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Exploring the Use of Tungsten-Based Hard Masks in BEOL Interconnects for 3nm Node and Beyond

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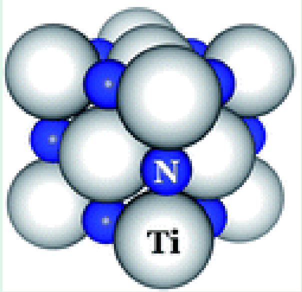
Outline

Hard Mask materials in Back End of Line (BEOL)

Photoresist is not etch-resistant

Hard Mask materials transfer the pattern to final stack



TiN is the main Hard Mask in BEOL

Why?

Advantages:
- ✓ F-based plasma resistant
- ✓ Cl-based plasma patterning
- ✓ Mature

But…
- ✗ Low selectivity for HAR dielectric etch
- ✗ High stress in layer → line wiggling tight pitches
- ✗ Residue formation

Is TiN getting outdated?

Alternative Hard Mask

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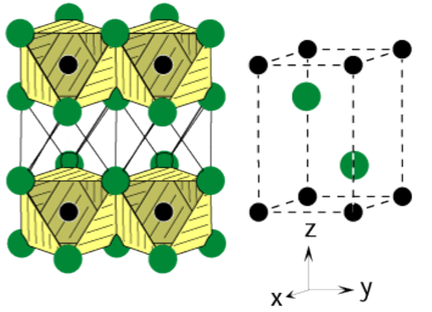


W_2C

Tungsten Carbide

"Exploring the use of W-based Hard Mask material in BEOL interconnects for 3nm Node and Beyond"

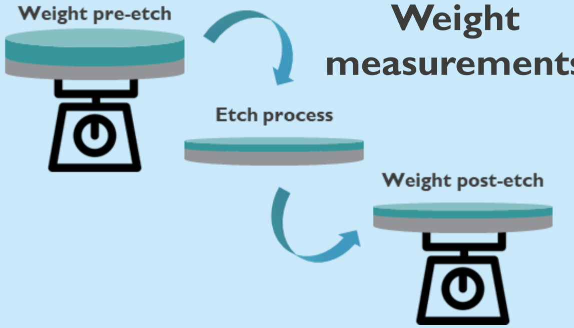
How to test Tungsten Carbide Hard Mask?

Experiments done in 300 mm Si wafers

1. Blanket wafers

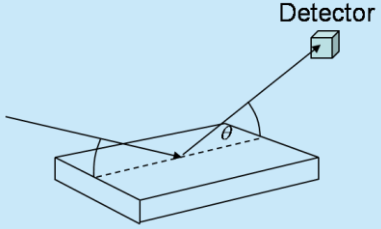
- Initial material screening → W content effect
  - 9 different WCx flavors
- RIE Etch rate tests and selectivity
- Ion Beam Etch test on coupons
- Target
  - Understand material properties
  - Best candidates for patterning exercise

RIE Blanket etch tests



Weight measurements

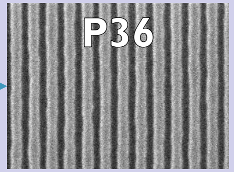
IBE coupon tests

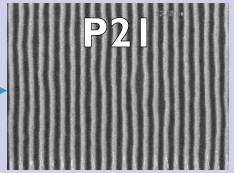


X-Ray Reflectivity

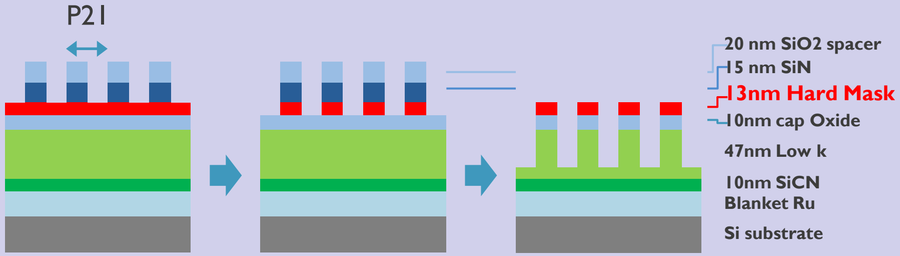
2. Line Space patterning (3nm node MP21)

- EUV patterning → M3 layer
- i193 SAQP → M2 layer
- Target:
  - Develop WCx etch recipe
  - Explore limitations on HM scaling
  - Improve line wiggling
  - Test selectivity





1. SAQP patterning **2. Hard Mask opening** **3. Trench etch**



Target of our research

<u>Test WCx Hard Mask properties in 300 mm Si wafers</u>

- Is WCx worth considering?
- Can we etch it?
- Can we etch it in small pitches?
- Is it that etch-resistant?
  - Selectivity
  - CD control
- Can it be integrated in our BEOL 3nm vehicle?

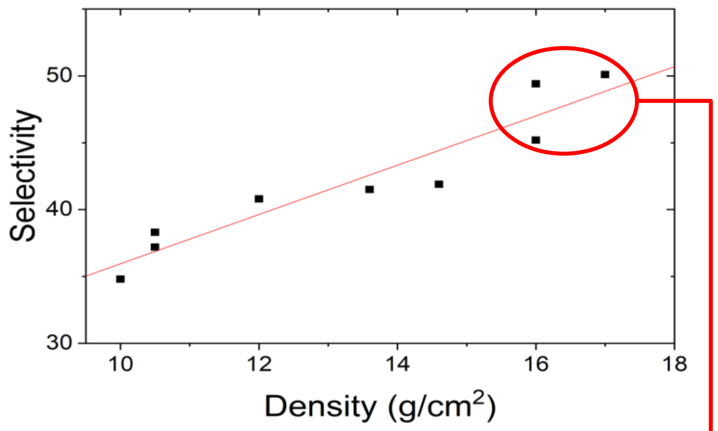
Part I: Blanket tests

Why Tungsten Carbide?

Is WCx worth studying?

