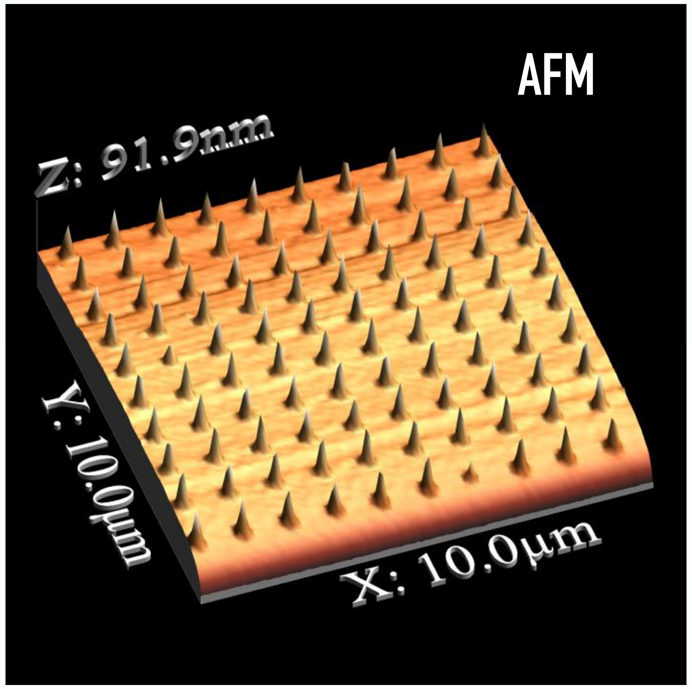



## STAMP

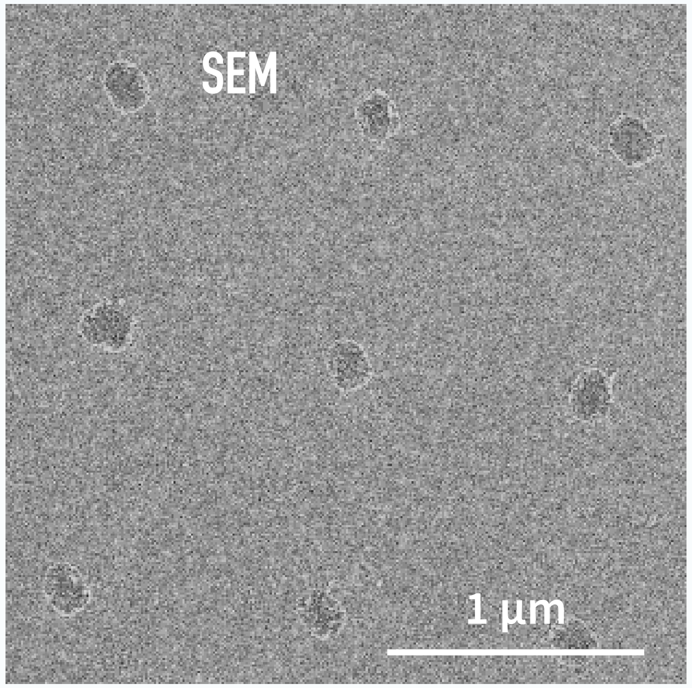
Mean length 42 nm

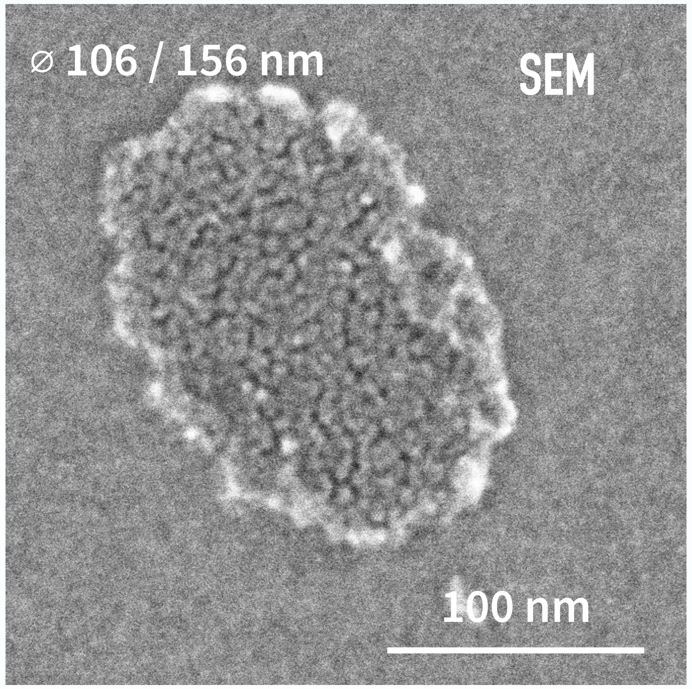



## IMPRINT

2nm Ge deposit



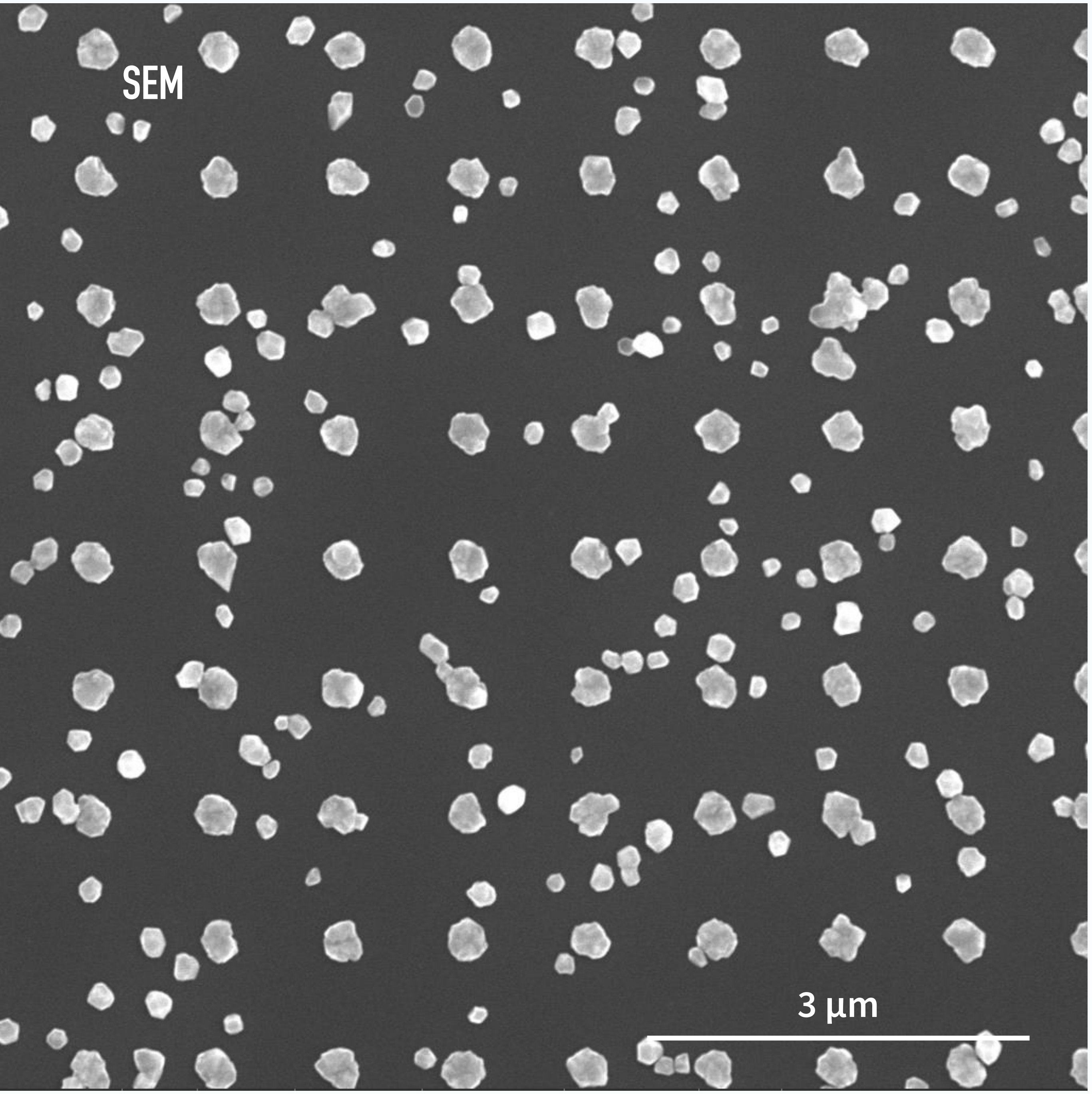



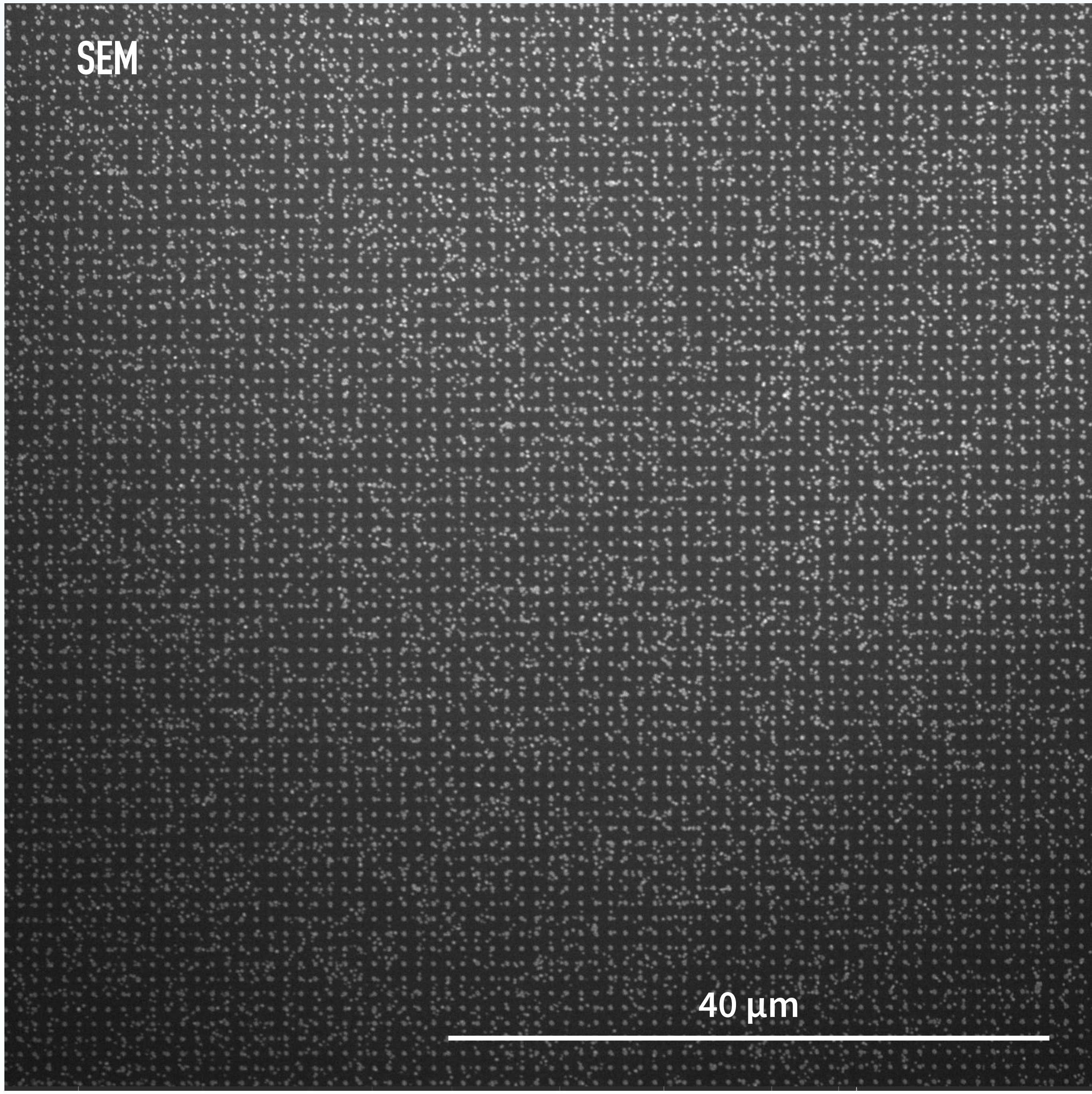

