EUV photoresists for the sub-10 nm node: EUV interference lithography as a powerful characterization tool

Elizabeth Buitrago[1], Marieke Meeuwissen[2], Oktay Yildirim[2], Rik Hoefnagels [2], Gijsbert Rispens[2], Roberto Fallica[1], Michaela Vockenhuber[1] and Yasin Ekinci[1]

[1]Paul Scherrer Institute, Switzerland
[2]ASML, Netherlands

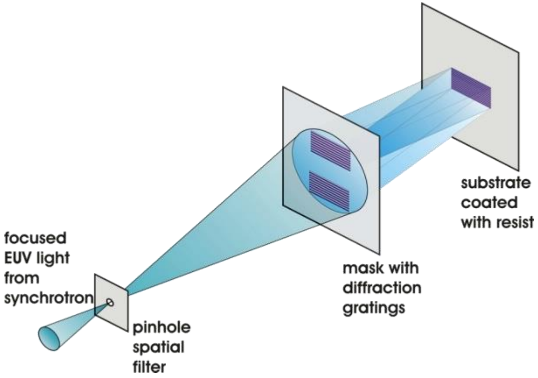
Outline

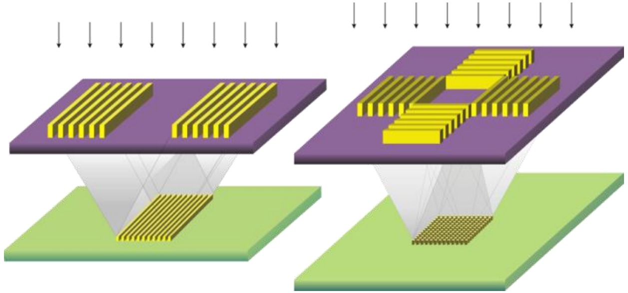
- EUV Interference lithography
- XIL-II: EUV-IL tool at PSI
- EUV resist challenges, motivation
- EUV-IL record resolution
- State-of-art EUV materials for the 7 nm node and beyond
- Summary

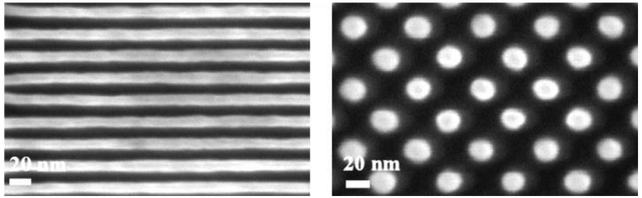
EUV-IL

XIL-II beamline at Swiss Light Source (SLS):

- EUV lithography: 13.5 nm wavelength
- Undulator source:
  - Spatially coherent beam
  - Temporal coherence: $\Delta\lambda/\lambda=4\%$
- Diffractive transmission gratings written with EBL on S_3N_4 membranes (~100 nm)
- Diffracted beams interfere
- Interference pattern printed in resist





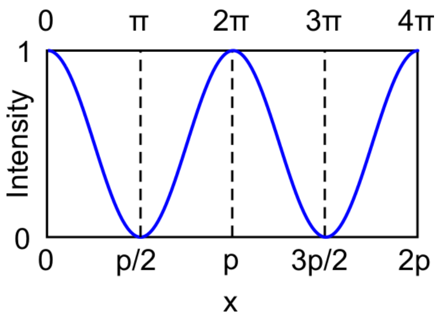


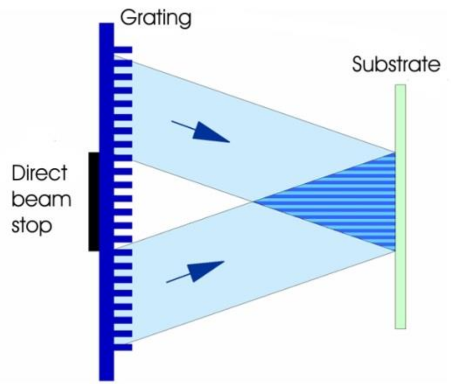
p: period on wafer
g: grating period on mask
m: diffraction order

$$p = \frac{\lambda}{2\sin(\theta)} = \frac{g}{2m}$$

Advantages of EUV-IL

- ❑ Stable source: Swiss light synchrotron source (SLS)
- ❑ Infinite depth of focus: mask-to-wafer (0.3-10 mm)
- ❑ High resolution:
  - ❑ Theoretical limit = 3.5 nm
  - ❑ Current limit = 6 nm (D. Fan, SPIE 2016)
    - → Limited by resist and mask writing/quality
- ❑ Well defined image
- ❑ Large area for cross-section analysis
- ❑ Low-cost technique for resist testing



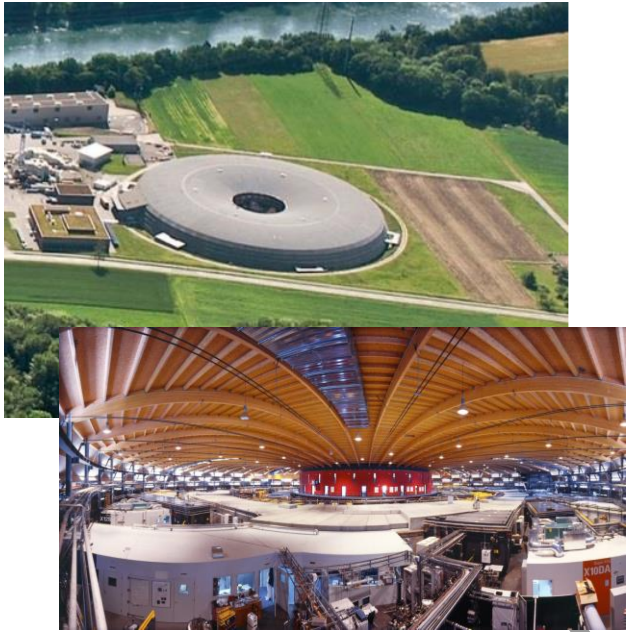


PAUL SCHERRER INSTITUT PSI

ASML

Large scale facility with nanotechnology infrastructure

Swiss Light Source



Laboratory for Micro and Nanotechnology

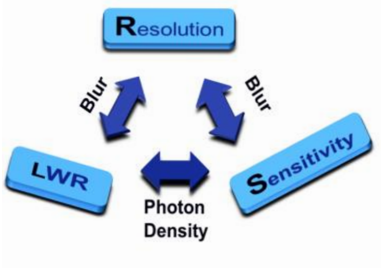
XIL-II: EUV-IL@SLS

EUV chemically amplified resist (CAR) challenges

- Resolution (R, HP in nm), line width roughness (LWR, 3σ in nm) and sensitivity (S, dose in mJ/cm^2) cannot be improved simultaneously