1st: Blanket etch Selectivity assessment

Selectivity to low-k etch



W_2C vs target in blanket tests

Etch process	Selectivity W_2C	Target selectivity
SIO2 etch	8	>10
Low k etch	50	>20
SiCN etch	360	>20
SOC etch	120	>50

Main conclusion

✓ WCx may perform on target

2nd: WCx etch assessment

- New development at IMEC → no baseline available
- Strategy:
  1. Find possible volatile compounds
  2. Choose main etchant
  3. Find passivation mechanisms
  4. Tune WCx profile
- Challenges:
  - Selectivity towards SiO2 during WCx etch
  - Etch profile
- Metal Inductively Coupled Plasma (ICP) chamber chosen

element(→) etchant(↓)	W	C
F	WF_6 (17.5) WOF_4 (187.5)	CF_4 (-127.8)
Cl	WCl_6 (346.7) WCl_5 (275.6) $WOCl_4$ (227.5)	CCl_4 (76.7)

NF_3: high F dissociation
Ar, N_2: to improve ionization

$SiCl_4$: Si source
O_2: to oxidize Si
→ **SiO_2 formation**
Dissociated Carbon from WCx

Complex chemistry to etch WCx

- Passivation mechanisms
  - $SiCl_4$, O_2, N_2
- Etching mechanisms
  - NF_3, Cl_2, O_2

Synergy

Based on AMAT US patent US20180337047A1

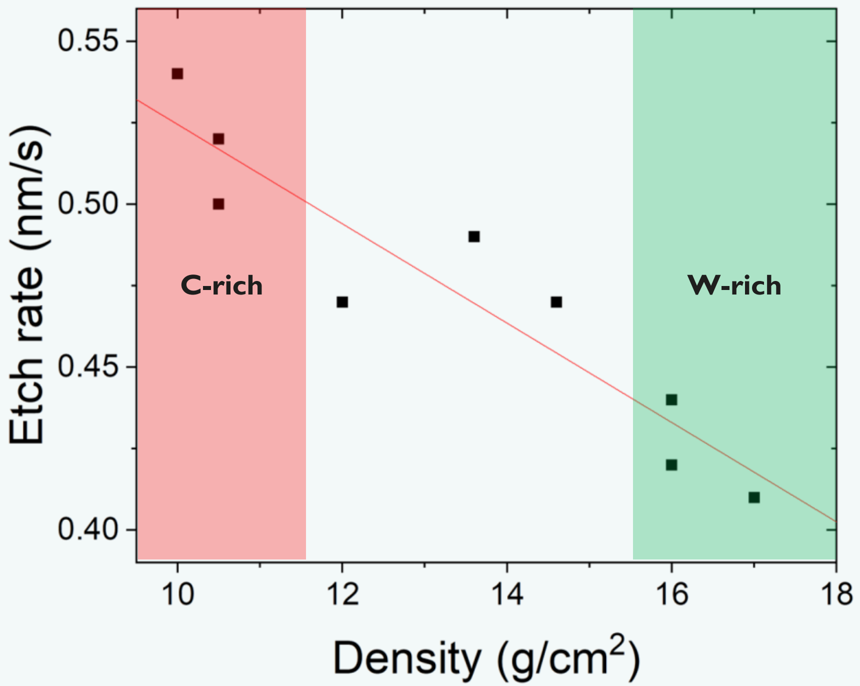
Reactive Ion Etch tests on blankets

Testing chemical and physical etch resistance

$$V = A \cdot t = \pi r^2 \cdot t$$
$$d = \frac{m}{V} \rightarrow V = \frac{m}{d}$$
$$\Rightarrow t = \frac{m}{\pi r^2 d} \rightarrow \Delta t = \frac{\Delta m}{\pi r^2 d}$$