*AFM: Atomic Force Microscope*

# Soft-UV NIL : NANO-IMPRINT LITHOGRAPHY

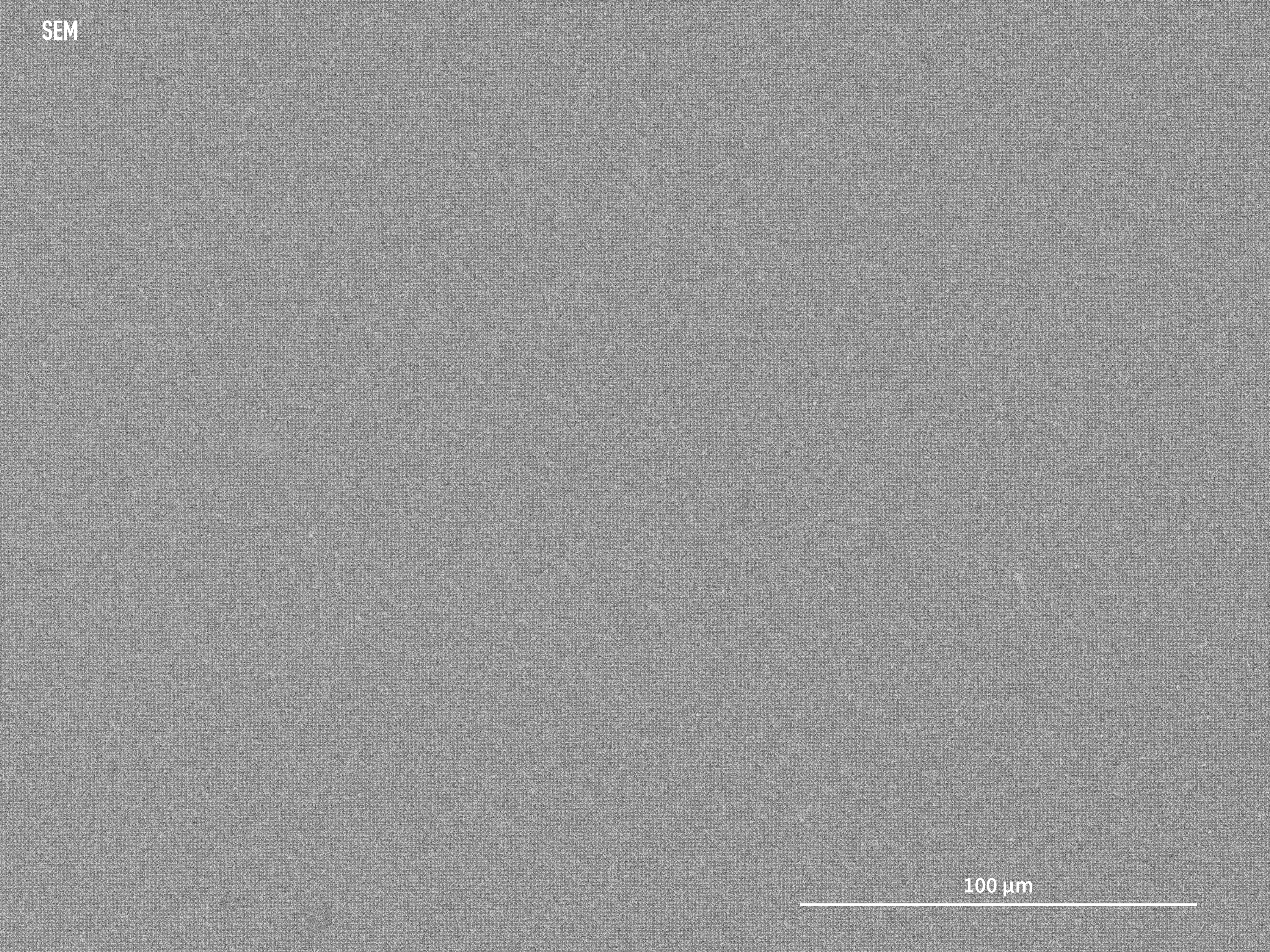
## GROWTH TEST

1h15 annealing at 675°C




**Proof-of-concept for localised growth by Soft-UV NIL**


SEM
100 µm

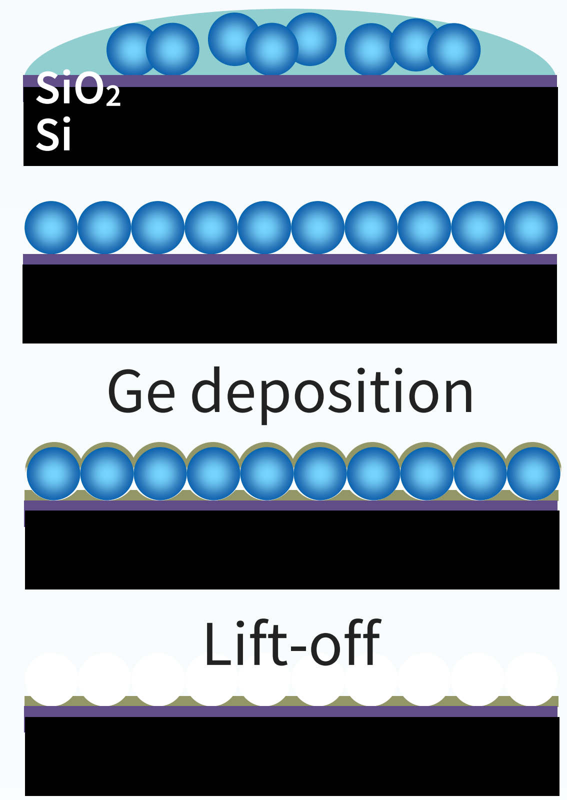
