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Electronics Materials Information

Lithography materials and EUV costs

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Disclaimer

This presentation represents the interpretation and analysis of information generally available to the public or released by responsible agencies or individuals. Data were obtained from sources considered reliable. However, accuracy or completeness is not guaranteed.

Ed Korczynski background

- 1984 B.S. MIT Materials Science and Engineering, *transducers thesis*
- 1985-1990 process engineering and R&D of LED and MEMS HVM fabs
- 1991-1995 OEM apps lab, marketing, product management
- 1996-1999, 2006-2010, 2015- trade press technical editor
- 2000-2005, 2011-2014 business management and technology marketing
  - *Applied Materials, Intermolecular, PDF Solutions, TruSi, UltraClean*
- 2015- technology analyst

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2018 ArFi Lithography Trends
SPIE updates

http://spie.org/conferences-and-exhibitions/advanced-lithography

2018 ArFi Resist Stacks

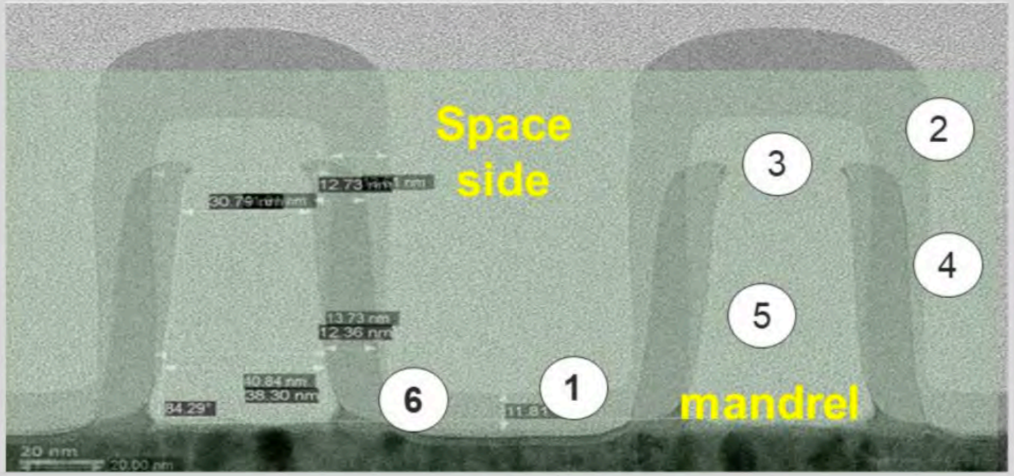
- ArFi resist stacks continue to evolve, Tri-Layer (TLR) to Quad-Layer (QLR)
- IBM Research showed [*De Silva et al. Proc. of SPIE Vol. 10589/10589-27*] a CVD hard-mask (HM) with HDMS priming allowed 16-26nm thin resist adhesion for 15-18nm half-pitches
- Alternate is QLR with organic spin-on adhesion layer over spin-on HM
- Different plasma etch strategy depending on TLR or QLR
  - TLR needs lower selectivity for HMO and more de-scumming
  - QLR needs higher selectivity chemistry for best pattern transfer

SAMP Not Simple

- **Self-Aligned Multi-Patterning (SAMP) PEALD SiO2 spacer film stress controls adhesion and shrinkage on PECVD carbon mandrel**

1. Footing
2. Shrinkage
3. "Bird's Beak"
4. Tilting
5. Kinking

SADP example (SiO_2 spacer on Carbon mandrel)