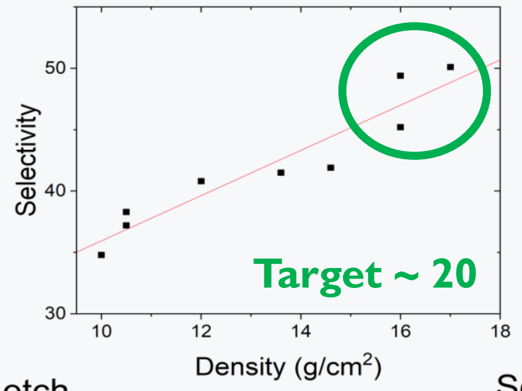
WCx opening etch chemistry

First version of the recipe

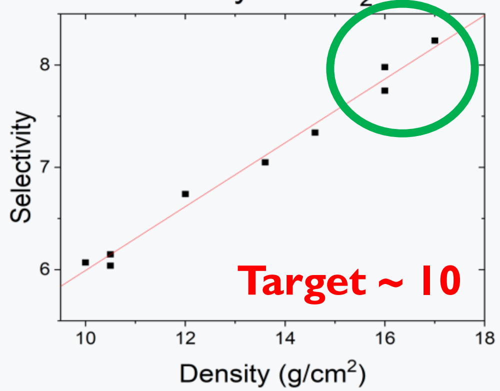


Endurance tests → dielectric chemistries

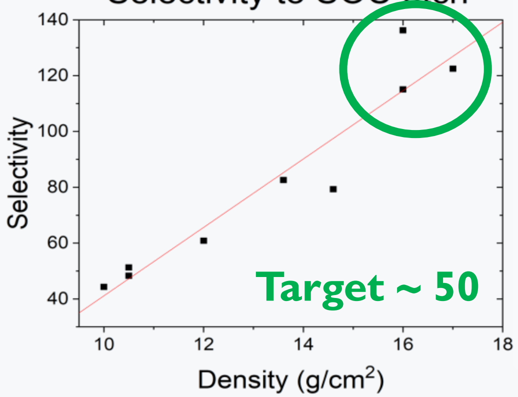
Selectivity to low-k etch



Selectivity to SiO_2 etch



Selectivity to SOC etch

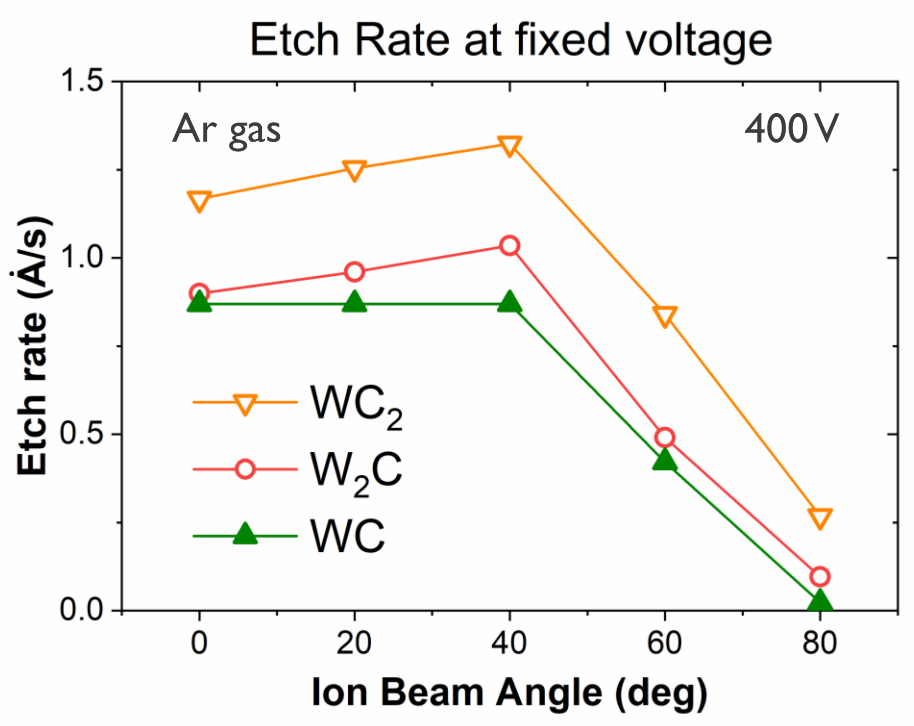


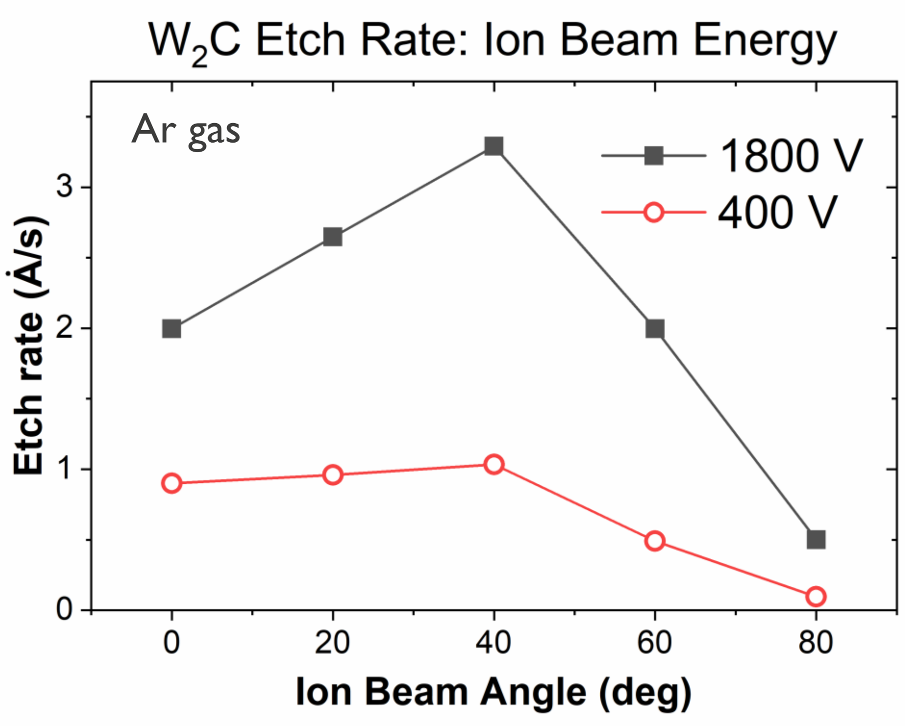
Data obtained from weight measurements

W-rich flavors → more etch resistant

Ion Beam Etch experiments on blanket coupons

Testing ion bombardment resistance



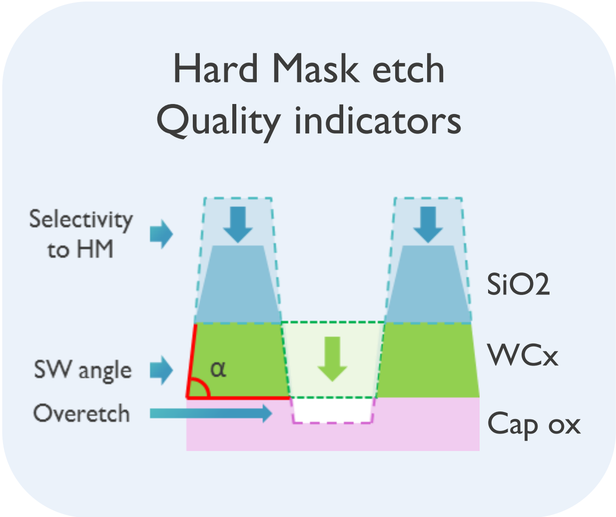


IBE experiments → W-rich flavors are more resistant to ion damage

Part II: Patterning exercise

W_2C etch development

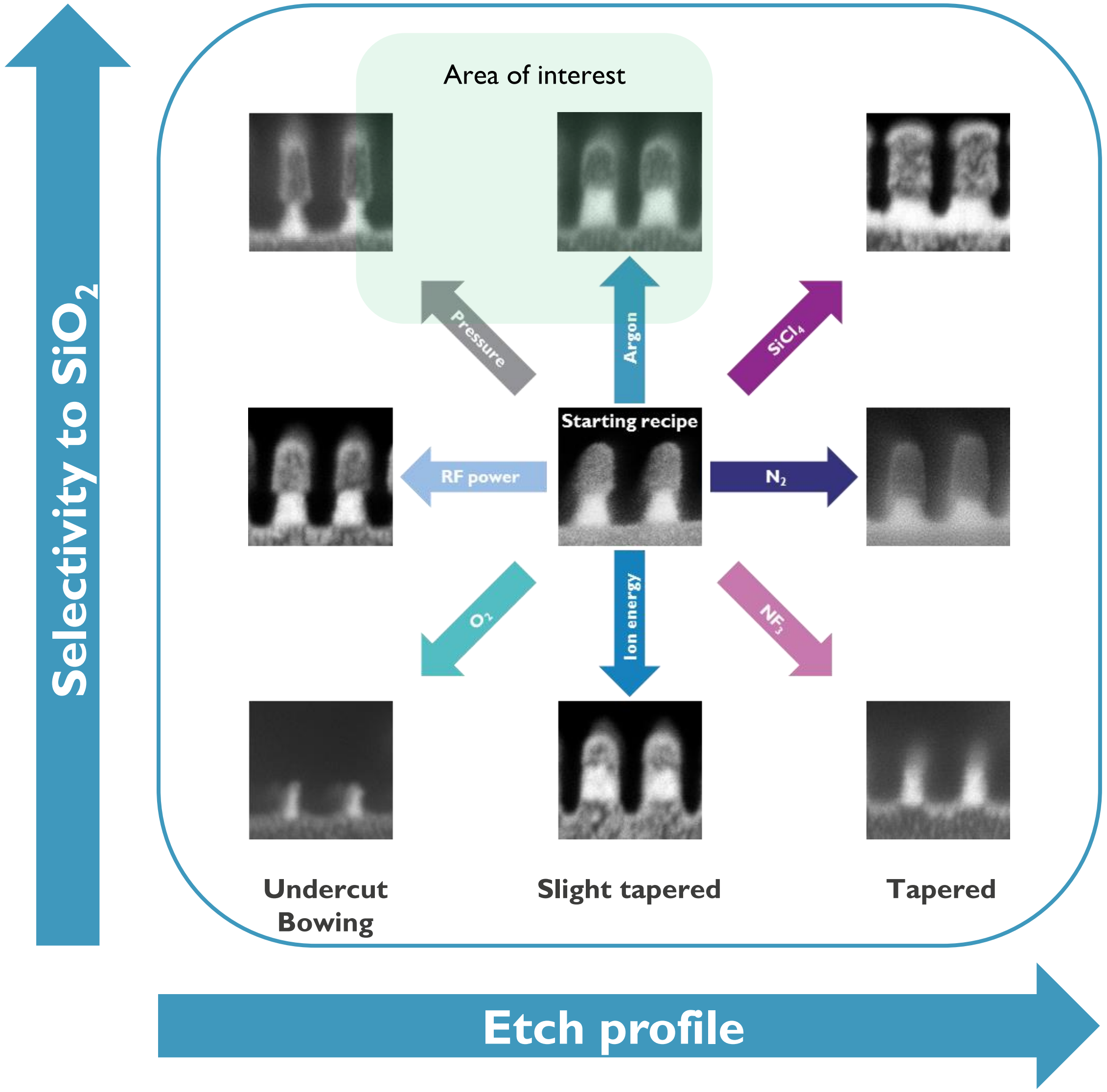
Line Space patterning on P36



Parameter	Target
Selectivity SiO2 HM (@ WCx etch step, WCx/SiO2)	> 2
SW angle	> 88 deg
Overetch	< 5 nm

Etch tool

Lam RESEARCH Kiyo Gx series

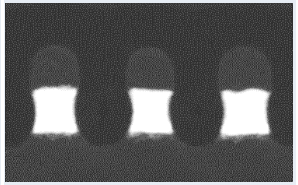
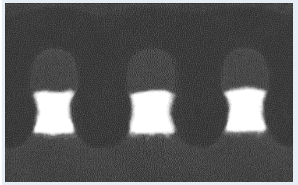
