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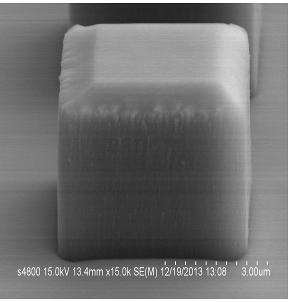

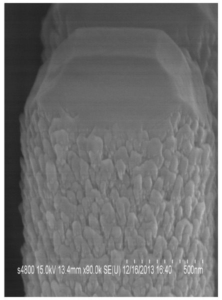

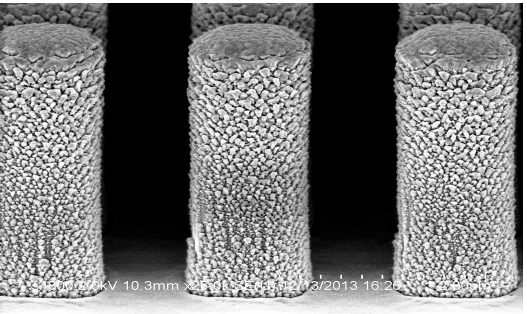

Low Temperature Ge on Si Epitaxy by High Density Plasma Chemical Vapor Deposition

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Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

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Outline

- Surface Preparation
  - Ex-situ
  - In-situ
- Effect of GeH_4 Flow
  - Growth morphology
  - XRD
- Effect of Argon Flow
- Effect of ICP

Motivation

Sandia National Laboratories

Ge on Si

- High electron (3900 cm/Vs^2) and hole mobility (1900 cm/Vs^2).
- Potential for integration with GaAs, closely lattice matched (solar cell applications).
- Ge has strong absorption in NIR (photodetectors).
- Indirect bandgap material, but can be engineered through strain (1.9%).

HDP-CVD Platform for Growth

- Back end of line (BEOL) CMOS compatible fabrication technique.
- High throughput growth using production capable HDP-CVD system.

Plasma Deposition Technique

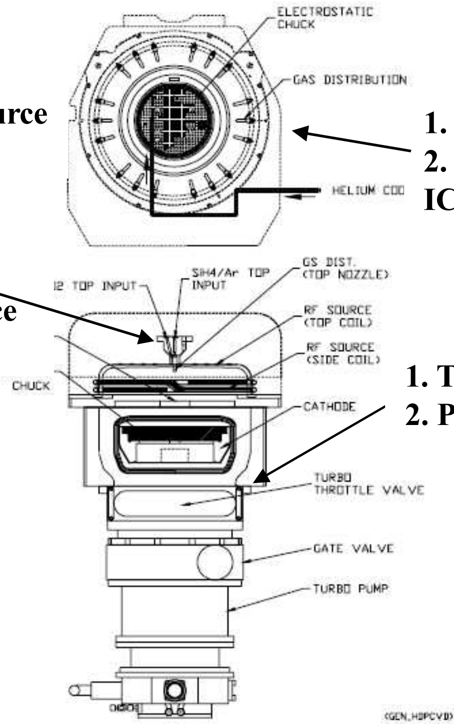
1. Electrostatic chuck
2. He cooling
3. 13.56 MHz Bias Source
4. No resistive heater

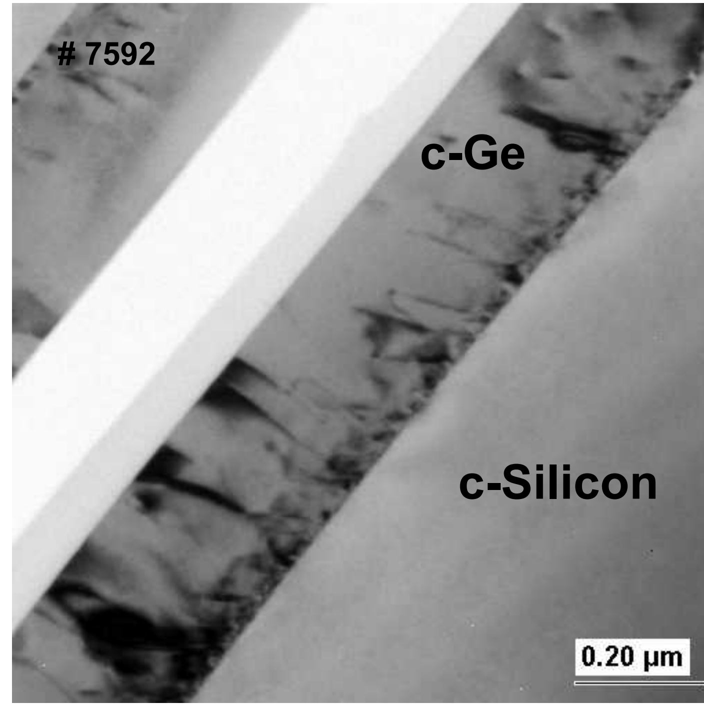
1. Side gas inject
2. 2 MHz side ICP source

1. Top gas inject
2. 2 MHz top ICP source
3. Heated dome (~ 120° C)

1. Turbo pump
2. P_{base} ~ 1 µtorr

Process Gasses:
Ar, SiH_4, GeH_4, O_2, N_2, and NF_3

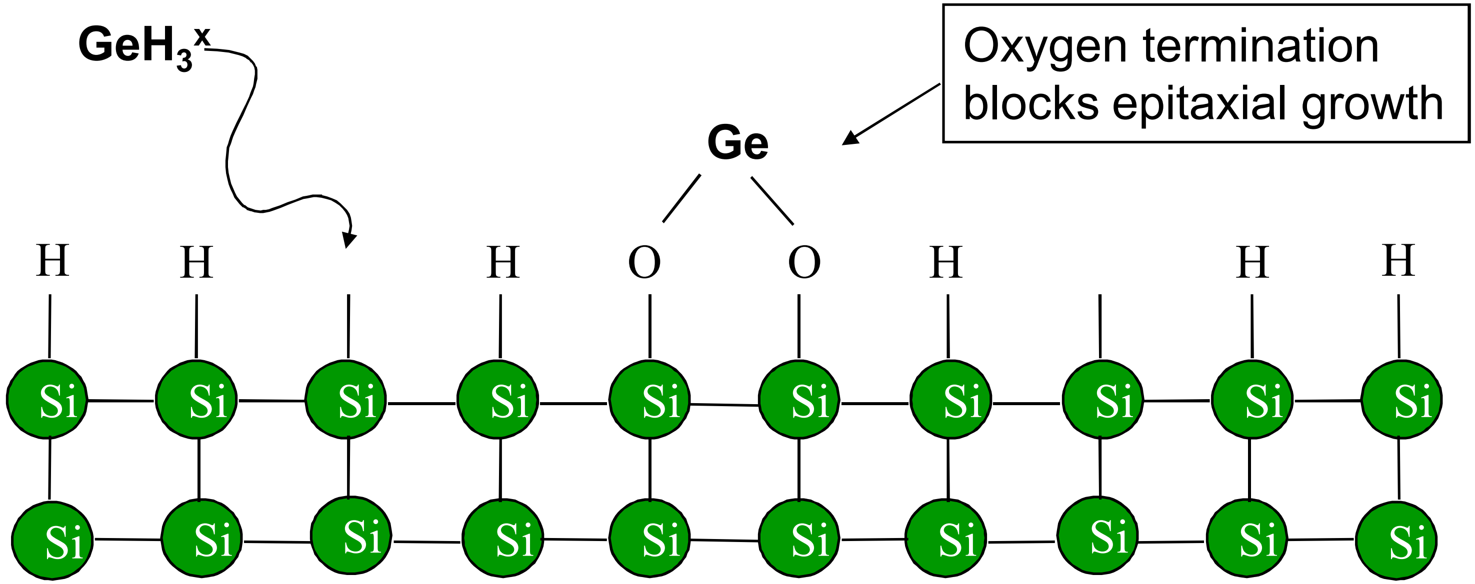




- Commercially available high density plasma chemical vapor deposition chamber
- Ar/GeH_4 plasma for Ge epitaxy: 3000W, T~450° C, P = 10 mtorr and P_{GeH4} ~ 50 µtorr

M. Carroll, et al. Mater. Res. Soc. Symp. Proc. 989, 2007.

Low Temperature Epitaxial Growth



- Epitaxy technique typically uses T > 750° C in-situ hydrogen bake to remove native oxide
- High quality Ge epitaxy on Si typically grown using thermal chemical vapor deposition (CVD) or molecular beam epitaxy (MBE)
- Epitaxy requires exposed crystal seed/template (often hydrogen terminated)
  - Deposition rate is highly dependent on temperature and hydrogen desorption rate