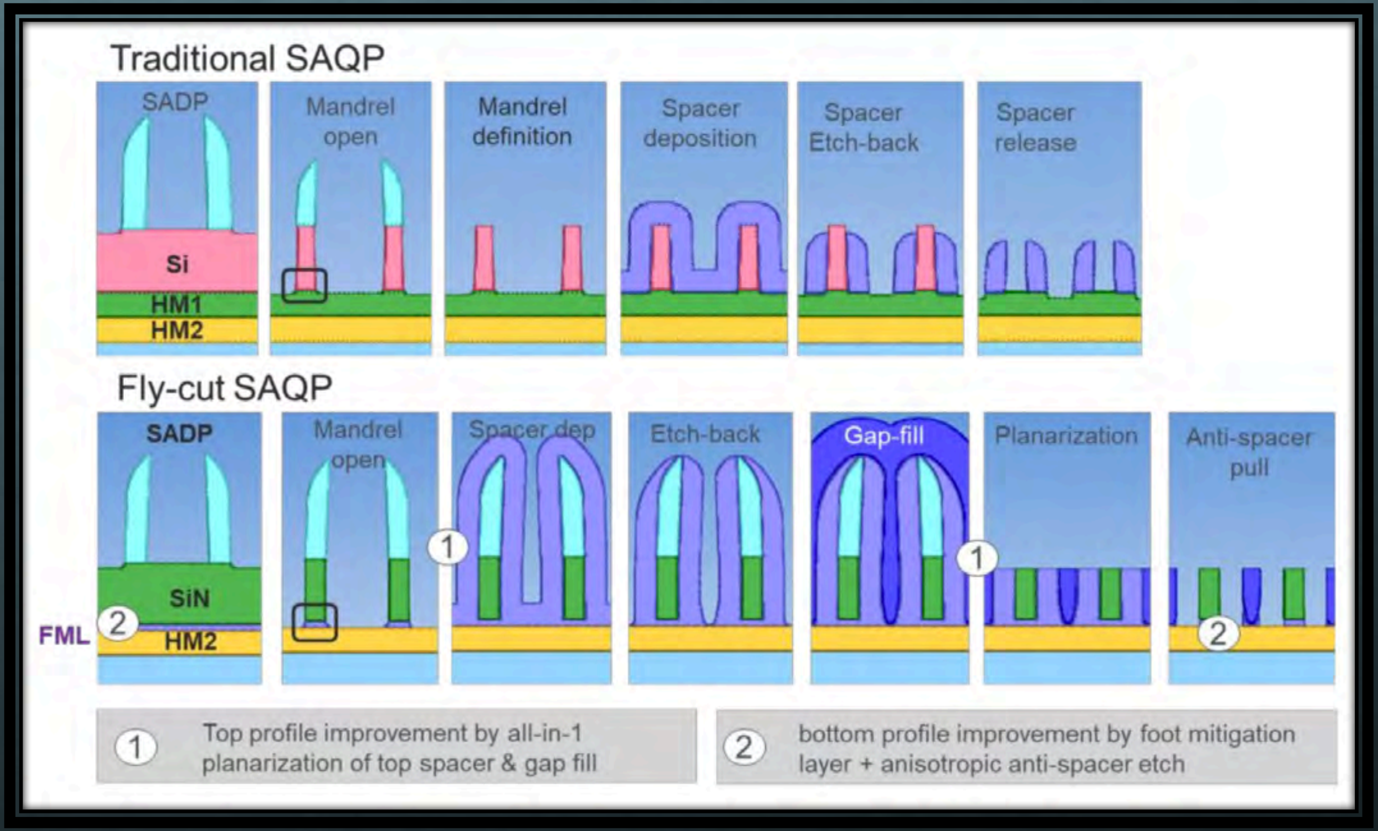


Superimposed TEM images
Background: spacer deposition
Foreground: spacer release

Source: 2018 SPIE, Farrell et al., DOI: 10.1117/12.2303004

TEL "Fly-Cut" SAQP

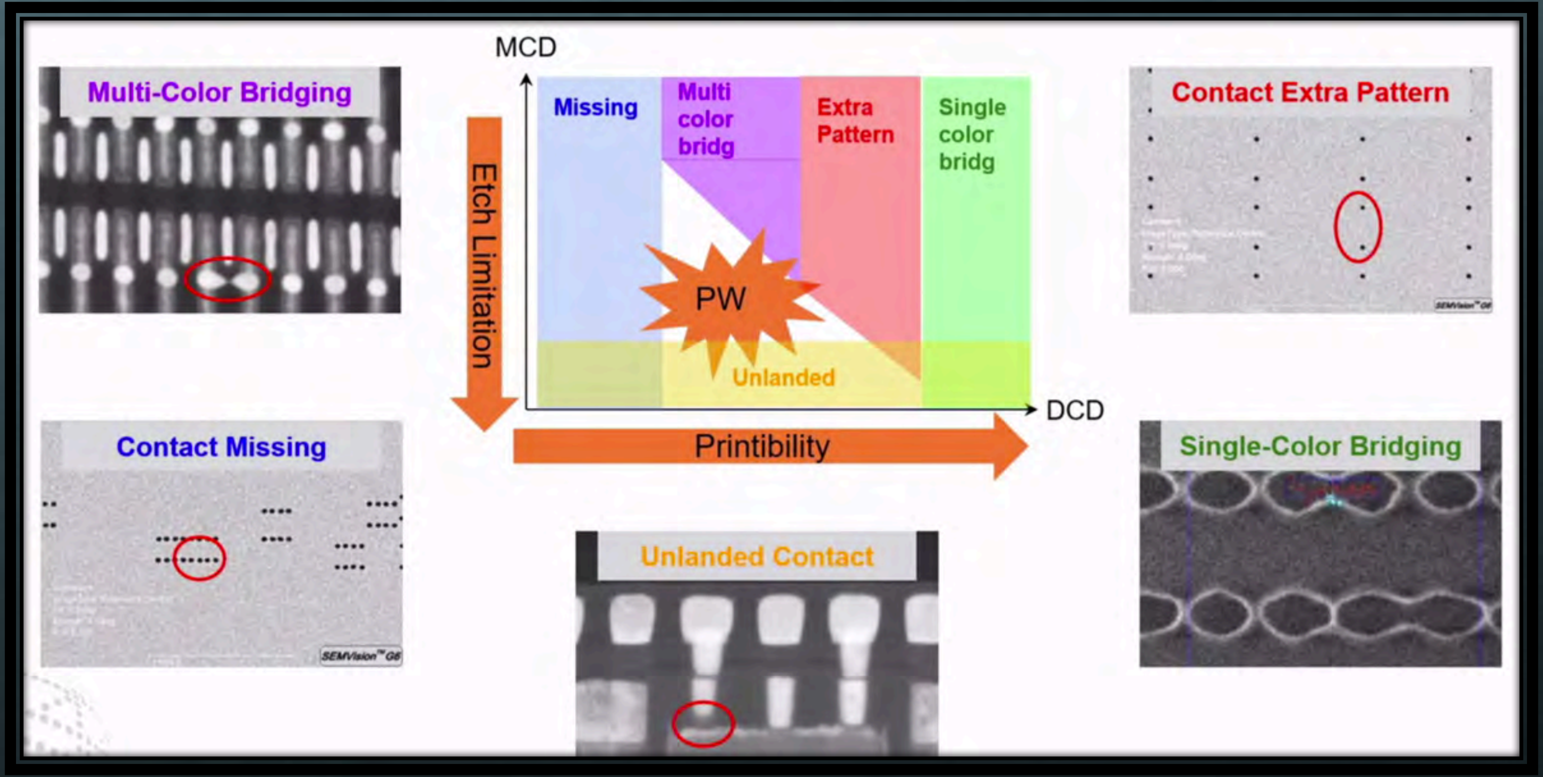
- SAQP subject to pitch-walk and pattern erosion from dep/etch
- FML dep + gap-fill dep + CMP "fly-cut" = SAQP fidelity increase
- Added sacrificial steps to control complexity



Source: 2018 SPIE, Farrell et al.,
DOI: 10.1117/12.2303004

"7nm Node" Foundry Contacts

- GlobalFoundries found the LELE Process Window (PW) could only be found by co-optimizing Developed CD (DCD) and etched Metal CD (MCD)
- Litho-only losses
  - Missing & Bridging
- Litho-Etch losses
  - Multi-color bridging
  - Extra contact
  - Unlanded contact



Source: 2018 SPIE, Liang et al., DOI: 10.1117/12.2297504

ArFi Cuts Multi-Colored

- 4 offset ArFi masks needed
  - EPE inherently challenging
  - Etch selectivity issues
- EDA and material tricks possible
  - Trench cuts
  - Self-Aligned trenches
- 1 EUV exposure can replace all 4 of these ArFi exposures