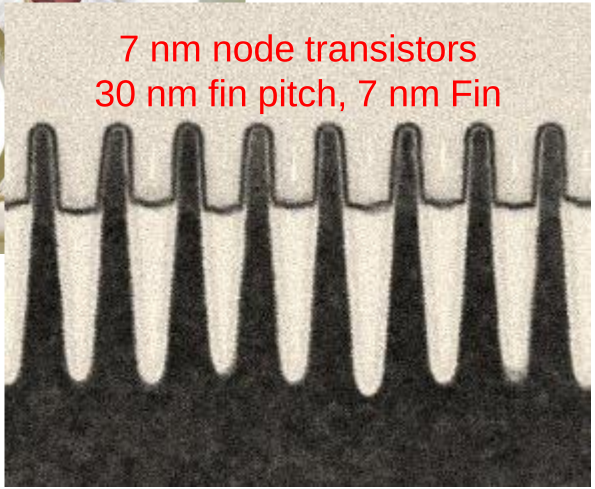
  → RLS trade-off

  - Higher photon density → better LWR → high dose (S)
  - Small Blur → better resolution (R) → high dose (S)
  - Larger Blur → lower roughness (L) → loss of resolution (R)



- Highly sensitive resists to increase productivity.
- CARs and other state-of-art EUV resists platforms need to be evaluated for future technology nodes→ access to EUV scanners limited, expensive
- XIL → powerful method in the development of EUV resists

"EUV likely be to be introduced in HVM at the 7 nm logic node" → (16 nm HP L/S resolution, 15 nm DRAM)

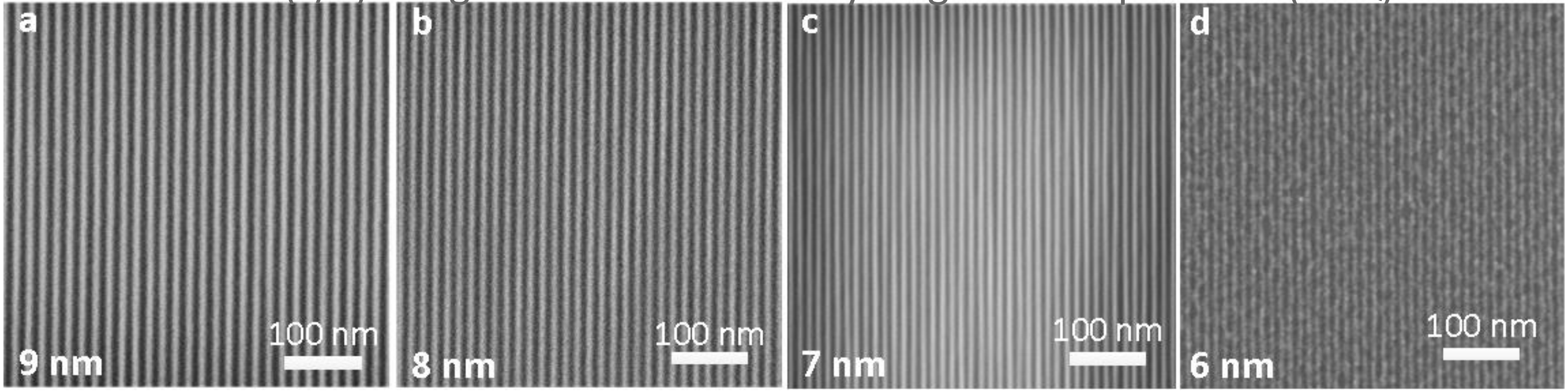


- IBM: "Industry's first 7 nm node test chips with functioning transistors
- Silicon Germanium (SiGe) channel transistors
- Extreme ultraviolet (EUV) lithography integration at multiple levels!!!
- 50 percent area scaling improvements over today's most advanced technology"

IBM press release, 9 July 2015.

World record resolution by photolithography

SEM (L/S) images HP = 9-6 nm on hydrogen silsesquioxane (HSQ)



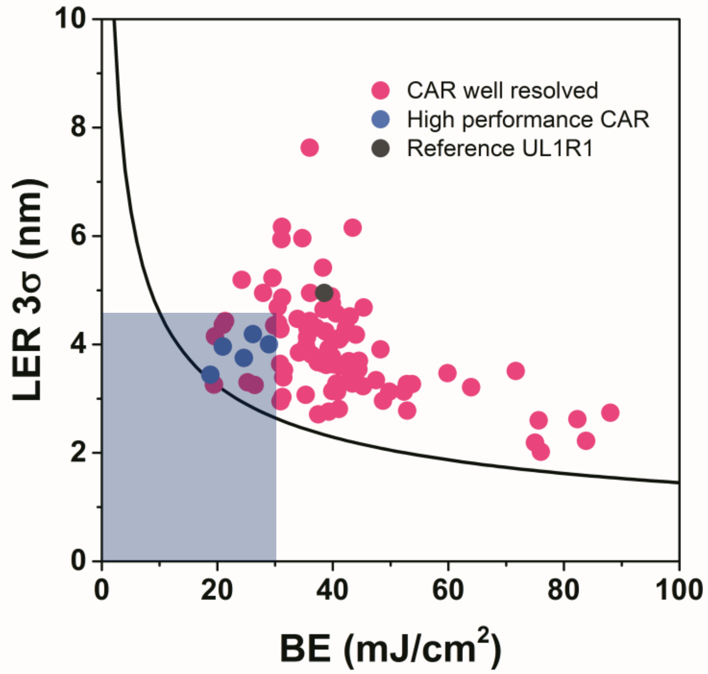
SnO_x (Inpria) | SnO_x (Inpria) | HfO_x (Inpria) | Iridium (ALD)

*Mask gratings fabricated by patterning high EUV absorbance materials

a, b: Buitrago E. et al., Microelectronic Engineering 155, 44-49 (2016).
c: N. Mojarad et al., Nanoscale 7, 4031-4037 (2015).
d: Fan D. et al., in SPIE Advanced Lithography, 97761-97711 (2016).

