EUV resist: the great challenge of small things

S. Castellanos

EUVL Workshop 11-14 June 2018, Berkeley

ARCNL

Motivation

“Looking ahead towards second-generation EUV lithography, resist stochastic effects are definitely one of the top concerns.” *Harry Levinson, Global Foundries (Semiconductor Engineering, March 2018)*

“The current resists may not take us into the future. Novel ideas and approaches for stochastics are needed.” *Anna Lio, Intel (Proc. SPIE, 2016)*

”Readiness of commercial resists will be a leading challenge for EUVL in future nodes.” *Vivek Bakshi, EUV Litho Inc. (EET Asia, February 2018)*

”New resists/chemistries are needed for next generation EUV.” *Anindarupa Chunder, Global Foundries (IEUVLI TWG Meeting, 2018)*

”What we would describe as challenge number one in imaging is in the extreme roughness events or the stochastic failures in places like nano-bridging, line breaking and merging or missing holes.” *Gregory McIntyre, Imec (Semiconductor Engineering, September 2017)*

Motivation

"Looking ahead towards second-generation EUV lithography, resist stochastic effects are definitely one of the top concerns." *Harry Levinson, Global Foundries (Semiconductor Engineering, March 2018)*

"The current resists may not take us into the future. Novel

Can we define common targets and goals in a roadmap for the whole EUV resists community?

Unlike the case of the EUV scanner, there are multiple parties working on resists but no general consensus.

2018)

"What we would describe as challenge number one in imaging is in the extreme roughness events or the stochastic failures in places like nano-bridging, line breaking and merging or missing holes." *Gregory McIntyre, Imec (Semiconductor Engineering, September 2017)*

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- Where are we?
  - Historic trends of EUV resists
  - What do we know about mechanisms in EUV resists?
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- How are we going to make resists ready?

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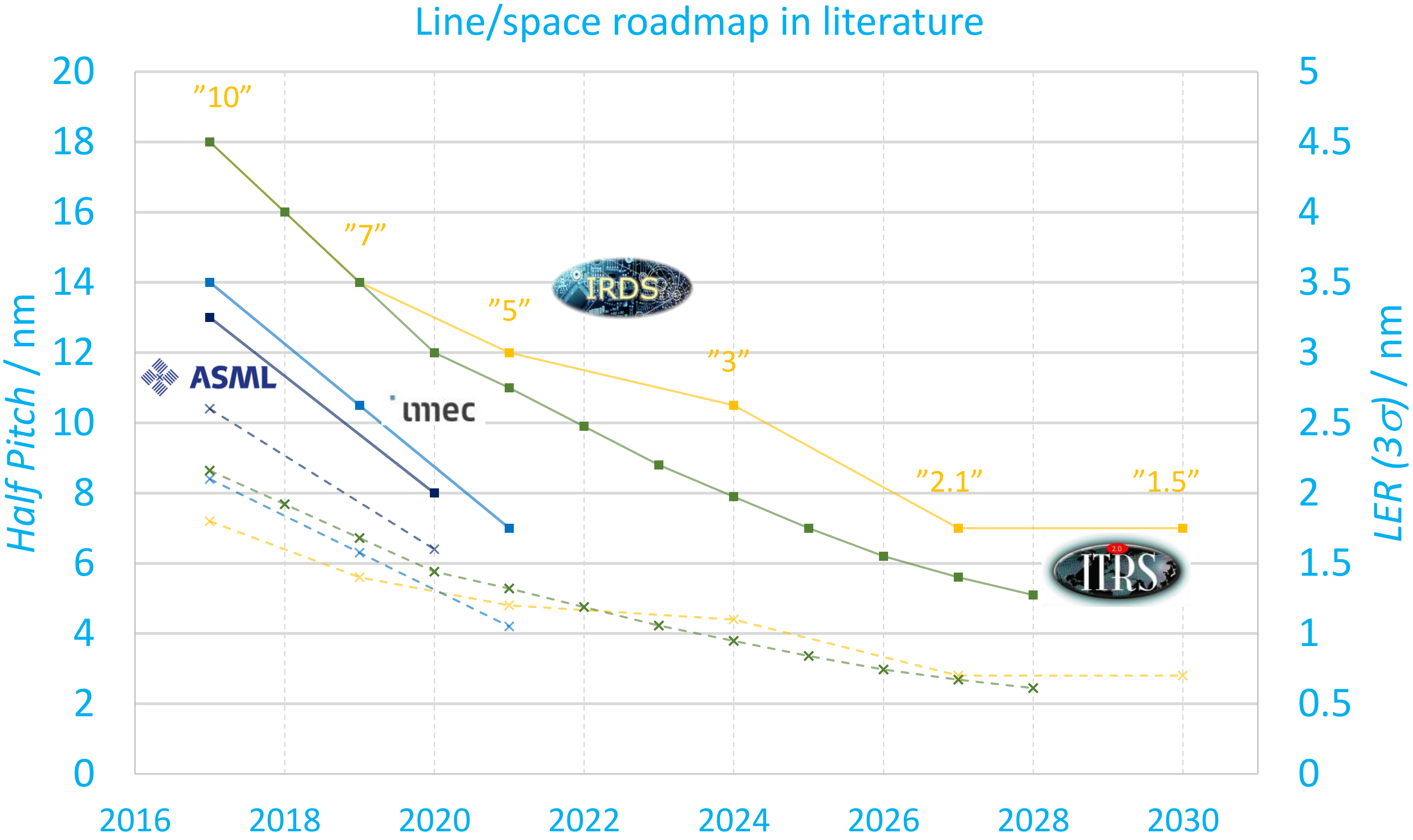
Where are we?



