Micro-loading effects in SiGe layers for recessed S/D

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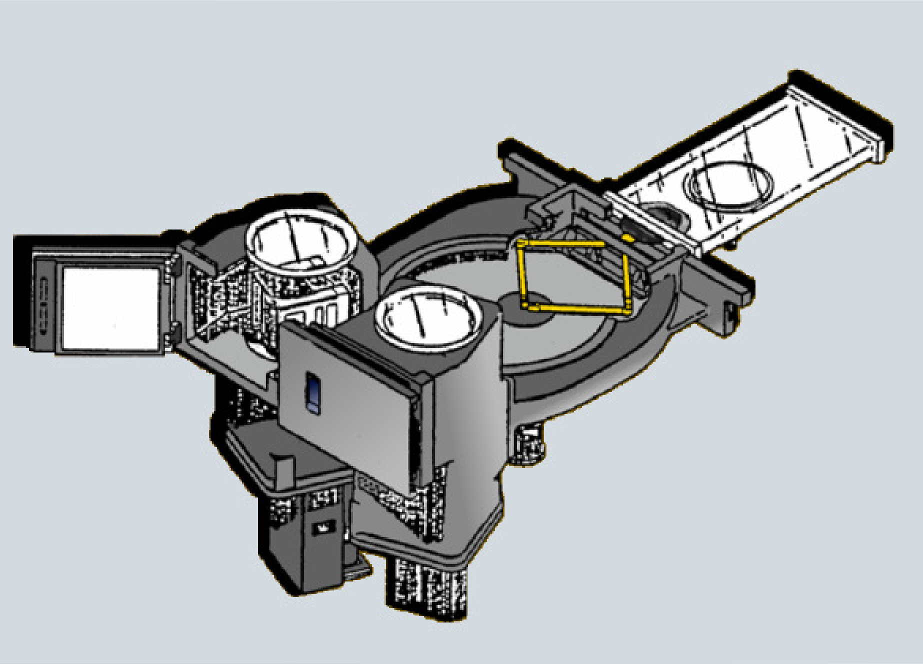
  - Thickness variations as function of
    - Window size
    - Pattern density
- Conclusions
- Future work

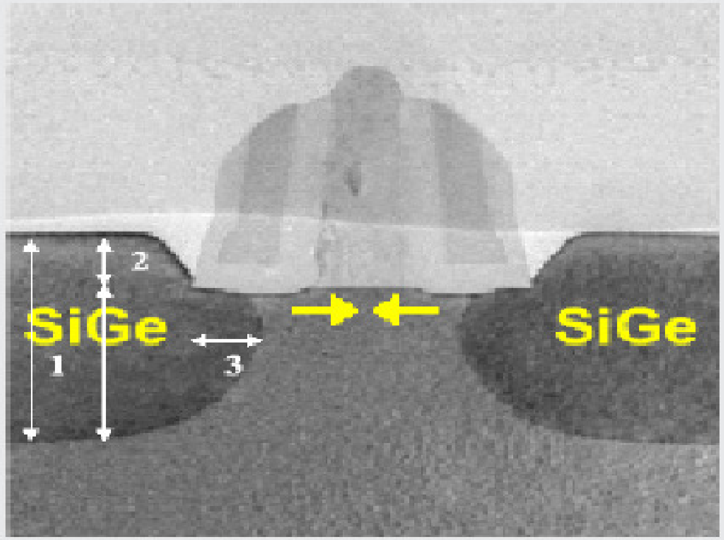
Epi reactor(s) at IMEC

- ASM Epsilon 2000 reactor

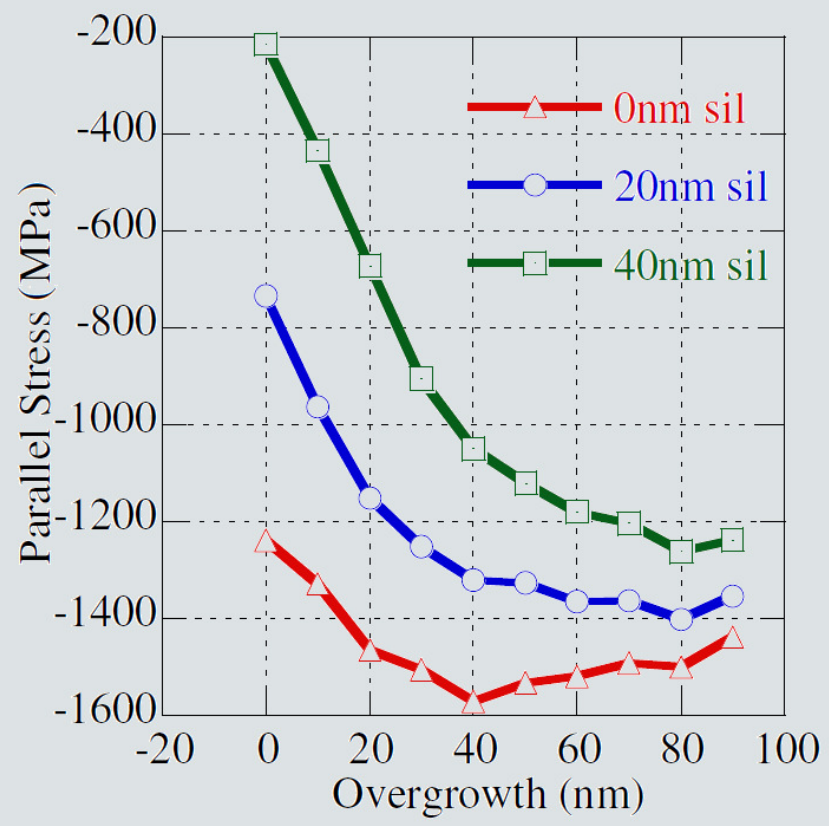


Horizontal, single wafer reactor
Load lock
Lamp heating
Gases: H_2
SiH_2Cl_2, GeH_4
HCl