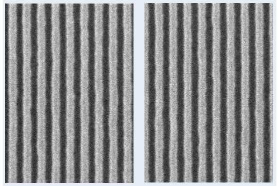
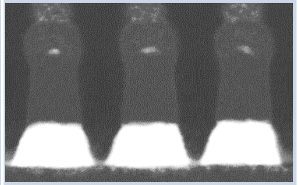
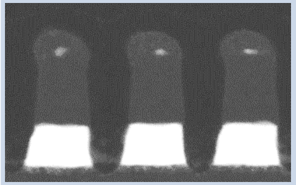
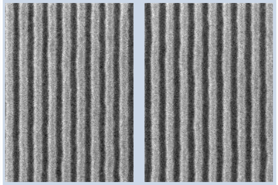
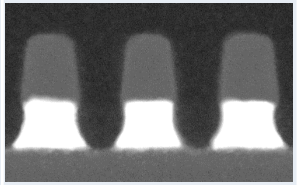
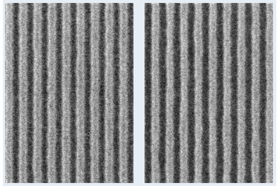
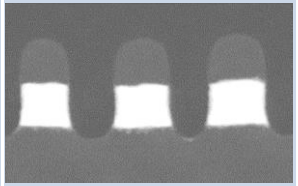
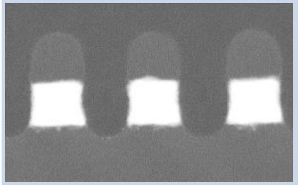
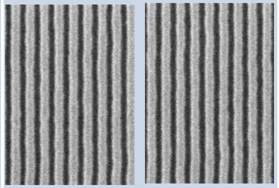


Complex relationship between WCx etch parameters

"Exploring the use of W-based Hard Mask material in BEOL interconnects for 3nm Node and Beyond"

Full wafer assessment of W_2C etch (M3 EUV line space patterning P36)

Going to full wafer

Hard Mask	Center die TEM full wafer	Edge die TEM full wafer	CDSEM Center | edge	Selectivity SiO2 HM	Profile	Overetch SiO2 (nm)
Target	-	-	-	>2	Straight (>88 deg)	< 5
W_2C Process A Low P, low $SiCl_4$				1.1	Bowing Straight	5.4
W_2C Process B Low P, high $SiCl_4$				∞	Tapered	0
W_2C Process C High P, low $SiCl_4$		Not available		3	Bowing Footing	< 1
W_2C Best Process Low P, mid $SiCl_4$				1.4	89	3.5

