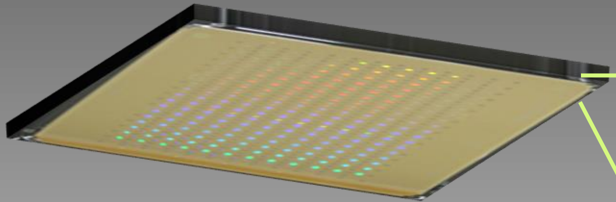
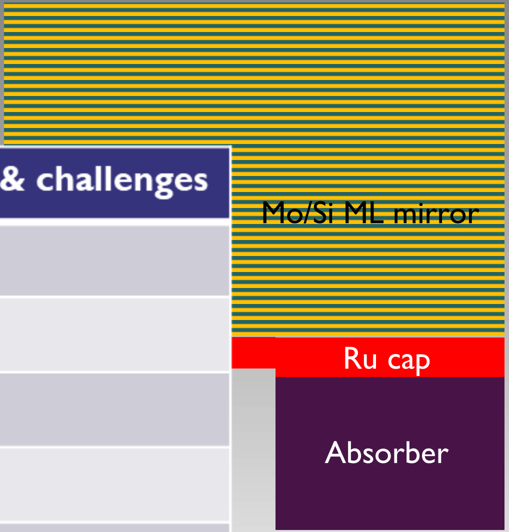
EUV masks: prospects and challenges

Vicky Philipsen, Devesh Thakare, Joost Bekaert, Peter De Bisschop,
Joern-Holger Franke, Andreas Frommhold, Emily Gallagher,
Rik Jonckheere, Tatiana Kovalevich, Lieve Van Look, Vincent Wiaux,
Eric Hendrickx

The EUV mask
Challenges in mask performance



cartoon X-section EUV mask



	Today	**Prospects & challenges**
Mask contribution to wafer		
Mask storage and lifetime		
Novel absorber mask		
High NA stitching enablement		
Pellicle		

Blank:
- Surface roughness
- Uniformity
- Durability
- Defectivity

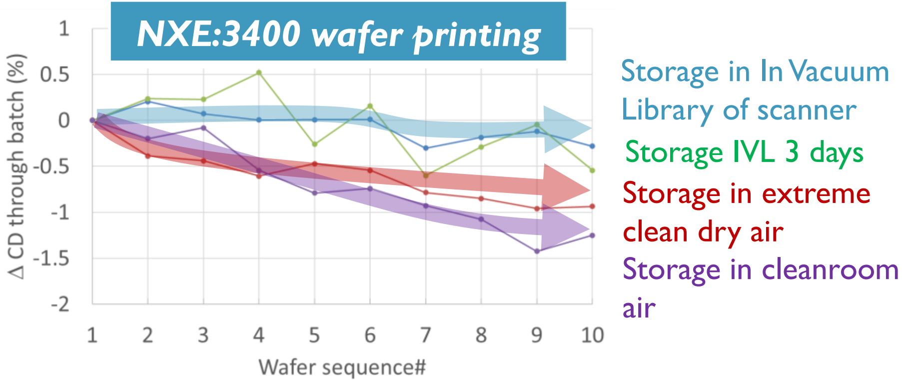
Absorber:
- Patterning & repair
- Resolution
- Absorber edge profile
- Contamination