Motivation

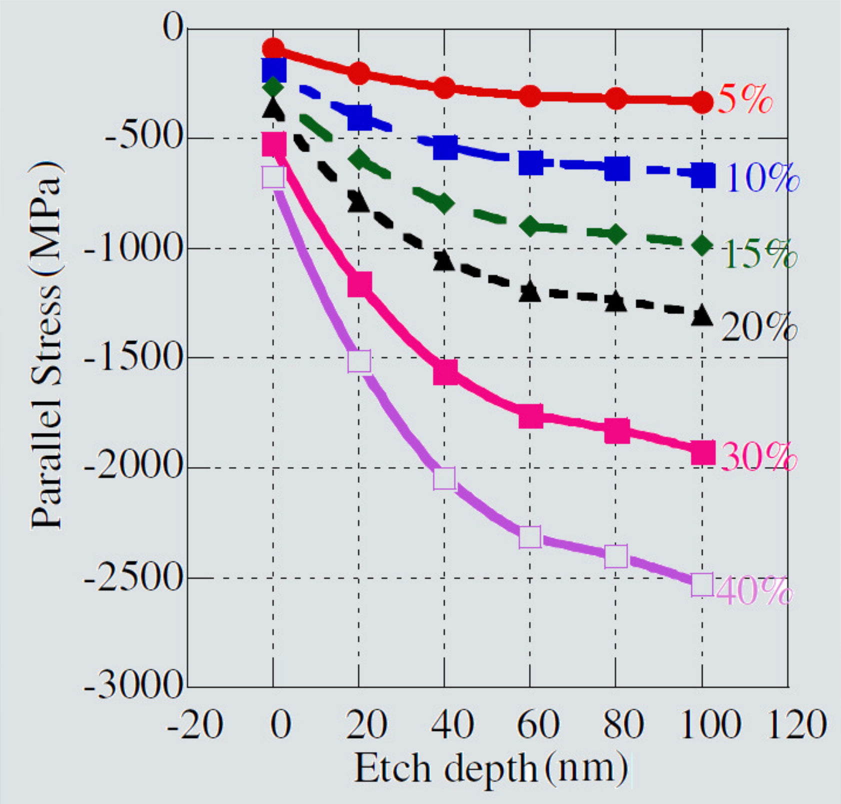


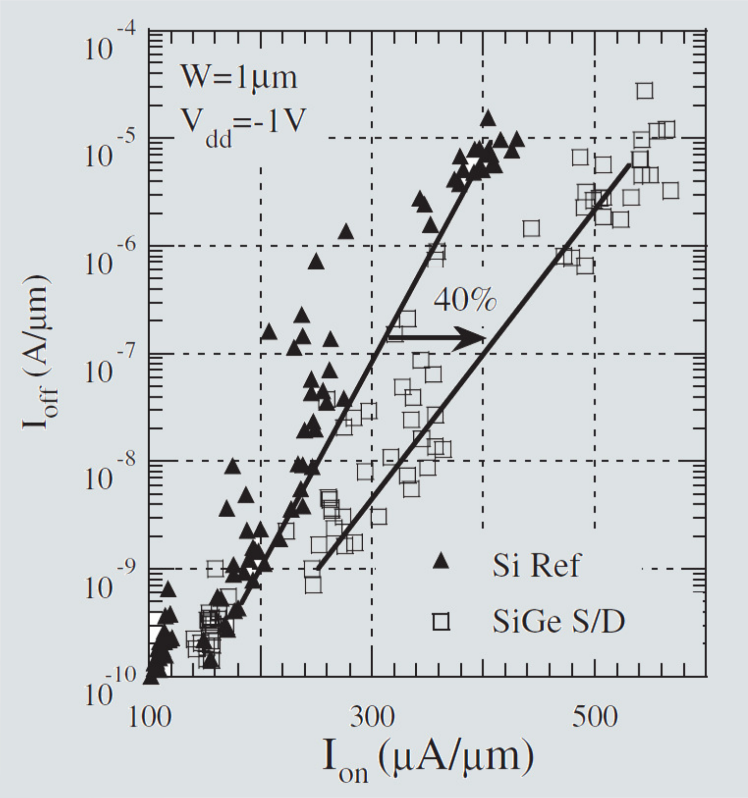
XTEM image: T. Ghani et al.: IEDM 2003, p. 978.



- After the recess, selective SiGe is deposited into the source/drain regions to induce uniaxial compressive strain in the channel
- Variations in the overgrowth can influence the stress level in the Si channel

Motivation



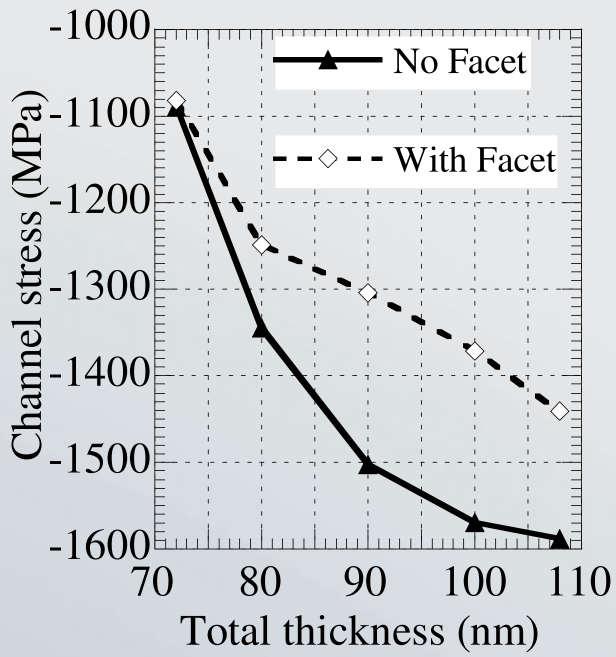


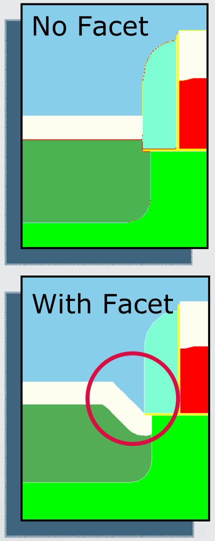
Software: Taurus-Process simulation

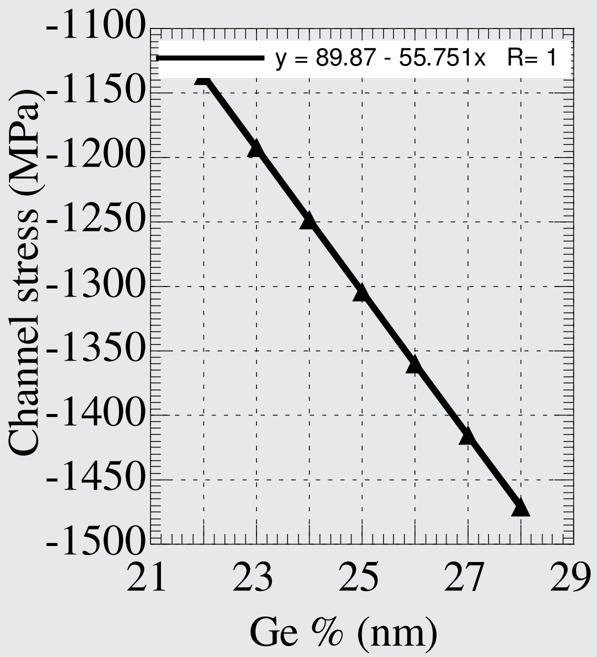
I_{on}/I_{off} plot: R. Loo et al.: Thin Solid Films 2005, p.269

- Variations in the growth rate, germanium and boron concentrations of the SiGe layer can directly influence the stress level in the Si channel and in this way effecting device performance as well

Motivation







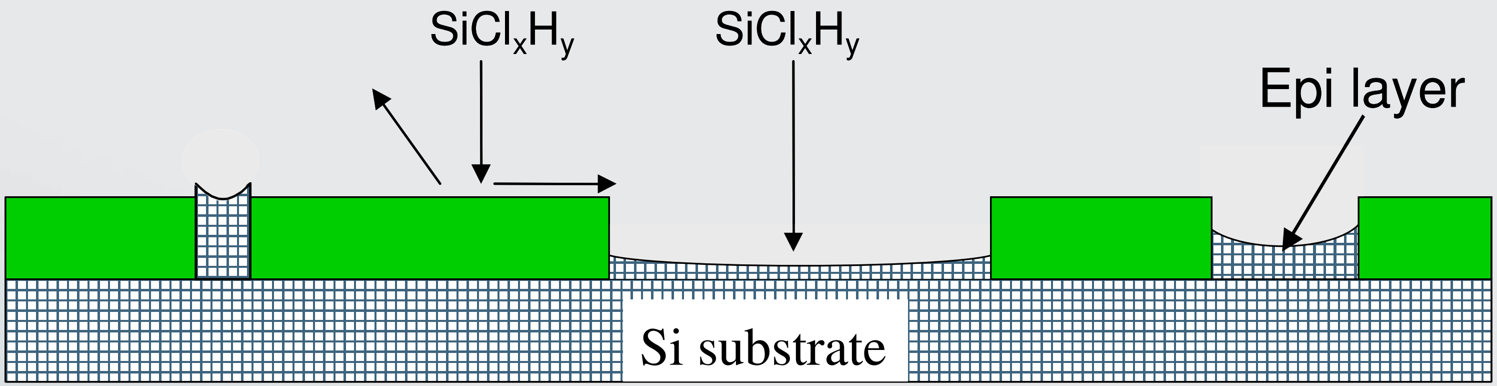
- Clear influence of SiGe thickness on stress level, even if the re-grown SiGe exceeds the original surface
- Simulator predicts nearly linear variation with Ge%
  - 20% Ge shift results in 20% stress shift

Motivation

- Variations in growth rate and layer composition (Ge and boron concentrations) during SEG of recessed S/D directly influence the stress level in the Si channel.