O. Yildirim, Proc. SPIE 2017; D. de Simone, Proc. SPIE 2018; ITRS, http://www.itrs2.net/2013-itrs.html; IRDS 2017

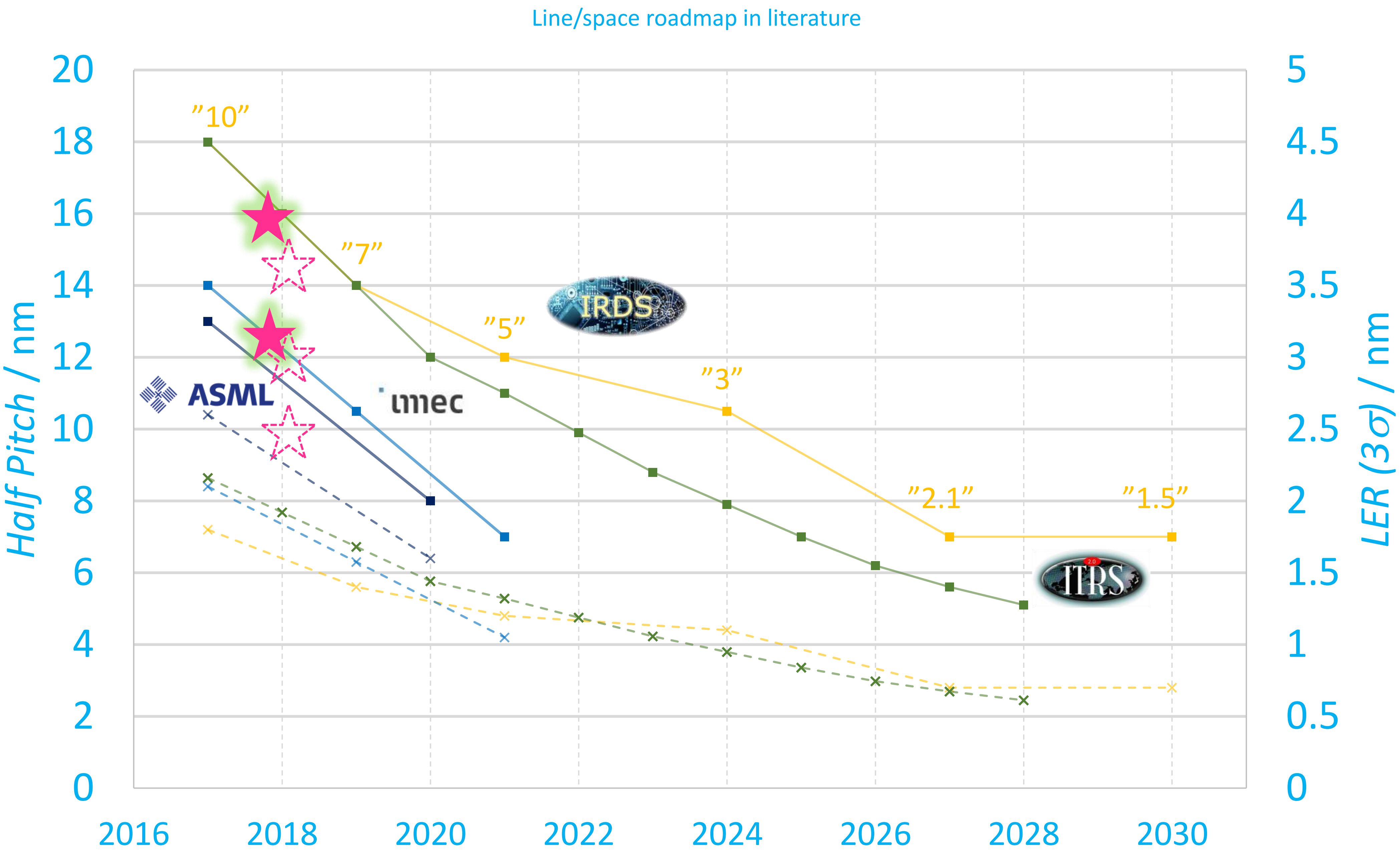
Requirements according to literature

	Dose (mJ/cm^2)	μ (μm^{-1})	LWR 3σ (nm)	LER 3σ (nm)	PSD(0)	defectivity
	<20[1,2,3,4]	15*[5]	< 20%[4]	< 12-15% CD[2,3,]	???	pixNOK (space) = 10^{-5}[5] VIA failure < 10^{-12}[1]
Some of best reported performances						
CAR (CD = 16 nm)[6]	45	5	2.91	2.01		pixNOK <D.L. (10^{-7})
CAR (CD = 13 nm)[2]	58	5	4.4			
nCAR (CD = 16 nm)[2]	47.5	20	4.0			
nCAR (CD = 13 nm)[2]	34	20	3.8			
PSCAR[7]	37.5 (15 J/cm^2 UV)			1.94	25.7	
IM[8]	38.5			3.7		
not specified[4]	21.4		5.2			

* Calculated for the requirement of OD = 36% in a 30 nm photoresist

[1] A. Lio Proc. SPIE 2016, 97760V; [2] O. Yildirim, Proc. SPIE 2017, 101430Q; [3] ITRS 2013; [4] De Simone, J. Photopolym. Sci. Technol 2017; [5] A. Chunder, IEUVI resists TWG 2018; [6] De Simone Proc. SPIE 2018, 105830G; [7] S. Nagahara Proc. SPIE 2018, 1058606; [8] Y. Vesters, Proc. SPIE 2018, 1058308; G. Denbeaux IEUVI resists TWG 2018

Where are we?


Line/space roadmap in literature
20
18
16
14
12
10
8
6
4
2
0
Half Pitch / nm
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
LER (3σ) / nm
2016
2018
2020
2022
2024
2026
2028
2030
"10"
"7"
"5"
"3"
"2.1"
"1.5"
IRDS
ITRS
ASML
imec

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Defectivity decreases with absorptivity!![5,9]

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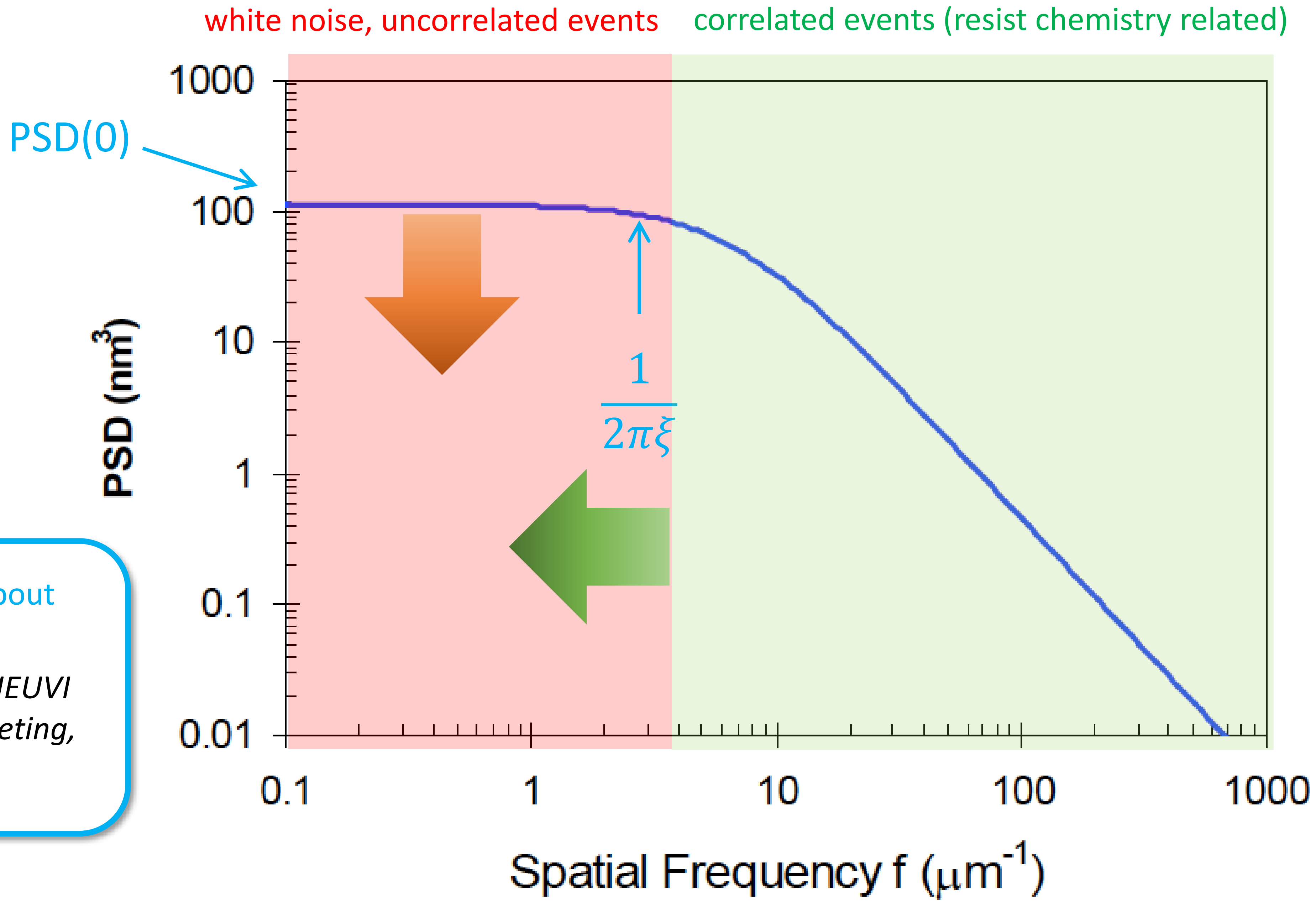
[1] A. Lio Proc. SPIE 2016, 97760V; [2] O. Yildirim, Proc. SPIE 2017, 101430Q; [3] ITRS 2013; [4] De Simone, J. Photopolym. Sci. Technol 2017; [5] A. Chunder, IEUVI resists TWG 2018; [6] De Simone Proc. SPIE 2018, 105830G; [7] S. Nagahara Proc. SPIE 2018, 1058606; [8] Y. Vesters, Proc. SPIE 2018, 1058308; G. Denbeaux IEUVI resists TWG 2018

What is needed from EUV resists?