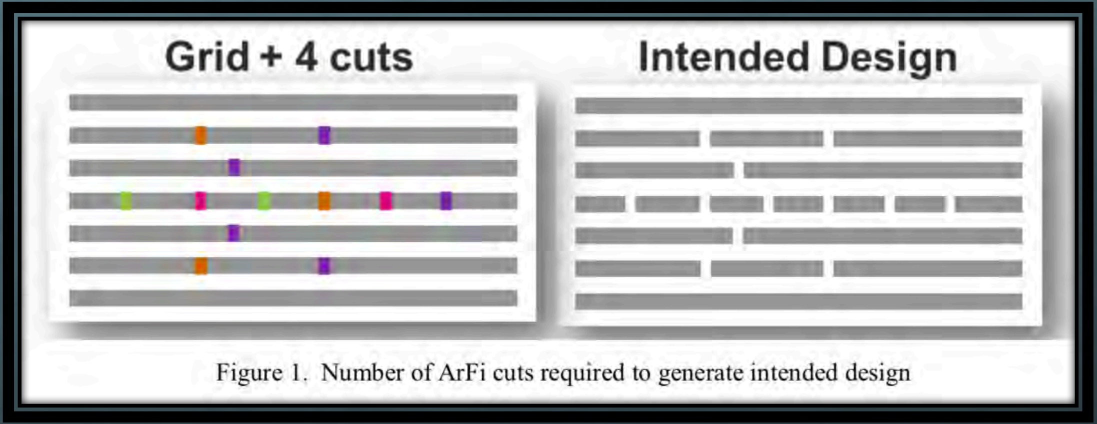


Figure 1. Number of ArFi cuts required to generate intended design

Source: 2018 SPIE, Farrell et al.,
DOI: 10.1117/12.2303004

Pattern Collapse: Now For Fins

- Resist polymer patterns can collapse due to rinse/dry capillary forces
  - Aspect ratios <2:1 needed, driving resist thickness to 15-30nm range
  - Nissan Chemical's Dry Develop Rinse (DDR) technology one option
- Fin silicon patterns can collapse during rinse when aspect ratios >10:1
- IMEC has shown Surface Functionalization Chemistry (SFC) to prevent fin collapse after rinse for 25nm pitch >15:1 AR structures
- SFC integration needs a special UV-clean for residue removal
- SFC not defined as "litho material" yet involved in pattern-transfer

"SEM Bias"

- The act of measurement alters that which is measured
- SEM measurement of CAR patterns after development biased
  - Typical 10 overlapping scans to obtain best image
  - Larger resist lines shrink more
  - Shrinking increases with SEM dose
- Tuning SEM parameters can reduce shrinkage… at expense of precision
- "Are those LCDU data biased or unbiased?"

EUV Lithography status update

https://euvlitho.com/

EUV Status Update

- Extreme Ultra-Violet (EUV) lithography 0.33 NA now in pilot
- ASML 1Q18 announces 0.33 NA EUV NXE:3400 tools orders from fabs for HVM
  - Shipped 10 steppers in 2017
  - Announced 20 shipments will happen in 2018
  - Claimed capacity to ship 30+ steppers in 2019
- Weston Twigg of KeyBanc Capital Markets counts cumulative manufacturing tool orders to ASML (not including NXE:3100 tools for R&D)
  - TSMC of 26 with ~10 delivered
  - Samsung of 15 with 6 delivered
  - Intel of 13 with 7 delivered

EUVL Resists

- With something near 250W source power (@ intermediate focus), steppers can provide 125 wph using 20 mJ/cm2 speed resists
- However, RLS-triangle cannot be defeated in single-exposures and to reach acceptable LER/LWR in tight-pitch features needs >=30 mJ/cm2
- 2017 champion data for resolution and LER use 60 mJ/cm2 for contacts
- Inpria Negative-Tone (NT) metal containing resist (MCR) based on tin
- Legacy Positive-Tone (PT) PS-CAR formulations extended

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EUVL Mask & Resist Tonality

- Due to inherent issues with particles and reticle transmission losses there is concern with use of reticles for 1st generation EUVL
- Darkfield masks have better resolution/DoF compared to brightfield masks due to reduced flare
- <20% open mask areas for cut-masks and contact-holes (CH)
- Darkfield CH needs positive tone (PT) resist or else NT+tone reversal
- Extensions (PAG loaded) of PT PS-CAR ArFi formulations may be used

Bright Field (BF) Dark Field (DF)

- SKhynix showed positive-tone (PT) CAR patterning diffraction tests
  - PT bright field (BF) → pillars
  - PT dark field (DF) → contact holes (CH)
- NT in DF needs extra tone-inversion to pattern contact holes or cuts/blocks
  - MCR stack simplicity vs. process complexity
  - MCR 3-level vs. CAR 4-5-level stacks

Source: 2018 SPIE
Lim et al., Proc. of
SPIE Vol. 10583-30

1st EUVL HVM Pilot in 2018

- Assume circular CH and “cuts” for SAMP grid lines first HVM use
  - Conservative approach allowing fall-back to 3-4 ArFi exposures
  - Relatively less yield loss from particles on mask
- Assume some manner of hole “smoothing” needed post-develop to allow for exposure reduction from today’s 60 to HVM target 30 mJ/cm2
- Two logical options for mask and resist tonality
  - Darkfield mask + PT PS-CAR (typically TMAH-based develop)
  - Darkfield mask + NT MCR tone-reversal (perhaps using deposition-etch)