BKM

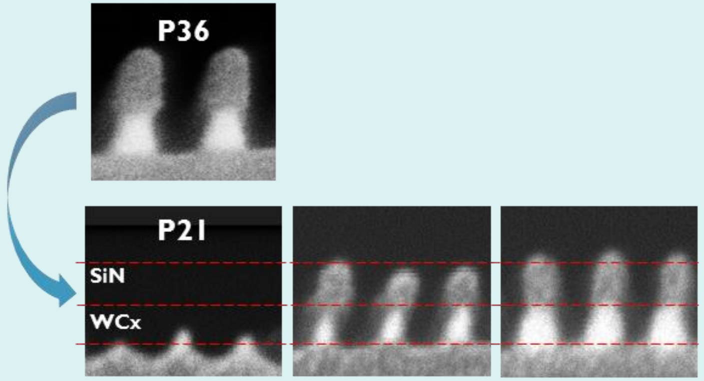
WCx etch in tight pitches → MP21 (M2 SAQP line space patterning)

Tighter requirements on L/S P21

- Less tapering allowed
- Stricter selectivity requirements
  - SiN is used i.o. SiO2 as HM for WCx
- Stricter center-edge uniformity
- Control of Line Roughness

Starting recipe on all samples

Retune process P21

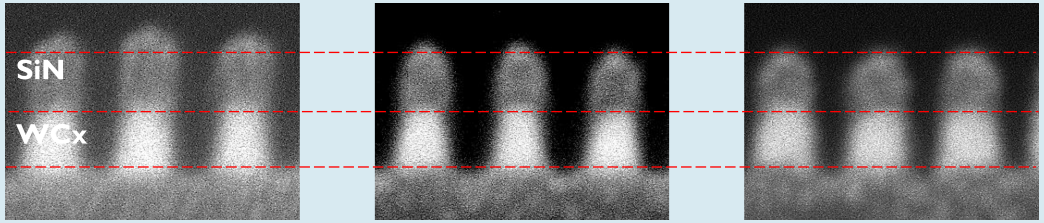


W_2C WC WC_2

Increasing C content
Increase in C passivation

Etch development for each flavor

Increasing C content



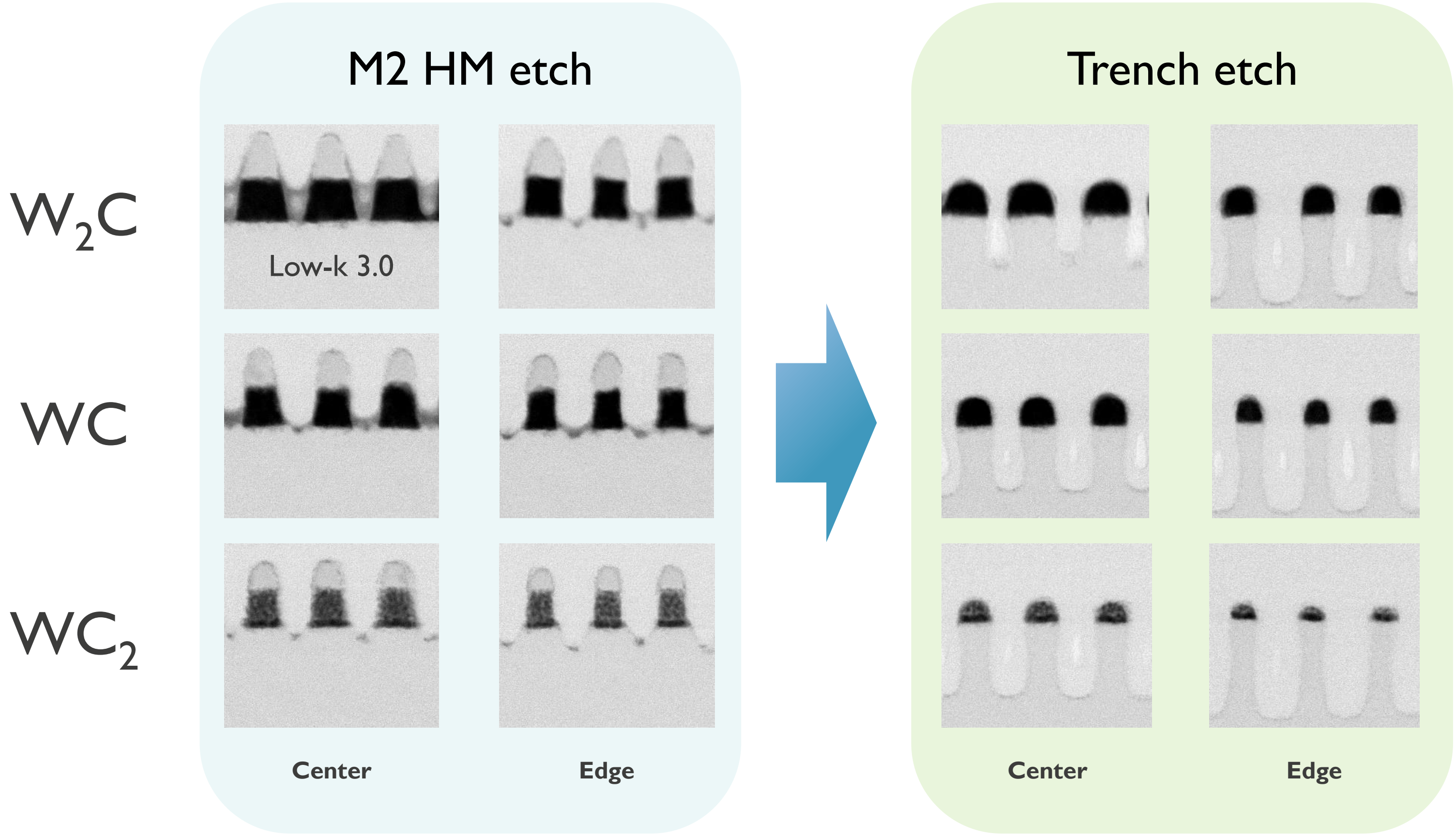
W_2C etch	WC etch	WC_2 etch
Higher passivation	Middle passivation	Low passivation