It is not only about decreasing 3σ

Chris A. Mack, IEUVI Resist TWG meeting, Feb. 25 2018

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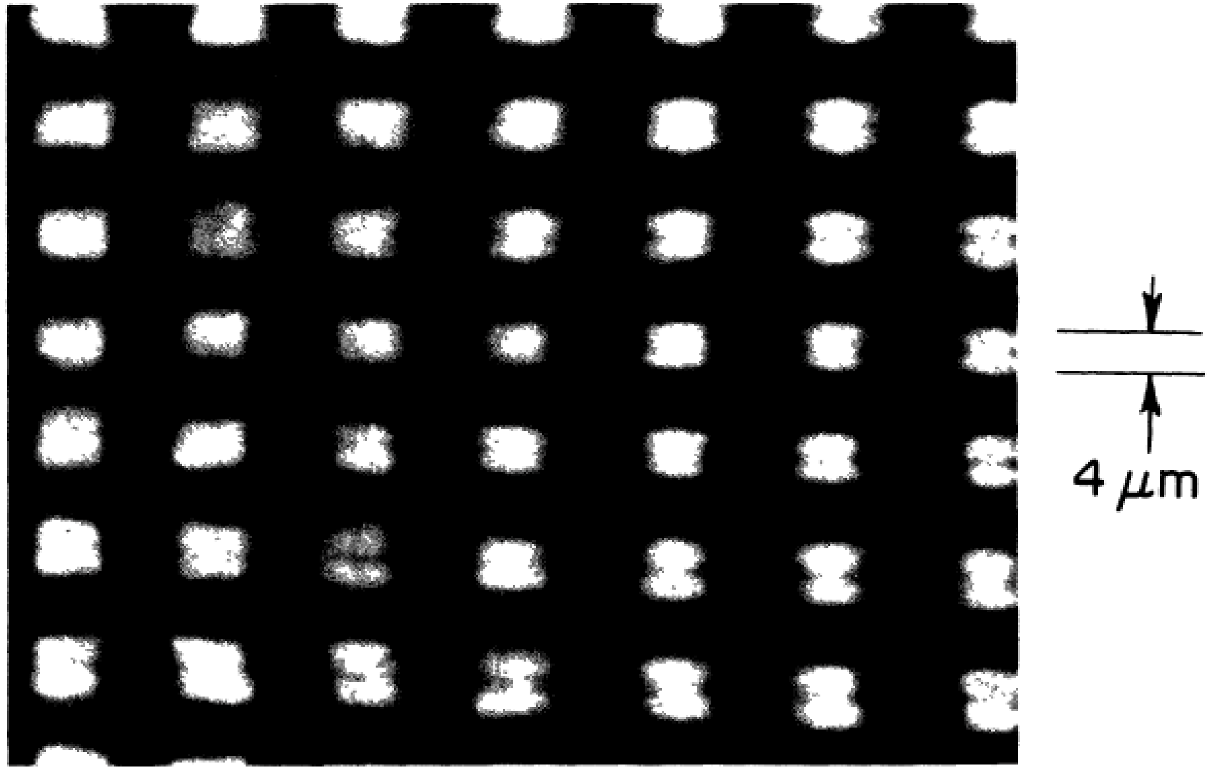
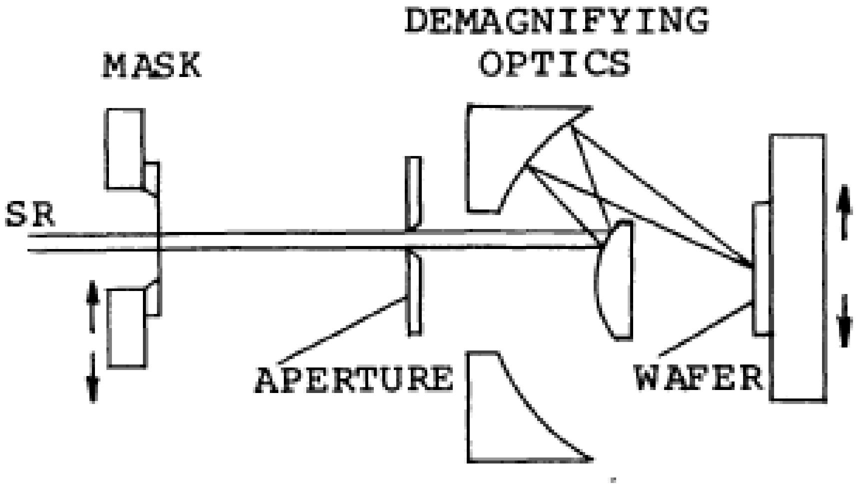
Historic trends

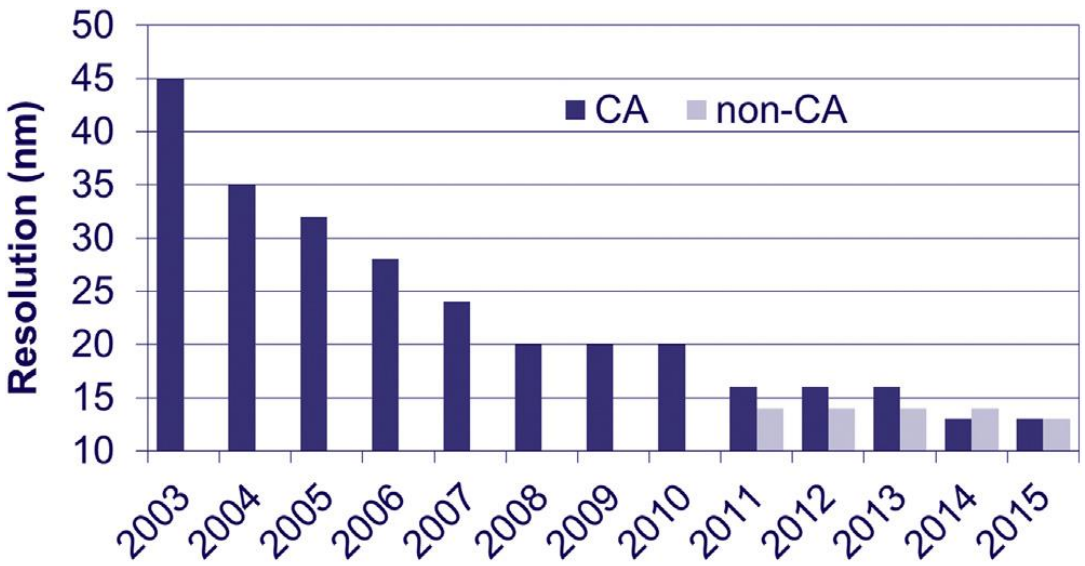
First tests with 11 nm in 1986 on PMMA by Kinoshita