…

Storage and lifetime effects

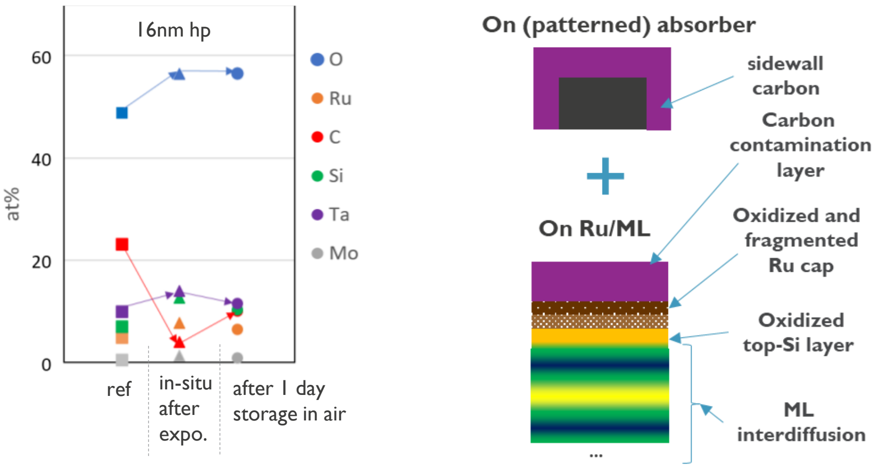
Stable mask printing performance requires controlling storage effects and minimizing lifetime effects

NXE:3400 wafer printing



- Printed CD through batch of 10 wafers depends on prior mask storage
  - Airborne contamination on mask is cleaned-off during EUV printing of first wafers, unless the mask was stored in vacuum.

TNO's EBL2, equipped with in-situ XPS



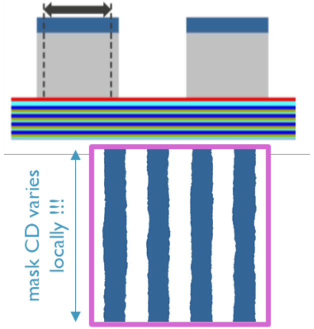
- Storage causes Ru oxidation and C growth
- EUV exposure reverses these effects

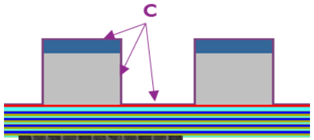
R. Jonckheere, SPIE 15170 (2020)

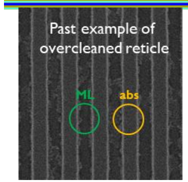
public

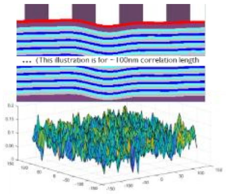
Contribution of mask defects in stochastic failure probability

Need for refined blank and mask roughness specs









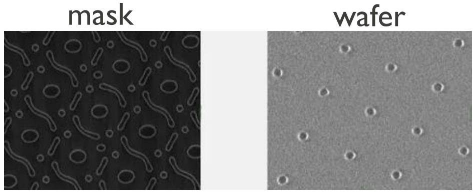
- Mask bias
  - within mask CD mean-to-target range (<4nm 4X) no impact on CD variability nor failure probability
- Absorber line edge roughness
  - Fast increase of CD variability with increasing LER, but influence is small for typical absorber LER
- Contamination growth
  - Negligible impact on CD variability and failure probability for typical 1-2nm carbon
- Surface roughening (ageing effect of ML)
  - CD variability increased faster with increasing surface roughening, but influence is small for typical rms roughness
- ML ripple (pristine state of ML)
  - One order of magnitude impact on failure probability for typical 50pm rms

R. Jonckheere, SPIE 11517 (2020)
L. Melvin, SPIE 11609 (2021)

Mask metrology to understand imaging impact

Massive quantification of mask contribution

- Multi-beam mask write enables
  - Smaller resolution and more precision
  - Curvilinear mask shapes to support aggressive OPC



(1)

- Understanding the mask contribution to wafer imaging performance requires massive mask metrology

- Edge placement error (CD, placement, LER)
- OPC effectiveness
- Stochastics (2)
- Contrast and dose

- CD, placement, LER
- Sidewall angle (profile)
- Contours
- Thickness uniformity
- …

Massive mask metrology:

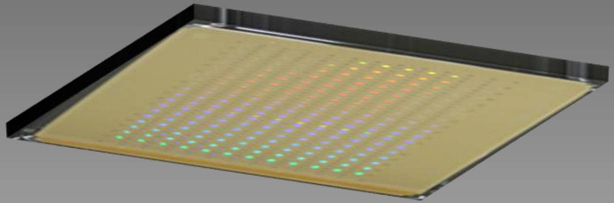
- (CD)SEM
- AFM
- EUV Reflectance
- AIMS
- Dedicated wafer methodologies (3)
- …

(1) D2S, The Quest For Curvilinear Photomasks (semiengineering.com)
(2) P. De Bisschop, JM3 17(4) (2018).
(3) V.V. Nair, SPIE11517 (2021).