# NSL : NANOSPHERE LITHOGRAPHY

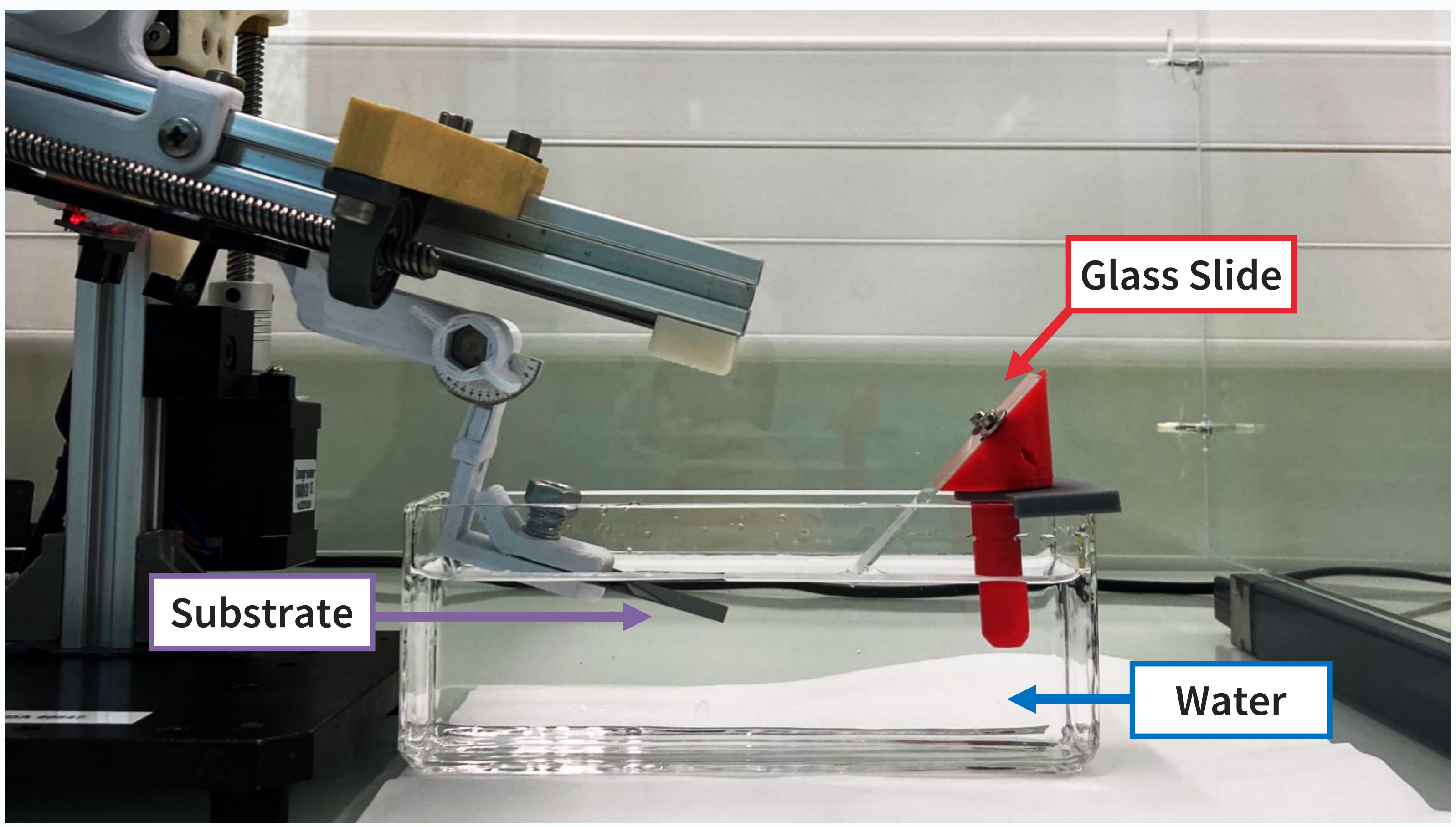


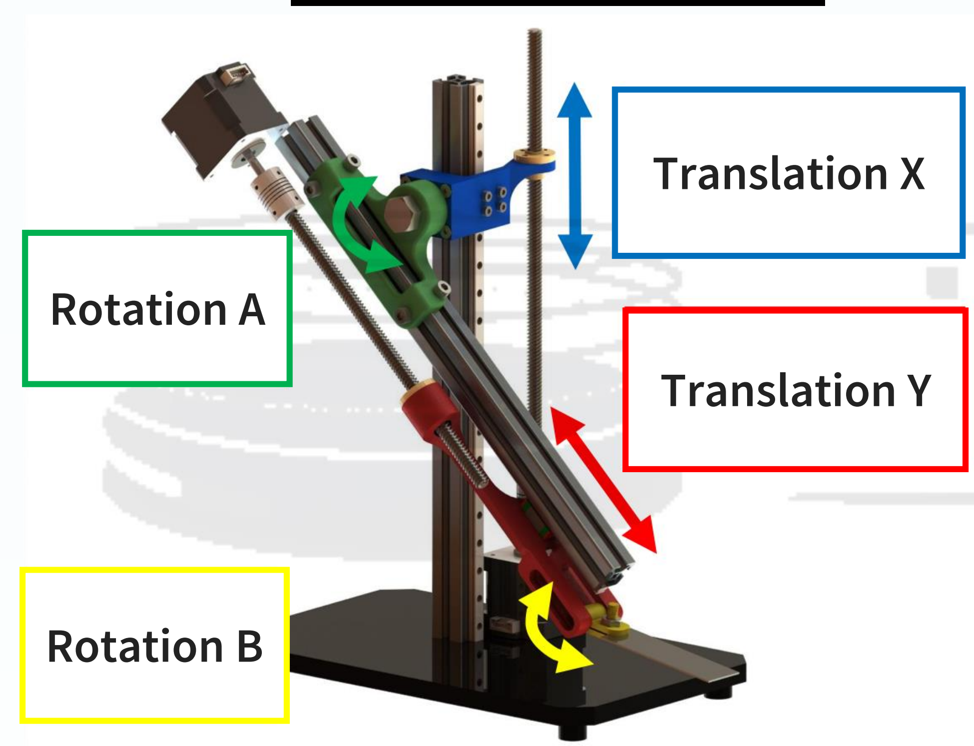
## DIP COATING

- Immerse the substrate
- Nanosphere deposit on the glass slide
- Slowly remove the substrate from the water
- Nanosphere self-assembly at the air-water interface