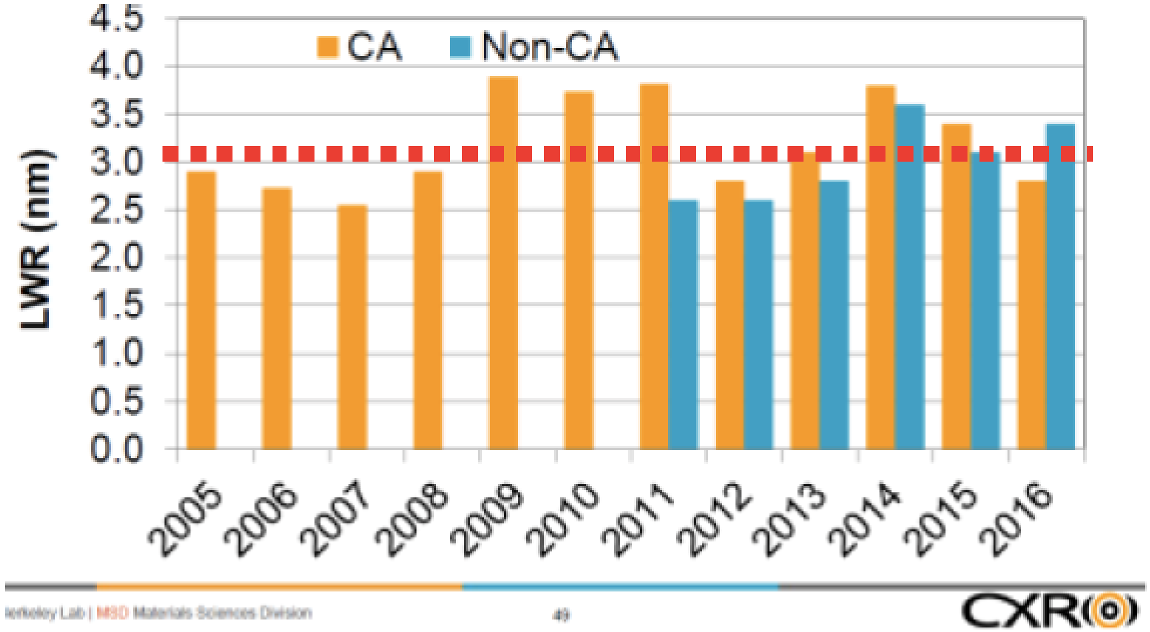


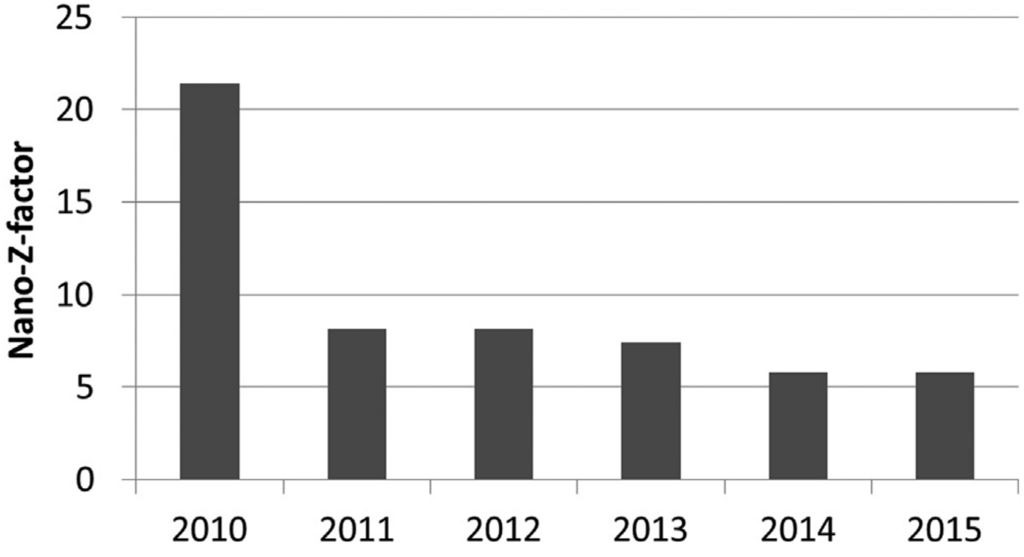


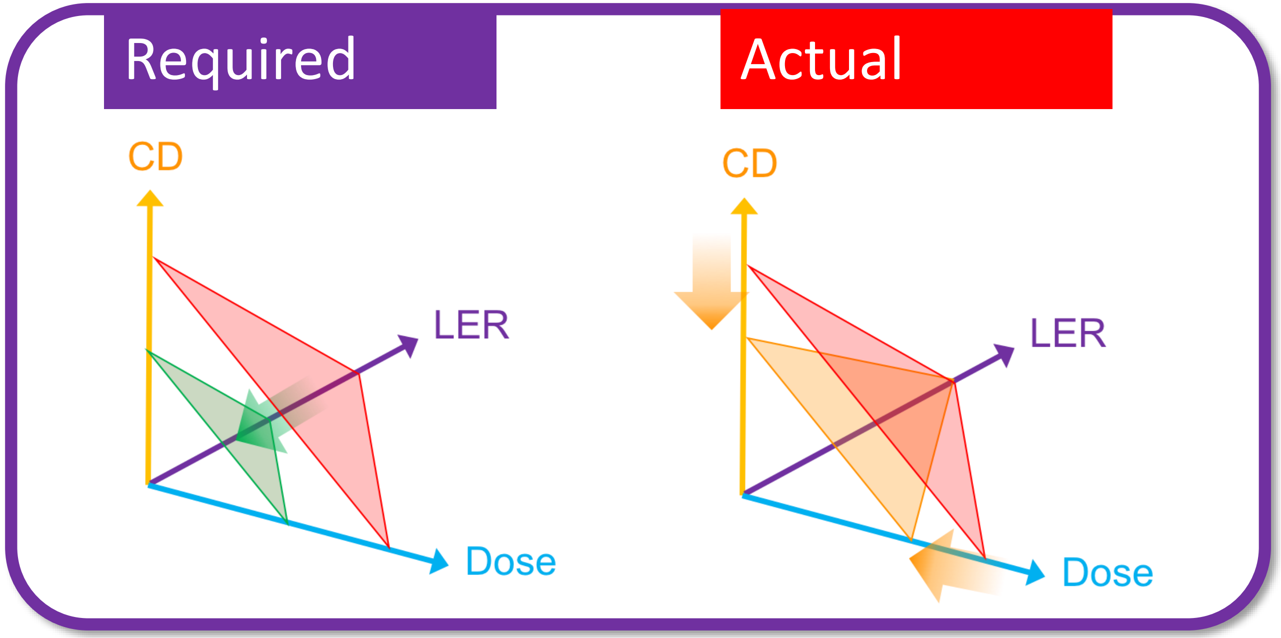
Namioka, *Revue Phys. Appl.* **1998**, *23*, 1711-1726

Historic trends





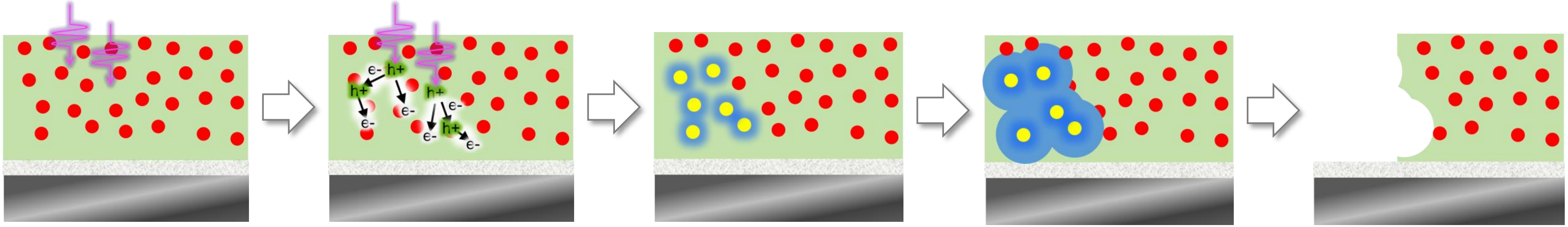




P. Naulleau, Frontiers Nanoscience 2016

What do we know?

Chemically amplified resists (CAR)

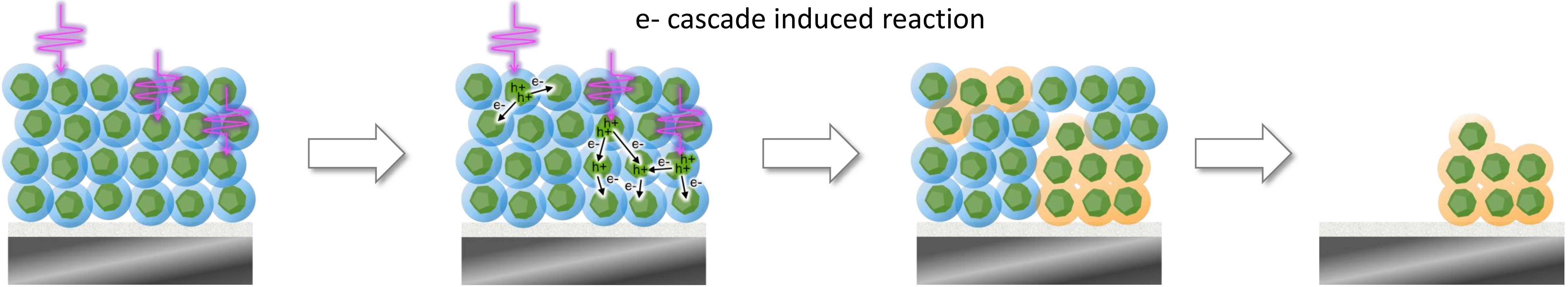


e- cascade induced reaction

H+ catalysis

Non-chemically amplified inorganic resists (nCAR)

e- cascade induced reaction



What do we know?

CAR

New formulations:

- Enhanced absorptivity
- Decreased acid diffusion
  - Covalently bonded PGA
  - Higher T_g (JSR)

Molecular based:

- Well defined structure => LER
- Tuneability

PSCAR

- More sensitive
- Improved contrast in latent image

Multitrigger (Irresistible materials)

- Improved contrast in latent image

General concerns:

- absorption of EUV photons
- resolving low CDs

nCAR

Sn-based Inpria molecular materials:

+High absorptivity (20 μm^{-1})

~ Sensitivity

Ligand loss not efficient enough?

Nanoparticles:

- **Ober**

+ High sensitivity (<3 mJ/cm2

- High LER

- **Inpria (peroxide HfOx)**

+ High sensitivity

Too dynamic bonding??

MORE (Brainard):

- **Sn-based**

+ low LER (2.1 nm CD = 16 nm)

- 600 mJ/cm^2

- **Other metals**

+ High sensitivity (5.6 mJ/cm^2, 35 nm Pitch)

MOCs (Castellanos, Ober)

+ Sensitivity tuned by metal content

- LER scumming

Chem. Soc. Rev., **2017**, 46,4855

What do we know?

CAR

Electron uptake generates acid (5.6/photon)[1]

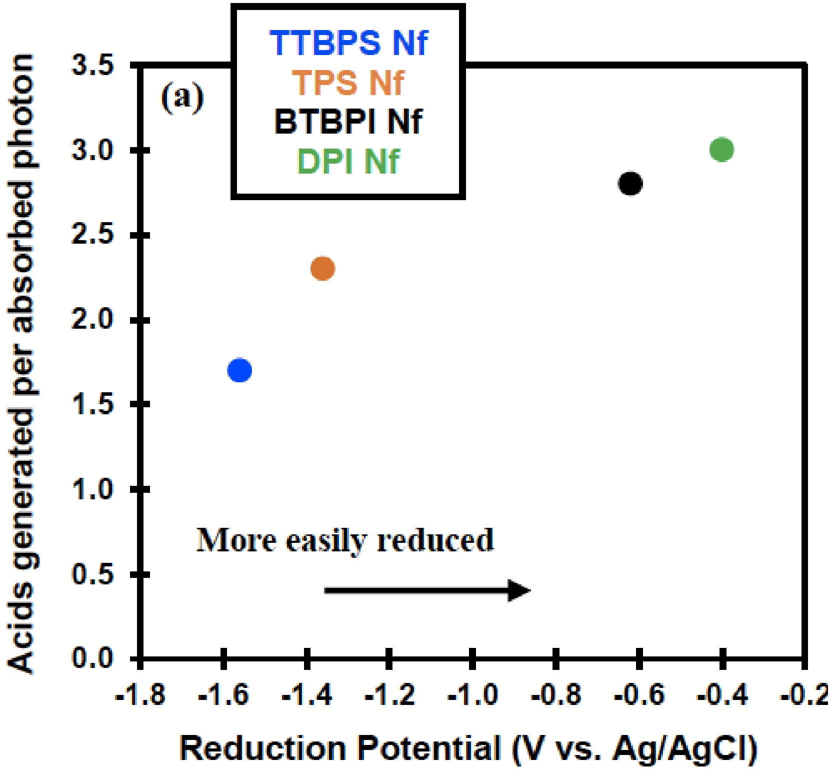
- Playing with IP of polymer (more secondary electrons
- Playing with EA of PAGs[1,2]