16 nm HP → 7 nm logic node
13 nm HP → 5 nm logic node
8 nm HP → 2x nm logic node

CAR screening for 16 nm HP resolution (7 nm node)



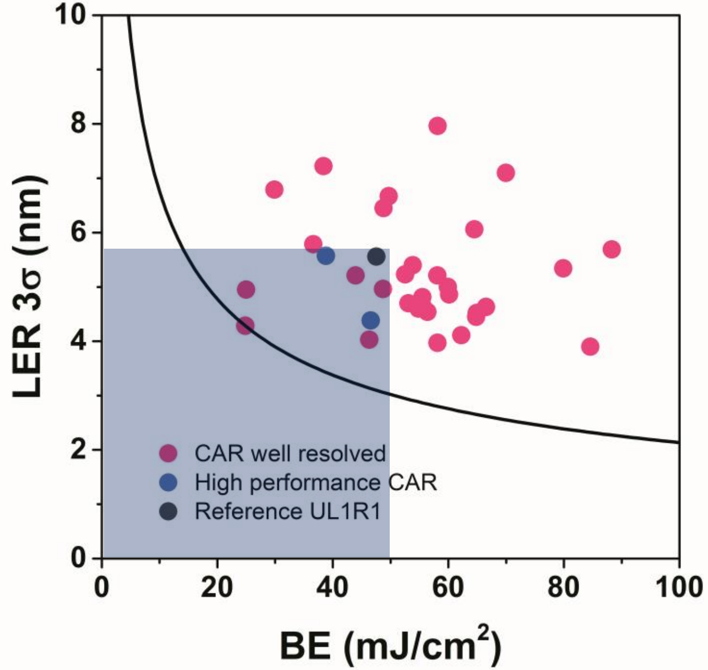
- 52 different CARs tested
- 47 CARs well resolved down to 16 nm HP
- Several CAR candidates meet high performance characteristics* simultaneously:
  - BE < 30 mJ/cm^2
  - LWR < 6.5 nm (LER < 4.6 nm)
  - EL > 15%

Industrial focus on CAR extension

*arbitrary threshold values, not set by industry

Buitrago. et al., in SPIE Advanced Lithography, 97760Z (2016).

CAR screening for 13 nm HP resolution (5 nm node)



- Many CARs well resolved
- Few meet high performance characteristics simultaneously*:
  - BE (dose) < 50 mJ/cm^2
  - LWR < 8 nm*
  - EL > 3%

Alternatives needed

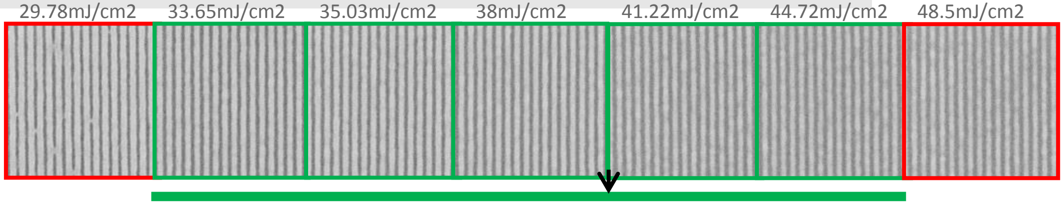
- ❑ Inorganic resists
- ❑ Nanoparticle
- ❑ PSCAR
- ❑ Rinse materials
- ❑ etc.

*arbitrary threshold values, not set by industry

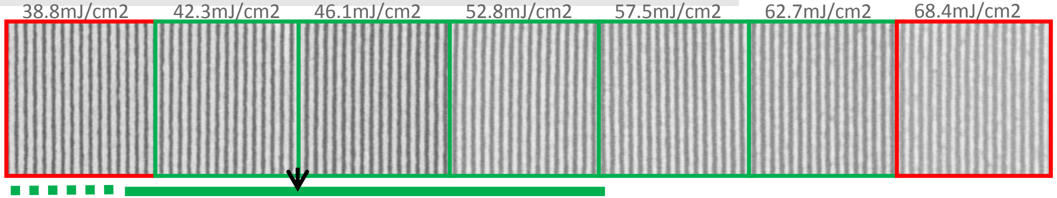
Buitrago. et al., in SPIE Advanced Lithography, 97760Z (2016).

Best CARs New Rinse HP = 16 nm (7 nm node)

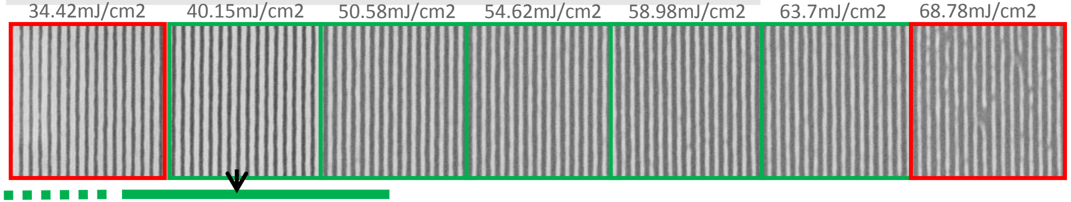
HP=16nm-UL1(15nm thk), R1(25nm thk)-PEB:110C-Std. Rinse (Reference)



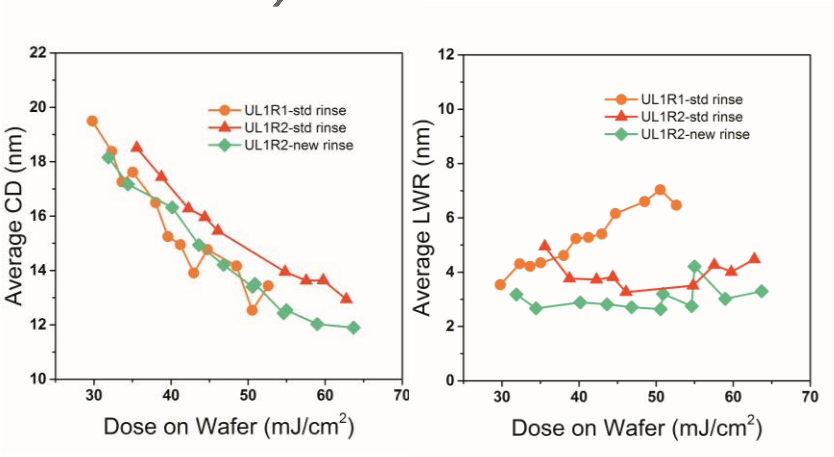
HP=16nm-UL1(15nm thk), R2(25nm thk)-PEB:110C-Std. Rinse