EUV Reticle Supply-Chain

- March 2018 ASML announces Teledyne DALSA will produce EUV pellicles, after 3 years of secret collaboration
- Pellicles = extremely thin membranes which allow EUV transmission while protecting photomasks from particles and contaminants, consumables
- Teledyne DALSA is division of Teledyne Technologies
  - MEMS manufacturing >20 years
  - Modern 200-mm diameter processing tools
  - Extensive IP and experience in the production of extremely thin films

0.55 "High" NA EUV Stepper

- "Twinscan EXE:5000" series from ASML
- Anamorphic projection 4:1 and 8:1 = ½-field exposure
  - Large chips would need interconnect stitching
  - Throughput of 2 EUV 0.55NA exposures ~ 2 EUV 0.33NA exposures
- ASML investment in Zeiss to support tool development
- ASML announces pre-orders from fabs 0.55NA EUV steppers
  - 4 R&D tool orders for delivery >2020
  - 8 pilot tool "options sold" for delivery >2021

Waddle-room for Black Swans

http://semimd.com/blog/2018/04/13/waddle-room-for-black-swans-euv-stochastics/

“Stochastic” Black Swans

- Semiconductor fab yield losses – working definitions (not academic)
  - “Systematic” = design-process effects & litho optical parameters
  - “Random” = controllable process effects & litho mechanical parameters
  - “Stochastic” = uncontrollable process effects at atomic scale
- In addition to Resolution-LineWidthRoughness-Sensitivity (RLS) tradeoff, new tradeoff within a line between Breaks-Collapse-MicroBridging
  - Breaks reduced by thicker resist or wider lines in pitch
  - Collapse reduced by thinner resist
  - Micro-Bridging reduced by narrower lines in pitch

"Line-edge roughness performance targets of EUV lithography" 2017 SPIE by Brunner et al. (Proc. of SPIE Vol. 10143, 10143E-2)

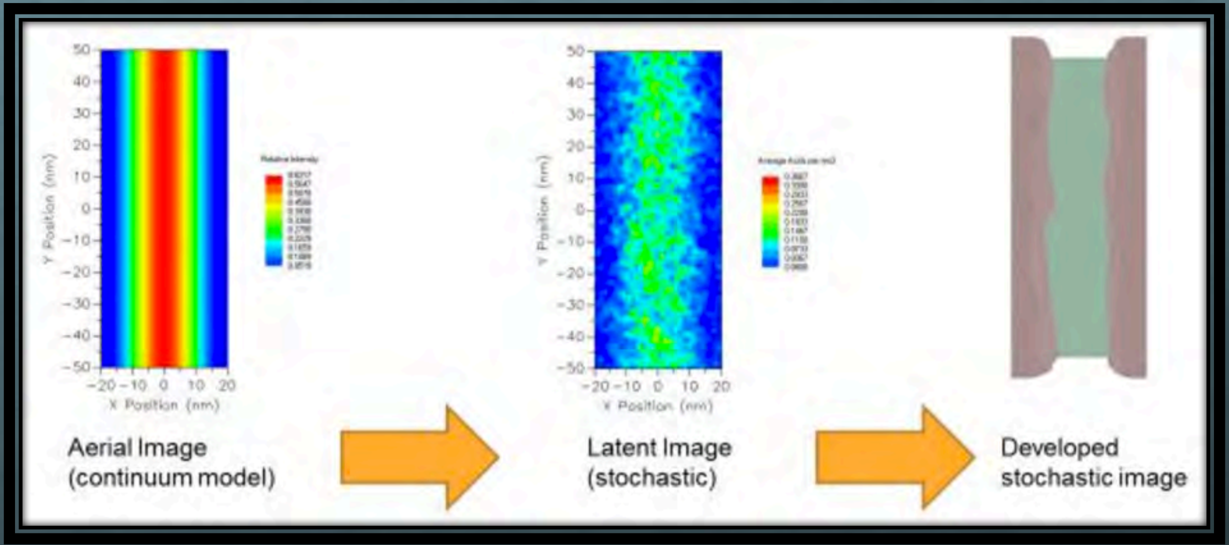
- Stochastic noise present for all lithographic processes but more worrisome for EUV
  - Fewer photons per unit dose, since each EUV photon carries 14X more energy than 193nm photon
  - Limited EUV power, since only ~1% of power at intermediate focus makes it to wafers
  - Smaller fraction of EUV photons absorbed by resist, typically <20% for CAR
  - Smaller features at more advanced nodes, and so less area to collect EUV photons