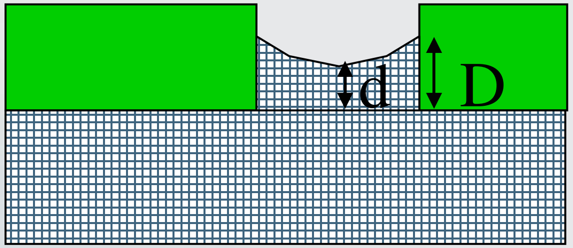
- Presence of loading effects needs some renewed attention, especially for boron doped layers
  - Effects layer thickness
  - Effects layer quality

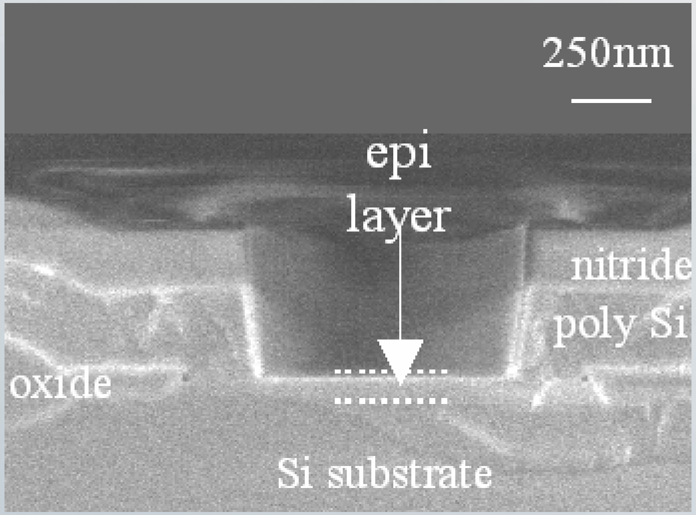
Micro-loading



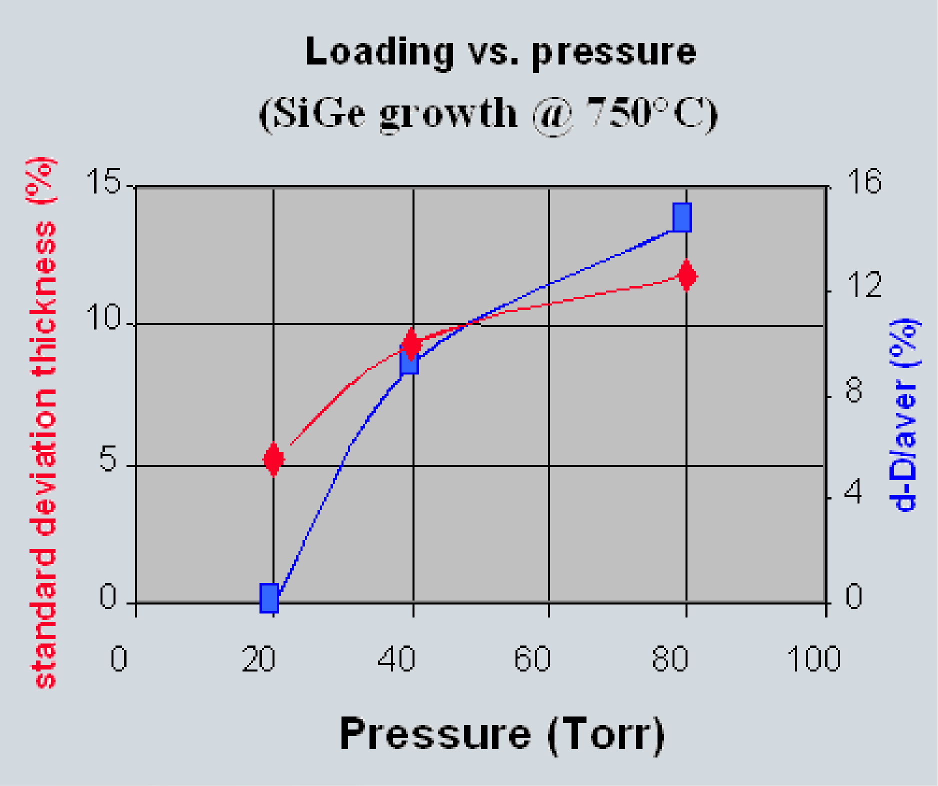
- Local variation in growth rate and composition
- In-window thickness non-uniformity
- Function of structure size and density
- Causes:
  - Chemical: local variation in gas phase concentrations
  - Thermal: (local) variation in surface temperature:
    Change in light absorption and emission due to variations in mask layout and in wafer architecture

Solving the Micro-loading Effect: Previous work





R. Loo et al.: ECS, vol. **150** (2003)



R. Loo et al.: ECS, vol. **150** (2003)

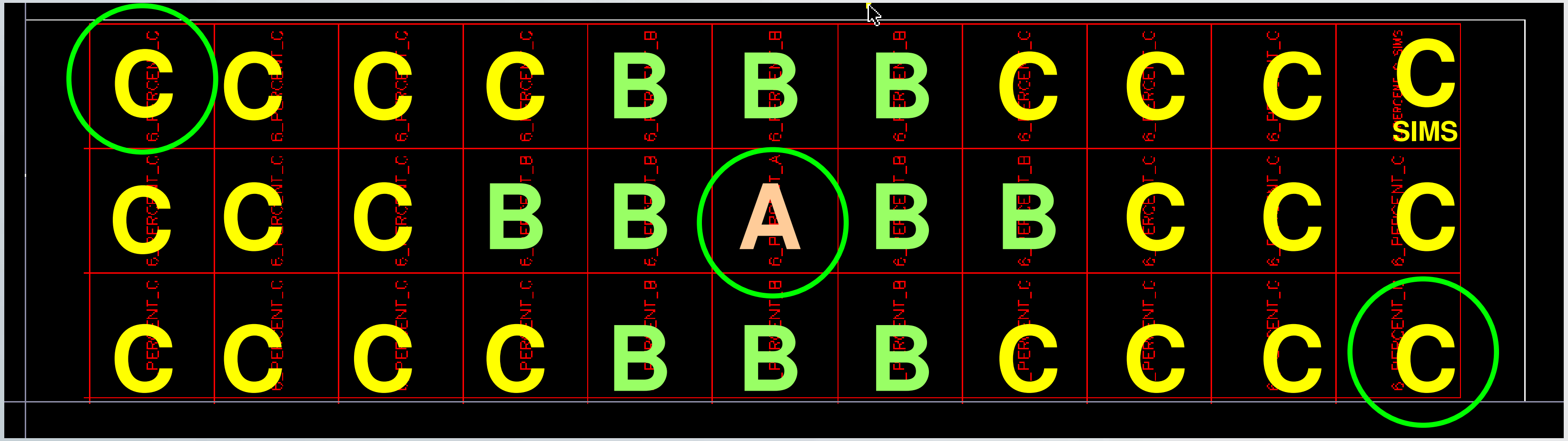
Experimental

- Undoped and doped (~20% Ge)
  - Split in growth conditions
    - 700 ℃, 20 Torr
    - 700 ℃, 10 Torr
    - 750 ℃, 10 Torr
  - Split in % open Si area (6% versus 15%)

- Analysis:
  - SE measurements: thickness and composition of SiGe (in SIMS windows and pad-oxide)
  - HRP measurements: stepheight as function of window size
  - Nomarski inspection, SEM and AFM