## NANOSPHERE



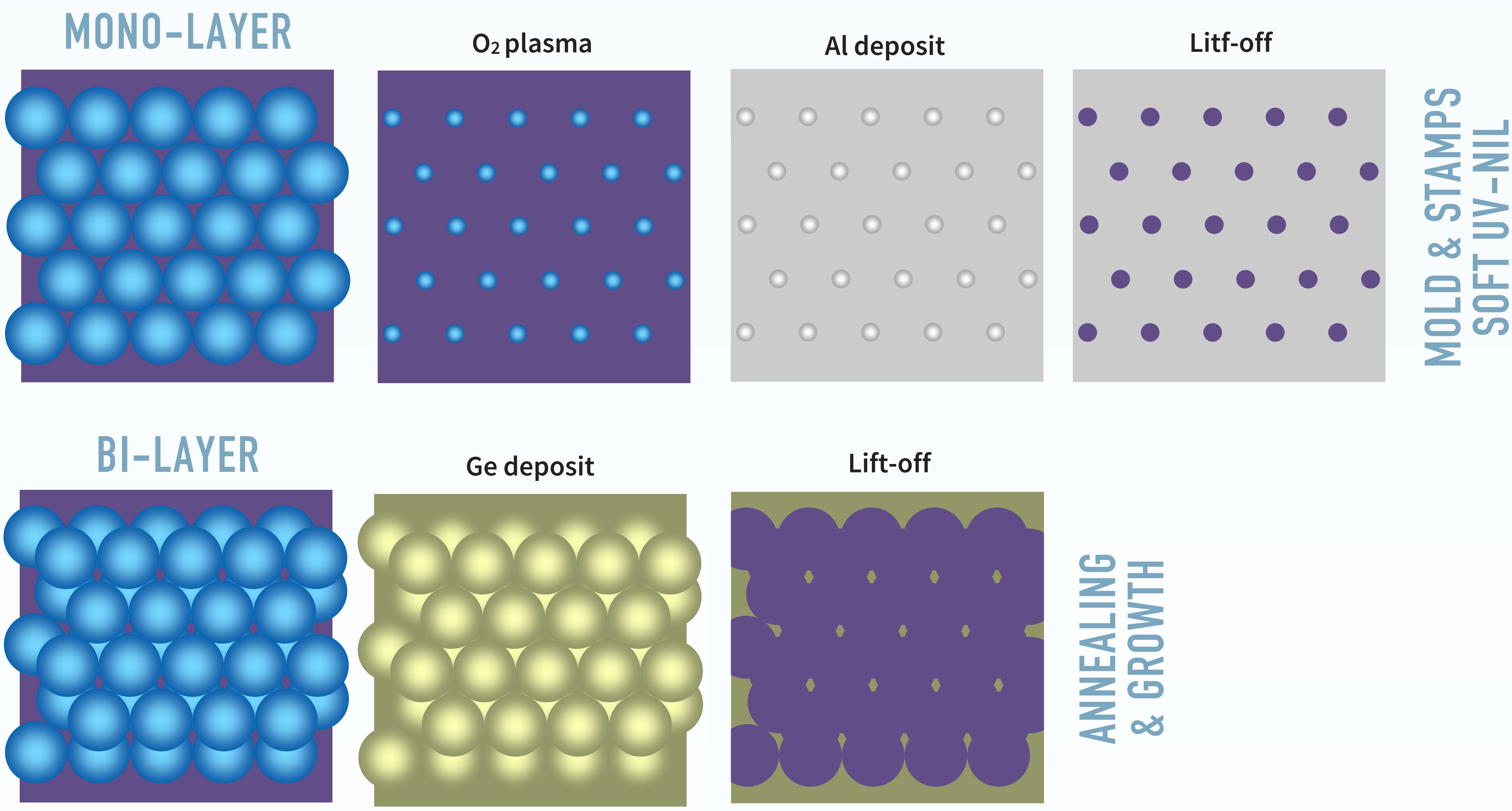

**SILSEF equipment loan*

# NSL : NANOSPHERE LITHOGRAPHY

## TWO POSSIBLE DEPOSITION

Self-organising into a **compact hexagonal lattice**

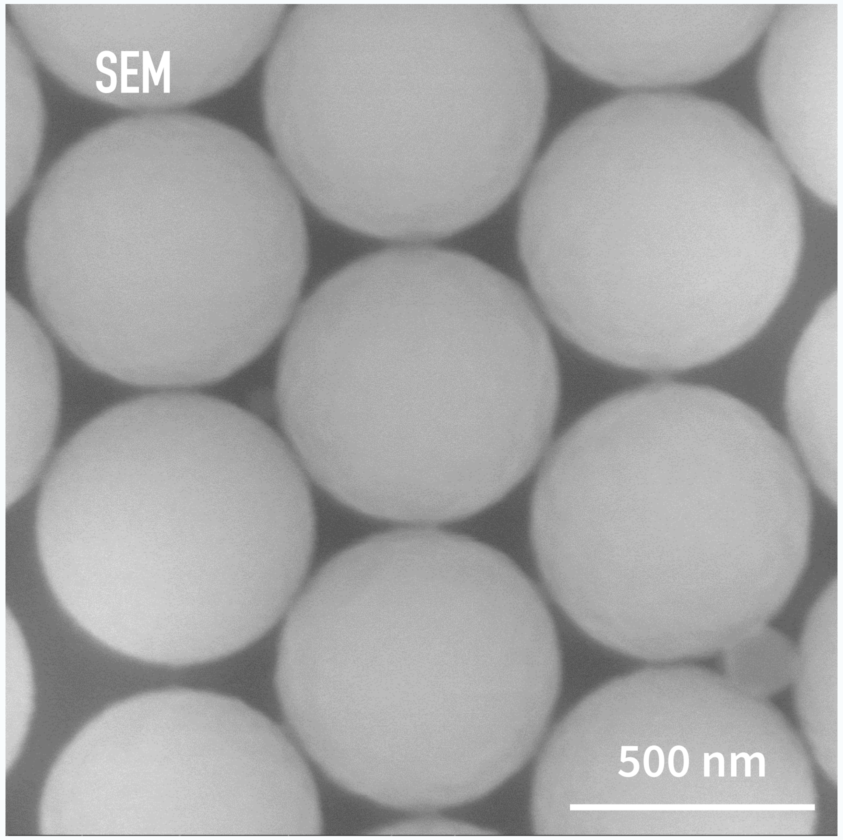
Control over aperture size and pattern size.



# NSL : NANOSPHERE LITHOGRAPHY



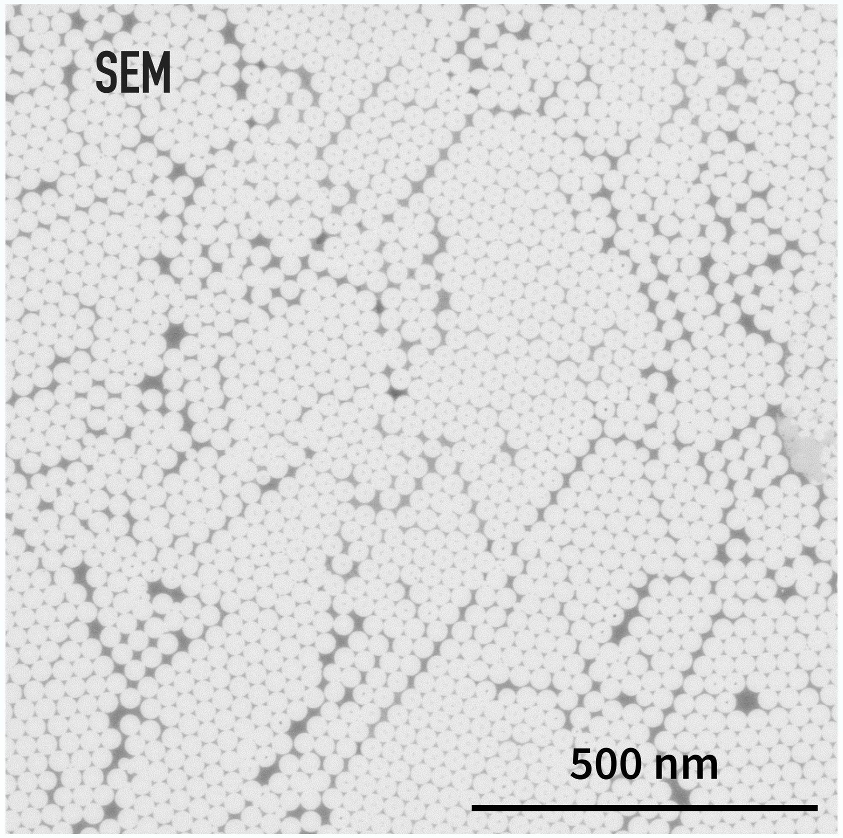
## GE DEPOSITION TEST

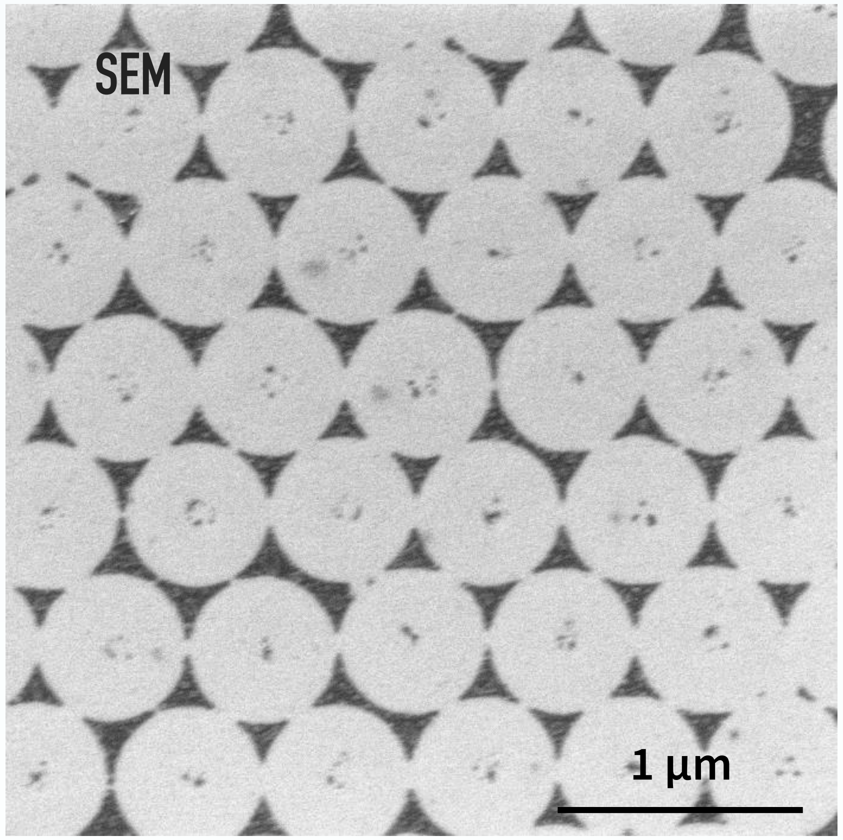


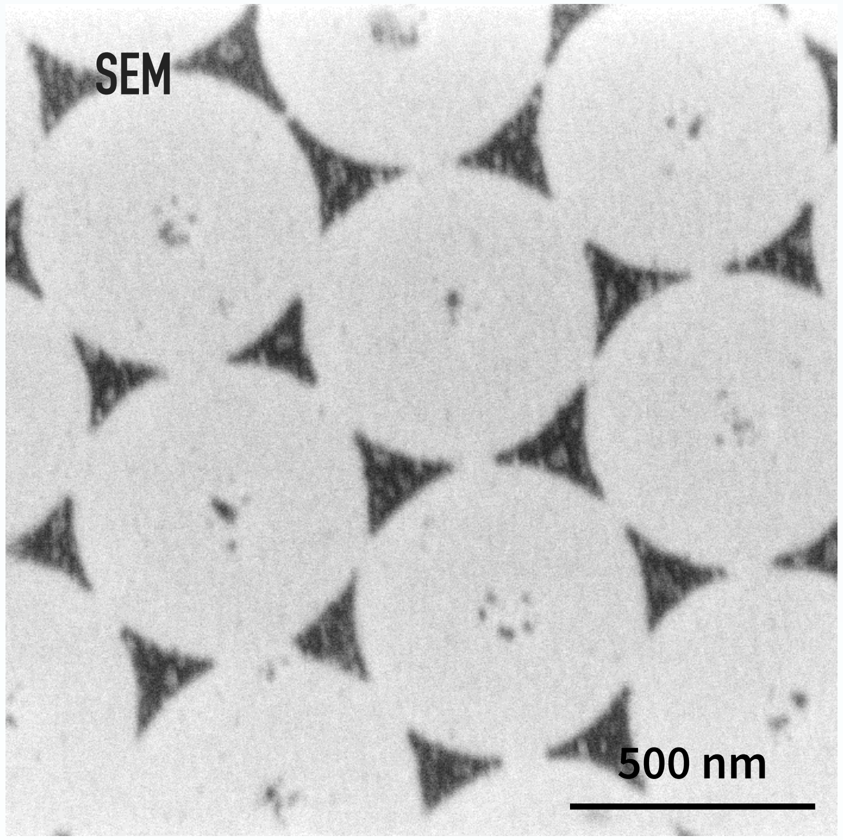

**⌀ 607 nm polystyrene nanosphere from VogelLab**

On Si(111), thin chemical oxide $SiO_2$ (<2nm)