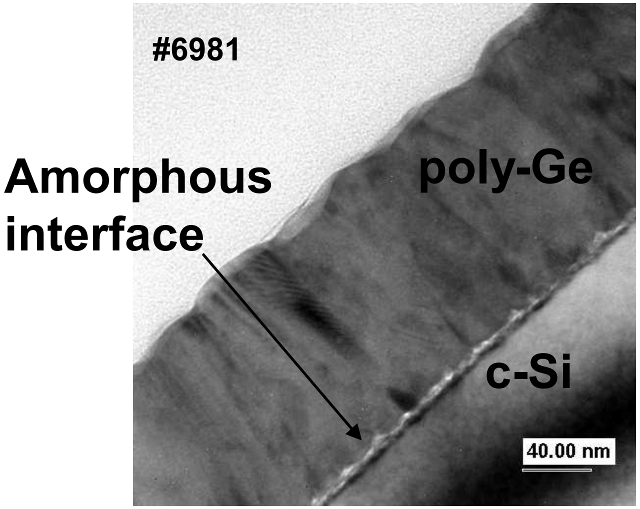
M. Carroll, et al. Mater. Res. Soc. Symp. Proc. 989, 2007.

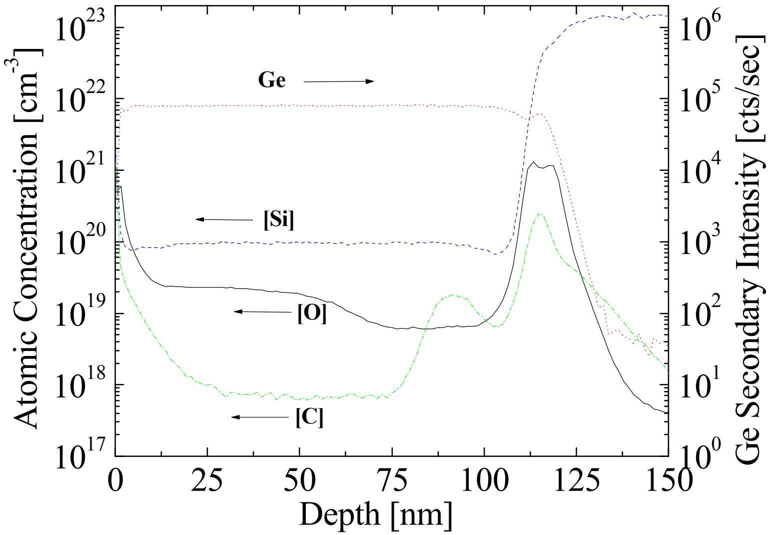
Surface Preparation: Ex-Situ

- Typical hydrogen plasma clean forms volatile SiO and steam:

$$SiO_2 + 2H \rightarrow SiO(g) + H_2O$$

- Ex-situ HF clean results in substantial removal of oxygen and terminates surface with H, not adequate for plasma assisted growth.



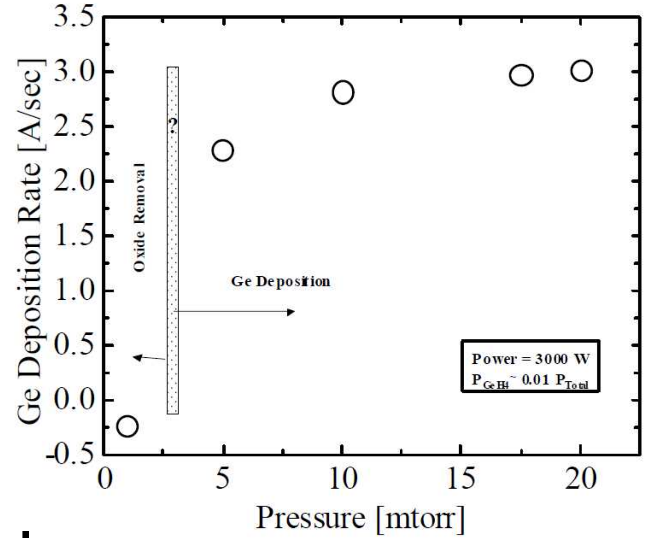


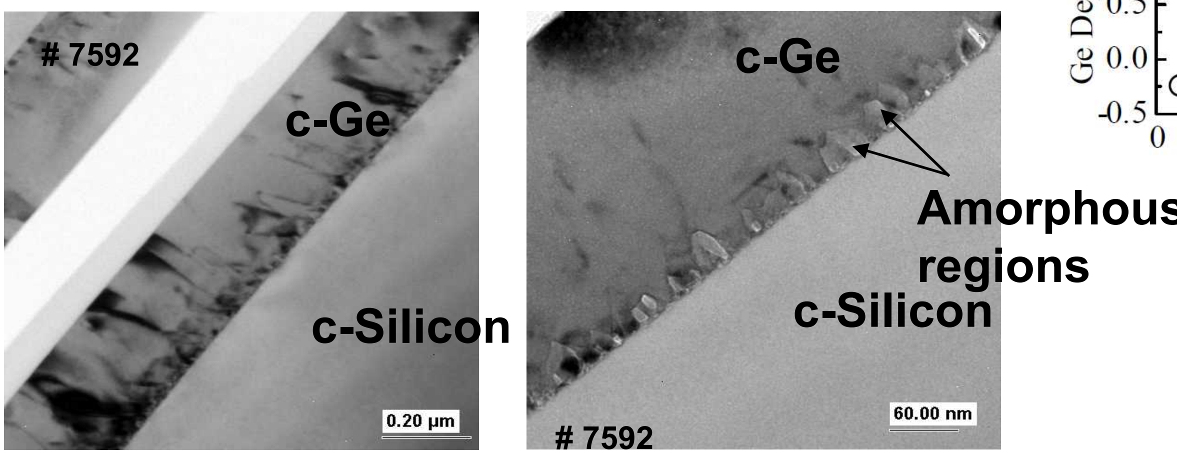
- Hydrogen termination of silicon after ex-situ dilute hydrofluoric acid known to be sufficient for epitaxial growth in thermal CVD
- TEM of Ge deposition indicates amorphous interface
- SIMS indicates considerable oxygen and carbon at interface
- Ellipsometry indicates that initial thin oxide forms during initial plasma stabilization phase

M. Carroll, et al. Mater. Res. Soc. Symp. Proc. 989, 2007.

Surface Preparation: In-Situ

- Germanium known to break Si-O bonds to create volatile Ge-O.
- Low fluxes of GeH_4 verified to remove residual oxygen on surface as an in-situ clean after 100:1 DI:HF ex-situ clean.