- Stochastic phenomena – photon shot noise, resist inhomogeneities, electron scattering events, etc. – now cause CD variation in EUV resist patterns at levels >= lithography variations such as defocus

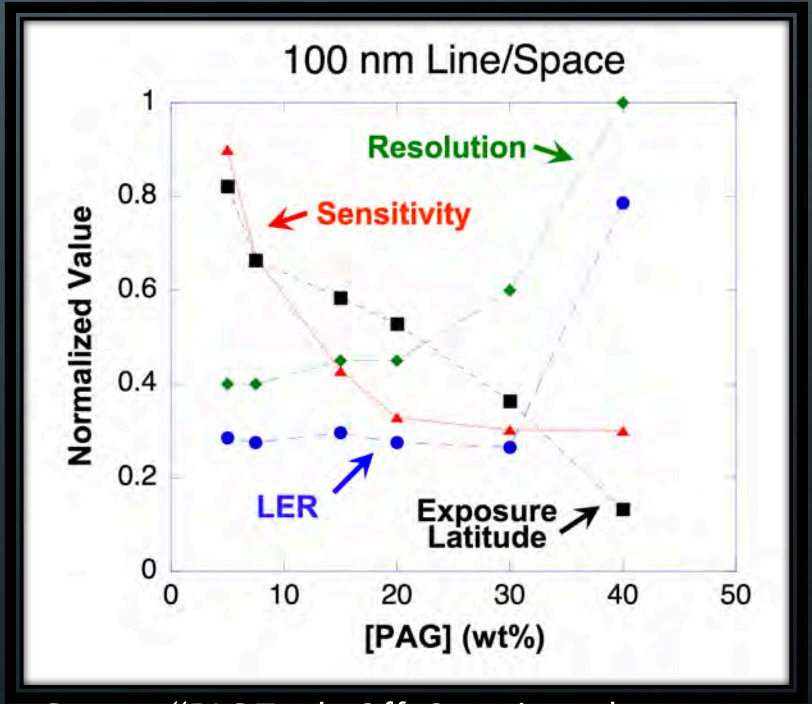
- Stochastics limit k1 to higher values (worse resolution), limiting benefits of high NA

- *"The quest to improve EUV lithography pattern quality will increasingly focus on overcoming stochastic barriers. Higher power EUV light sources are urgently needed as features shrink. Photoresist materials with higher EUV absorption will also help with stochastic issues. Alternative non-polymeric resist materials and post-develop smoothing processes may also play a future role."*