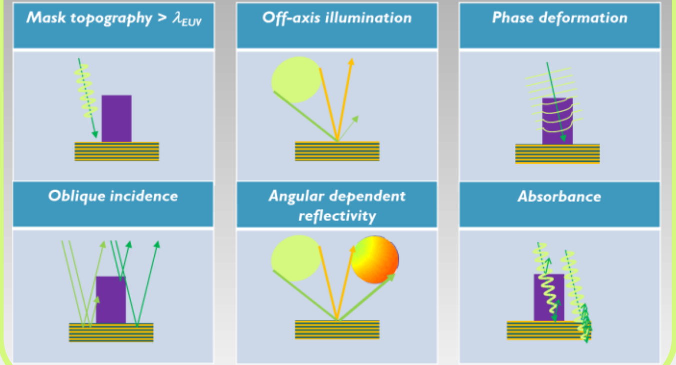
EUV masks

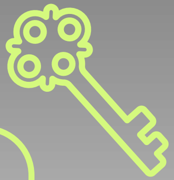
	Today	Prospects & challenges
Mask contribution to wafer	• Stochastics: contributors are ML ripple and ML roughening • EPE	• Refined blank and mask roughness specs • Massive dedicated metrology
Mask storage and lifetime	• EUV reversible effect of oxidation and contamination	• Storage requirements for masks in wafer fab
Novel absorber mask		
High NA stitching enablement		
Pellicle		

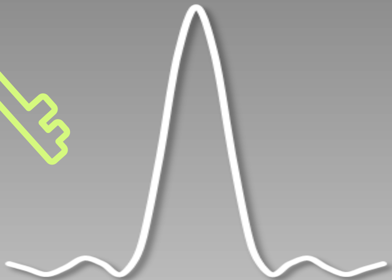
The EUV mask
is responsible for delivering the perfect aerial image

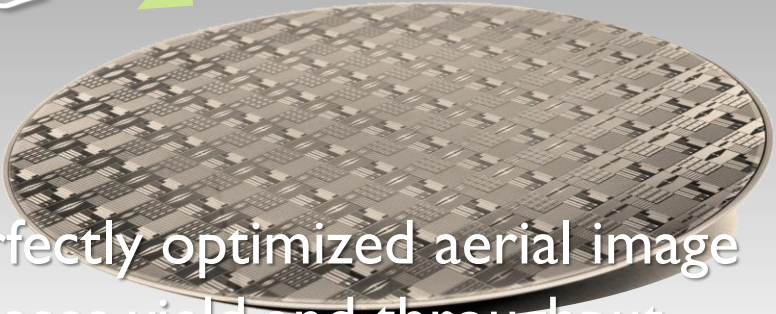


Mask 3D effects distort the aerial image









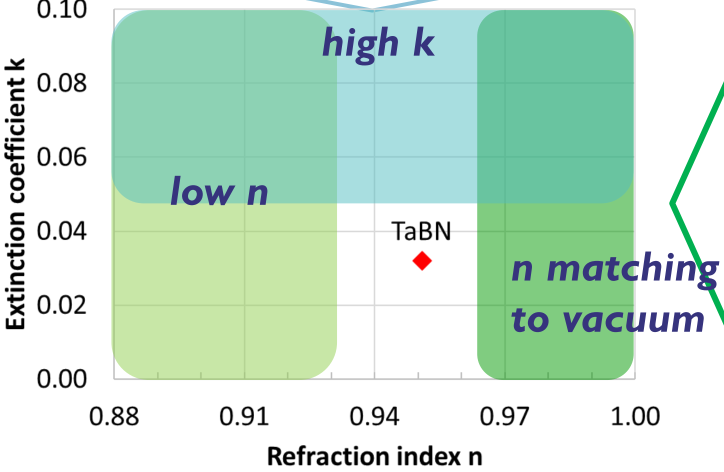
The perfectly optimized aerial image increases yield and throughput