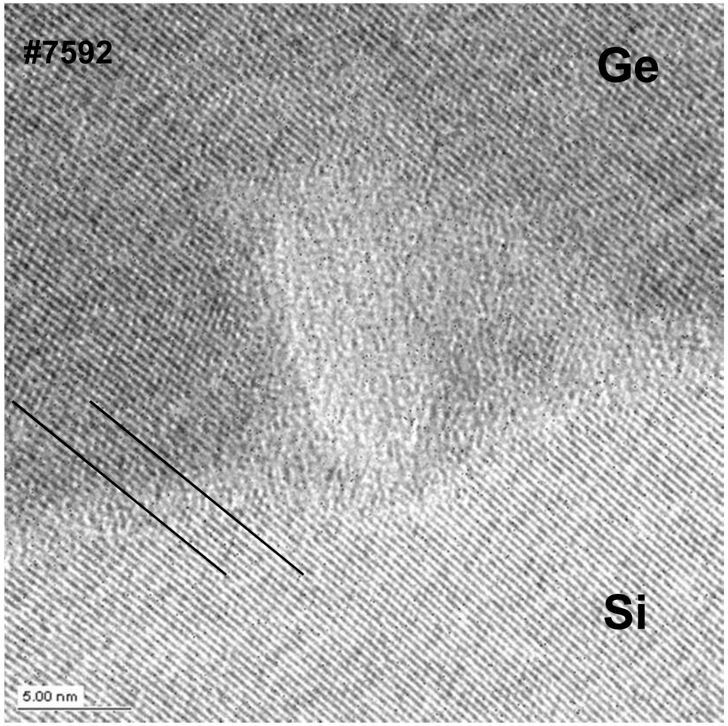


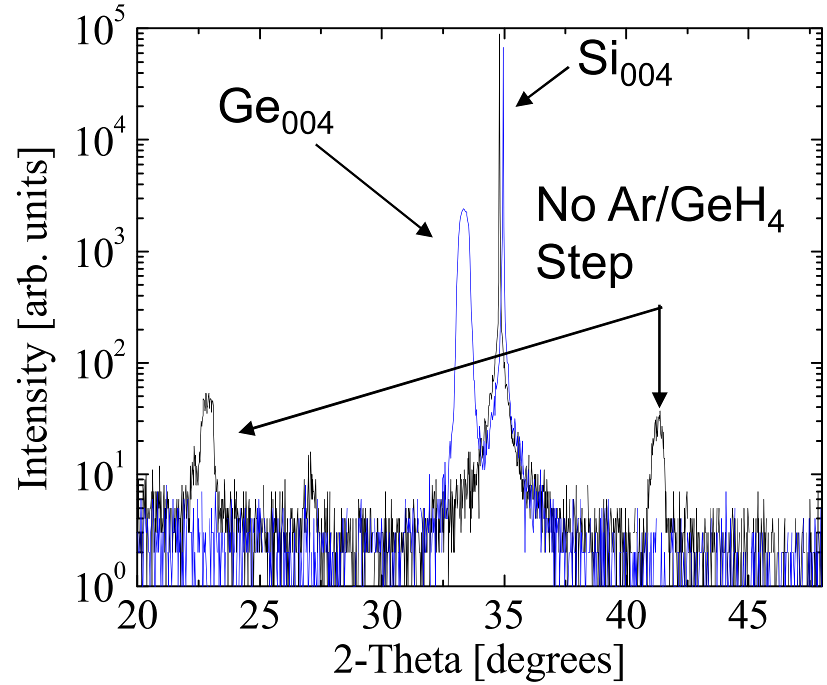


- Insertion of 300 second, 1 mtorr Ar/GeH_4 plasma before deposition at 10 mtorr produces coherent Ge epitaxy.
- No epitaxial growth observed after using other in-situ oxide removal approaches like NF_3 or soft argon sputtering
- Ge crystal growth appears at Si/Ge interface between relatively thick amorphous regions
- Dislocation density is approximately between 10^{10} and 10^{11} cm^{-2}

M. Carroll, et al. Mater. Res. Soc. Symp. Proc. 989, 2007.

Surface Preparation: In-Situ (2)



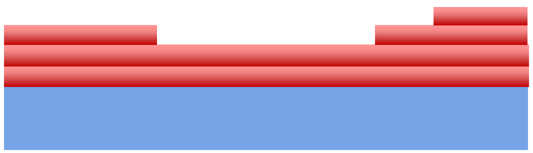


- High resolution TEM shows coherent positioning of Ge and Si atomic planes
- Numerous amorphous regions interrupt the Ge/Si coherent interface
- X-ray diffraction rocking curves also show no sign of misoriented poly-grains (blue scan)

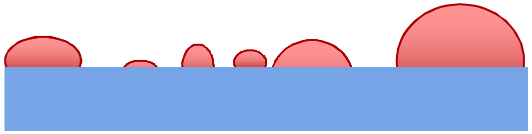
M. Carroll, et al. Mater. Res. Soc. Symp. Proc. 989, 2007.

Growth Morphology

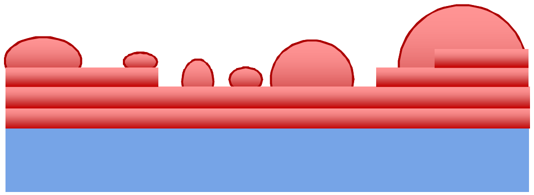
Frank-van der Mewre growth:
2D layer-by-layer

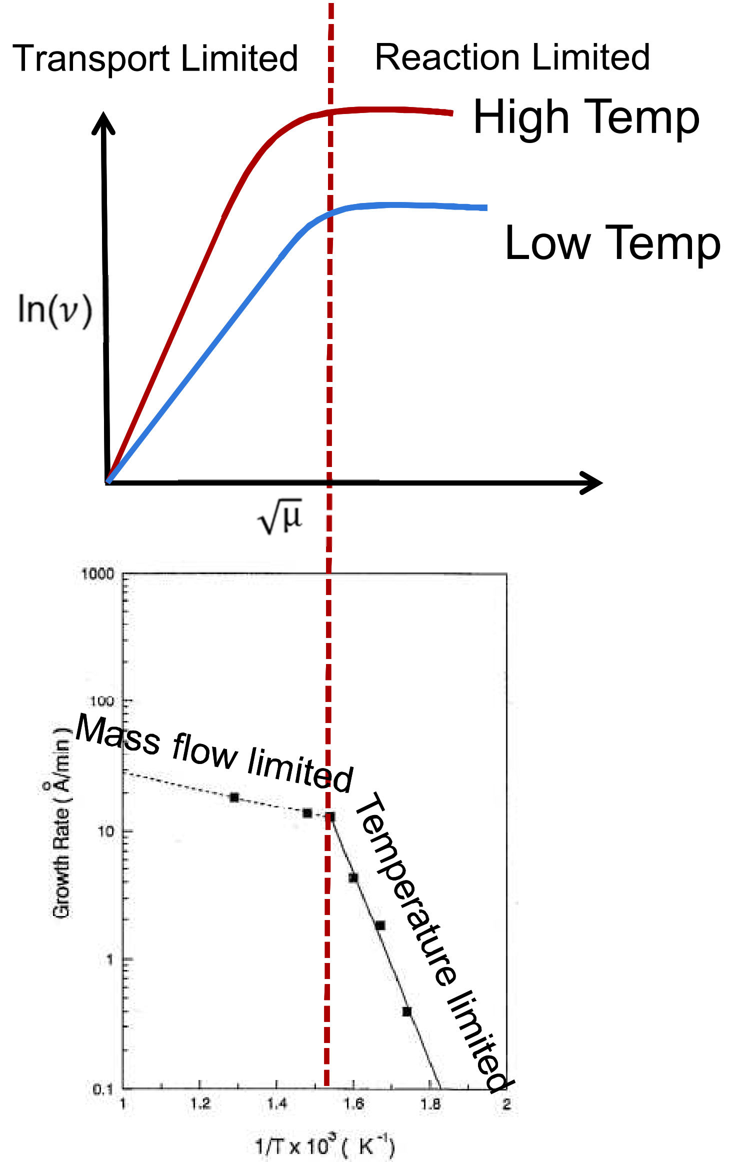


Volmer-Weber growth: 3D



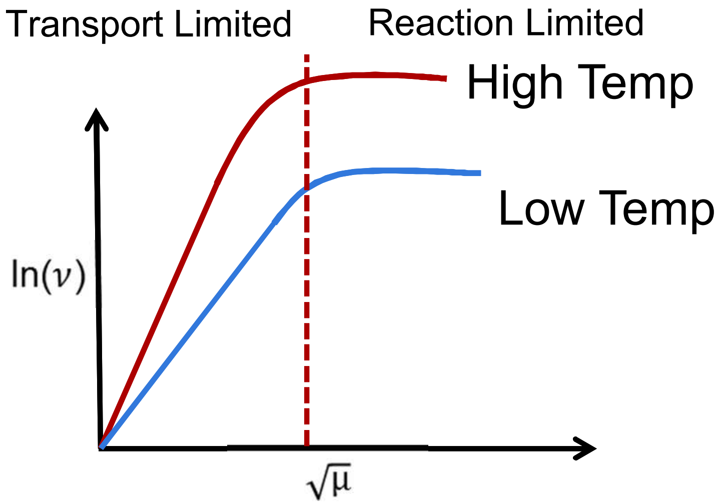
Stranski-Krastanov growth





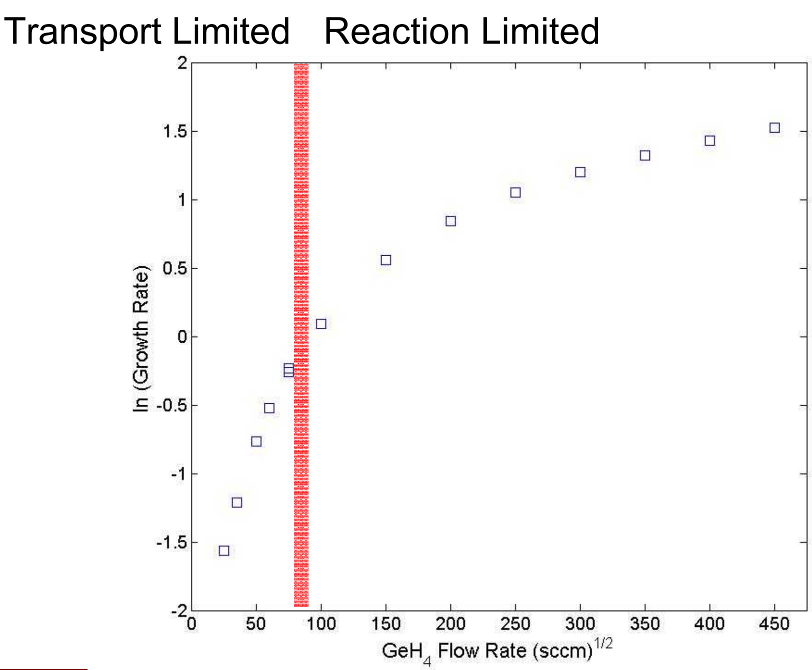
Cunningham, et al., Appl. Phys. Lett. **59** (27) 1991.