EUV PS-CAR Stochastics



Source: 2018 SPIE
Brunner et al., 10143E-2

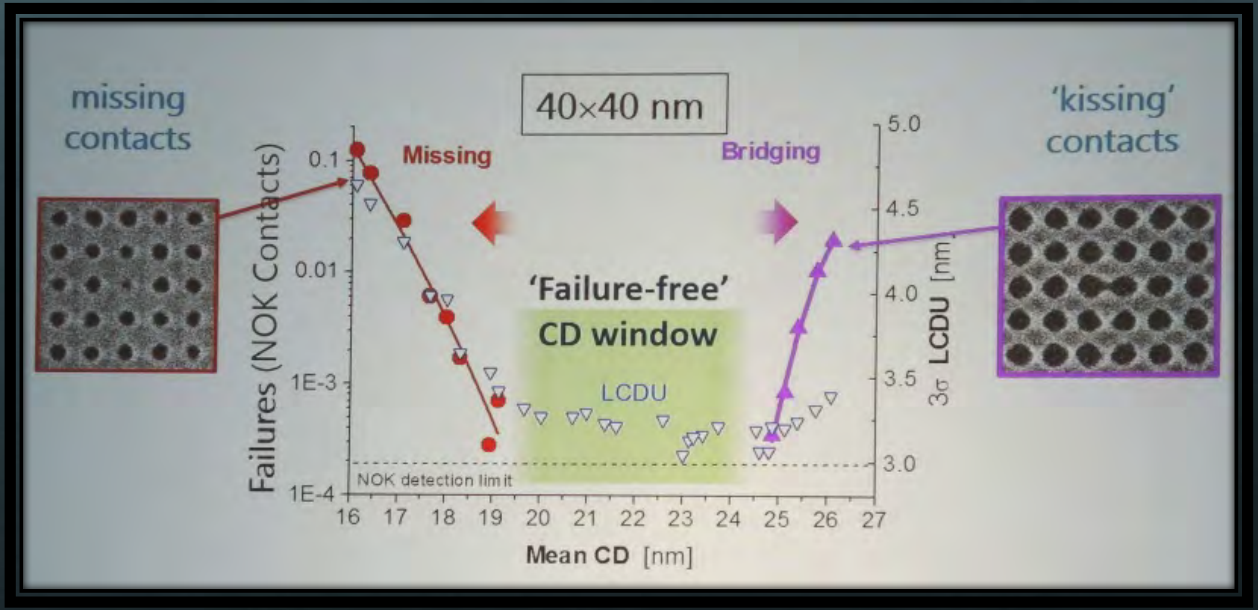


Increasing PAG and quencher (base) wt% in blend reduces stochastic variation…with limits ~20%…

Source: "RLS Trade-Off: Questions about Molecular Size and Quantum Yield" by Robert Brainard and Craig Higgins, 2008

Black Swans in Contacts

- IMEC showed stochastic failures in 22nm Contact Holes (CH) +-2nm
- Note LCDU data show minimal failures >24nm, ∴ "Black Swans"
- Not OK = "NOK"
- Found in SEM images



Source: IMEC

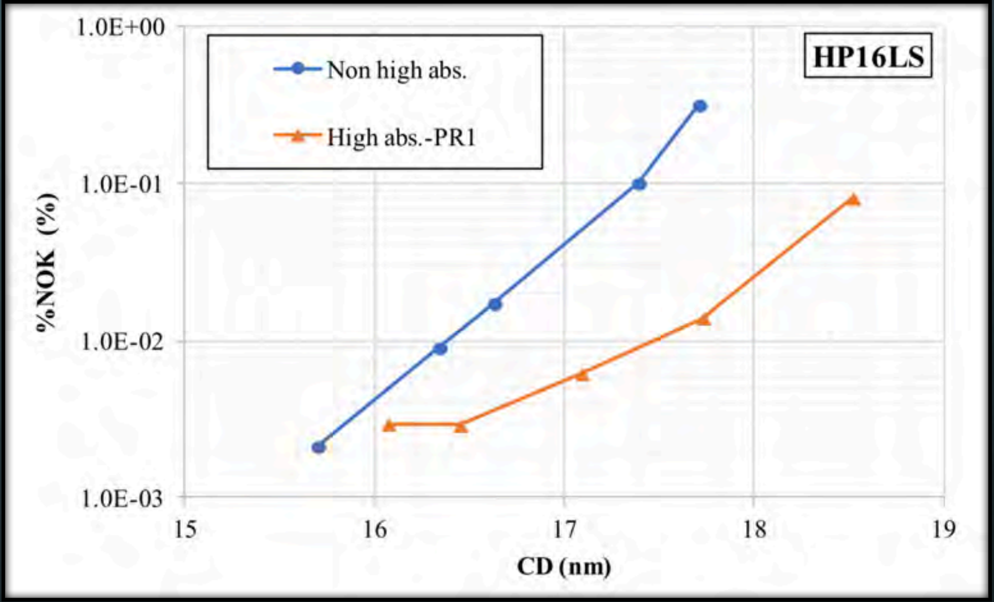
CAR Stochastics & Sensitivity

- **FujiFilm shows that engineering molecules can tune absorption of EUV**
- **Achieves 15-20% dose reduction for same LWR, with much lower %NOK**

16nm-HP EUVL Stochastics

PS-CAR "D"	LWR (nm)
EUV Photons	2.0
Acid Generation	1.2
Photo-Acid Generator	0.6
Quencher (base)	1.9
Protecting Groups	0.1
TOTAL	3.0

Source: 2018 SPIE Brainard, Trefonas & Gallatin, Proc. of SPIE Vol. 10583/10583-40



Source: 2018 SPIE Lim et al., Proc. of SPIE Vol. 10583/10583-30

MCR Absorb More EUV Photons

- Metal Containing Resists (MCR) such as SnOx nanoparticles from Inpria absorb higher % photons compared to Chemically-Amplified Resist (CAR)
- Higher absorption reduces stochastics – Inpria MCR (“YABA” & “YF”)