Mask Layout

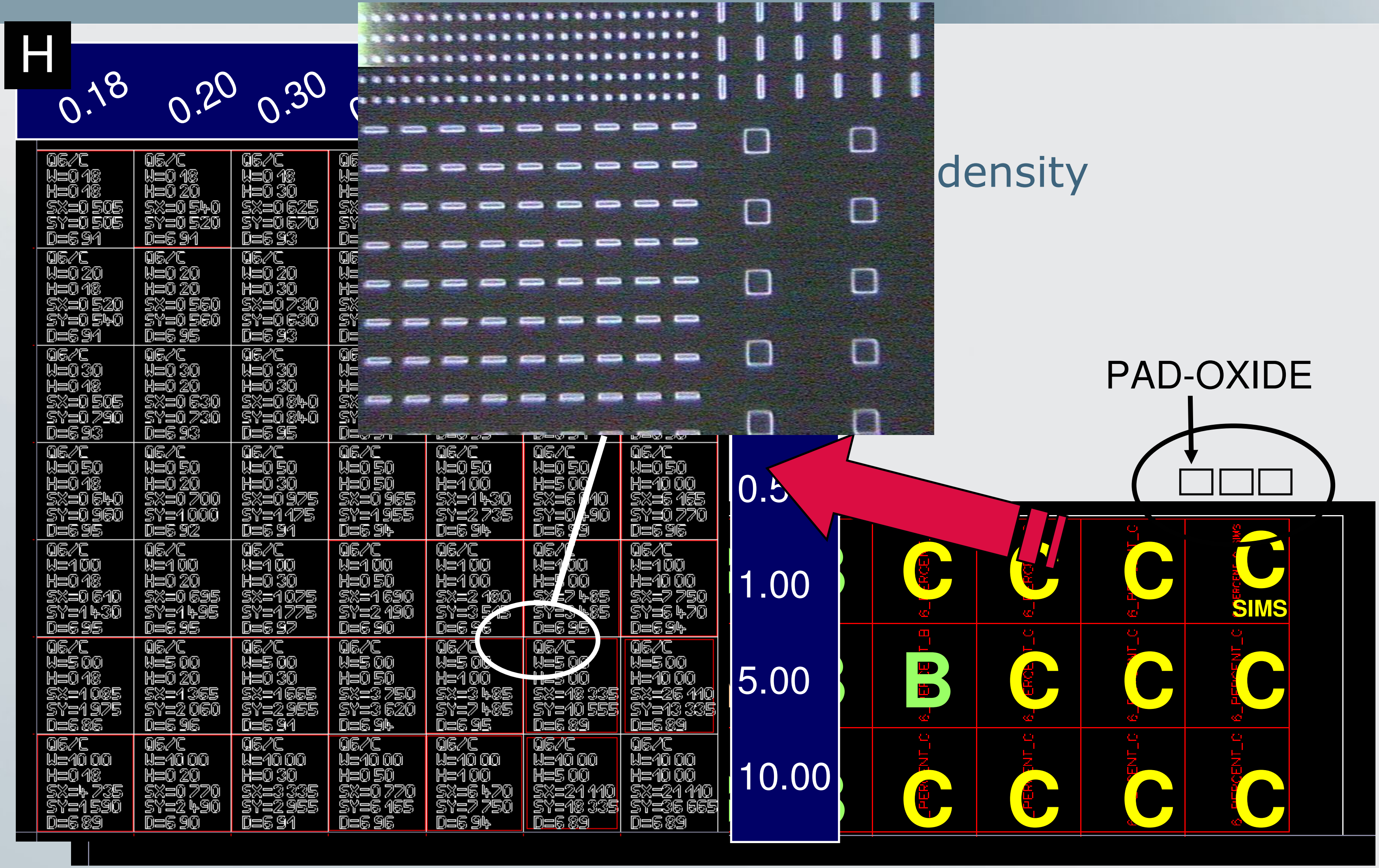
- The die consists of different blocks (A,B,C), which have different global densities.
- Every block is sub-divided in sub-blocks, with structures with different sizes and spacing.



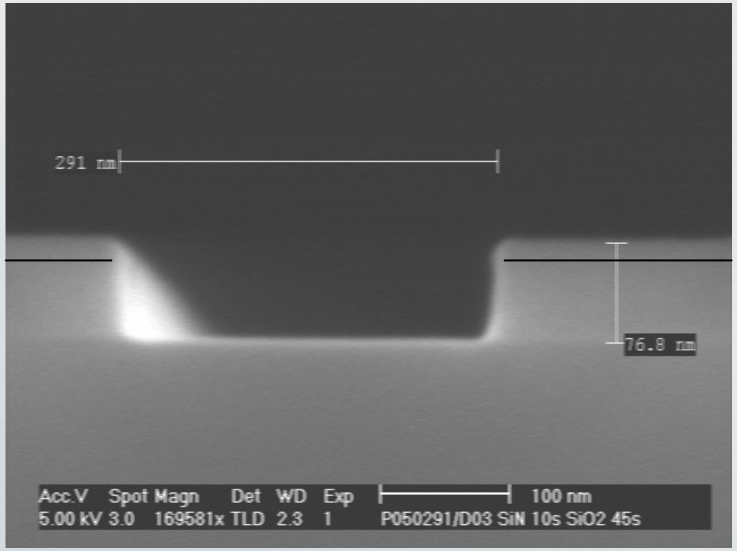
C	C	C	C	B	B	B	C	C	C	C SIMS
C	C	C	B	B	A	B	B	C	C	C
C	C	C	C	B	B	B	C	C	C	C