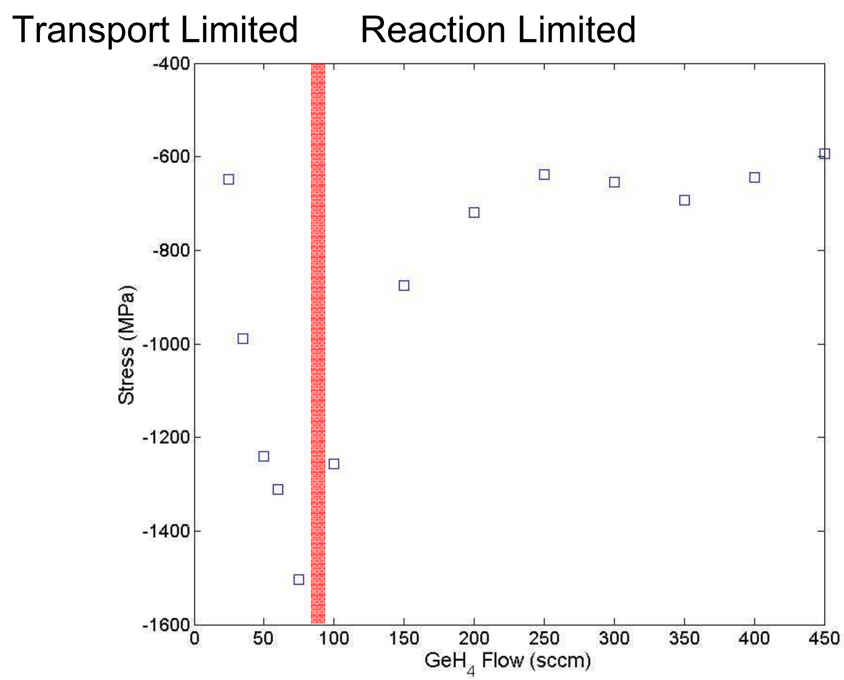
GeH_4 Side Flow



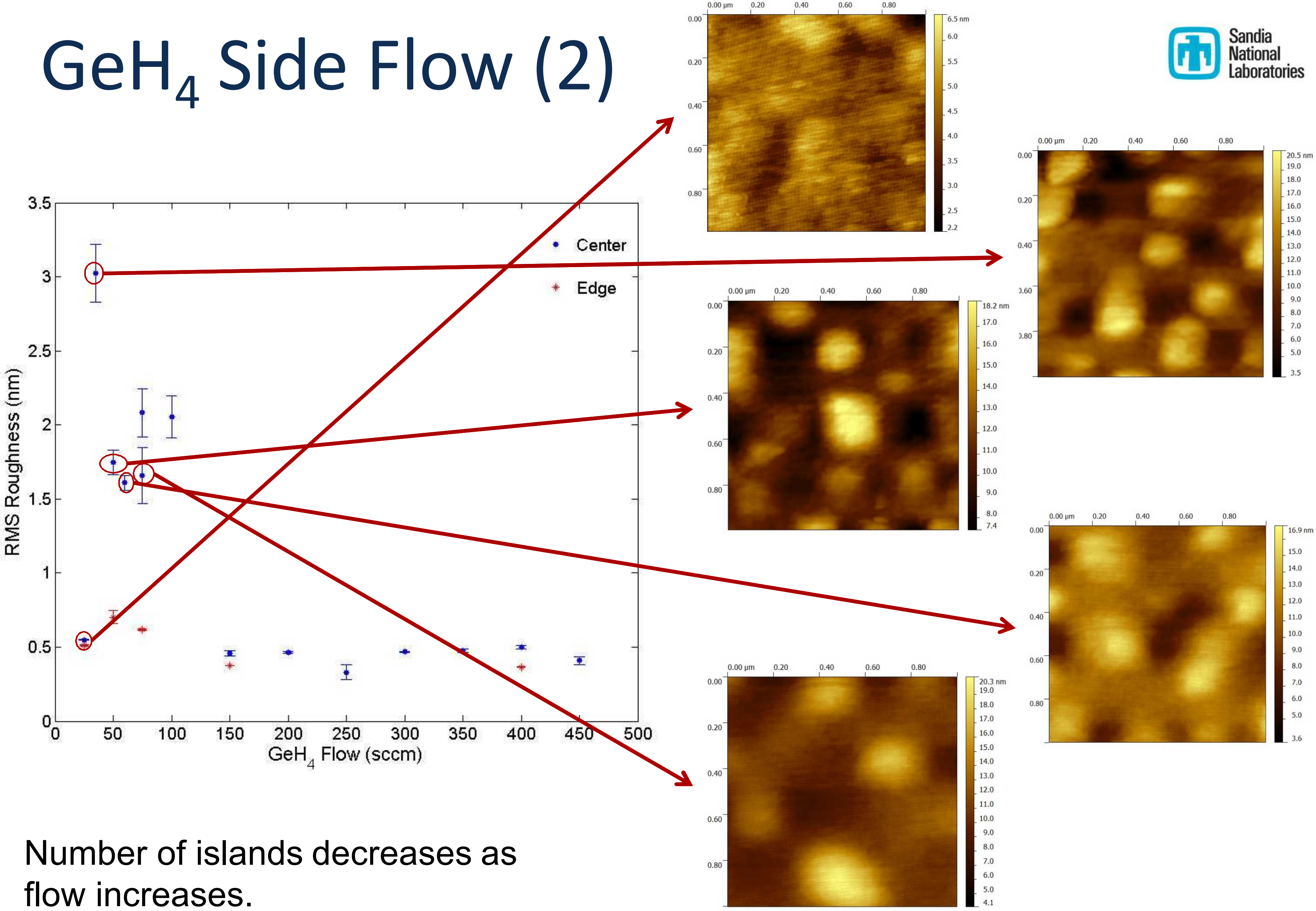
- Investigated effect of GeH_4 flow on growth.
- All films 1kÅ.

- Even with 1% GeH_4/Ar, able to achieve reaction limited regime.





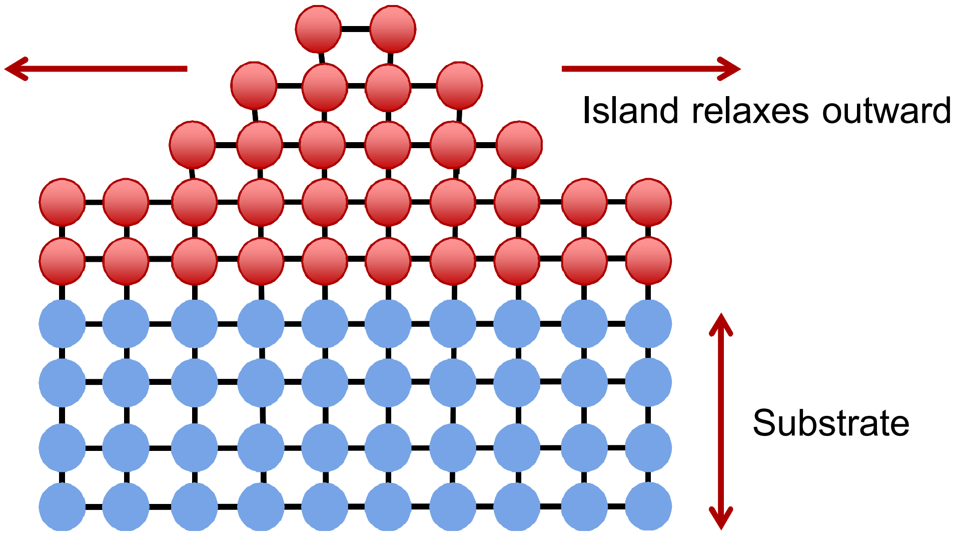
GeH_4 Side Flow (2)



Number of islands decreases as flow increases.