Increasing $SiCl_4$ passivation

WCx composition plays a big role
→ Retuning needed for each WCx flavor

TEM on full wafer

WCx flavor comparison: TEM results

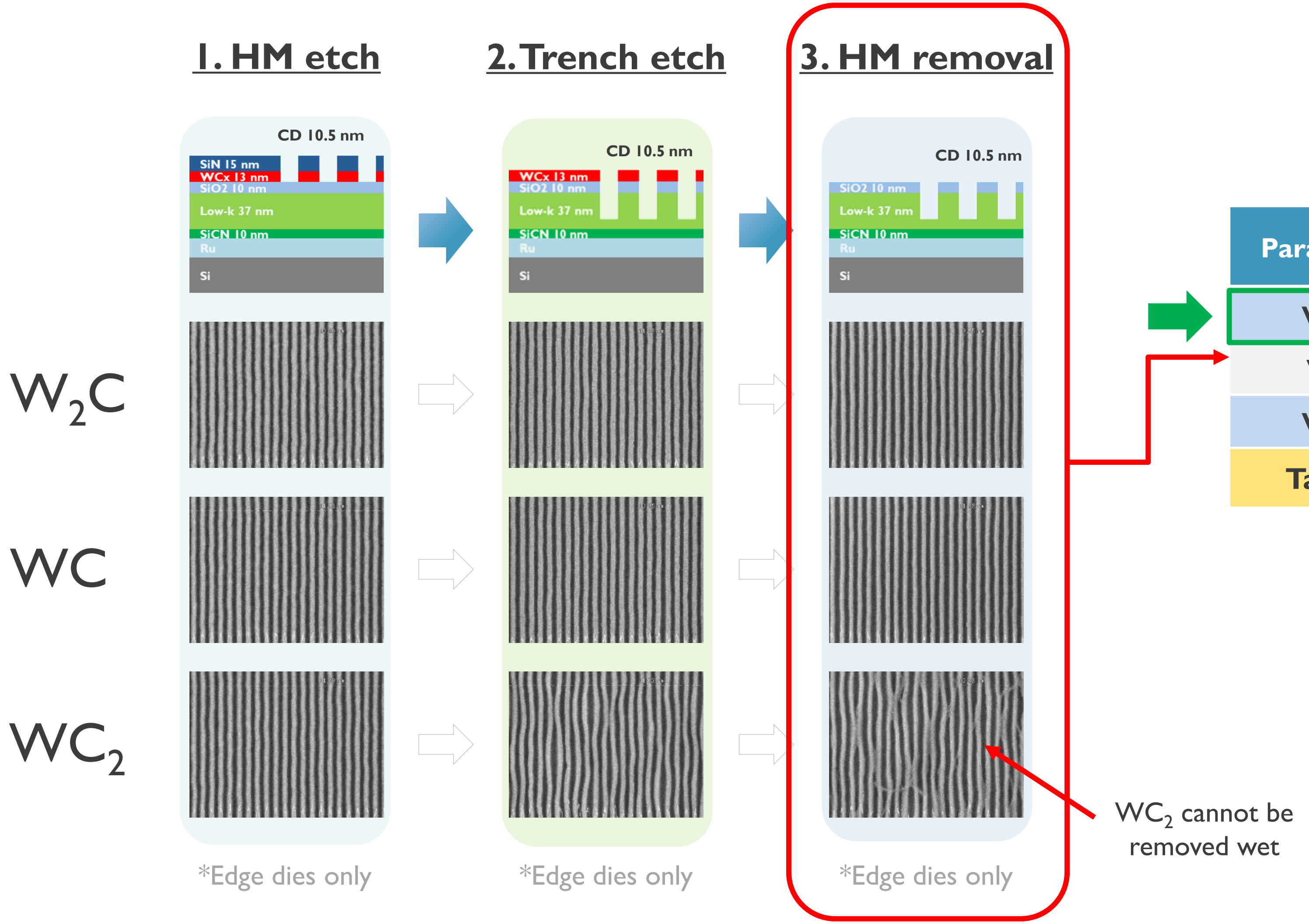


→ Center to edge uniformity to be improved

Hard Mask	Uniformity Center to edge	CD BIAS CD_{HMetch} – $CD_{trenchetch}$ (nm)	Remaining HM (nm)
W_2C		0.9	10.5
WC		0.4	8.8
WC_2		0.3	5.9
Target	Good	0	>10

- ✓ W_2C best selectivity
- ✓ WC best compromise
  - ✓ CD control
  - ✓ Selectivity
- ✓ WC_2 not suitable
- ✓ Uniformity to improve