HP=16nm-UL1(15nm thk), R2(25nm thk)-PEB:110C-New Rinse

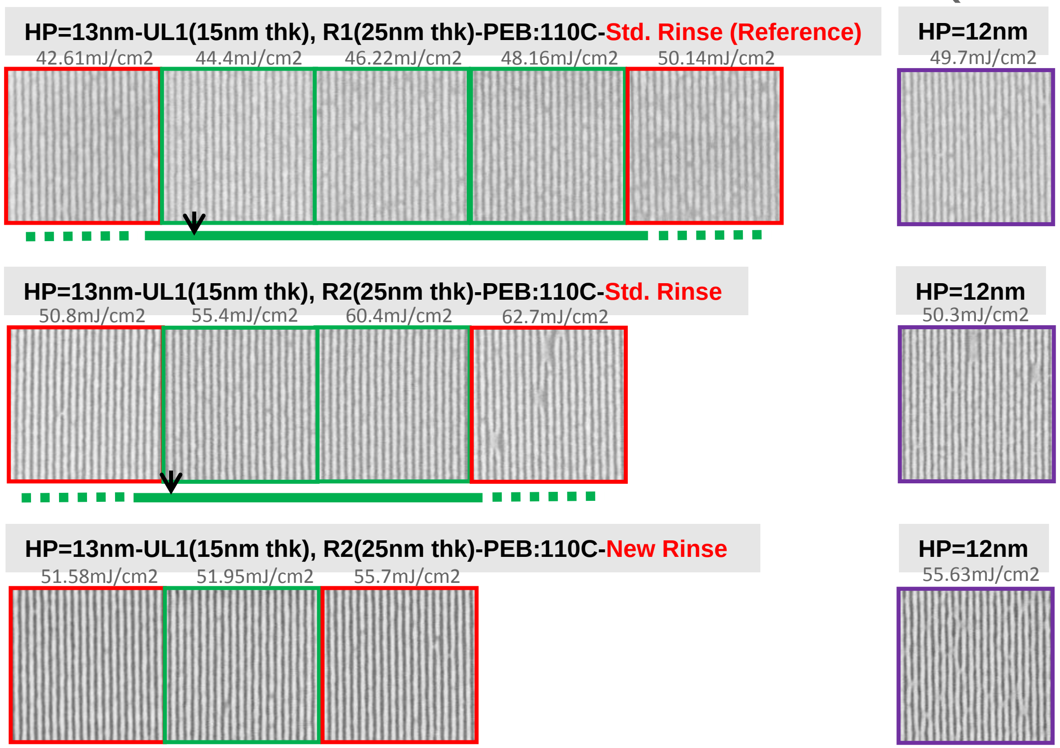


Name	BE (mJ/cm2)	EL (%)	LWR (nm)	Z-factor
UL1R1-std rinse (Ref)	38.5±6.3	22.6±5.2	6.5±1.3	2.9E-08
UL1R2-std rinse	44.7	30	3.7	1.3E-08
UL1R2-new rinse	40.1	24	2.9	6.8E-09



- UL1R2 was shown to have similar performance with respect to reference UL1R1 except for lower LWR (3.7 nm)
- UL1R2 processed with new rinse material reduces BE → 40 mJ/cm^2 and LWR→ 2.9 nm while maintaining high EL > 20%.
- Rinse material shown to improve BE and LWR of CARs.

Best CAR and Rinse HP = 13 nm (5 nm node)



Name	BE (mJ/cm2)	EL (%)	LWR (nm)	Z-factor
UL1R1-std rinse (ref)	44.0	9	6.8	1.5E-08
UL1R2-std rinse	52.3	10	4.4	9.3E-09
UL1R2-new rinse	45.7	0	3.8	6.5E-09

- Both UL1R2 and reference are well resolved down to 12 nm HP with some pattern collapse and pinching with Std. and new rinse.
- UL1R2 also has high EL down to 13 nm HP ~ 10% and lower LWR (~ 4.4 nm) but BE is relatively high ~ 52 mJ/cm^2 when Std. rinse is used.
- BE and LWR improves for UL1R2 when processed with new rinse (~46 mJ/cm^2 and 3.8 nm).
- No EL below 13 nm nevertheless for UL1R2 with new rinse.

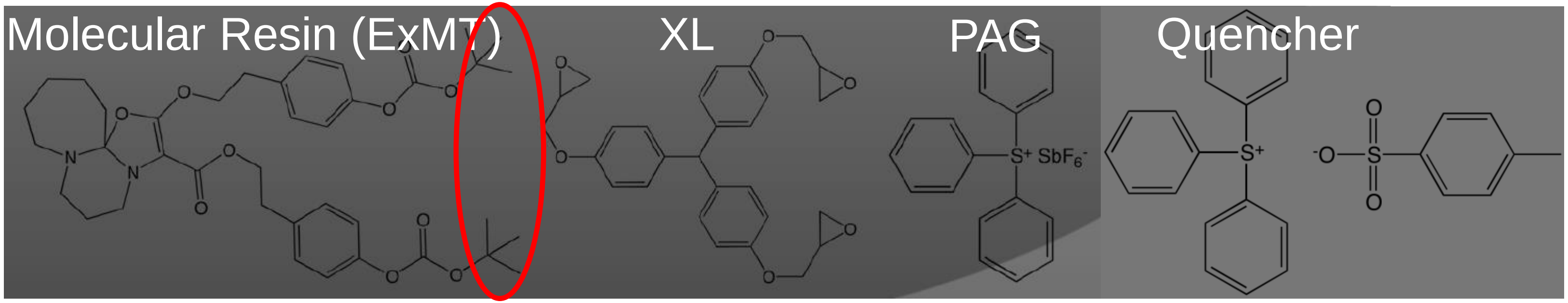
Negative tone chemically amplified molecular resists

xMT:

0.2:2:1 xMT:XL:PAG + 2%, 5% Quencher

ExMT:

0.2:2:1 ExMT:XL:PAG + Quencher

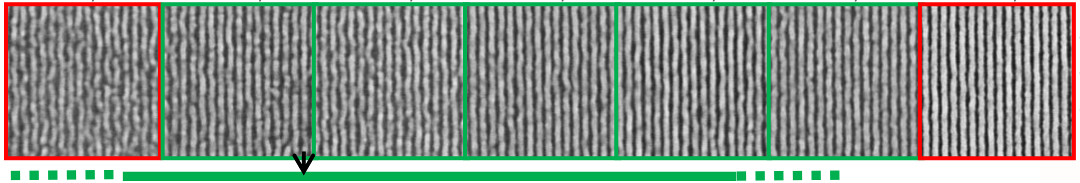


ExMT designed for enhanced crosslinking and increased sensitivity!