Our playground as chemists

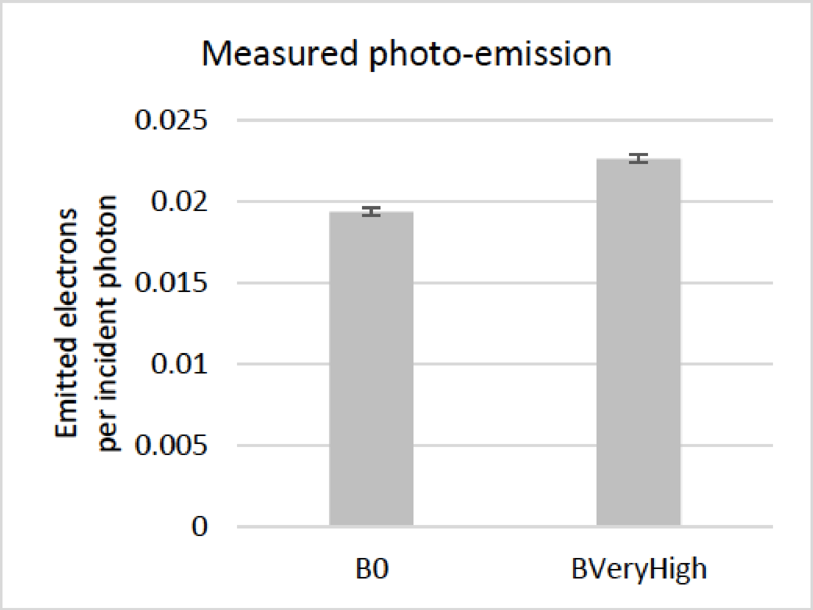
[1] Narasimhan, SPIE 2016; [2] Denbeaux SPIE 2018

Reminder:

High contribution of photoelectrons from the valence band! (80 eV)



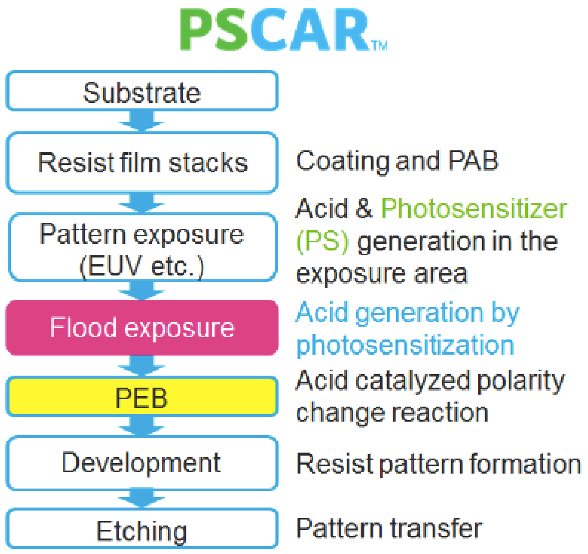
Denbeaux SPIE 2018



Vesters SPIE 2018

What do we know?

PSCAR®


PSCAR™

Substrate

Resist film stacks — Coating and PAB

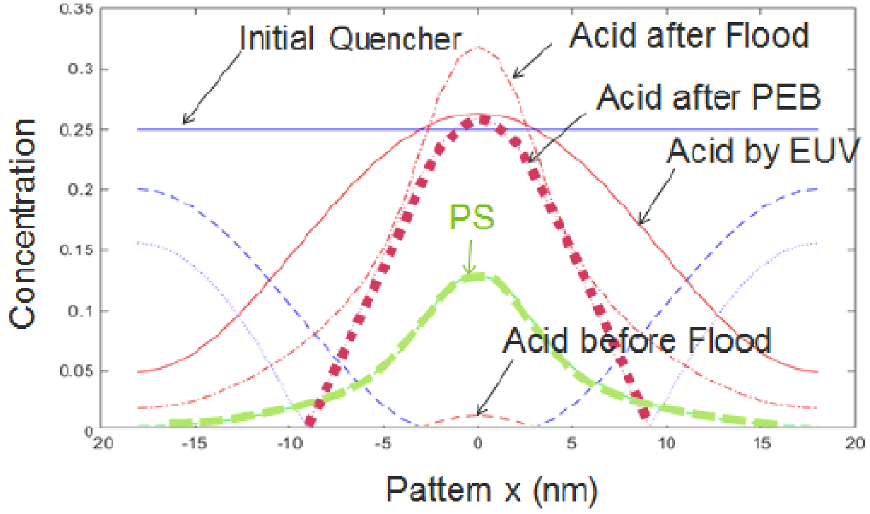
Pattern exposure (EUV etc.) — Acid & Photosensitizer (PS) generation in the exposure area

Flood exposure — Acid generation by photosensitization

PEB — Acid catalyzed polarity change reaction

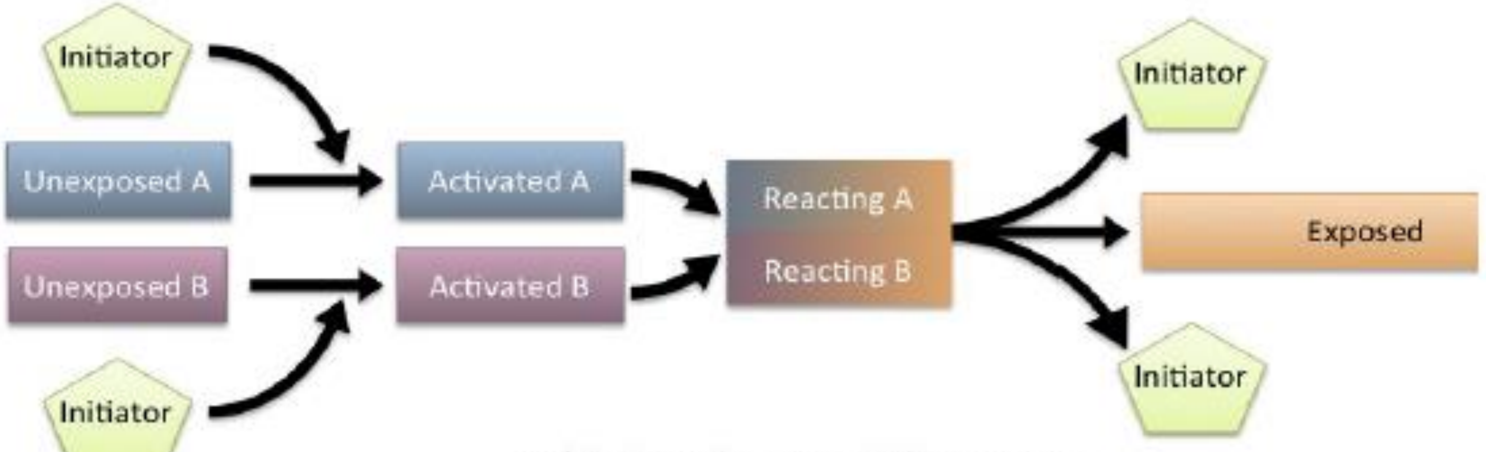
Development — Resist pattern formation

Etching — Pattern transfer



Proc. of SPIE (2016), 9776, 977607

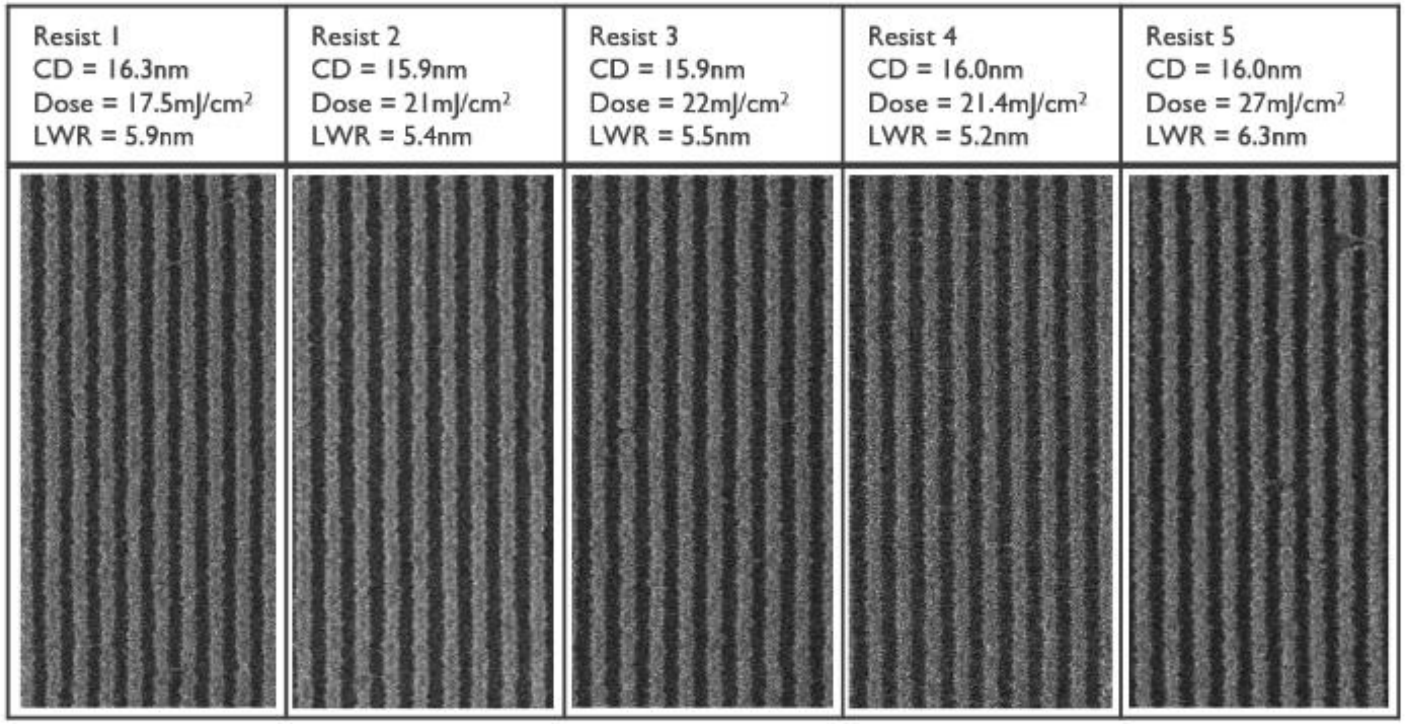
Irresistible Materials®



Multi-Trigger Concept – High Dose Area

Proc. of SPIE 2018, 10583, 1058308

What do we know?