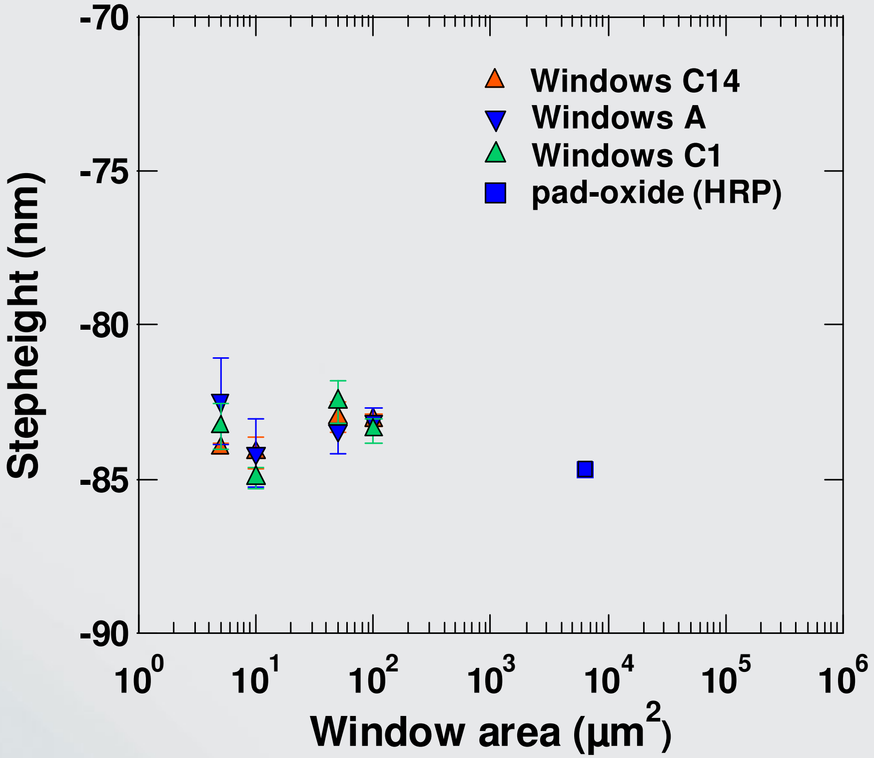
Mask Layout

density



P050291: after dry etch

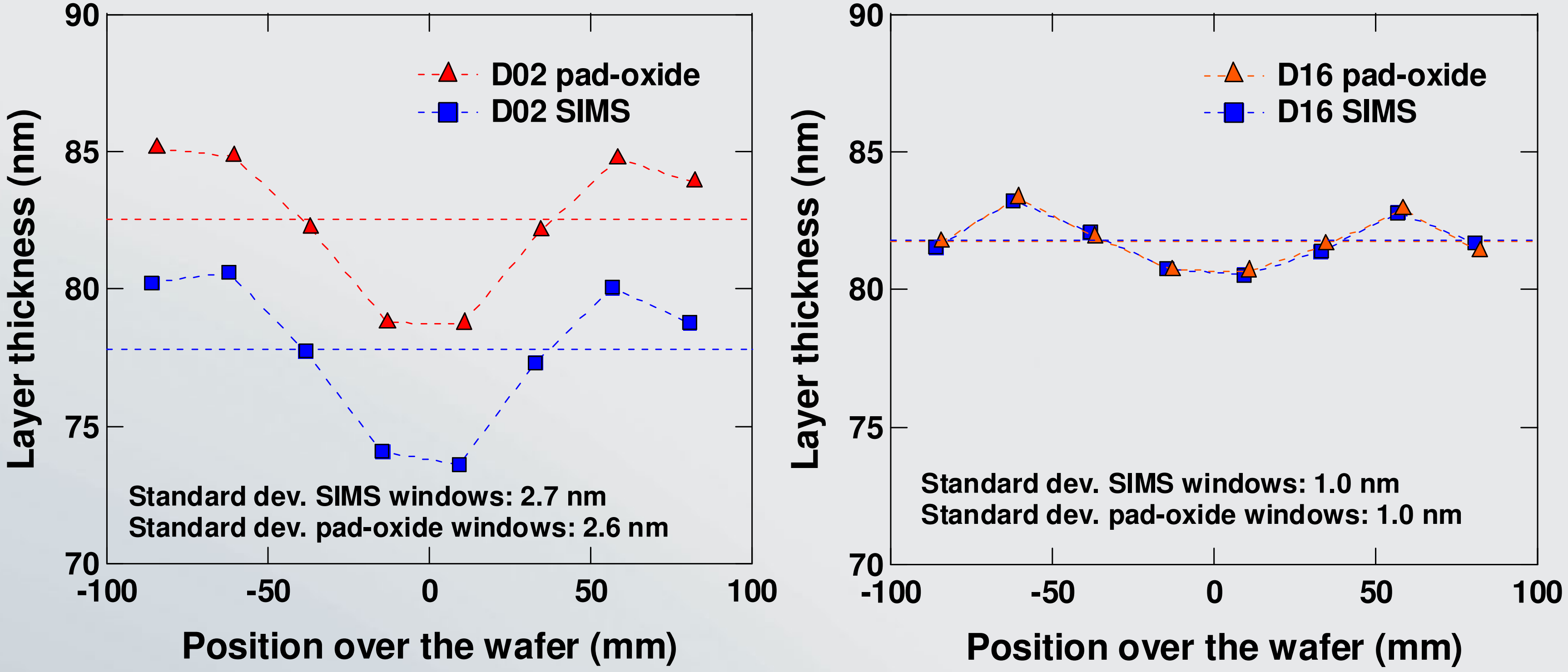




- Spectroscopic Ellipsometry:
  Total stack: 77.1 nm (SiO$_2$: 58.3 nm, Si$_3$N$_4$: 18.8 nm)
- Variations in etch-depth as function of the window size are marginal and within the accuracy of the measurement

Spectroscopic Ellipsometry

(700 °C, 20 Torr and 10 Torr, 15% open Si)



- SIMS window (~270x270 µm2) is surrounded by patterned areas
- PAD-oxide window is a single window (80x80 µm2), no other windows around
- Difference in layer thickness for SIMS-windows and pad-oxide windows could indicate presence of micro-loading effects.

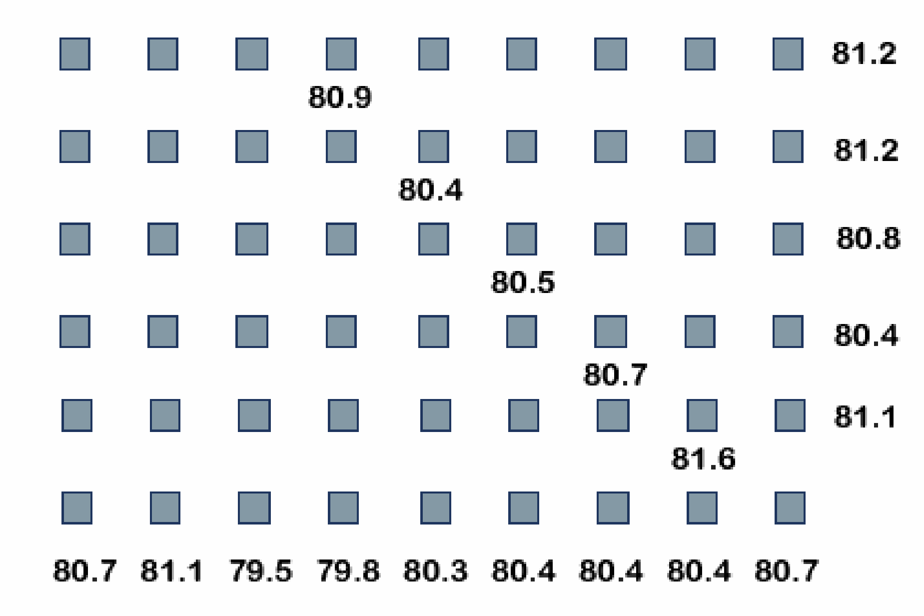
Summary SE measurements
(wfr center)

		6% open Si				15% open Si			
Wfr	Growth Conditions	SIMS window		PAD-oxide		SIMS window		PAD-oxide	
		Thickn. [nm]	% Ge	Thickn. [nm]	% Ge	Thickn. [nm]	% Ge	Thickn. [nm]	% Ge
D05/ D15	750 °C, 10 Torr					80.9	20.6	79.9	21.4
D06/ D16	700 °C, 10 Torr					81.1	21.9	81.1	22.4
D02/ D14	700 °C, 20 Torr	73.6	23.8	78.7	24.4	76.8	22.1	85.2	22.9
D07/ D17	650 °C, 20 Torr	43.1	20.4	46.7	22.3	39.7	20.8	44.5	22.7

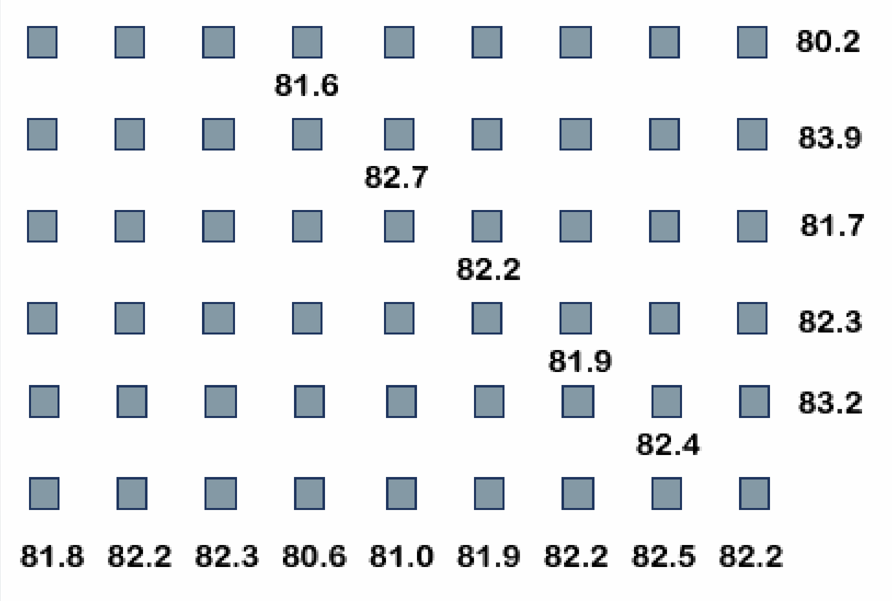
Step-height Measurements:

D02 (700 ℃, 20 Torr) center die, 10x10 μm^2

C(11-3): 80.6 ± 0.5 nm

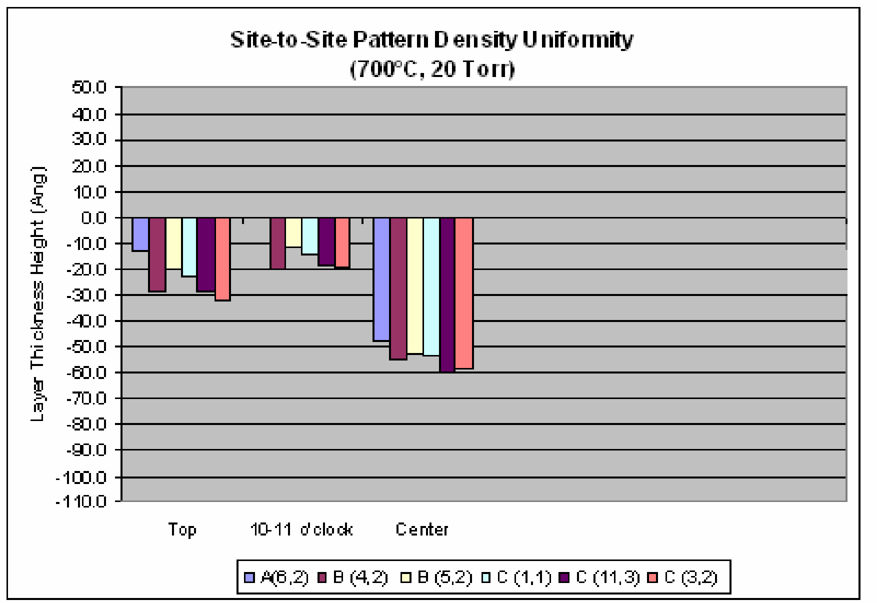


C(1-1): 82.0 ± 0.8 nm

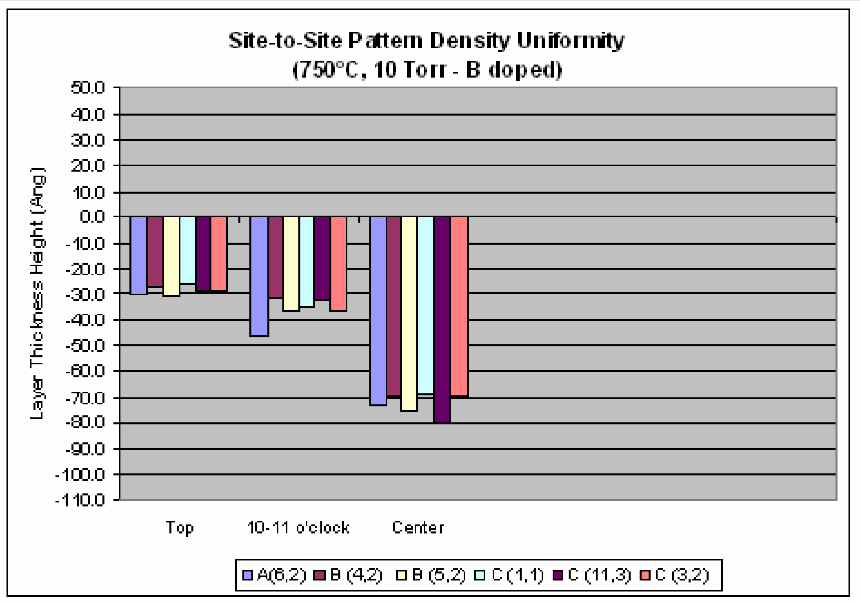


- Variations in layer thickness are within measurement accuracy
- Within one block: no thickness variation from “edge” to center

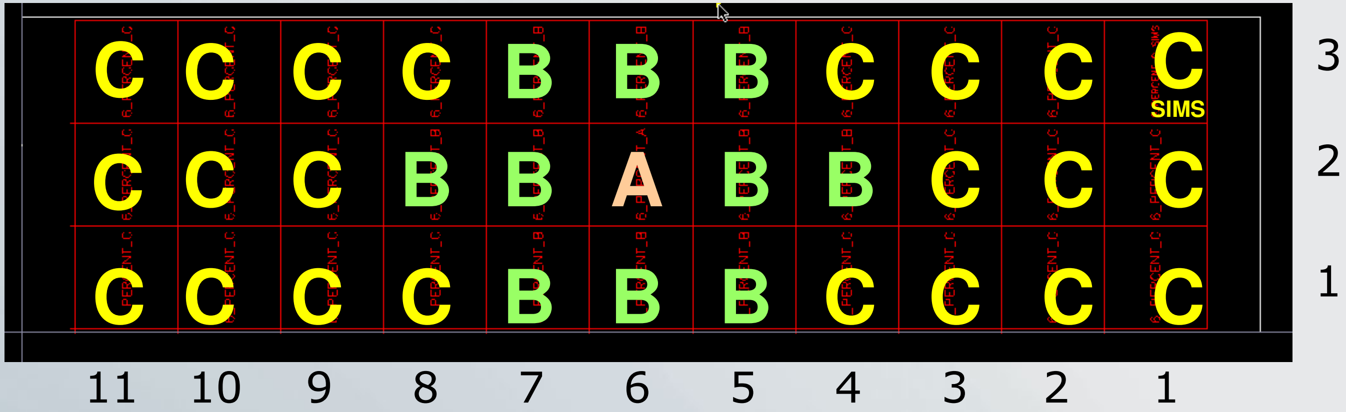
Step-height Measurements: 10x10 µm^2



Site-to-Site Pattern Density Uniformity
(700°C, 20 Torr)



Site-to-Site Pattern Density Uniformity
(750°C, 10 Torr - B doped)

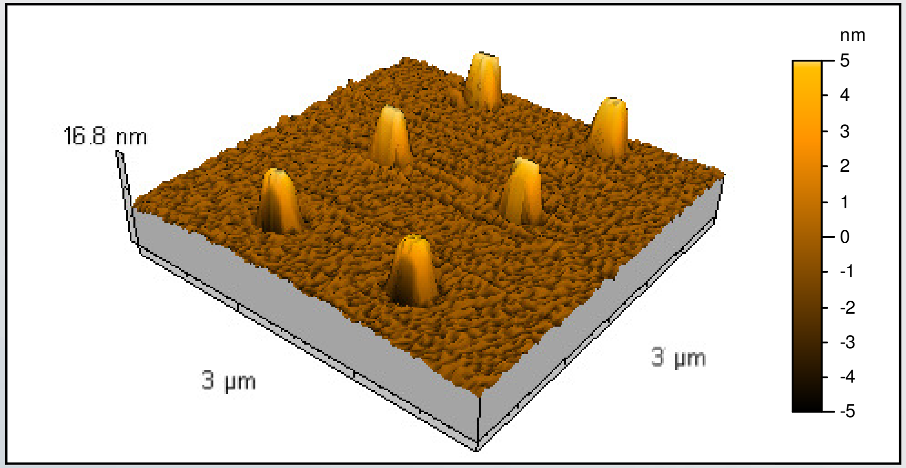


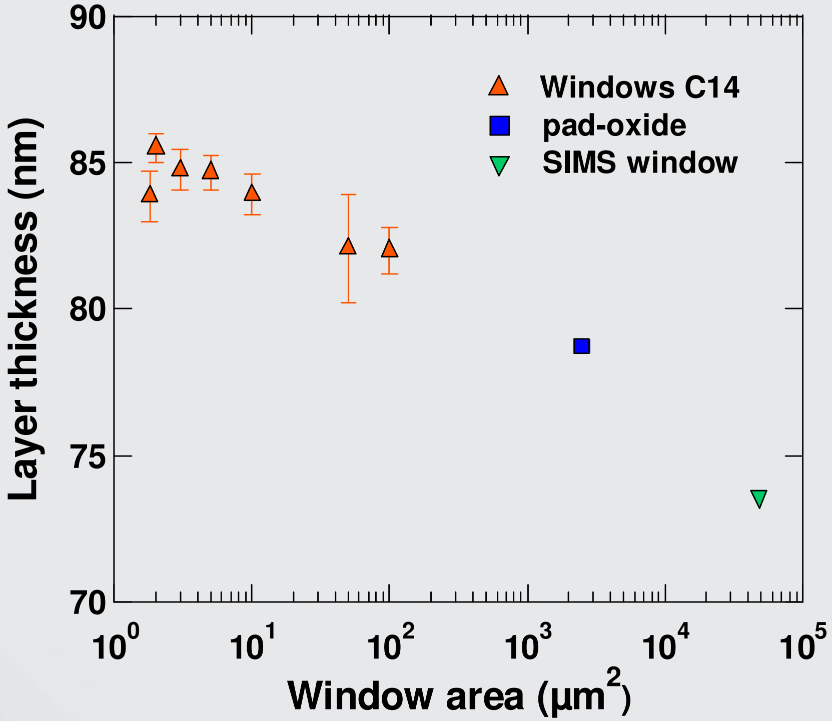
	11	10	9	8	7	6	5	4	3	2	1
3	C	C	C	C	B	B	B	C	C	C	C SIMS
2	C	C	C	B	B	A	B	B	C	C	C
1	C	C	C	C	B	B	B	C	C	C	C