Molecular Resists (xMT) compared HP =16 nm

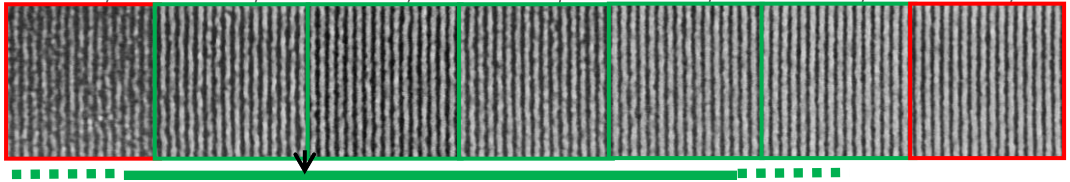
HP=16nm-Carbon UL (15nm thk), EX1-213-010 (25nm thk)

19.6mJ/cm2 20.29mJ/cm2 21.36mJ/cm2 22.12mJ/cm2 23.28mJ/cm2 24.1mJ/cm2 27.65mJ/cm2



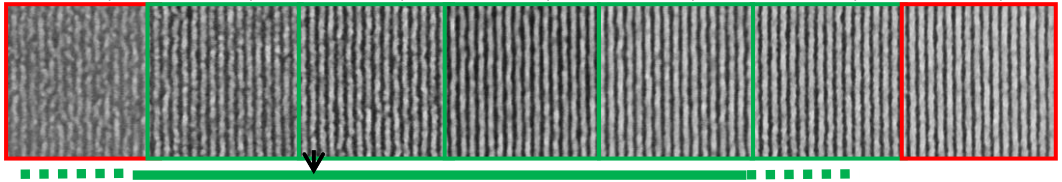
HP=16nm-Carbon UL (15nm thk), xMT-213-200 (20nm thk)

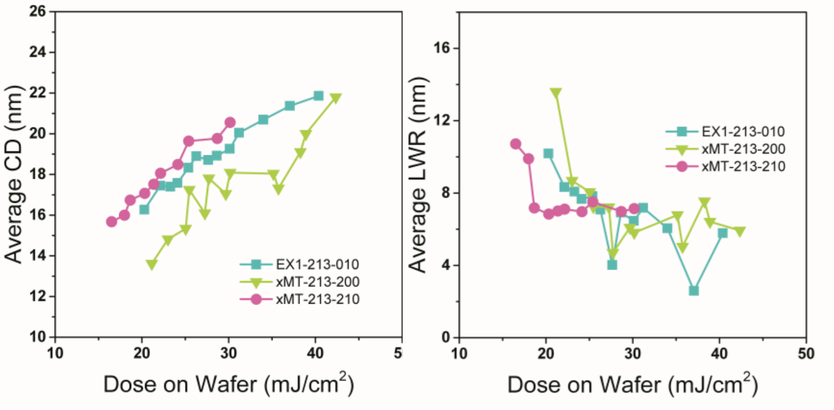
21.14mJ/cm2 23.01mJ/cm2 23.39mJ/cm2 25.05mJ/cm2 25.46mJ/cm2 27.72mJ/cm2 29.67mJ/cm2



HP=16nm-Carbon UL (15nm thk), xMT-213-210 (25nm thk)-no PEB

15.15mJ/cm2 16.51mJ/cm2 17.99mJ/cm2 18.65mJ/cm2 20.32mJ/cm2 21.37mJ/cm2 22.15mJ/cm2





- Lines are rough with elevated LWR values →Possible adhesion/development issues.
- Resist performance improved from previous year (BE ~ 30mJ/cm^2, EL~20%) at 16 nm HP.
- Particularly, xMT-213-210 and EX1-213-010 have very low BE < 20 mJ/cm^2 and apparent high EL > 20% at 16 nm HP.

Name	BE (mJ/cm2)	LWR (nm)	Z-factor
EX1-213-010-25nm	18.3	7.4	2.5E-08
xMT-213-200-20nm (5% Quencher)	26.3	7.2	3.0E-08
xMT-213-210-25nm-no PEB (2% Quencher)	17.2	10.4	4.7E-08

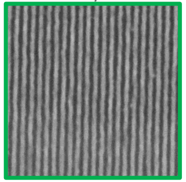
IRRESISTIBLE MATERIALS

Molecular Resists (xMT)

Carbon UL (15nm thk), EX1-213-010 (25nm thk)

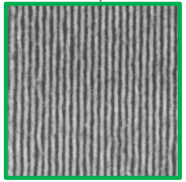
HP=16nm

19.1mJ/cm2



HP=14nm

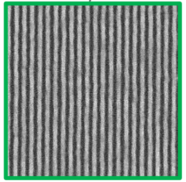
20.7mJ/cm2



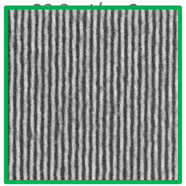
Carbon UL (15nm thk), xMT-213-200 (25nm thk)

HP=16nm

33.7mJ/cm2



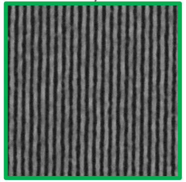
HP=14nm



Carbon UL (15nm thk), xMT-213-210 (25nm thk)