GeH_4 Side Flow (3)

Strain-induced surface roughening:



Lattice constant of Ge is 4% larger than Si.

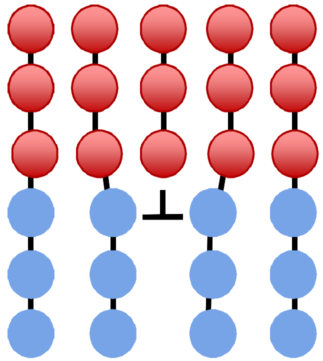
Results in intrinsic elastic strain energy:

$$E_{elas} \propto \varepsilon^2 t$$

where ε is lattice constant misfit:

$$(a_{Ge}-a_{Si})/a_{Si}$$

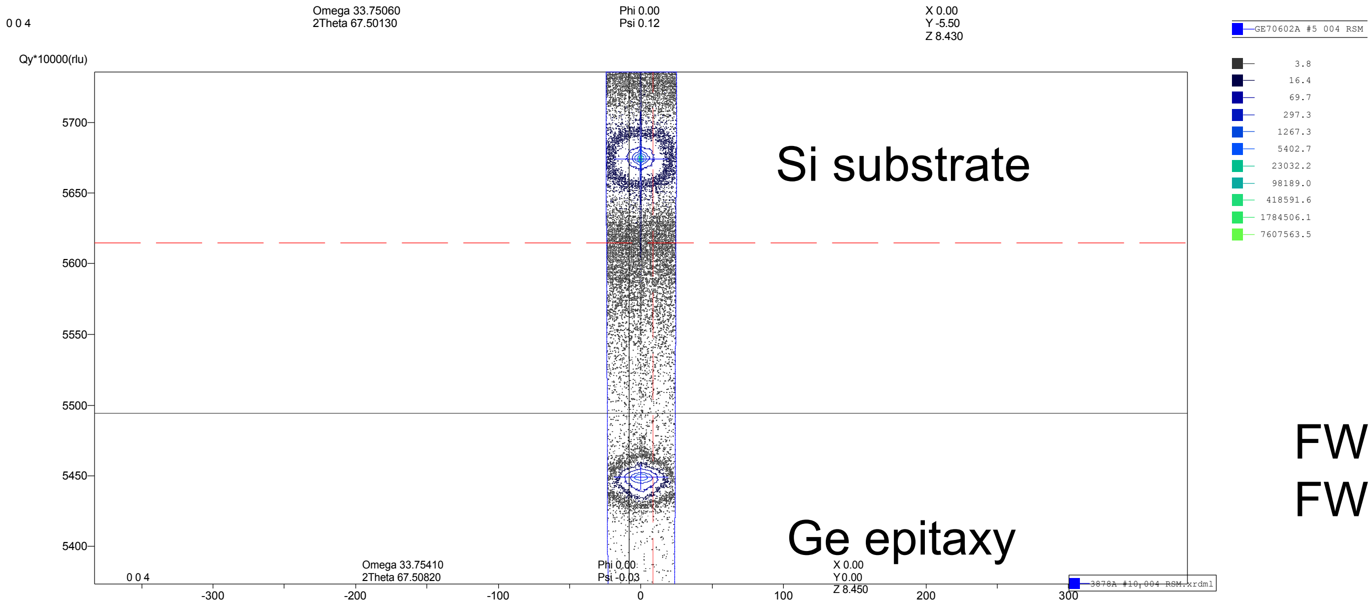
Ge growth transitions from 2D to 3D at ~ 3 ML



Strain relaxation can also occur via misfit dislocations.

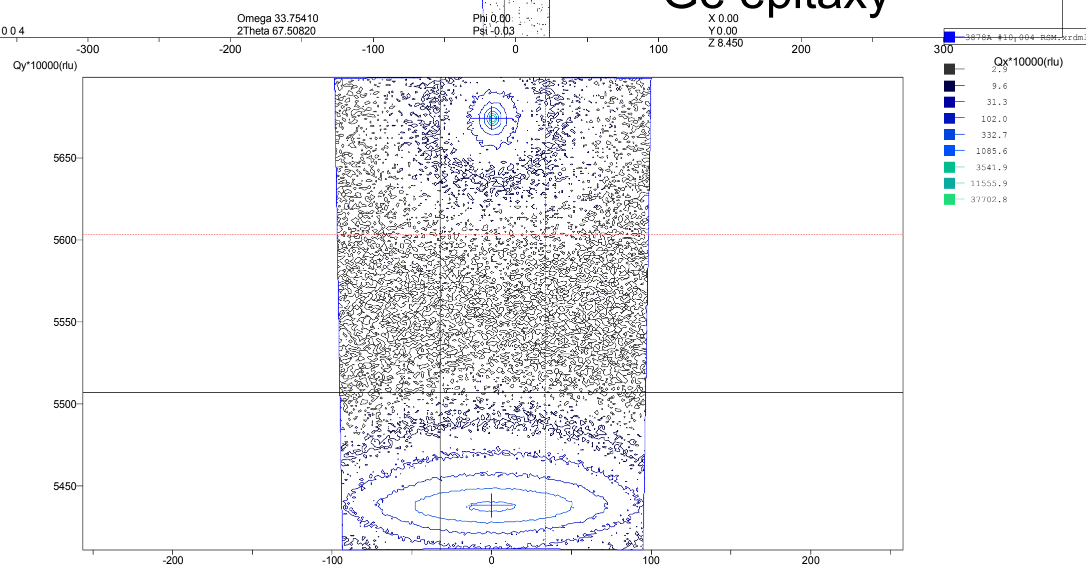
For Stranski-Krastanov growth, both strain relaxation modes compete.