WCx flavor comparison: CDSEM results



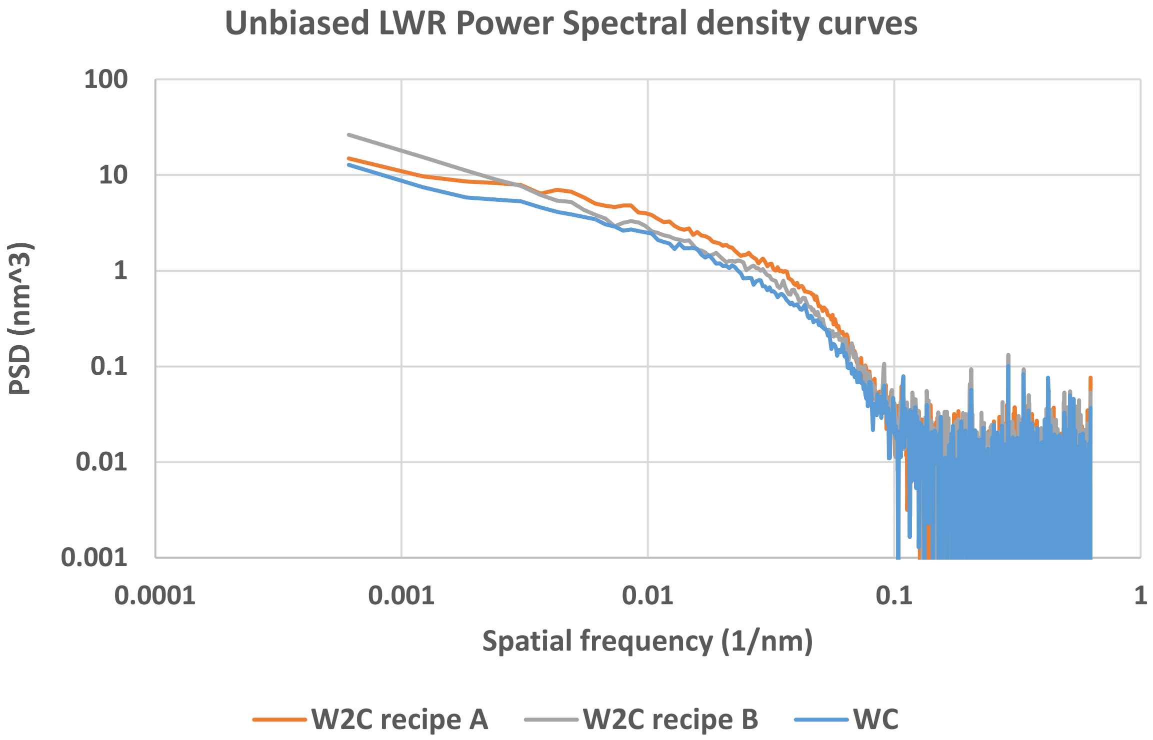
Parameter	Line CD	LER (biased)	LWR (biased)	CD Bias
W_2C	9.89	2.16	2.68	2.2
WC	8.88	2.20	2.70	1.1
WC_2	9.28	5.74	4.16	0.2
Target	10.5	2.1	2.5	0

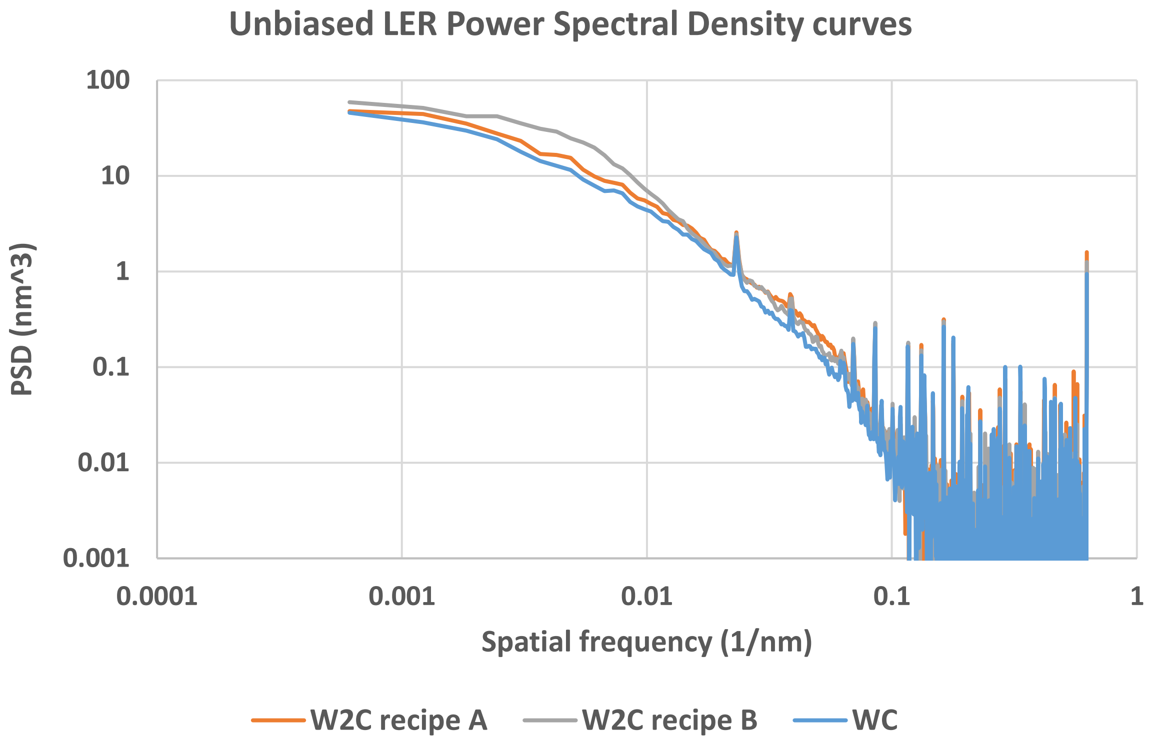
*CDSEM values

- ✓ W_2C best LER, LWR
- ✓ WC best compromise
  - ✓ CD control
  - ✓ LER, LWR
- ✓ WC_2 not suitable