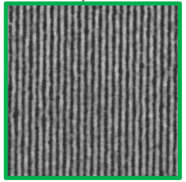
HP=16nm

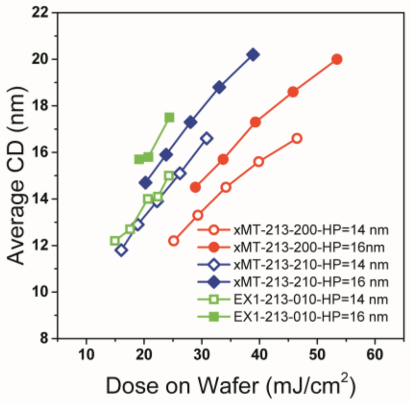
23.8mJ/cm2

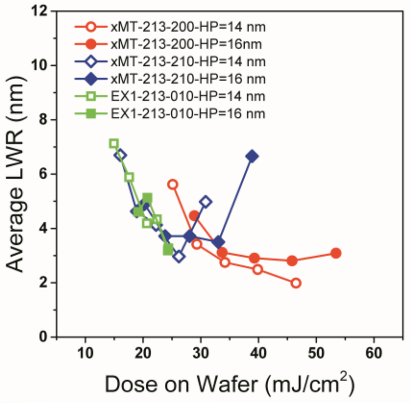


HP=14nm

18.9J/cm2







IRRESISTIBLE MATERIALS

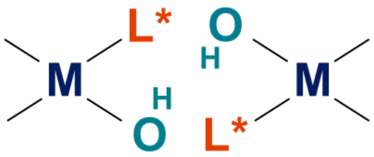
- Materials were subsequently tested (different mask used, slightly different process conditions).
- Adhesion/development issues resolved → LWR values improved drastically <4.6 nm.
- Excellent, low BE values for EX1-213-010 and xMT-213-210.

Name	HP	BE (mJ/cm2)	LWR (nm)	Z-factor
EX1-213-010-25nm	16	20.5	4.5	1.4E-08
EX1-213-010-25nm	14	21.3	4.3	8.7E-09
xMT-213-200-25nm (5% Quencher)	16	34.8	3.0	1.1E-08
xMT-213-200-25nm (5% Quencher)	14	32.9	2.9	7.7E-09
xMT-213-210-25nm (2% Quencher)	16	24.2	3.7	9.8E-09
xMT-213-210-25nm (2% Quencher)	14	22.7	4.1	7.3E-09

Courtesy of Alexandra McClelland, IM

Sn-based Resist

Inpria YA
negative tone
organo-oxo molecule
stable after exposure
Sn-based
forms SnO_2
high absorption (Sn)
Excellent etch resistance*

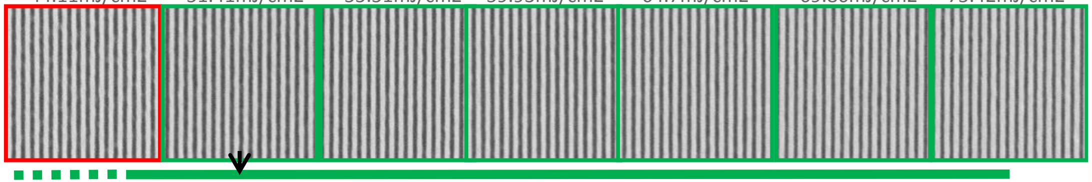


L* = radiation sensitive ligand

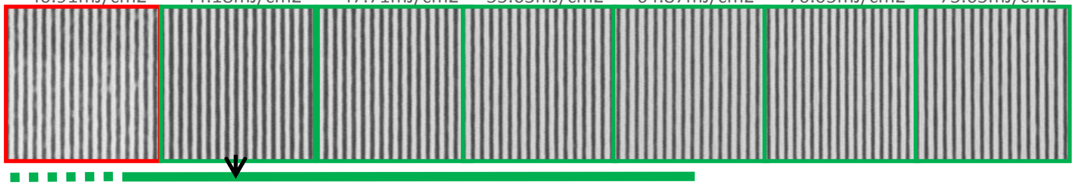
*etch resistance into an organic layer ~40:1 selectivity in an O_2/N_2 etch.

Sn-based Resist-HP=16 nm

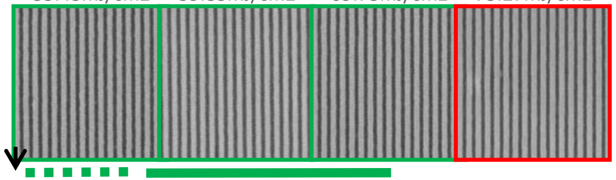
HP=16nm-YF(18nm thk)



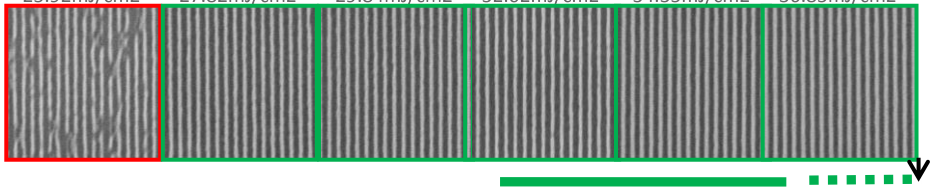
HP=16nm-YA(18nm thk)

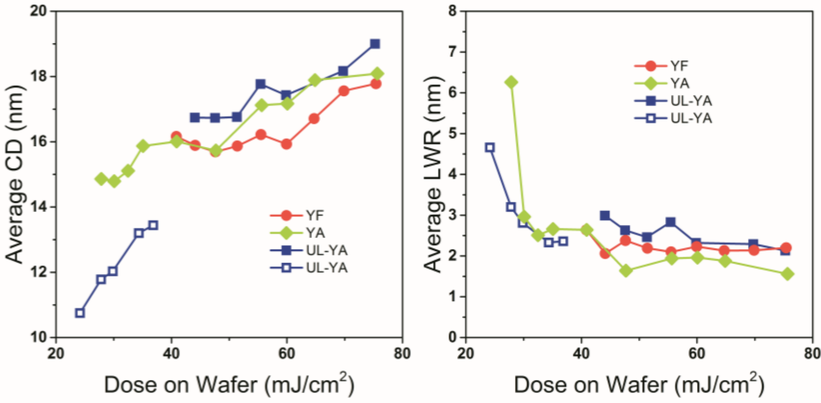


HP=16nm-UL3(30nm thk)-YA(18nm thk)



HP=16nm-UL3(30nm thk)-YA(18nm thk)





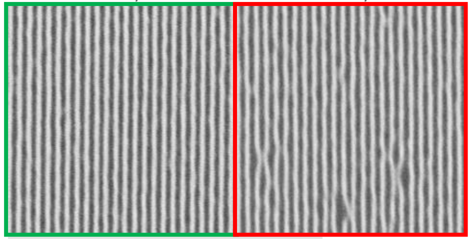
- YA results with UL are estimated as best dose rage was missed in both exposures.
- Both YA and YF resists are highly performing with extremely high ELs >45% and low LWR values ~ 2.3 nm @ 16 nm HP.
- YA with and without an UL has similar best energy in comparison to reference CAR UL1R1 ~ 40 mJ/cm^2.