XRD



RPCVD Ge
H_2 in-situ clean
Growth at 800°C

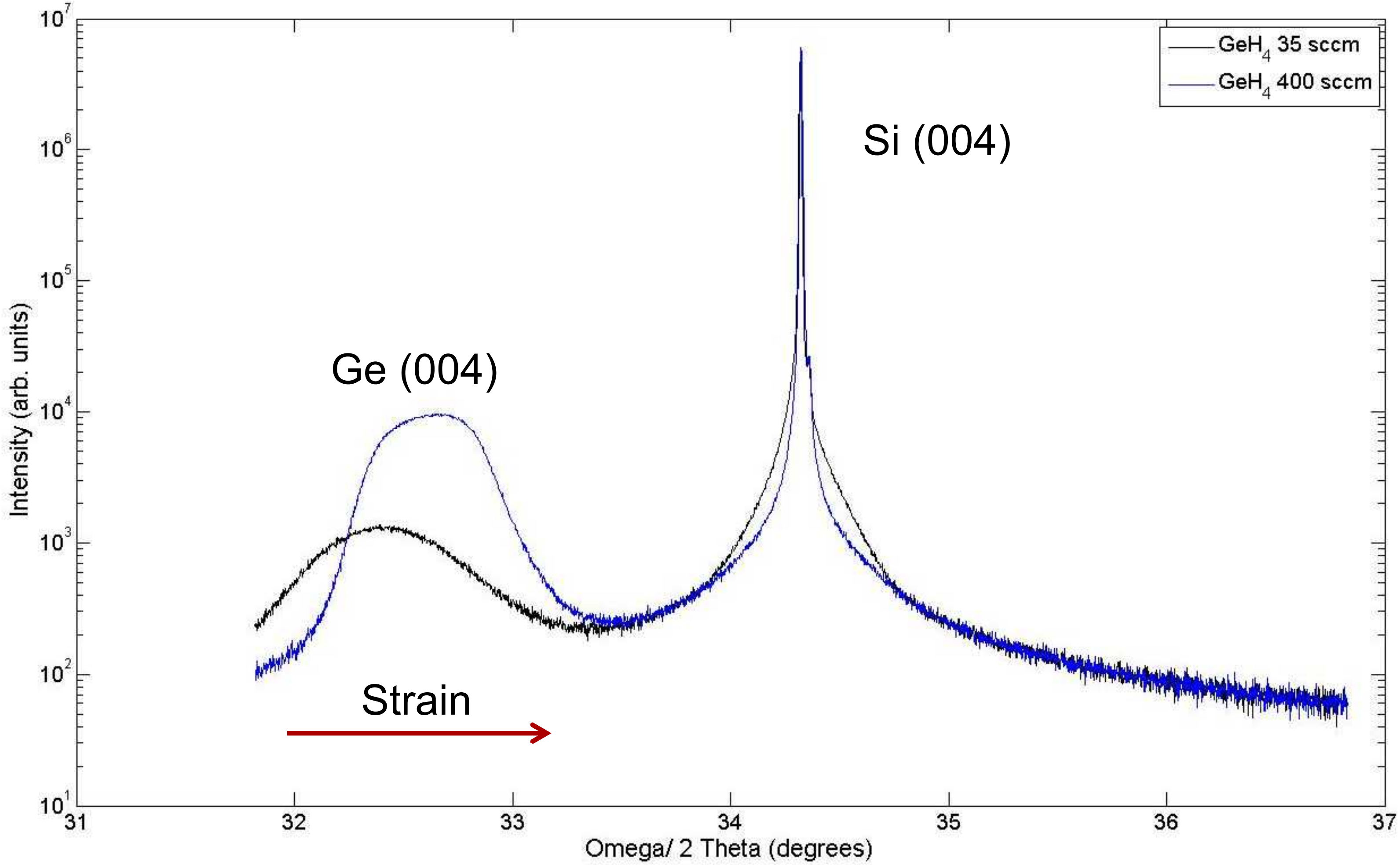
FWHM 2T = 0.04°
FWHM O = 0.06°



HDP-CVD
Growth at 460°C

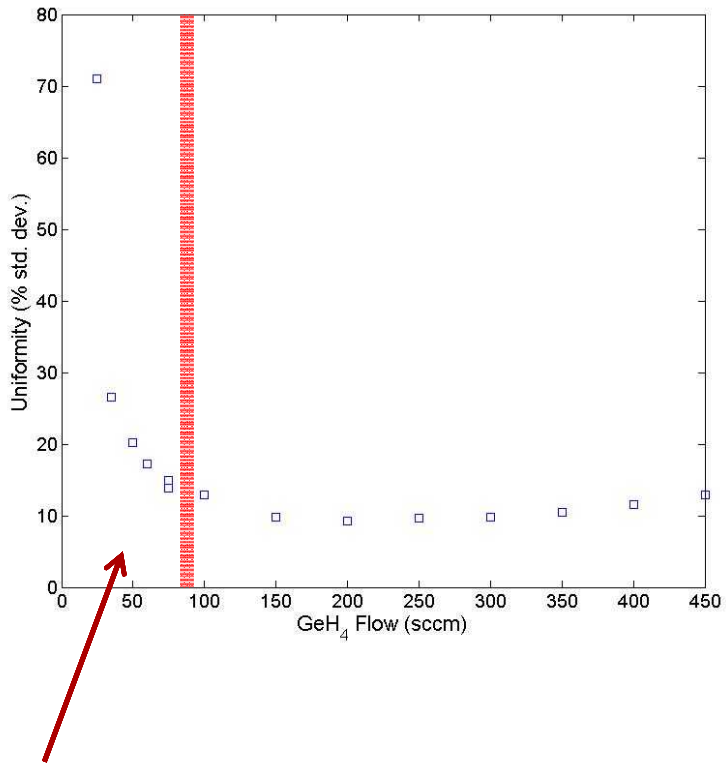
FWHM 2T = 0.18°
FWHM O = 0.70°

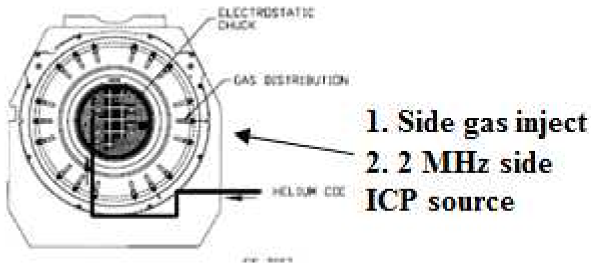
XRD (2)



GeH_4 35 sccm: Ge (004) FWHM = 0.676°
GeH_4 400 sccm: Ge (004) FWHM = 0.506°

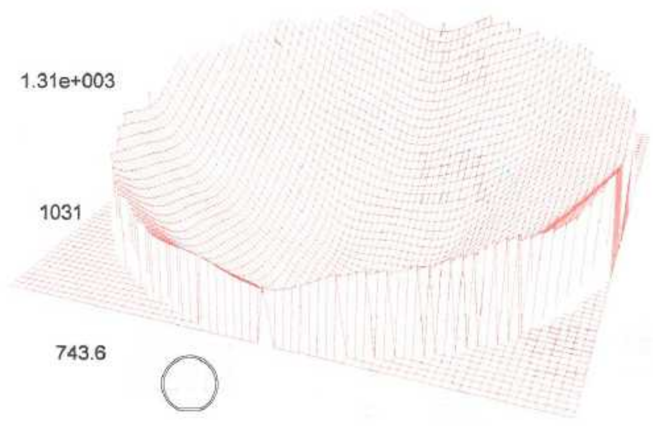
GeH_4 Side Flow (4)



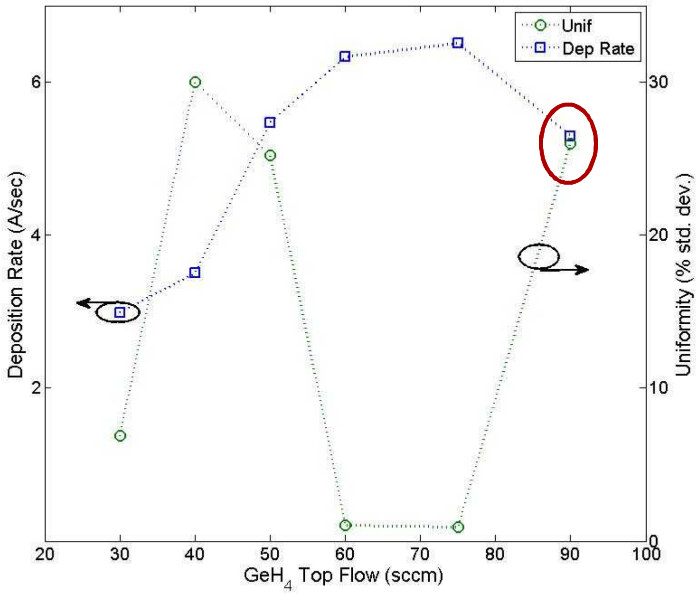


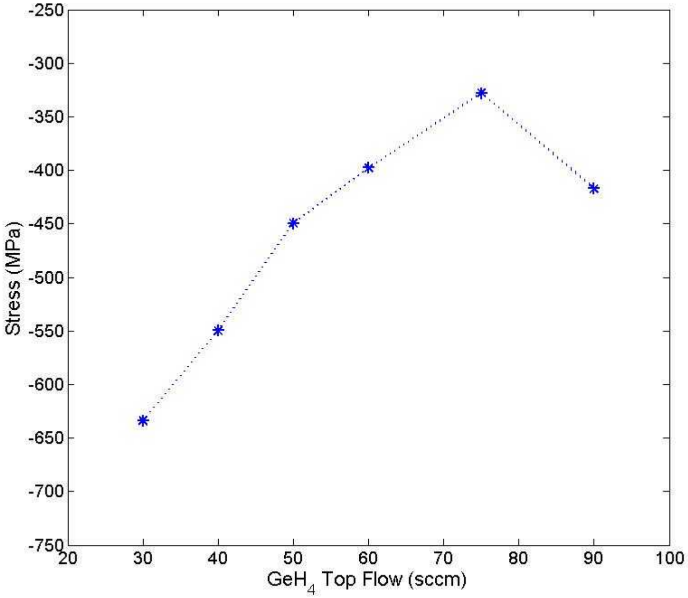
Non-uniform plasma density: Results indicate that center of plasma is GeH_4 - poor