Mask absorber material space vs. reference TaBN

Application and optimization metric determine best n&k region

- Thickness ~ 60nm
- Reduction in dose due to larger mask biasing
- M3D reduction depends on careful thickness optimization and is feature specific

- Thickness << 60nm
- Strong M3D reduction for all features
- No contrast or dose gain

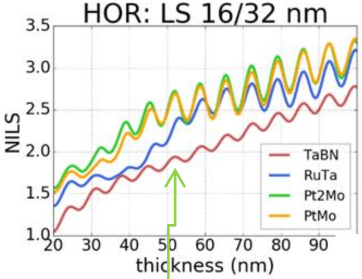


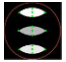
@ 13.5nm

- Thickness ≥ 60nm to compensate contrast loss
- Strong M3D reduction for all features

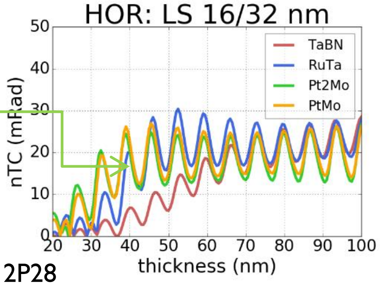
Mask absorber material space vs. reference TaBN

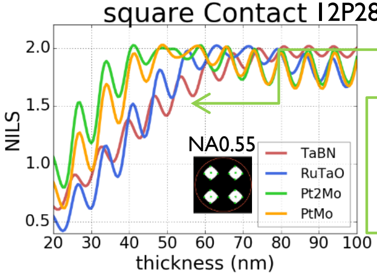
Thickness optimization required for best imaging trade off





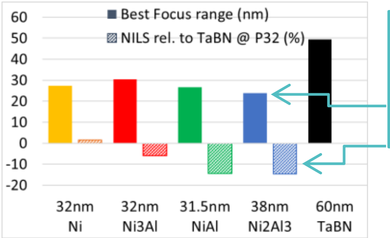
PtMo > 60nm: increased NILS for LS at similar TCE



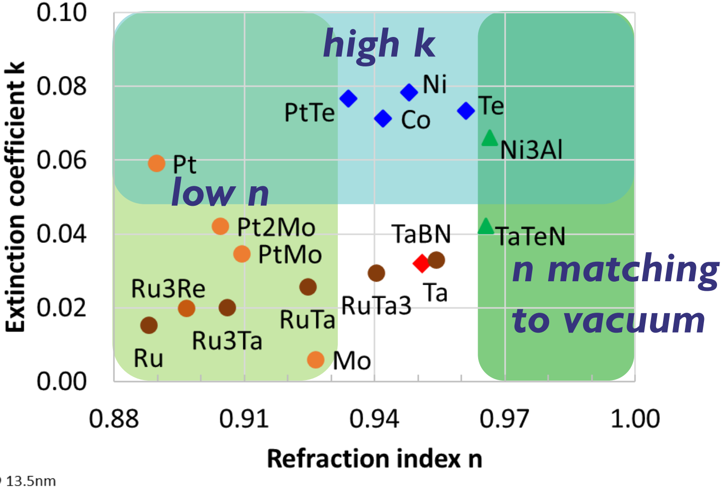


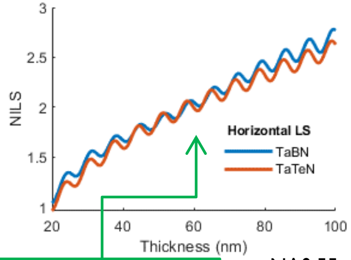
PtMo & RuTa ~50nm: improved NILS for CH

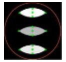
Horizontal 16nm LS through pitch at NA0.33