De Simone, *J. Photopolym. Sci. Technol.* **2017**, 30, 613

Main issues

- Roughness (PSD)
- Defectivity (NOK)

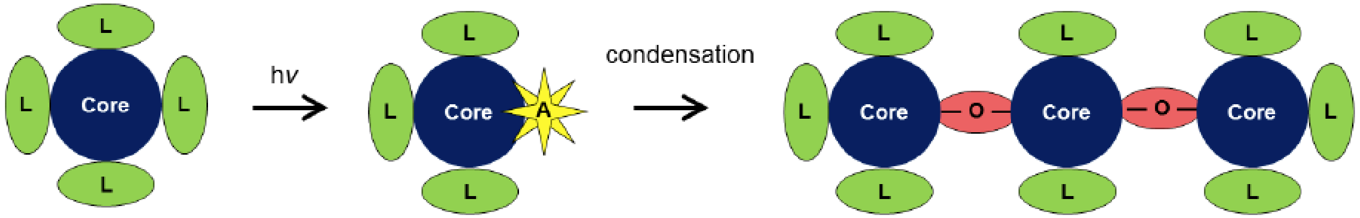
Claims

- At 5 nm CARs fail too much[1]
- At lower node CARs cannot operate[1]
- Chemical stochastics in the range of photons stochastics[2]

[1] A. Vaglio Pret, SPIE 2017; [2] Naulleau Frontiers of Nanoscience

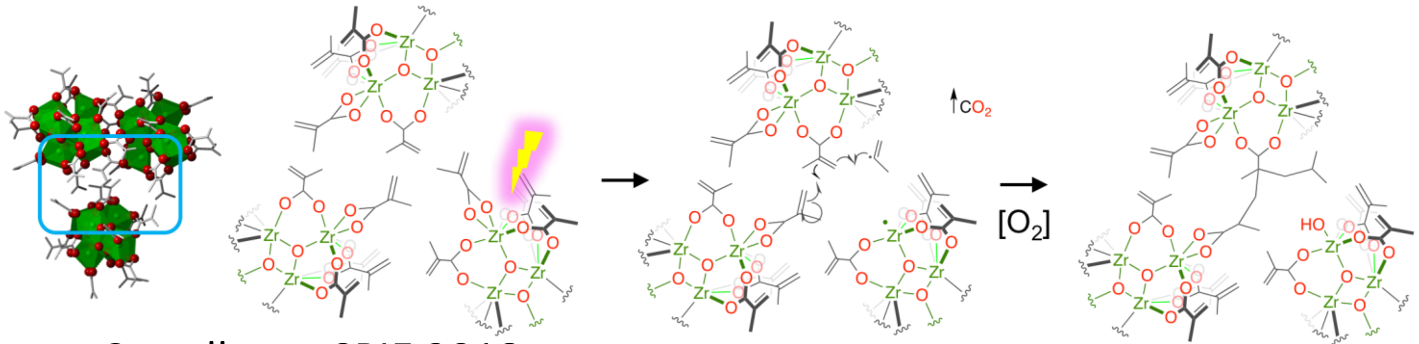
What do we know?

Ligand cleavage + aggregation



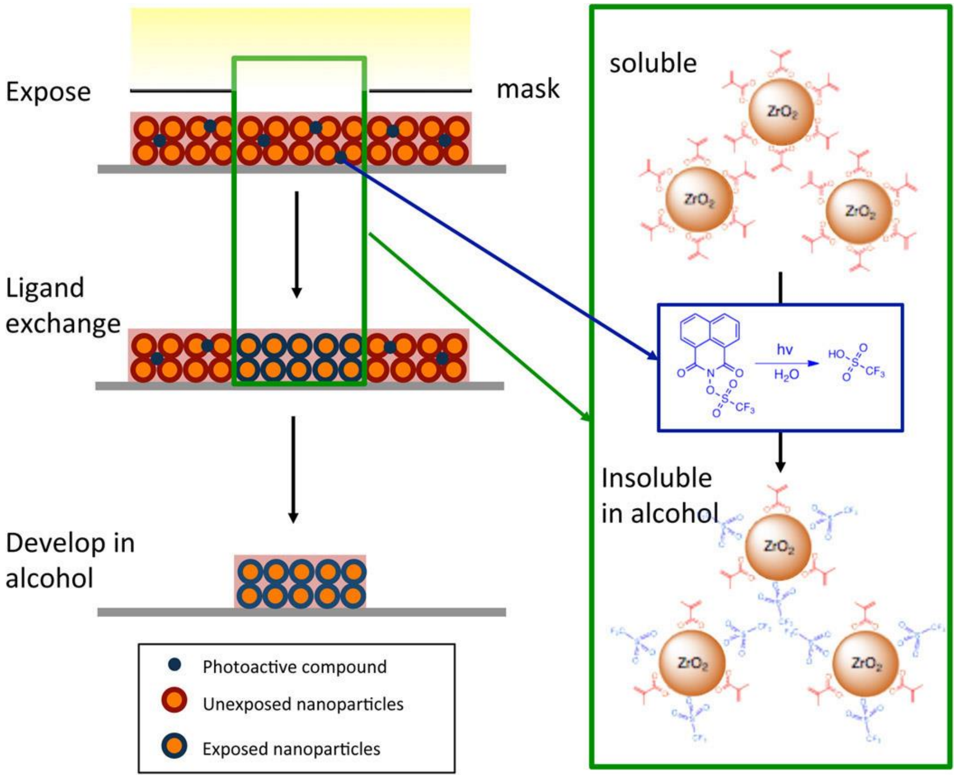
Hinsberg SPIE 2017

Ligand cleavage + aggregation



Castellanos SPIE 2018

Ligand exchange: polarity



Ober Newsroom SPIE 2014

- **Inorganic core** defines the **absorption** and **photoelectron yield**
- **Organic shell** defines the type of **chemistry** and the **secondary electron yield**

work in progress in ARCNL:
-> absorption tuning with metal
-> promoting electron-induced cleavage in ligands
-> low ionization potential

Where are we?

CAR

Polymer based:
- Increased absorptivity (F?, metals (JSR))
- Decreased acid diffusion
  -
  -

Molec
- We
- Tur
- Abs

PSCA
- More sensitive
- Improved contrast in latent image
- Number of absorbed EUV photons?

Multitrigger (Irresistible materials)
- Improved contrast in latent image
- Absorptivity
- CD

nCAR

Sn-based molecular materials:
- Increased absorptivity
- Sensitivity??

MORE (Brainard):
- Low LER!
- High sensitivity (??)

MOCs (Castellanos, Ober)
- Molecular control
- Cross-linking of shell

Can we find some guidelines with so many variables??