Transport limited regime also contributes to non-uniform film growth



GeH_4 Top Flow

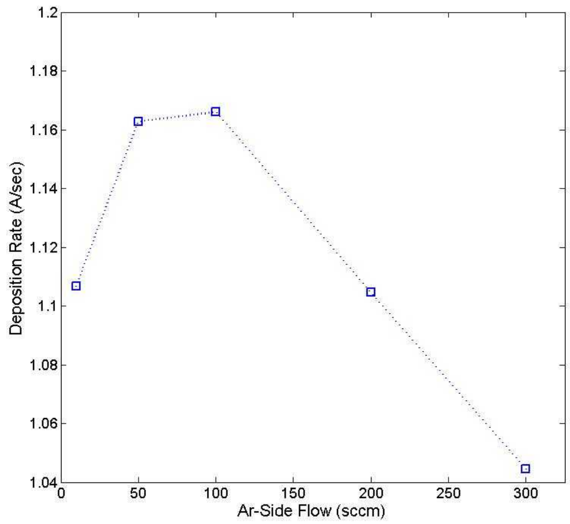


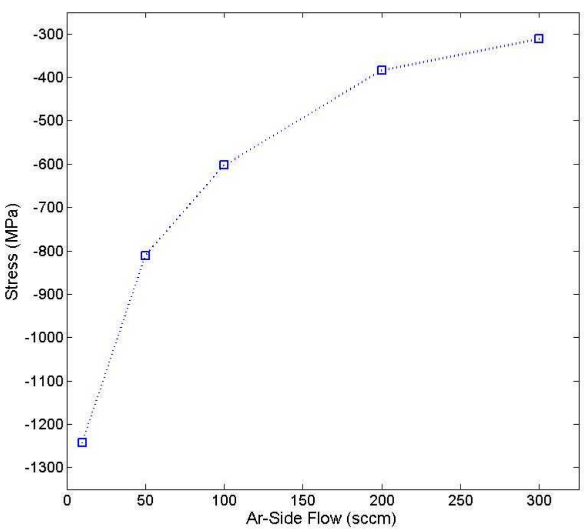


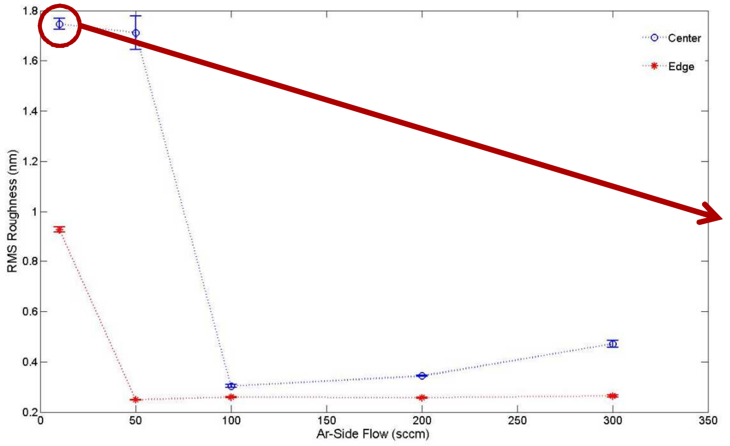
Increase in uniformity at GeH_4 top flow of 90 sccm due to center-thick deposition

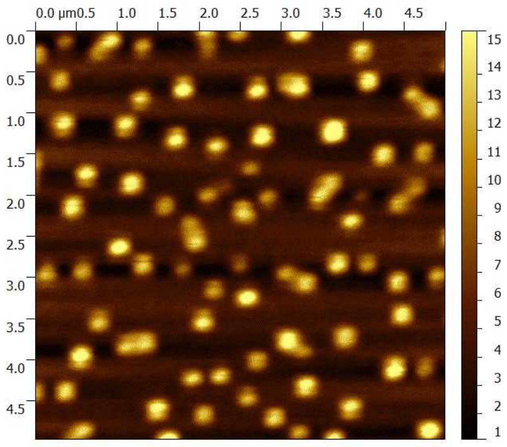
GeH_4 side flow = 200sccm
Top Power = 1000 W
Pressure = 2 mTorr

Effect of Ar Flow

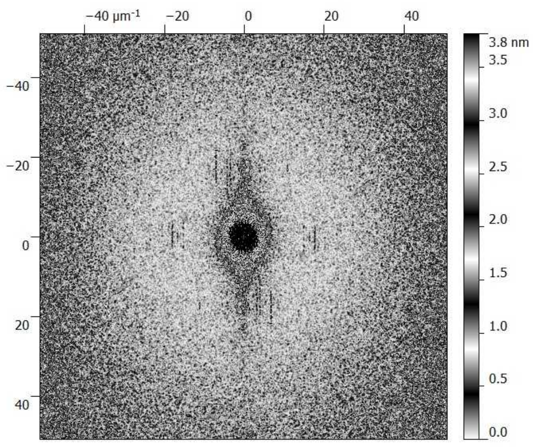






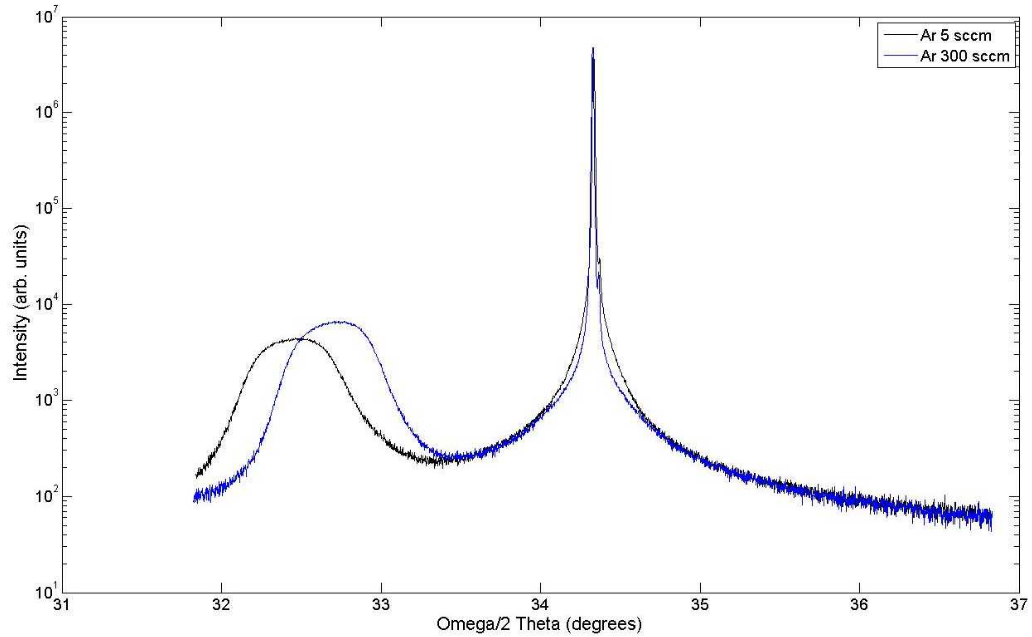


AFM



FFT of AFM

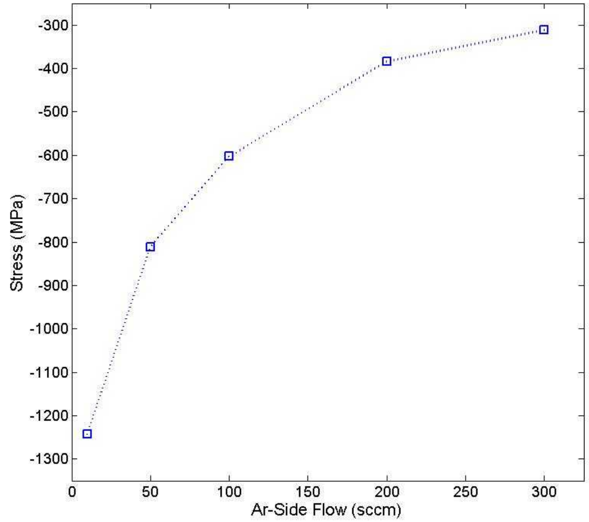
Effect of Ar Flow (2)



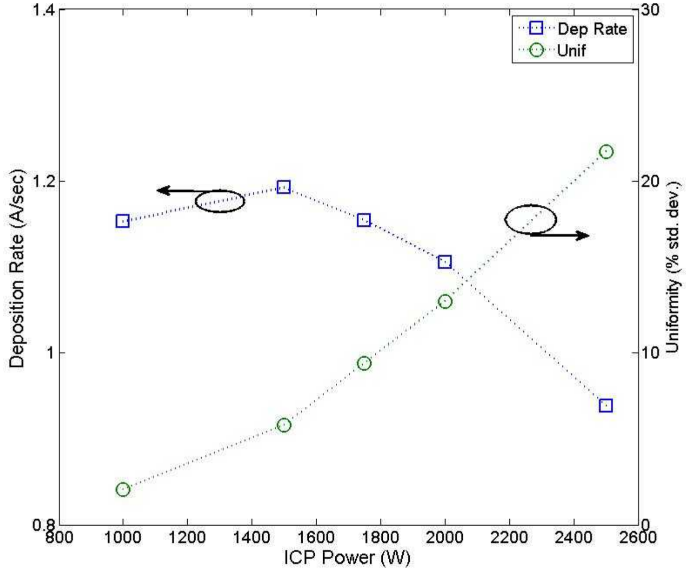
Ar 5 sccm: Ge (004) FWHM = 0.526°
Ar 300 sccm: Ge (004) FWHM = 0.51°