Window Size Influence

(700 °C, 20 Torr) (wfr D02/center)

0.3x0.3 µm^2





- No variation as function of pattern density (confirmed for windows down to 0.3x0.3 µm^2)
- No thickening at the edge for smallest window
- “Large” windows: some thickening at the edge seen, some non-uniformity
- Slight increase in thickness if window size decreases

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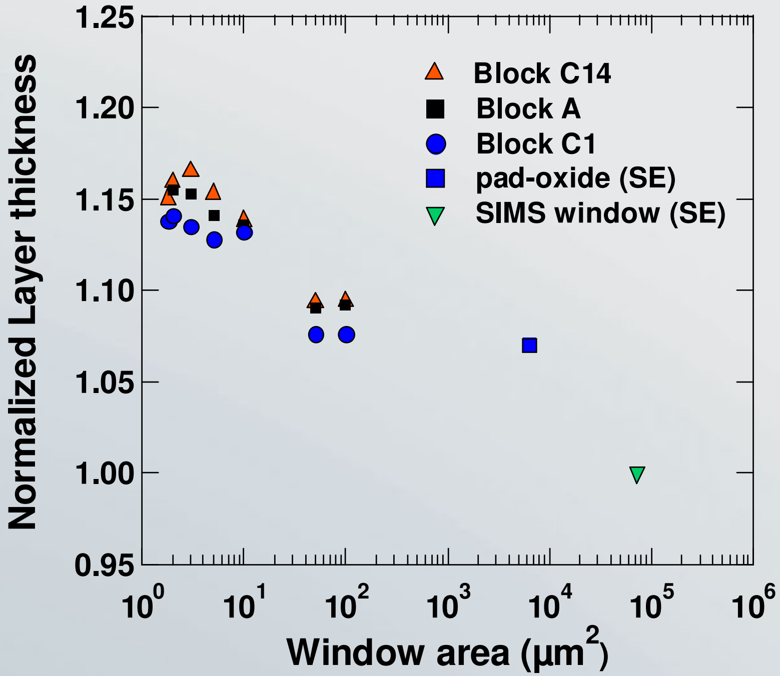
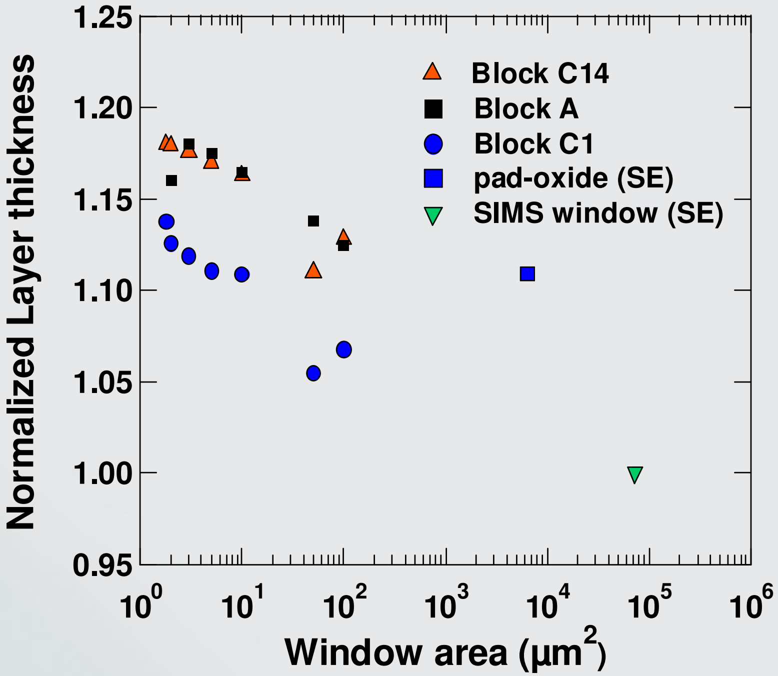
Influence of Mask Layout

(700 °C, 20 Torr, 6% open Si)

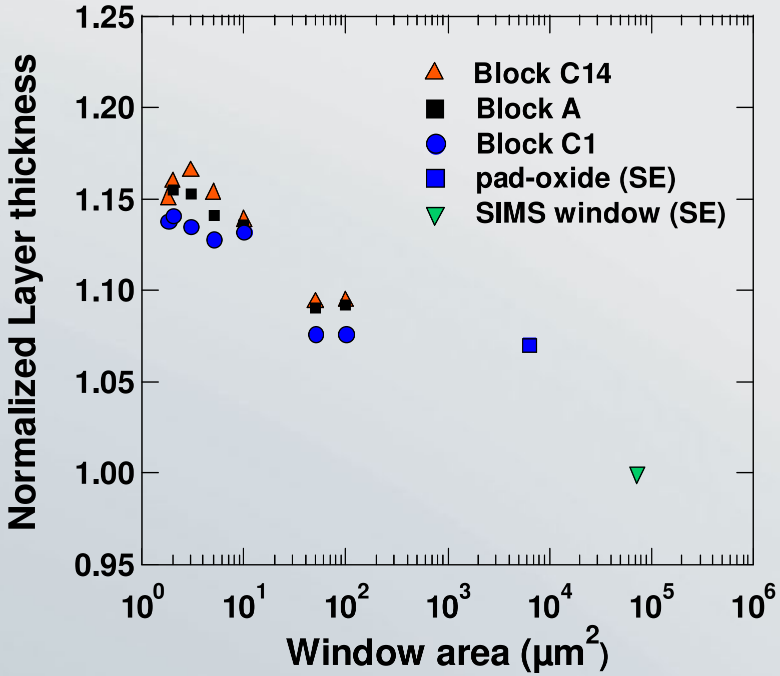


(700 °C, 20 Torr, 15% open Si)

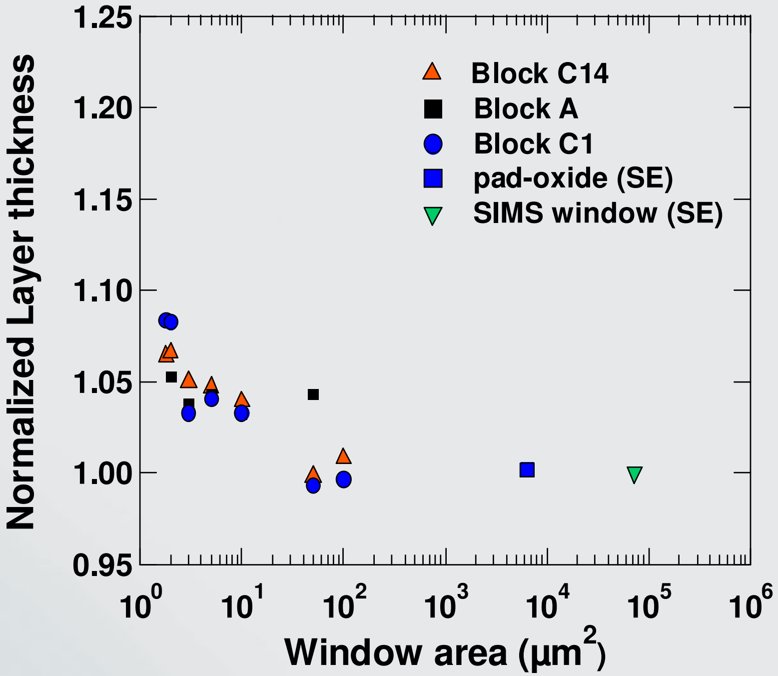


Influence of Growth Pressure

(700 °C, 20 Torr, 15% open Si)