<u>3 nm Ge deposit & lift-off :</u>



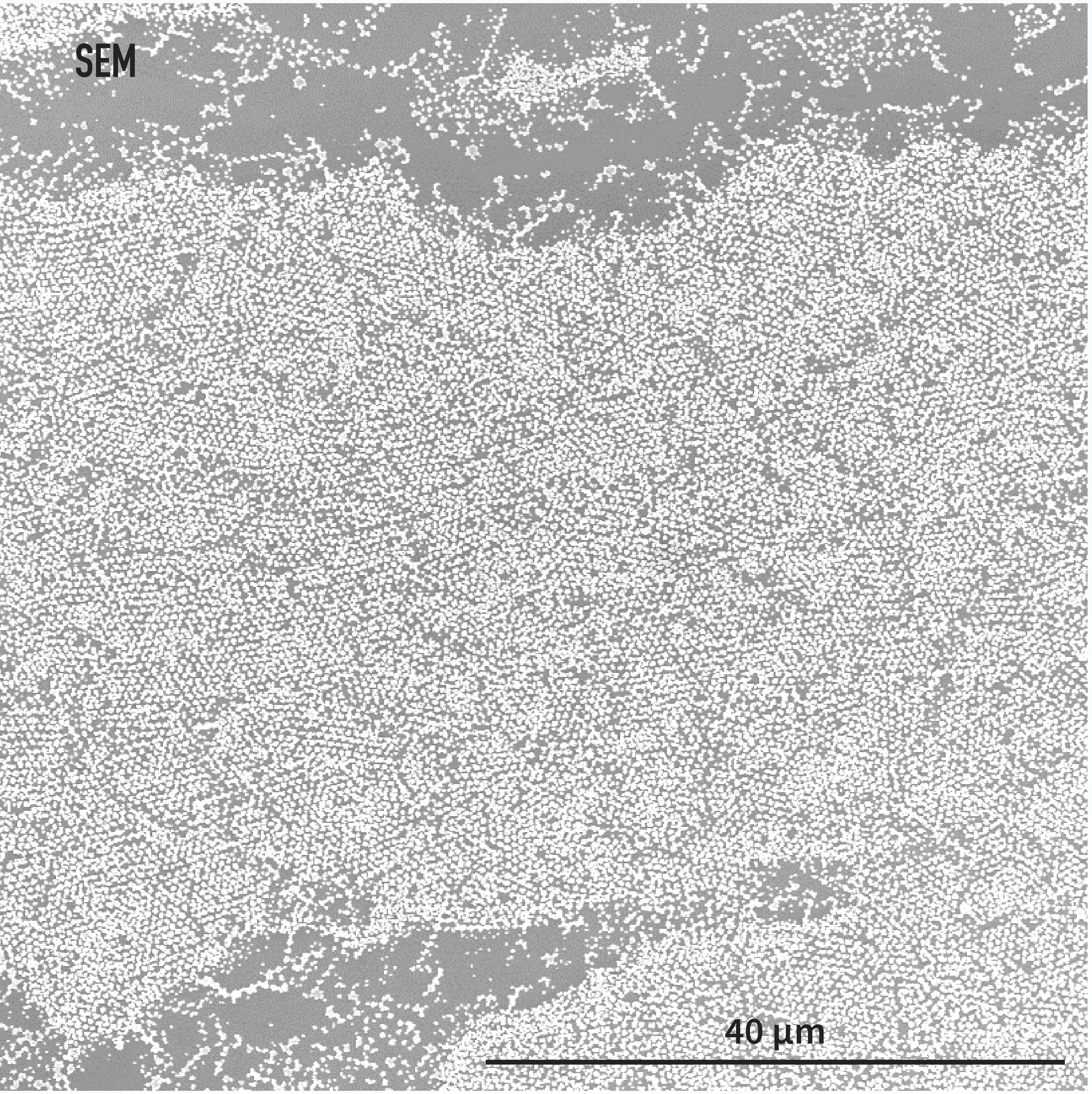



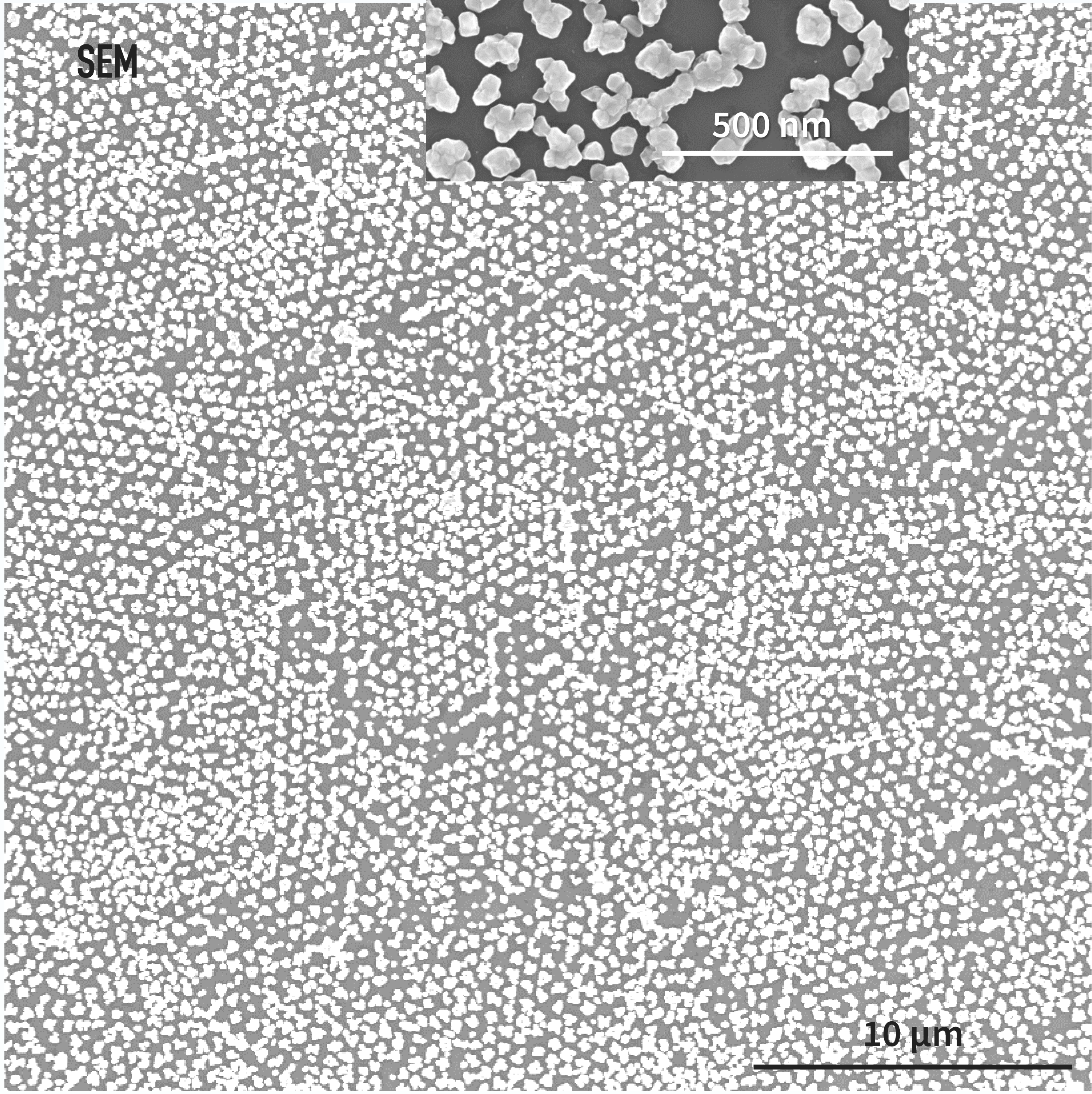
# NSL : NANOSPHERE LITHOGRAPHY

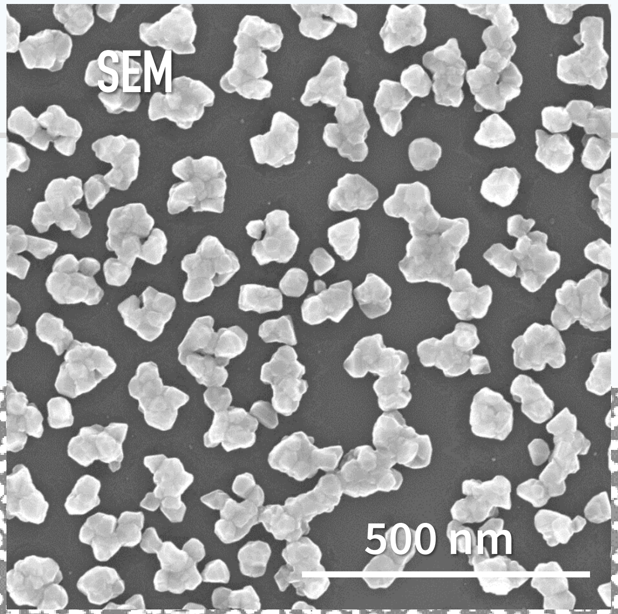


## GROWTH TEST

1h annealing at 700°C