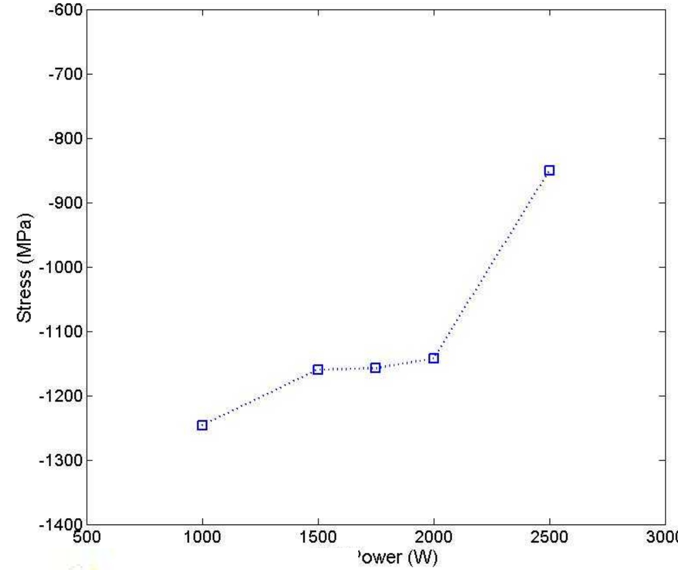
Ar flow > 100 sccm results in surface roughness < 5Å.

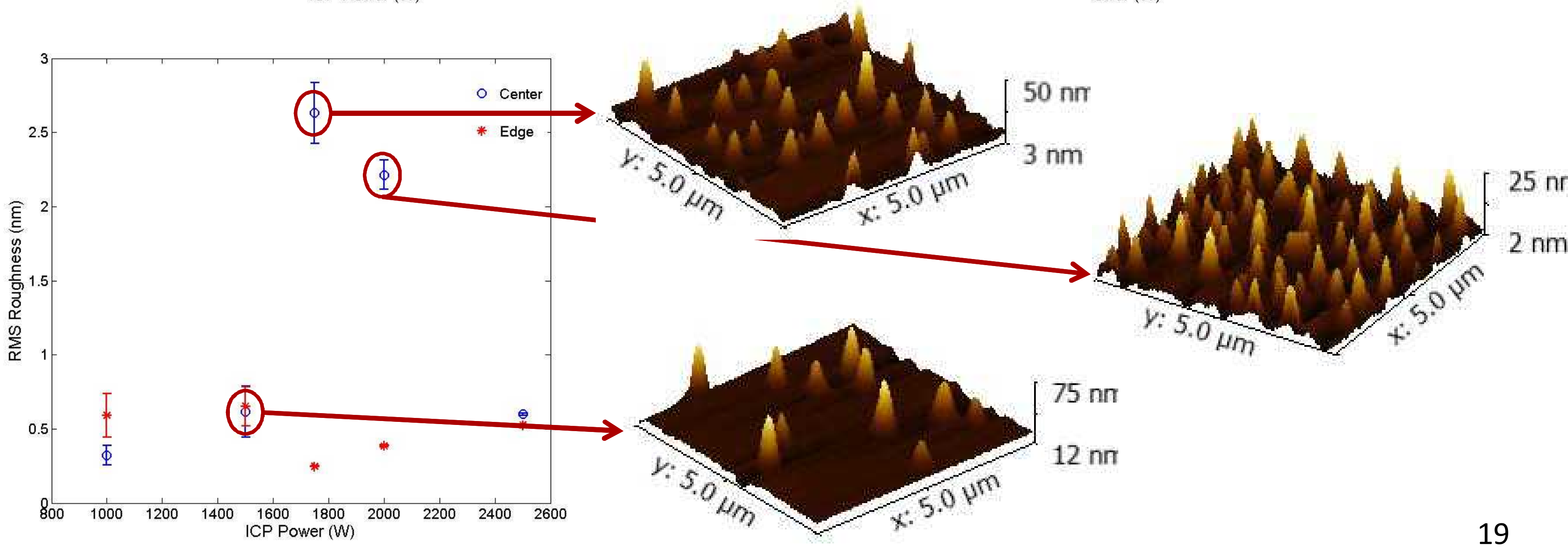
Addition of Ar to plasma allows for stress to be highly tuned without effecting crystallinity.



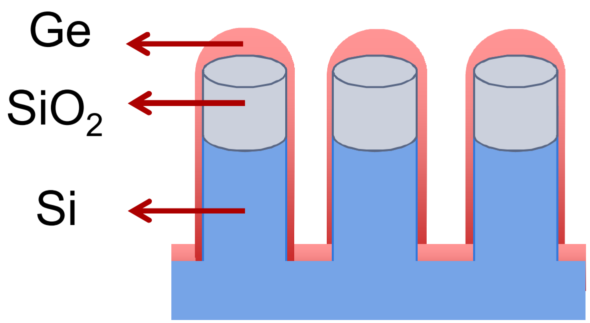
Effect of ICP Power

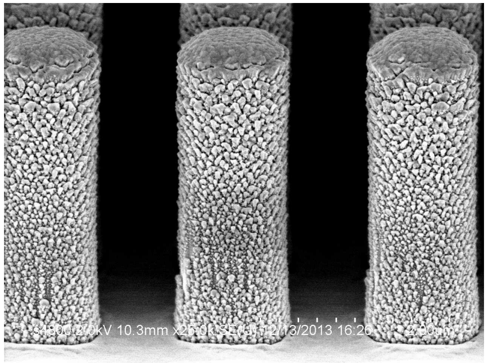






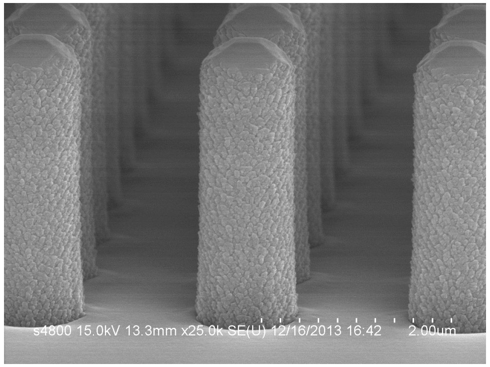
Ge on Si Nanostructures





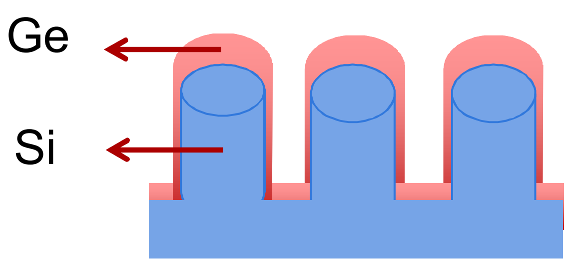
Top and Bias power
Side GeH_4 only
No ex-situ clean

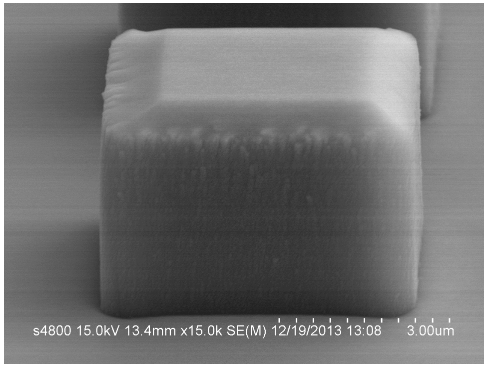
Ballistic deposition



Top and Bias power
Side GeH_4 only
Full surface clean

Ballistic deposition
with faceting





Top power only
Side GeH_4 only
Full surface clean

Smoother sidewalls

Conclusion

- Surface preparation, in absence of H_2 in-situ clean, is exceptionally important to obtain epitaxial quality Ge growth.
- Even with 1% GeH_4 in Ar, able to obtain reaction limited regime.
- Side flow of GeH_4 results in a plasma with Ge-poor center. Addition of top GeH_4 leads to better uniformity, as well as tuning stress.
- Ar flow is a good process knob for optimizing stress as well as surface roughness.

Acknowledgements

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