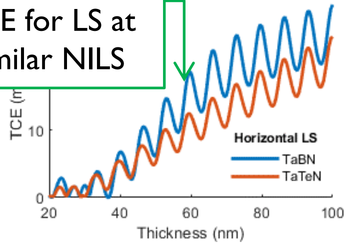
Tradeoff
lower best focus range vs. smaller NILS







TaTeN~60nm: reduction in TCE for LS at similar NILS



M. Wu et al., JM3 20(2) 021002 (2021).

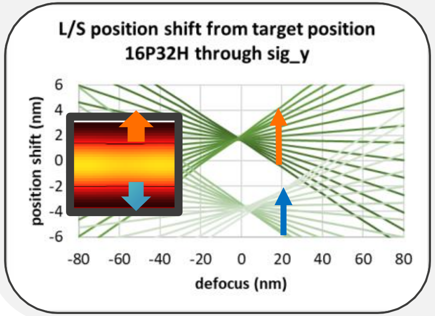
nTC = TCE = Telecentricity error

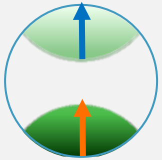
(1) J.-H. Franke, SPIE 11147 (2019)
(2) J.-H. Franke, SPIE 11517 (2020)
(3) J.-H. Franke, SPIE 11609 (2021)
(4) D. Rio, SPIE 11609 (2021)

Source Optimization to mitigate M3D effects

Sacrificing 50% pupil fill ratio through well-chosen source pixels & injected aberrations

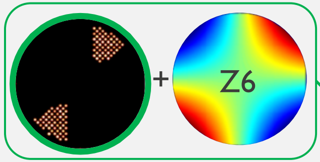
Problem: M3D phase effects lead to pole-specific center offsets

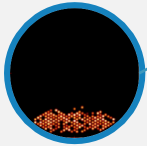


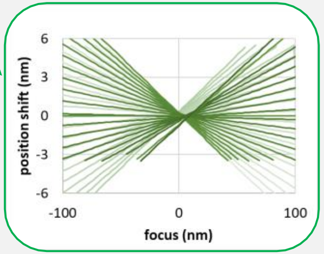


Root cause of fading (NILS loss), best focus shift through pitch, Bossung tilts

Solution: align images from poles or remove poles

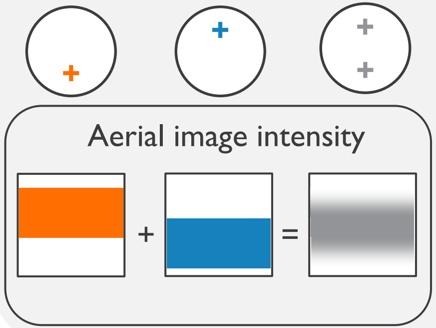


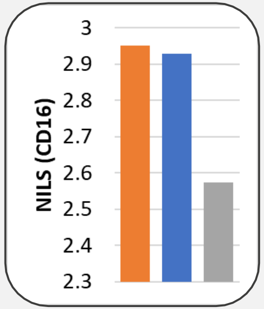


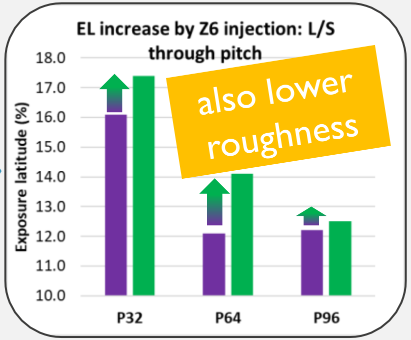


Need to sacrifice 50% pupil fill ratio

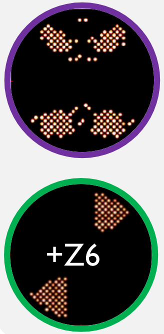
1) fading (NILS loss):