Unbiased roughness values after HM removal

Unbiased → SEM noise is subtracted via Fractilia MetroLER software

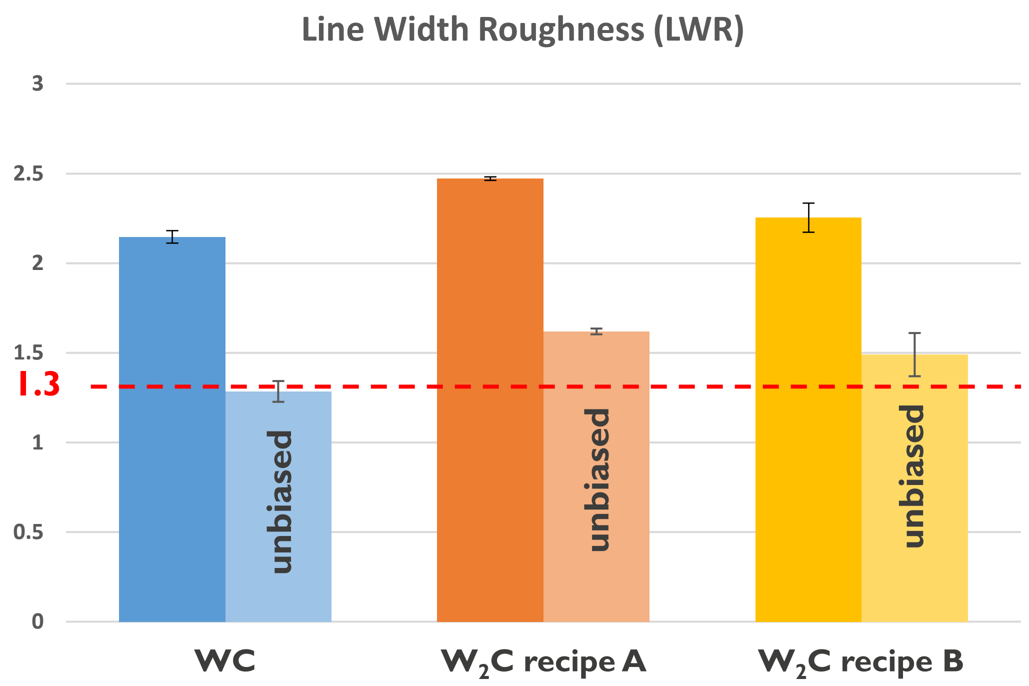


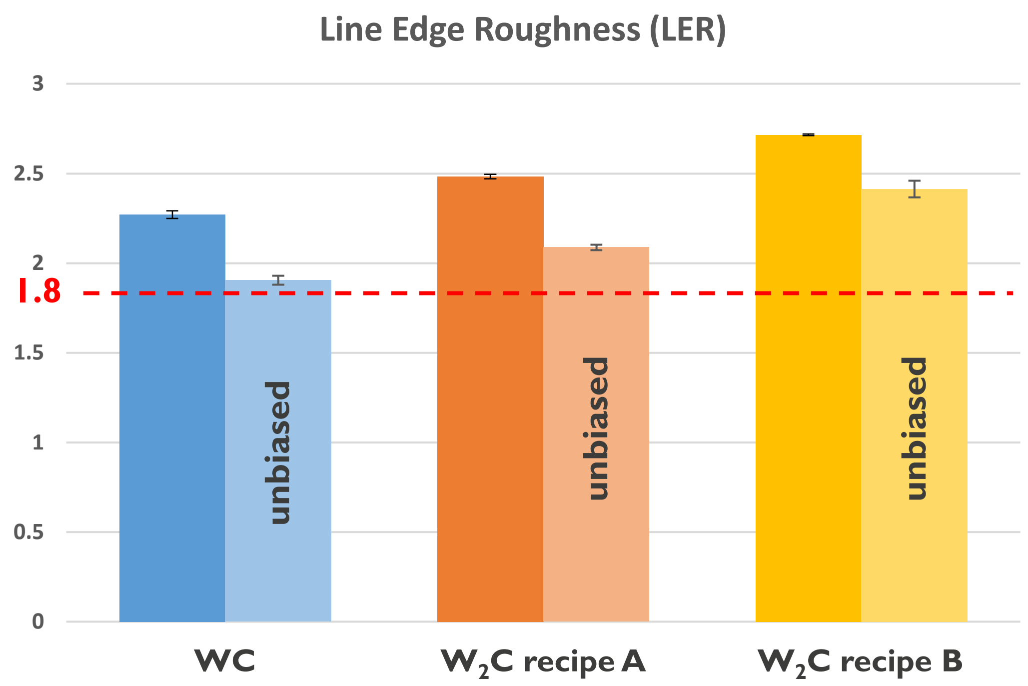


✓ WC is confirmed as best candidate
✓ Etch recipe affects LWR, LER

Unbiased roughness values → Fractilia MetroLER software

W-rich flavors, after HM removal





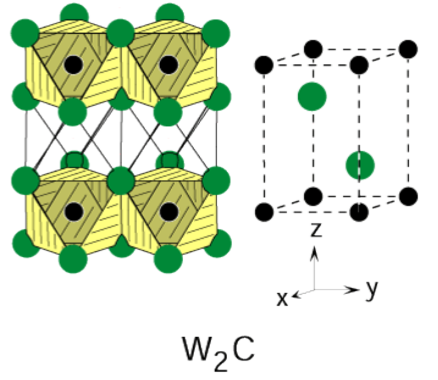
- ✓ WC is confirmed as best candidate
  - ✓ On target value
- ✓ Etch recipe affects LWR, LER

Final thoughts

Conclusions

Tungsten Carbide is valuable candidate

- Is WCx worth considering? → **Yes!**
  - ✓ Selectivity on target for low-k and SiCN etch
- Can we etch it? → **Yes!**
  - ✓ Blanket etch rates → W-rich flavors with higher selectivity
- Can we pattern it in small pitches? → **Yes!**
  - ✓ Line space patterning MP21 (HP10.5 nm)
- Is it that etch-resistant?
  - ✓ Selectivity on target → **W_2C** is best
  - ✓ CD control on target → **WC** is best
- Can it be integrated in our BEOL 3nm vehicle? → **Yes!**
  - ✓ Unbiased line roughness on target → **WC** is best
  - ✓ Dry etch and wet removal for **W-rich flavors**



Outlook and future work

- Improve WCx opening step
  - Uniformity
  - Selectivity towards SiO2
  - Profile (straight, > 88 deg)
- WCx endurance on other dielectric chambers
- Dual Damascene endurance tests
- Explore new WCx flavors

Acknowledgements

Tungsten Carbide development has been possible thanks to the big effort and cross-collaboration between several teams across IMEC:

- **Dry etch**: F. Lazzarino, H. Puliyalil, R. Blanc, F. Schleicher, S. Decoster et al.
- **Litho**: Janko Versluijs, Murat Pak et al.
- **Wet etch**: Q. Toan, N. Bazzazian, H. De Coster et al.
- **Integration**: V. Vega-Gonzalez, C. Wu et al.
- **NanoIC**: Z. Tokei et al.
- **Inline TEM**: J. Geypen, D. Batuk, G. Martinez et al.
- **SEM**: I. Manders et al.
- **Thin Films**: T. Witters, S. Mertens et al.
- **Lam Research:** G. Jurczak, D. Hellin, J. Nie, E. Camerotto et al.
- **Engdesi**
- **FAB operations**

Thanks for your attention!

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