…well, there are some features in common

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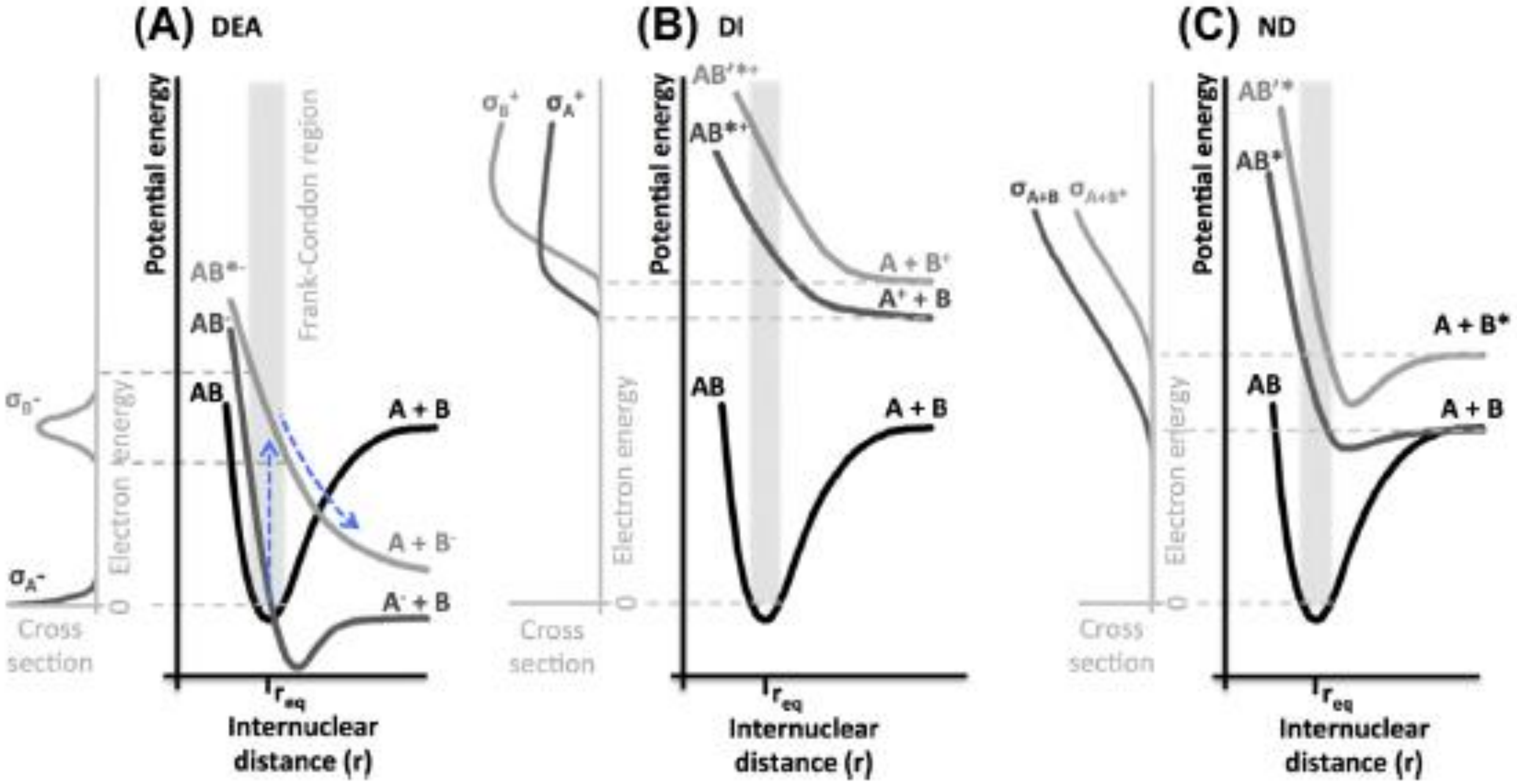
What we do not know?

Some personal thoughts

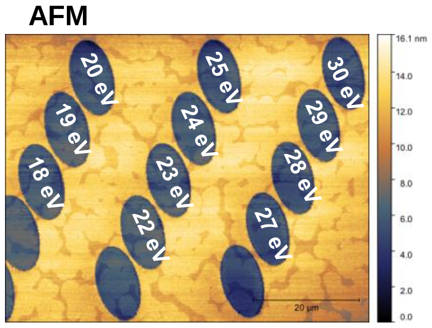
- Electrons above IP generates electrons
- Electrons below IP interact resonantly with the molecules => need of potential curves
- Contribution of holes??

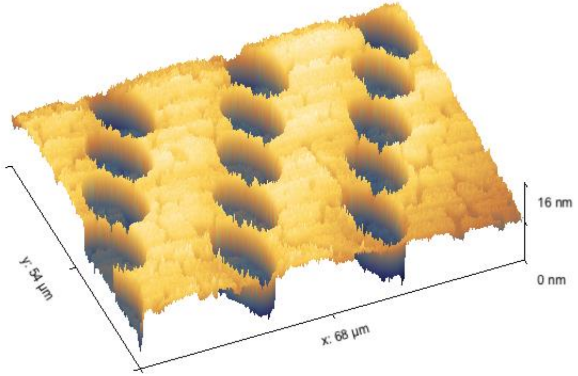


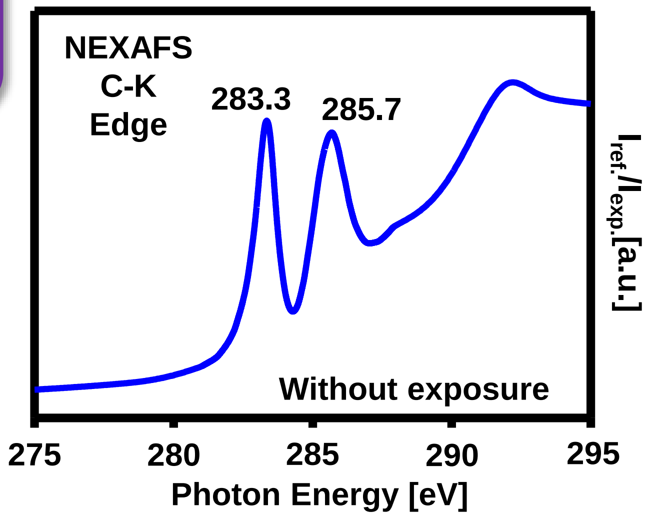
W. Van Dorp Frontiers Nanoscience 2016

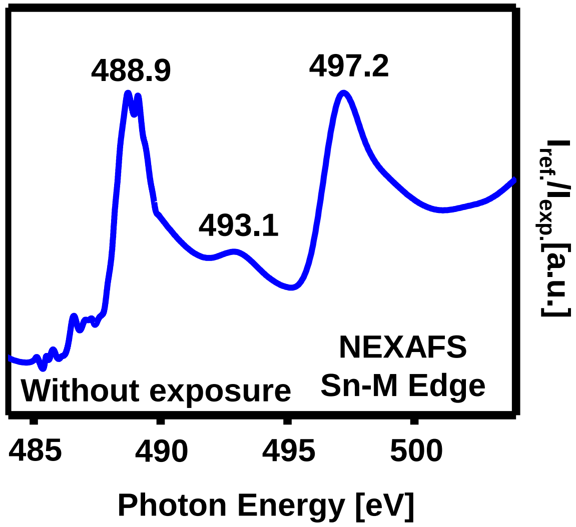
What we do not know?

Currently at ARCNL: chemistry of secondary electrons



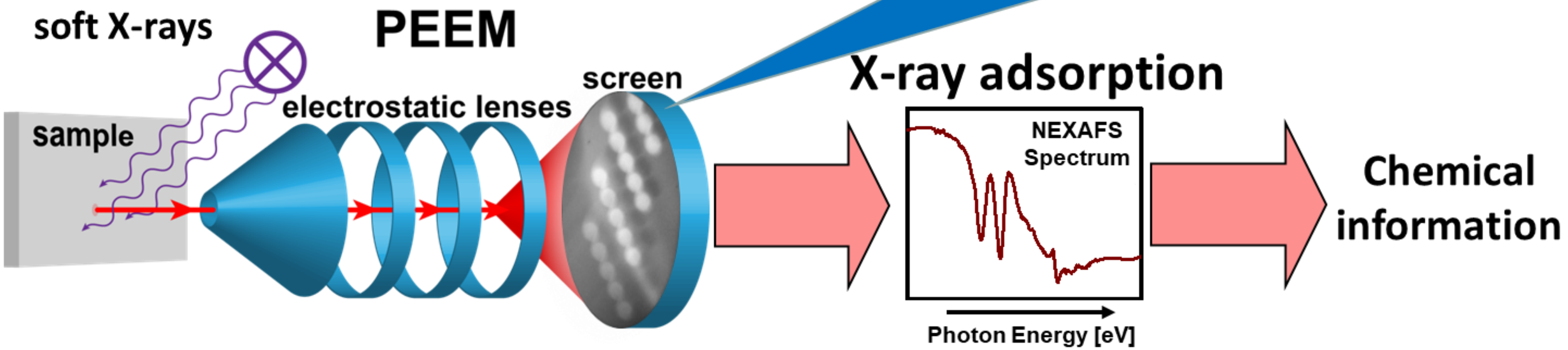






Photoemission Electron Microscope (PEEM)

Measures the electrons that are created by the absorbed x-rays.



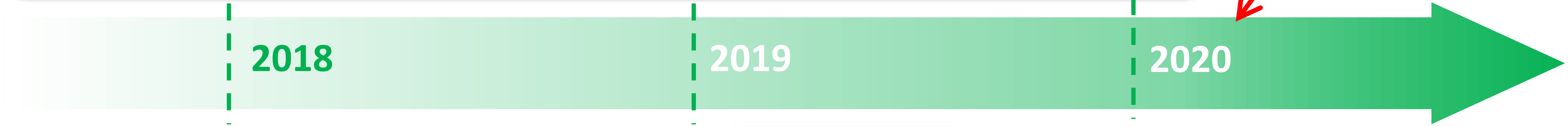
Gain fundamental knowledge

Photoelectron yield (Auger, valence) [Ogletree]

Study of low energy electrons:

- Cross-sections for specific reactions
- **Secondary electrons per photoelectron** [Thete, 2017 PRL]
- Mean free paths

HP = 7nm!!