Name	BE (mJ/cm2)	EL (%)	LWR (nm)	Z-value
YF-18nm	50.2	54	2.3	6.5E-09
YA-18nm	43.1	49	2.3	5.2E-09
UL3-YA-18nm	~40	>30	~2.5	~5.8E-09

Sn-based Resist-ultimate resolution

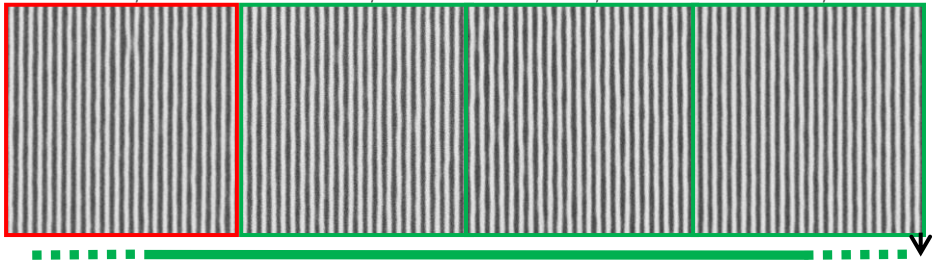
HP=11nm-YF(18nm thk)

58.65mJ/cm2 63.32mJ/cm2



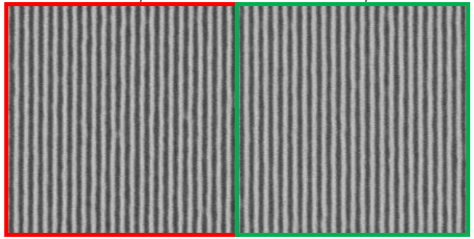
HP=11nm-YA(18nm thk)

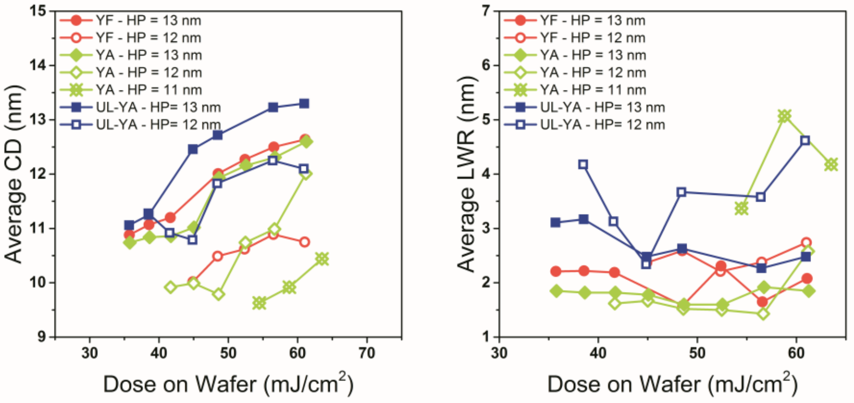
50.44mJ/cm2 54.46mJ/cm2 58.81mJ/cm2 63.51mJ/cm2



HP=11nm-UL3(30nm thk)-YA(18nm thk)

58.54mJ/cm2 63.2mJ/cm2





- Both YA and YF resist are highly performing down to 12 nm HP with EL > 10% and LWR < 4 nm.
- YA with UL has lowest BE ~ 58 mJ/cm^2 down to 12 nm HP.
- EL ~ 8% down to 11 nm HP for YA with an LWR ~ 4.2 nm.

Name	HP	BE (mJ/cm2)	EL (%)	LWR (nm)	Z-value
YF-18nm	13	64.0	25	2.0	4.2E-09
YF-18nm	12	80.1	15	2.5	5.5E-09
YA-18nm	13	64.6	19	1.8	3.3E-09
YA-18nm	12	67.2	11	1.7	2.6E-09
YA-18nm	11	71.0	8	3.4	7.4E-09
UL3-YA-18nm	13	55.6	13	2.4	4.2E-09
UL3-YA-18nm	12	57.6	14	3.9	7.5E-09

Summary

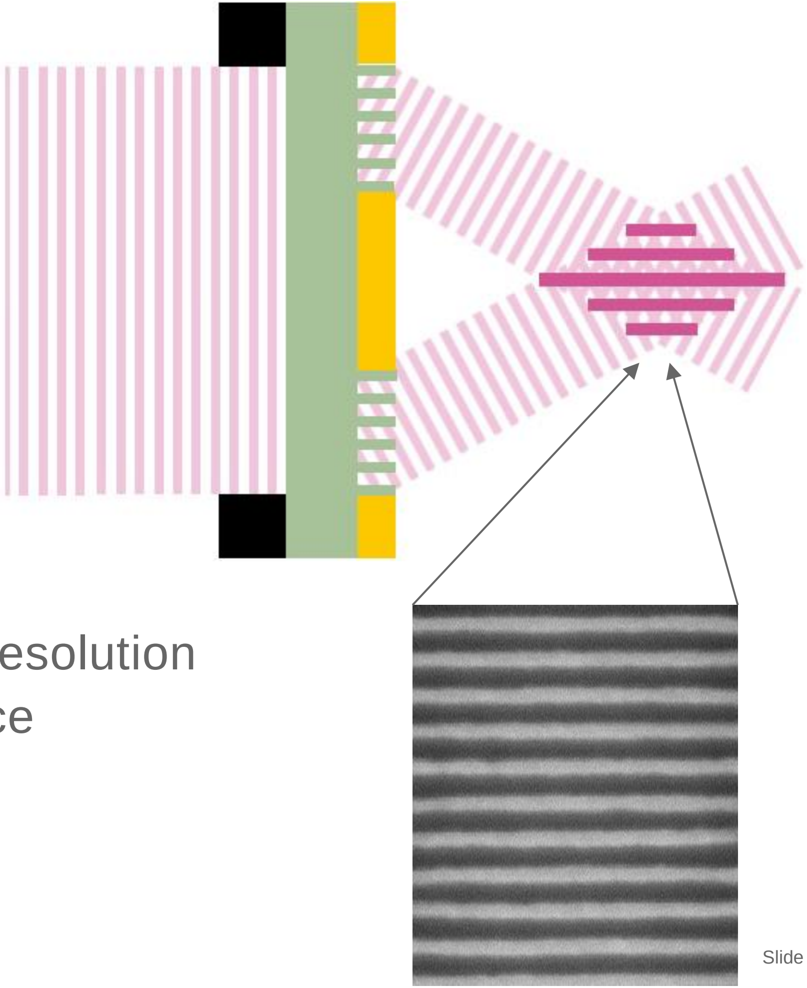
- ❑ Several promising CAR candidates meeting high performance requirements found down to 16 nm HP (7 nm node)→ Alternative processes, materials needed for the 5 nm and beyond.
- ❑ **New rinse material** shown to improve BE and LWR down to 14 nm HP (for UL3R2) → extendibility of CARs.
- ❑ Promising **molecular resists** EX1-213-010 and xMT-213-210 have very low BE < 25 mJ/cm^2 down 16 nm HP. LWR improved in subsequent tests (< 4.6 nm).