**Proof-of-concept for localised growth by NSL**

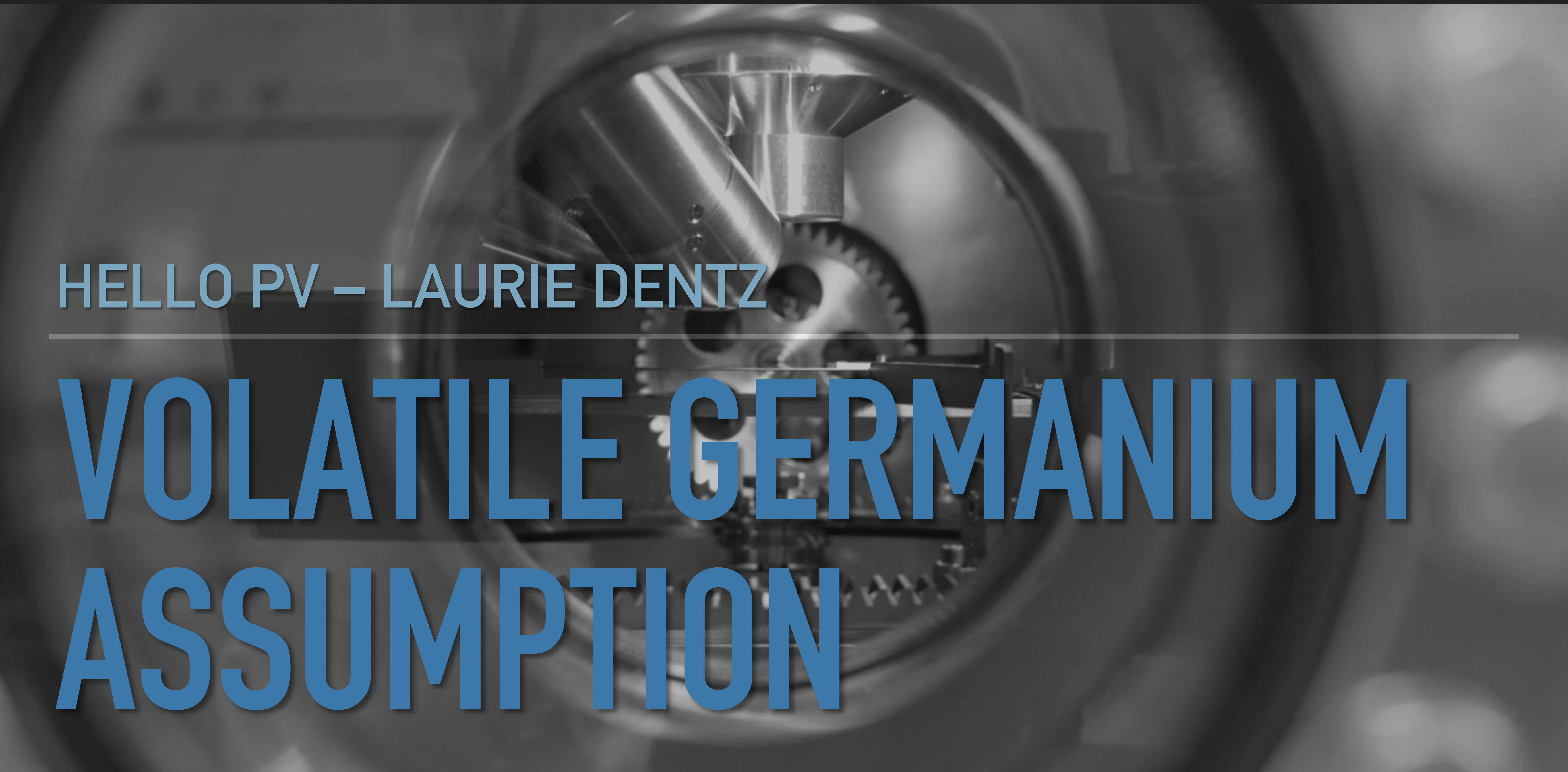
C2N

cnrs

GeePs
Génie électrique et électronique de Paris

IPVF

université
PARIS-SACLAY



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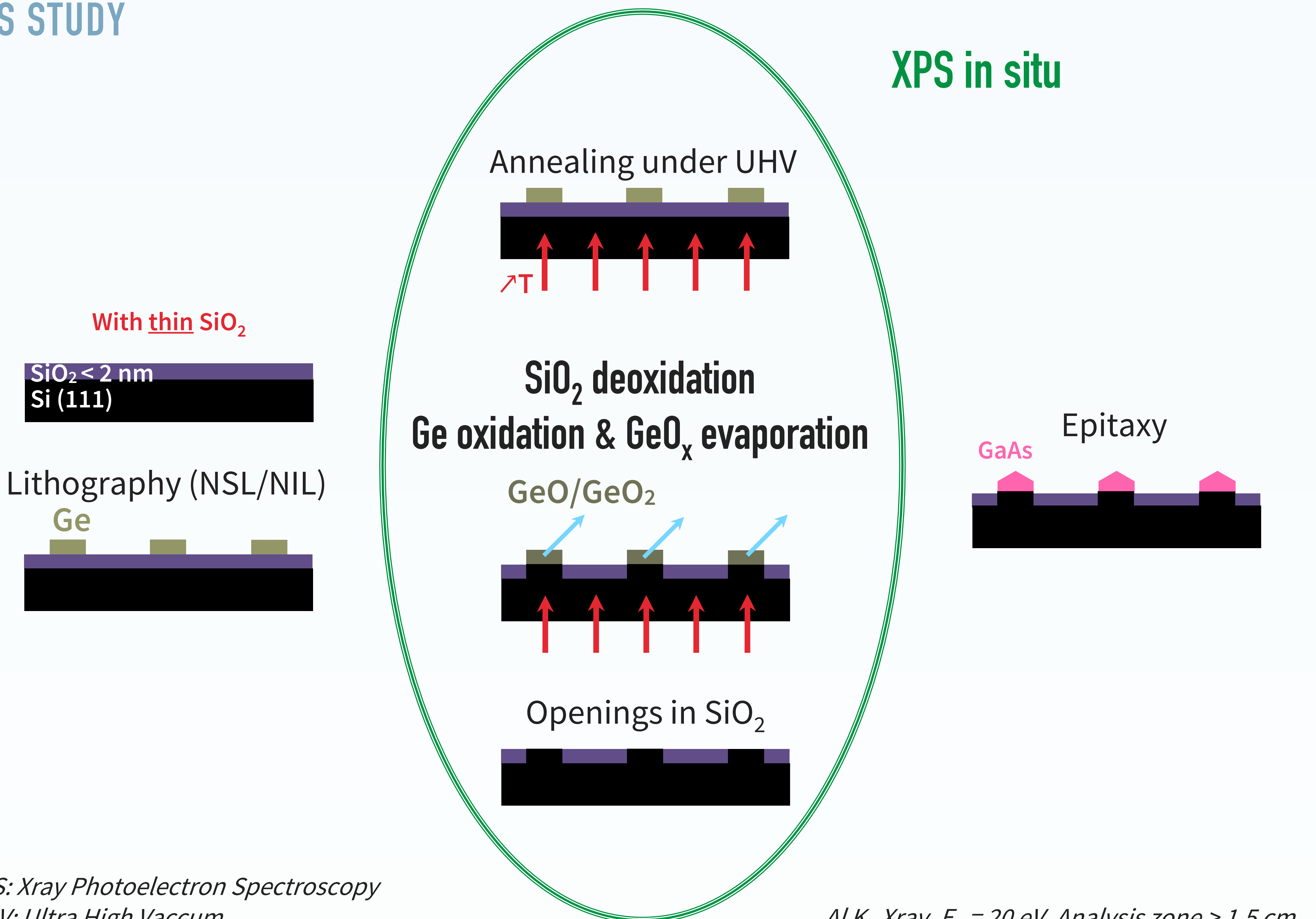
# VOLATILE GERMANIUM ASSUMPTION