Improvement on current systems

Increase solubility contrast/sensitivity

Decrease of defects

- **Absorption**
- Photoelectron yield
- More effective chemistry (hole, electron induced)
- Play with underlayer

Breakthrough!!

- Use the knowledge on:
  - Photoelectrons yield
  - Secondary electrons
  - Electron and hole chemistry

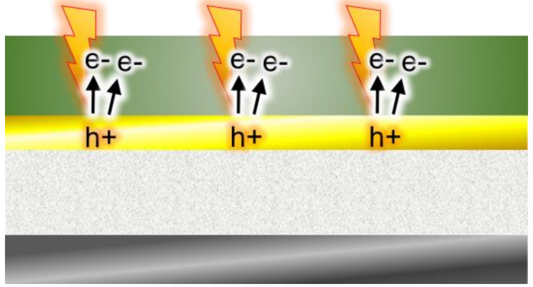
for **new concepts**.

New concepts

Simplify systems

- Smaller and more dense units: metal halogens?
- Rule out muliple components with random distribution: CAR, ligand exchange

Separating absorption and chemical events

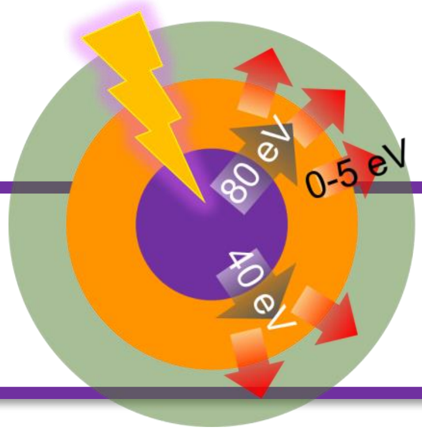


- Layer of dense and ordered metal absorbers
- Use of hot electrons to do chemistry on resist
  - Thin film resists with high etching resistance:
  - Promoting a change in the oxidation state of the underlayer to switch etching resistance
- Avoid development? (volatile inert products?)

Introducing anisotropy

- Propagation of the image only perpendicular to the plane (less shot noise)

”Transforming” high energy electrons in low energy electrons



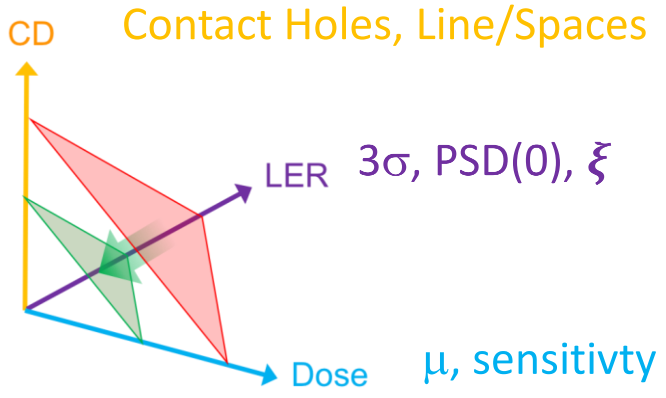
- Electron scattering through layer that yields plasmons/hot electrons

(*similar idea by AZ Electronic Materials Manufacturing, Proc SPIE 2014, 9051, 905117)

Summary

A roadmap should be proposed in the photoresist community to set targets and priorities. This should cover:

- Roadmap of photoresist performance



+ defectivity!

- Fundamental understanding of EUV induced processes, with main emphasis in **low energy electrons induced chemistry and stochastics**
    - Ionization potential, amplification of secondary electrons
    - Resonant processes (electron attachment reactions)
    - Chemistry of radical anions (thermalized electrons)
    - Modeling (molecule specific)

Summary

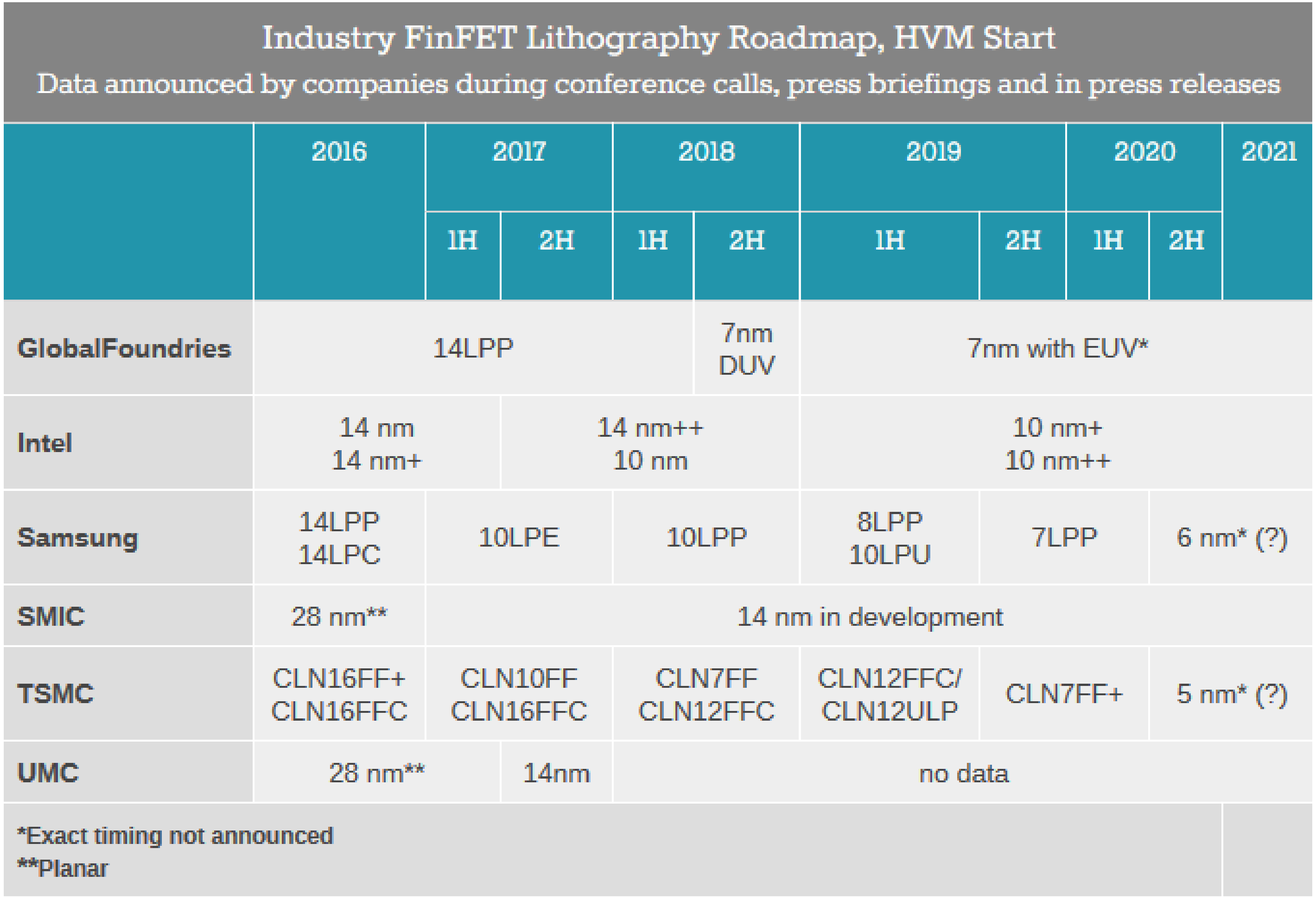
- Currently, there are many attractive strategies to improve the performance of EUV resists:
  - Boosting non-linear response (PS-CAR, Irresistible materials)
  - Simplifying systems: molecular resists with metal content (Inpria, MORE, metal oxoclusters)
- **Disruptive designs are needed within the next 2 coming years to fight stochastics and the SLR trade-off.** Some ideas:
  - Anisotropy
  - Separating absorption and electron-induced chemistry
  - Narrowing electron energy distribution (valence band electrons always there!)

Acknowledgements

- Vivek Bakshi
- Harry Levinson
- Anindarupa Chander
- Danilo de Simone
- Yasin Ekinci
- Wim van der Zande
- Claire van Lare

Thanks for your attention!

What is needed from EUV resists?



Industry FinFET Lithography Roadmap, HVM Start

Data announced by companies during conference calls, press briefings and in press releases

	2016	2017		2018		2019		2020		2021
		1H	2H	1H	2H	1H	2H	1H	2H	
GlobalFoundries	14LPP				7nm DUV	7nm with EUV*				
Intel	14 nm 14 nm+		14 nm++ 10 nm			10 nm+ 10 nm++				
Samsung	14LPP 14LPC	10LPE		10LPP		8LPP 10LPU	7LPP		6 nm* (?)	
SMIC	28 nm**	14 nm in development								
TSMC	CLN16FF+ CLN16FFC	CLN10FF CLN16FFC		CLN7FF CLN12FFC		CLN12FFC/ CLN12ULP	CLN7FF+		5 nm* (?)	
UMC	28 nm**		14nm	no data						

*Exact timing not announced

**Planar

https://www.extremetech.com/computing/249075-foundry-futures-tsmc-samsung-globalfoundries-intel-gear-7nm-beyond