Summary

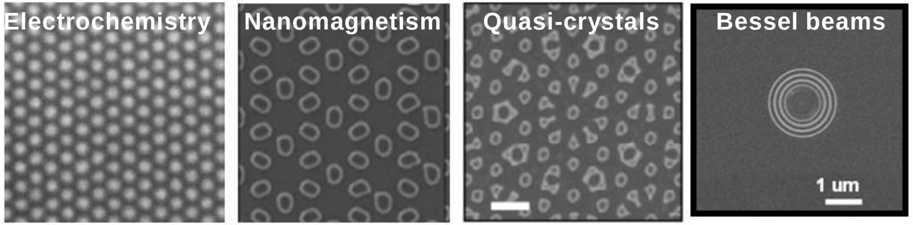
- Both **Sn-based resist** formulations (YA and YF, 18 nm thk) tested were found to be highly performing with extremely high EL >45%, low LWR values ~ 2.3 nm and sensitivities comparable to CARs ~ 40 mJ/cm^2 @ 16 nm HP.
- **Sn-based resists** highly performing down to 11 nm HP. YA has high EL ~ 8% down to 11 nm HP, LWR ~ 4.2 nm and BE ~ 70 mJ/cm^2.

→ 2015, Sn-based resist (25 nm thk) @13 nm HP: EL ~ 11.8%, LWR ~ 3.3 nm, BE > 75 mJ/cm^2.

EUV-IL at PSI



- EUV resist characterization, world record resolution
- High resolution periodic patterns for science



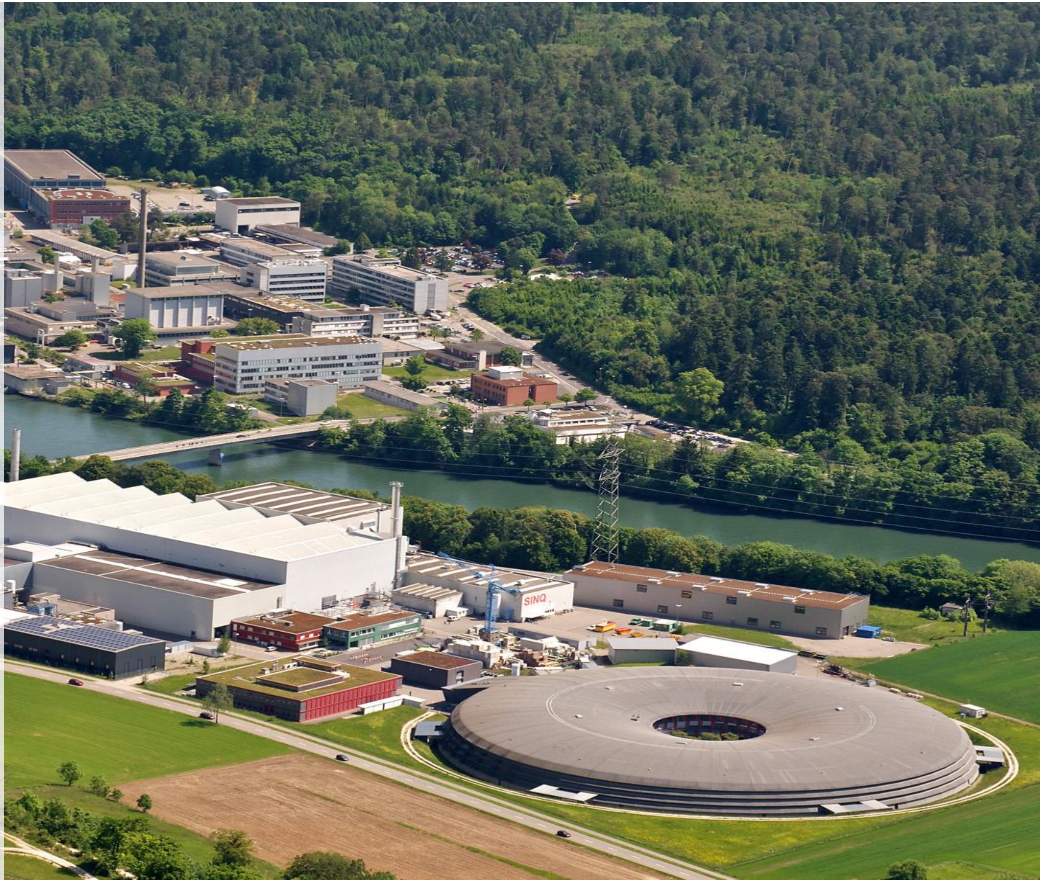
PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Acknowledgements:

- ASML team
- ALM team
- Members of LMN and SLS collaborators
- All of our resist and UL suppliers
- Alexandra McClelland

Thank you for your attention!



http://www.psi.ch/sls/xil