# LITHOGRAPHY TO GROWTH – GERMANIUM EVAPORATION

## XPS STUDY




*XPS: Xray Photoelectron Spectroscopy*
*UHV: Ultra High Vaccum*

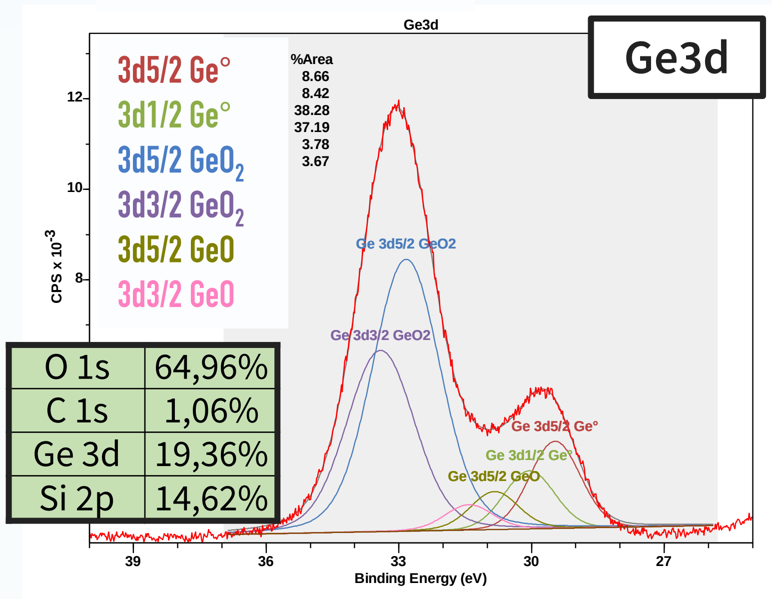
*Al $K_{\alpha}$ Xray, $E_p$ = 20 eV, Analysis zone > 1,5 cm*

# GERMANIUM EVAPORATION

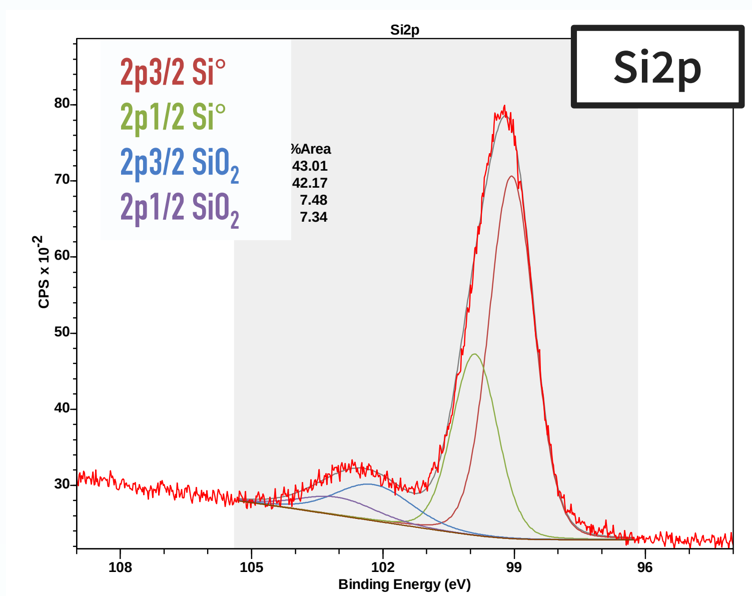


## Ge 2nm + $O_2$ plasma

### Before annealing

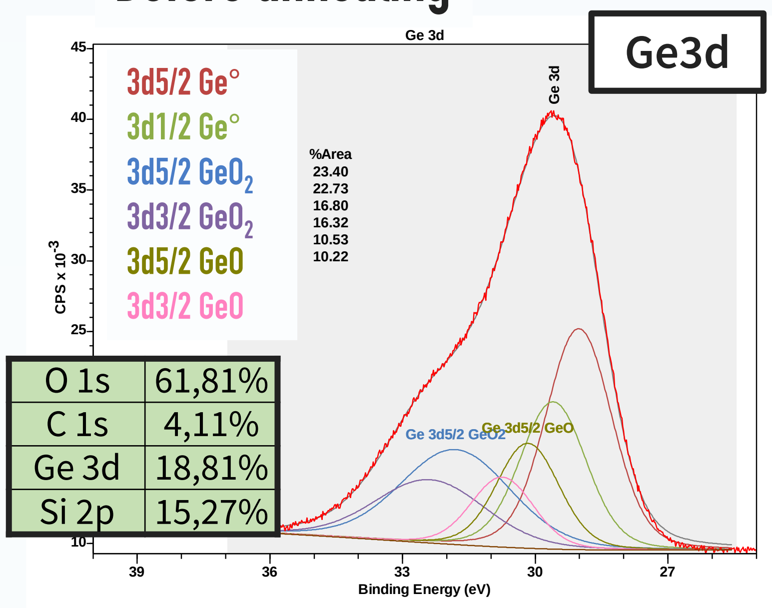



| | |
|---|---|
| O 1s | 64,96% |
| C 1s | 1,06% |
| Ge 3d | 19,36% |
| Si 2p | 14,62% |

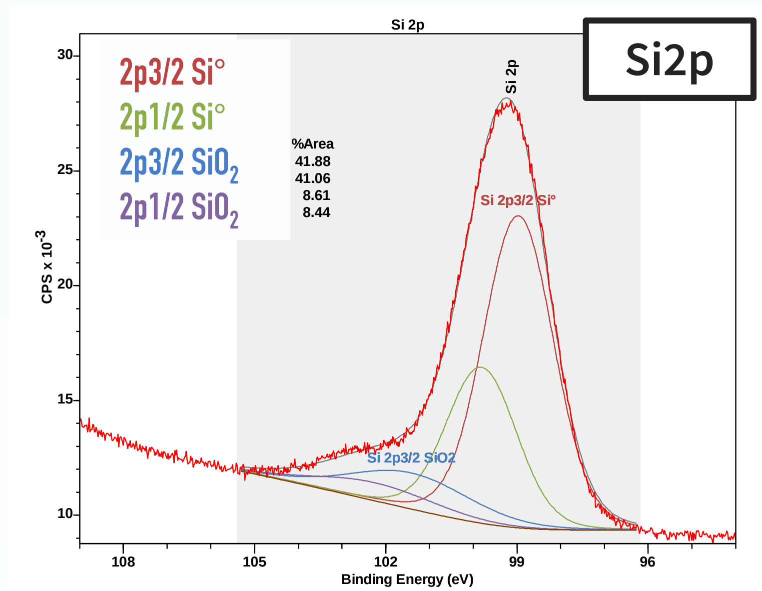



## Ge 2nm

### Before annealing

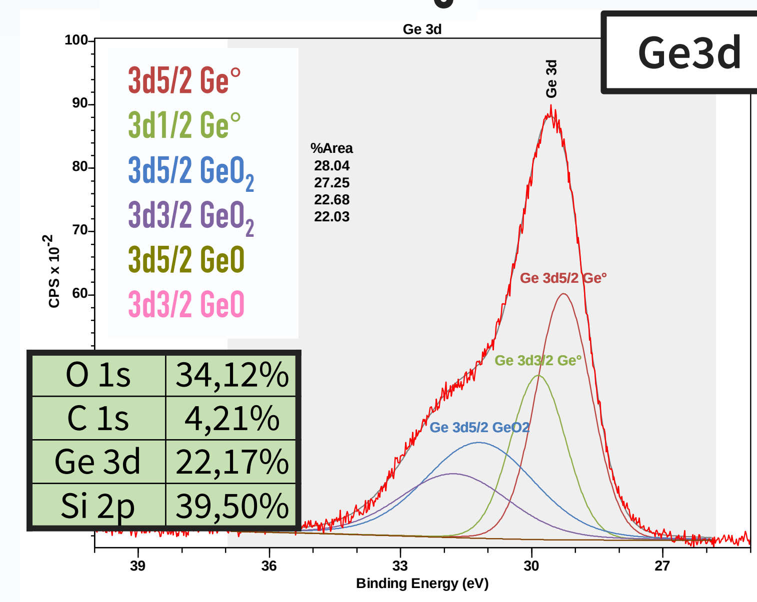



| | |
|---|---|
| O 1s | 61,81% |
| C 1s | 4,11% |
| Ge 3d | 18,81% |
| Si 2p | 15,27% |

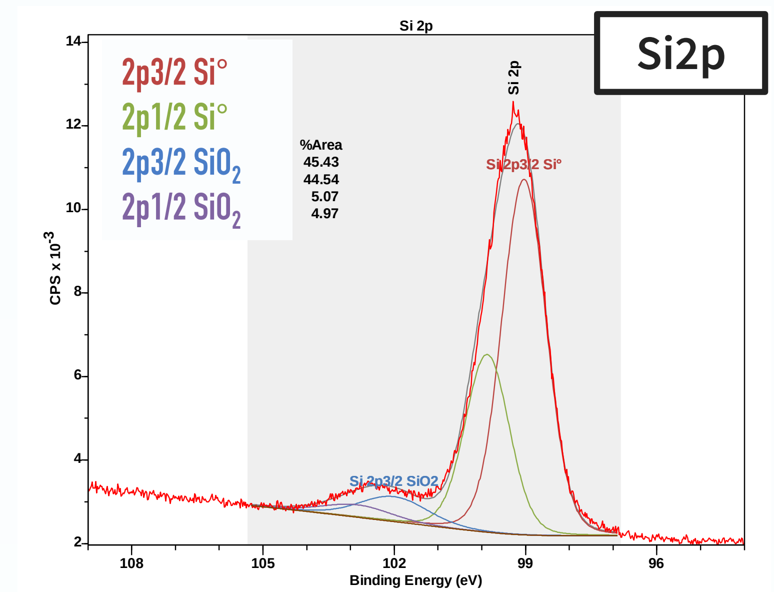



## Ge 1,4nm

### Before annealing




| | |
|---|---|
| O 1s | 34,12% |
| C 1s | 4,21% |
| Ge 3d | 22,17% |
| Si 2p | 39,50% |