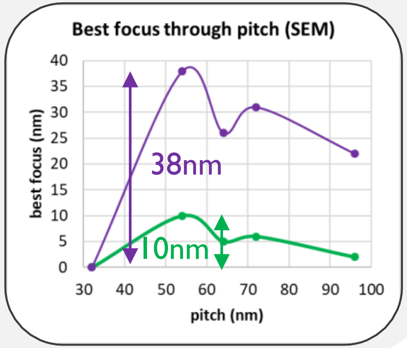






2) best focus alignment:



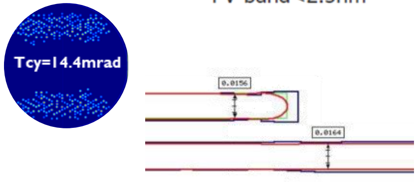


Design optimization aka Source Mask Optimization

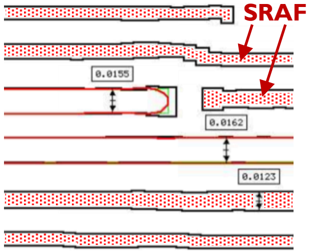
Novel absorber allows for symmetric pupil & relaxed mask complexity

N5 Metal 2 layer (32nm pitch) @ NA0.33 benefits from high-k w/o SRAFs [(1)]

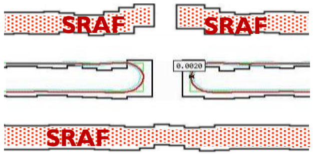
32nm high-k (SRAF - no)
PV-band<2.5nm ✓

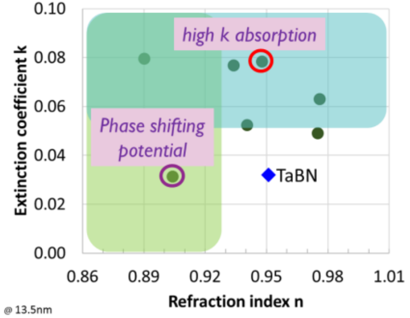


60nm Ta (SRAF – yes)
PV-band<2.1nm



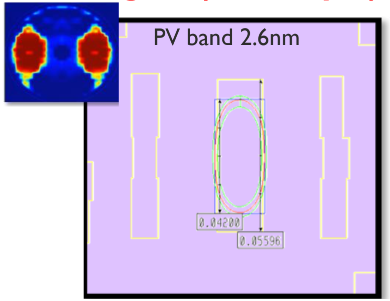
32nm low-n (SRAF - yes)
PV-band =2.0nm



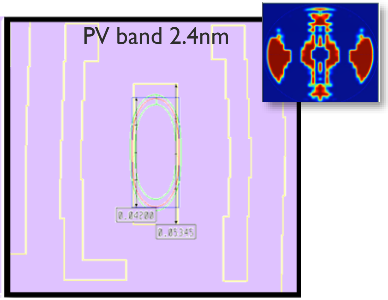


N3 block layer (18x42nm min. block) @ NA0.33 benefits from low-n w/o SRAFs [(2)]

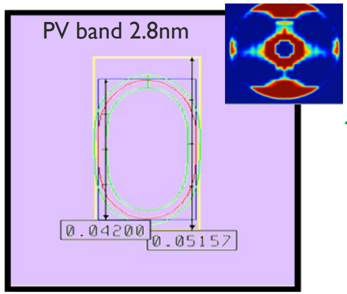
32nm high-k (SRAF - yes)



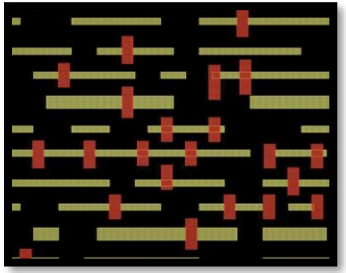
60nm Ta (SRAF – yes)



42nm low-n (SRAF – no)