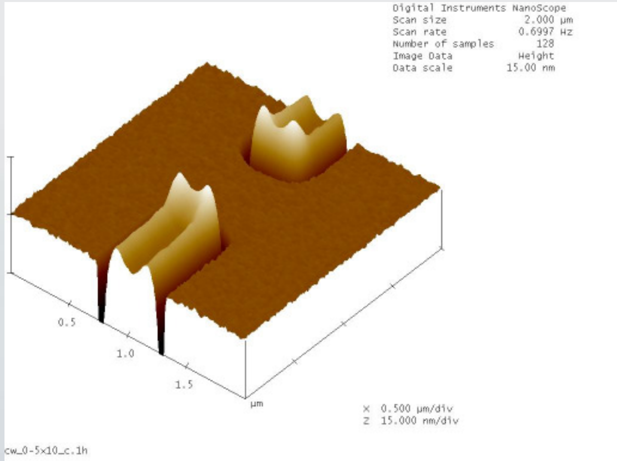


(700 °C, 10 Torr, 15% open Si)



Micro-Loading: non-uniform thickness variation within a window

AFM: 0.5x10 µm2 Fenster



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Digital Instruments NanoScope
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Scan rate             0.6997 Hz
Number of samples        128
Image Data            Height
Data scale          15.00 nm
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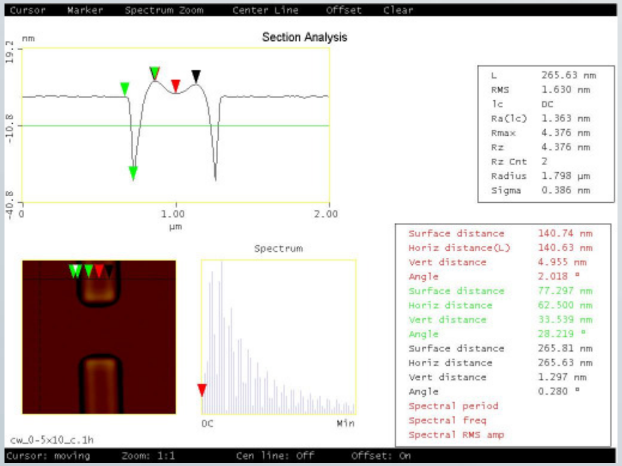
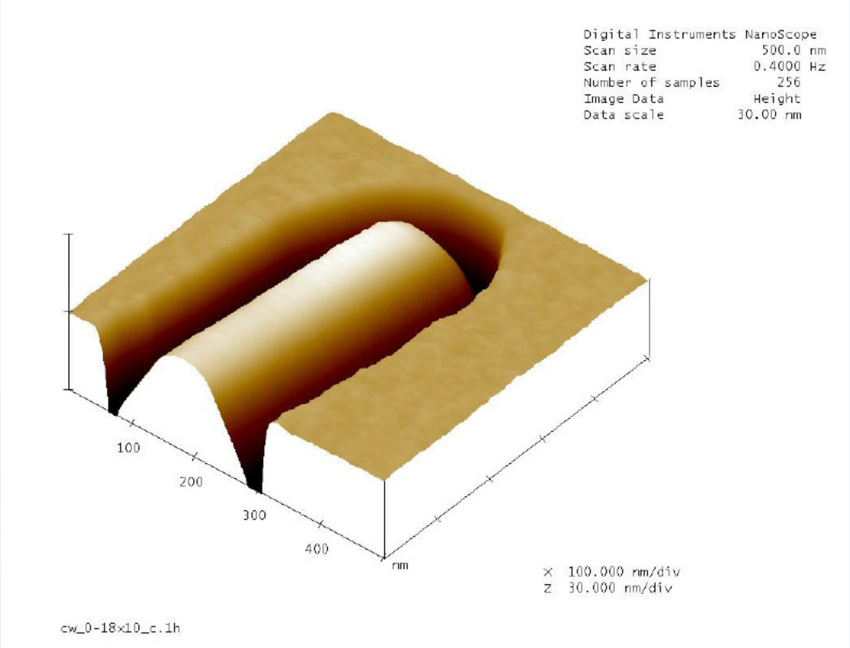


```
L           265.63 nm
RMS         1.630 nm
lc          DC
Ra(lc)      1.363 nm
Rmax        4.376 nm
Rz          4.376 nm
Rz Cnt      2
Radius      1.798 µm
Sigma       0.386 nm
```

```
Surface distance      140.74 nm
Horiz distance(L)     140.63 nm
Vert distance         4.955 nm
Angle                 2.018 °
Surface distance      77.297 nm
Horiz distance        62.500 nm
Vert distance         33.539 nm
Angle                 28.219 °
Surface distance      265.81 nm
Horiz distance        265.63 nm
Vert distance         1.297 nm
Angle                 0.280 °
Spectral period
Spectral freq
Spectral RMS amp
```

```
Cursor: moving     Zoom: 1:1     Cen line: Off     Offset: On
```

AFM: 0.18x10 µm2 Fenster



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Digital Instruments NanoScope
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Data scale          30.00 nm
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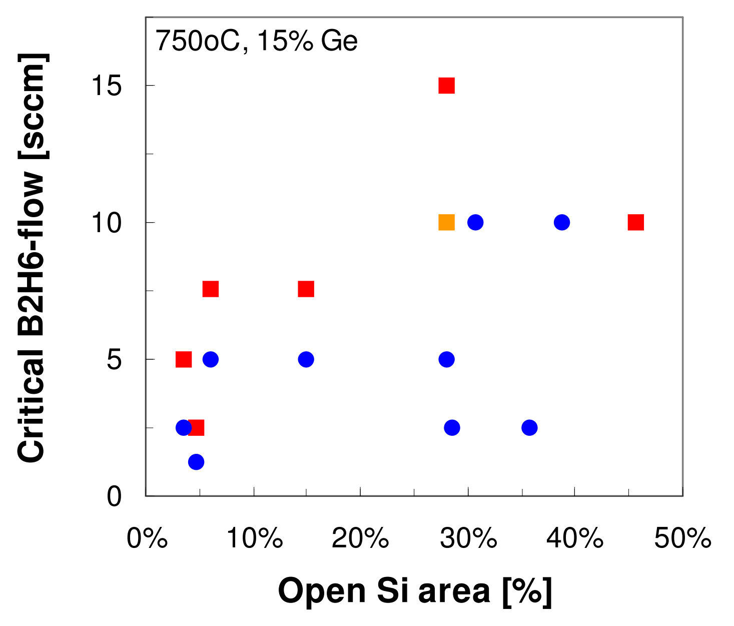
Impact of mask layout on critical B_2H_6 flow



🟥 rough epi or defects
● smooth epi
🟨 o.k. but defects in the center die

- Tend between critical B_2H_6 flow for surface roughening and mask layout
- Might be explained by "gas depletion":
  - Linear correlation between boron content and B_2H_6 flow
  - Higher "effective" flow per window if total Si area is decreased

Conclusions

- Influence of growth pressure on thickness variation as function of window size
  - 20 Torr: thicker layers for smaller windows
  - Reducing pressure and/or increasing H_2 gas flow reduces micro-loading
- No measurable effect for pattern density variations within one mask
- No measurable effect for pattern density variations for 6% and 15% global density
- “Large” windows: some thickening at the edge seen, some non-uniformity

Outlook

- Extraction of Ge and boron concentration as function of window size
- H_2 flow (carrier gas):
  - Thickness analysis for smallest windows
- Fundamental understanding of the causes for micro-loading

aspire invent achieve

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