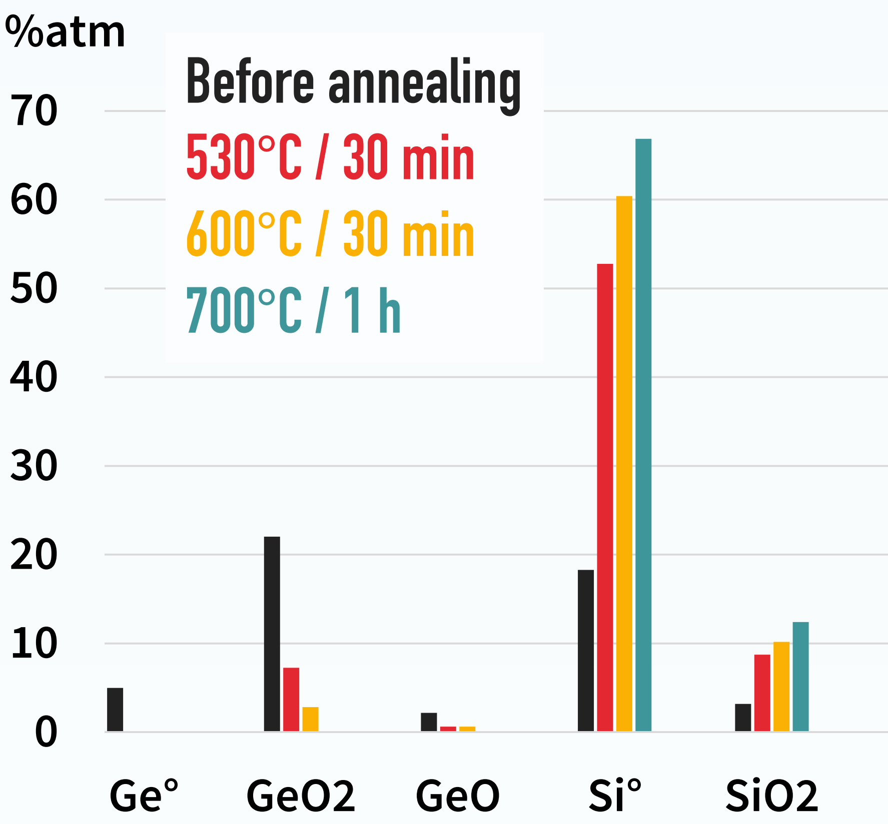



*Si (111) cleaned with solvents / HF / $H_2SO_4$+$H_2O_2$ / HF*
*$SiO_2$ (< 2nm) Shiraki chemical oxidation with $H_2O_2$ + $H_2O$ + HCl*

# GERMANIUM EVAPORATION

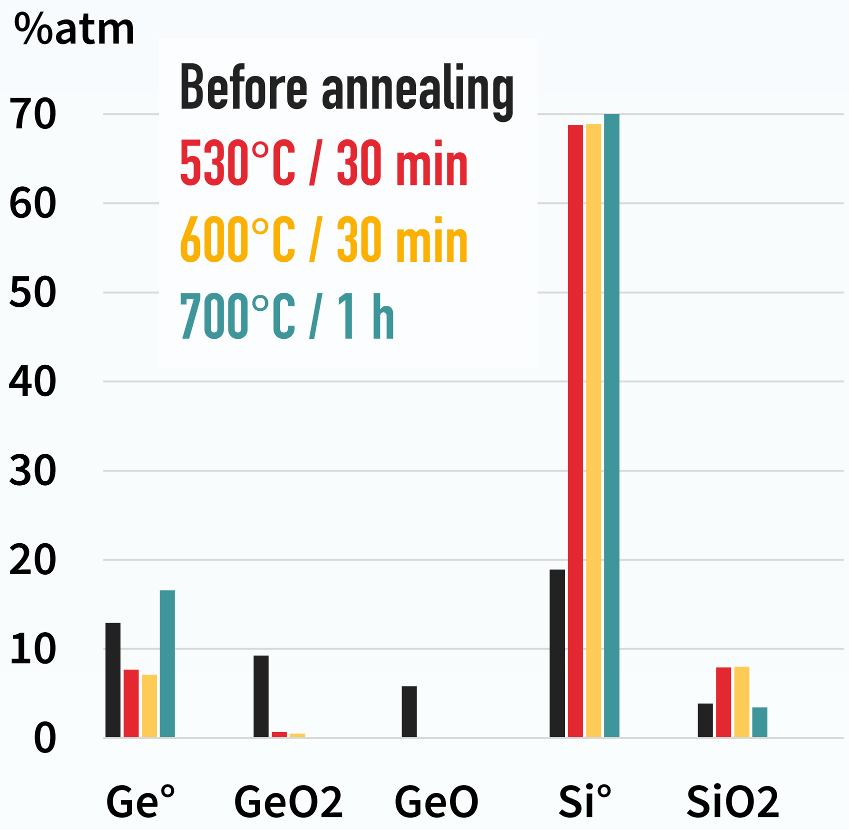


## Ge 2nm + $O_2$ plasma



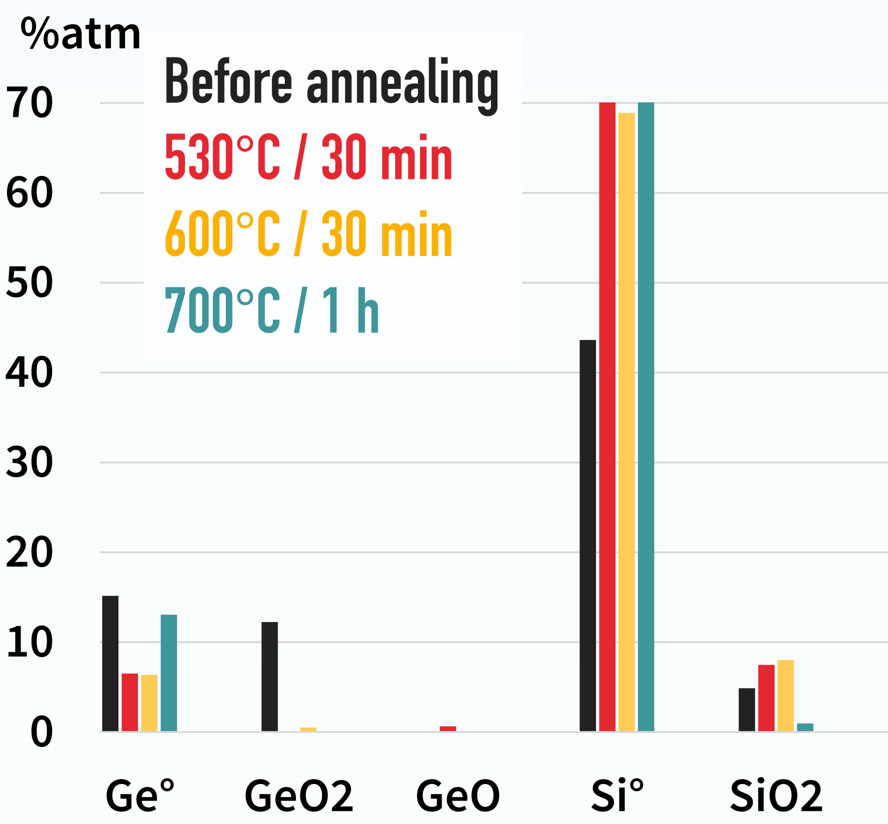

- Ge, then GeO/$GeO_2$ leave
- $SiO_2$ stays

## Ge 2nm




- GeO/$GeO_2$ leaves but
- Ge and $SiO_2$ stays
- $SiO_2$ begins to leave.

## Ge 1,4nm




- GeO/$GeO_2$ and $SiO_2$ leave
- Ge stays

**This assumption has been demonstrated to be false**

C2N cnrs GeePs Génie électrique et électronique de Paris IPVF

université PARIS-SACLAY

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# CONCLUSION

# CONCLUSION



## ALTERNATIVE LITHOGRAPHY PROCESSES

- NSL & Soft-UV NIL : low-cost & good candidates for growth localization

## VOLATIL GERMANIUM STUDY

- Ge does not absorb oxygen from $SiO_2$ layer < 700°C

## PERSPECTIVES

- Find a metal that can oxidize with oxygen from $SiO_2$ layer & evaporate at low temperature

- Improve the integration of localised GaAs on Si

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# THANK YOU FOR YOUR ATTENTION