✓

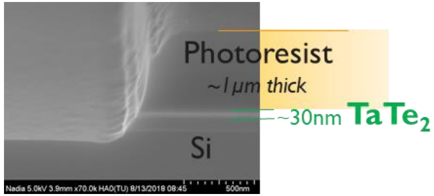


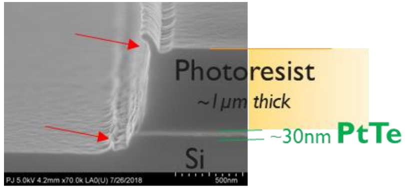
(1) A. Armeanu, SPIE 10810 (2018)
(2) R. Sejpal, SPIE 11148 (2019)

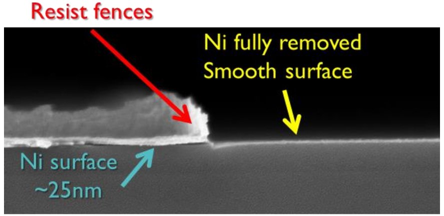
Mask patterning

Traditional: reactive plasma ion etch

- Based on volatile formation of absorber material

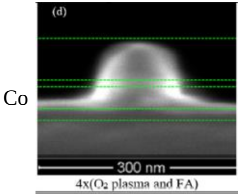




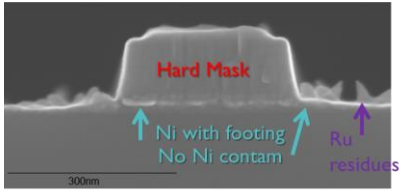


- Metals, like Ni and Pt, are difficult to etch with known chemistries [1, 2]

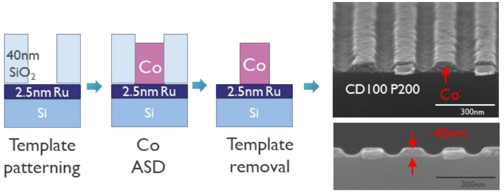
Other patterning techniques are needed to allow metal alloys as novel EUV absorber



Directional and selective etching using ALE [3]



Physical etching by IBE [2]



Metal-on-metal ASD [1]

(1) V. Philipsen, SPIE 10810 (2018)
(2) V. Philipsen, SPIE 10143 (2017)
(3) J.K.C. Chen, JVSTA35 (2017)

EUV masks

	Today	Prospects & challenges
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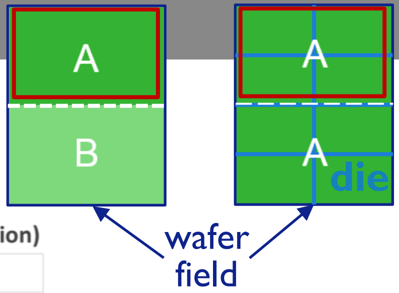
Mask storage and lifetime	• EUV reversible effect of oxidation and contamination	• Storage requirements for masks in wafer fab
Novel absorber mask	• Imaging improvements are evident (M3D reduction, contrast increase, balanced pupil) • First masks being tested on EUV scanners	• SMO including mask stack to optimize a specific application • Novel patterning techniques needed to allow metal absorbers
High NA stitching enablement		
Pellicle		

Mask for high-NA anamorphic imaging

Tighter mask dark image border requirements

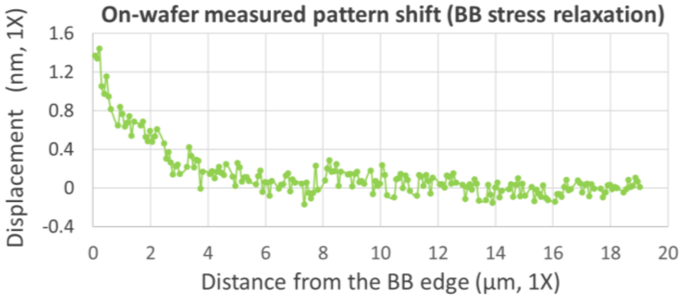
- In-die stitching of two reticles A&B
- Scribe lane stitching of same reticle A

⇨ Abutting images



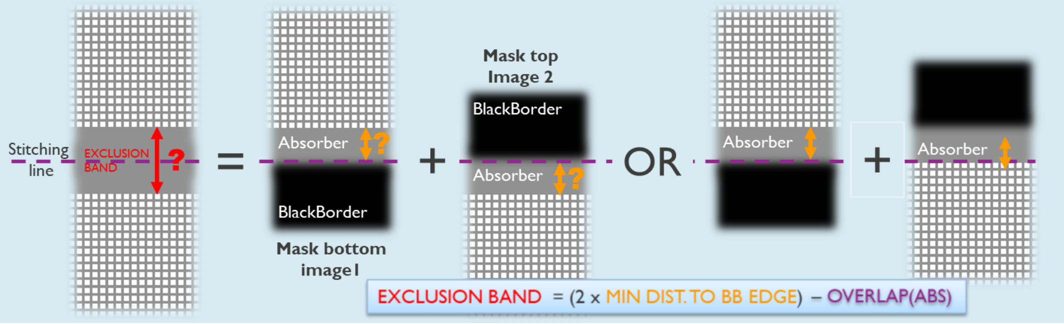
Exclusion band required

- To avoid cross talk between two images
- To avoid placement error on wafer in vicinity of dark image border due to multilayer stress relaxation



Exclusion band can be reduced by

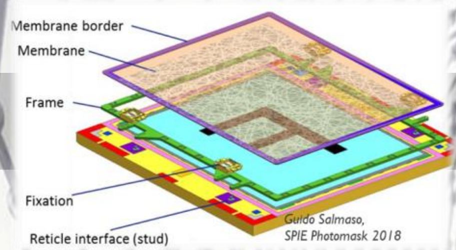
- Novel dark image border with less multilayer stress impact

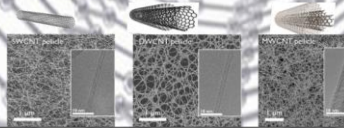


CNT pellicle

To avoid yield loss by particles

- Carbon nanotube (CNT) is building-block for configurable pellicle
  - Highest single pass EUV transmission
  - Full-field reticle coverage
- Current status of CNT development
  - Excellent imaging confirmed by exposure tests on imec's EUV scanner in 2020 (1)
    - Impact on intrafield uniformity of P32 L/S < 0.2nm 3σ
    - No increase of LWR and same exposure latitude
  - Through pellicle non-actinic optical mask inspection demonstrated (2)
  - Current uncoated CNT pellicle does not yet meet lifetime spec: focus is on CNT membrane durability in scanner environment (e.g., coating)





Membrane property	HVM target	SW-CNT	DW-CNT	MW-CNT
EUV Trans. (mean)	>90%	98%	97%	95%
EUV Trans. (3σ unif)	<0.4%	0.2%	0.3%	0.3%
EUV scattering	<0.3% (tbd)	0.12%	0.14%	0.25%
EUV scanner lifetime	>600W w/plasma	Survived 30 min 600W with membrane degrade		
Through-pellicle, non-actinic metrology	achievable	Optical demonstrated, SEM feasibility	Optical demonstrated	Anticipated by extension

(1) J. Bekaert, SPIE 116090Z (2021)
(2) M. Keshet, SPIE 1160910 (2021)

EUV masks

Measuring is mastering

	Today	Prospects & challenges
Mask contribution to wafer	• Stochastics: contributors are ML ripple and ML roughening • EPE	• Refined blank and mask roughness specs • Massive dedicated metrology
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Novel absorber mask	• Imaging improvements are evident (M3D reduction, contrast increase) • First masks being tested on EUV scanners	• SMO including mask stack to optimize a specific application • Novel patterning techniques needed to allow metal absorbers
High NA stitching enablement	• Exclusion band is defined by image cross talk and ML stress relaxation	• Novel dark image border to reduce ML stress relaxation
Pellicle	• High transmission CNT pellicle	• Lifetime extension >600W scanner exposure

Thank you

imec

embracing a better life

Collaboration is key