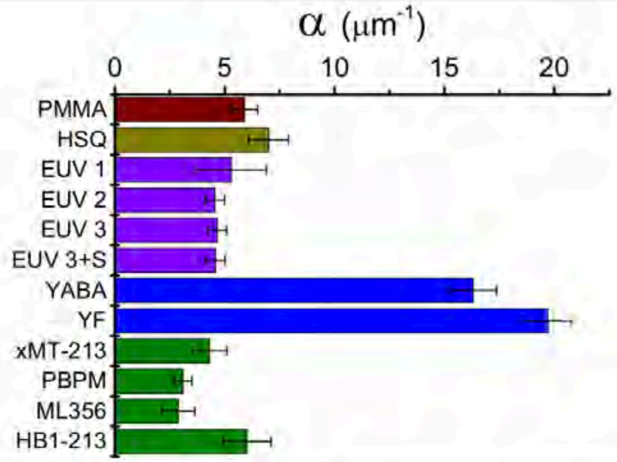


Figure 4. Measured linear absorption coefficient α. All polymer-based resist have approximately the same value, while the tin oxide-based resists (YABA and YF) have a remarkably higher α.

Source: 2016 SPIE
Paul Scherrer Inst.

Lithography Cost Modeling

https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10589/105890R/Cost-modeling-22nm-pitch-patterning-approaches/10.1117/12.2297454.short

Korczynski at 2018 SPIE

Cost Per Wafer Pass (CPWP)

- "Cost modeling 22nm pitch patterning approaches" Paper 10589-25
- By Ed Korczynski, TECHCET – Tuesday evening poster presentation
- Proc. of SPIE Vol. 10589 (2018) 10589-25
- ABSTRACT: No single lithography technology can create<24nm pitch patterns in a single pass except for direct-write e-beam which is too slow and expensive for HVM. Various complex multi-patterning process flows can be scompared by Cost Per Wafer Pass (CPWP), a term defined as the cost-of-ownership (CoO) with all yield losses set to zero in high volume smanufacturing (HVM). CPWP modeling allows for the evaluation of alternate 1D and 2D patterning paths, including EUV LE2, EUVL SADP, ArFi LE4, ArFi SAQP + EUVL cut-mask, and ArFi SADP + DSA + ArFiblock-mask.

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CPWP Model Input Assumptions

- HVM IC fab
- Tool Cost/Wafer assumes depreciation over 10M wafers
- Materials costs based on TECHCET models
- Overhead for facilitization assumed 20% over sum of other per-wafer costs

IC HVM Unit Process Cost-Per-Wafer-Pass (CPWP)

300mm Wafer Process	ArFi	EUV	CVD	ALD	Etch	DSA
Wafers/Hour	240	120	180	120	80	120
Available Hours/Year	7700	6700	8000	7500	7500	8000
Product Wafers/Year (M)	1.848	0.804	1.44	0.9	0.6	0.96
Tool Cost (US$M)	60	120	5	6	6	3
Tool Cost/Wafer (US$)	6	12	0.5	0.6	0.6	0.3
Materials/Wafer (US$)	0.6	1.2	0.5	0.2	0.2	2
Labor/Wafer (US$)	0.03	0.07	0.04	0.06	0.09	0.06
Overhead/Wafer (US$)	1.33	2.65	0.21	0.17	0.18	0.47
Unit Process CPWP (US$)	**7.96**	**15.92**	**1.25**	**1.03**	**1.07**	**2.83**

CPWP Model Outputs

- **EUV can be cost-effective, but materials engineering of resist stacks needed**

22nm Pitch IC Lithography Cost Per Wafer Pass (CPWP) Estimates in HVM

300mm Wafer Patterning Flow	1D EUV SADP + EUV cut	1D ArFi SAQP + EUV cut	1D ArFi SADP + DSA + ArFi cuts	2D EUV LE2	2D ArFi LE4
Litho ArFi	0	7.96	23.88	0	31.84
Litho EUV	31.82	15.92	0	31.84	0
Litho total	31.82	23.88	23.88	31.84	31.84
CVD	1.25	2.50	1.25	0	0
Etch	3.21	4.28	4.28	2.14	4.28
ALD	1.03	2.06	1.03	0	0
DSA	0	0	2.83	0	0
movements	2.50	3.50	2.00	2.00	4.00
Total Flow CPWP (US$)	$39.81	$36.22	$35.27	$35.98	$40.12

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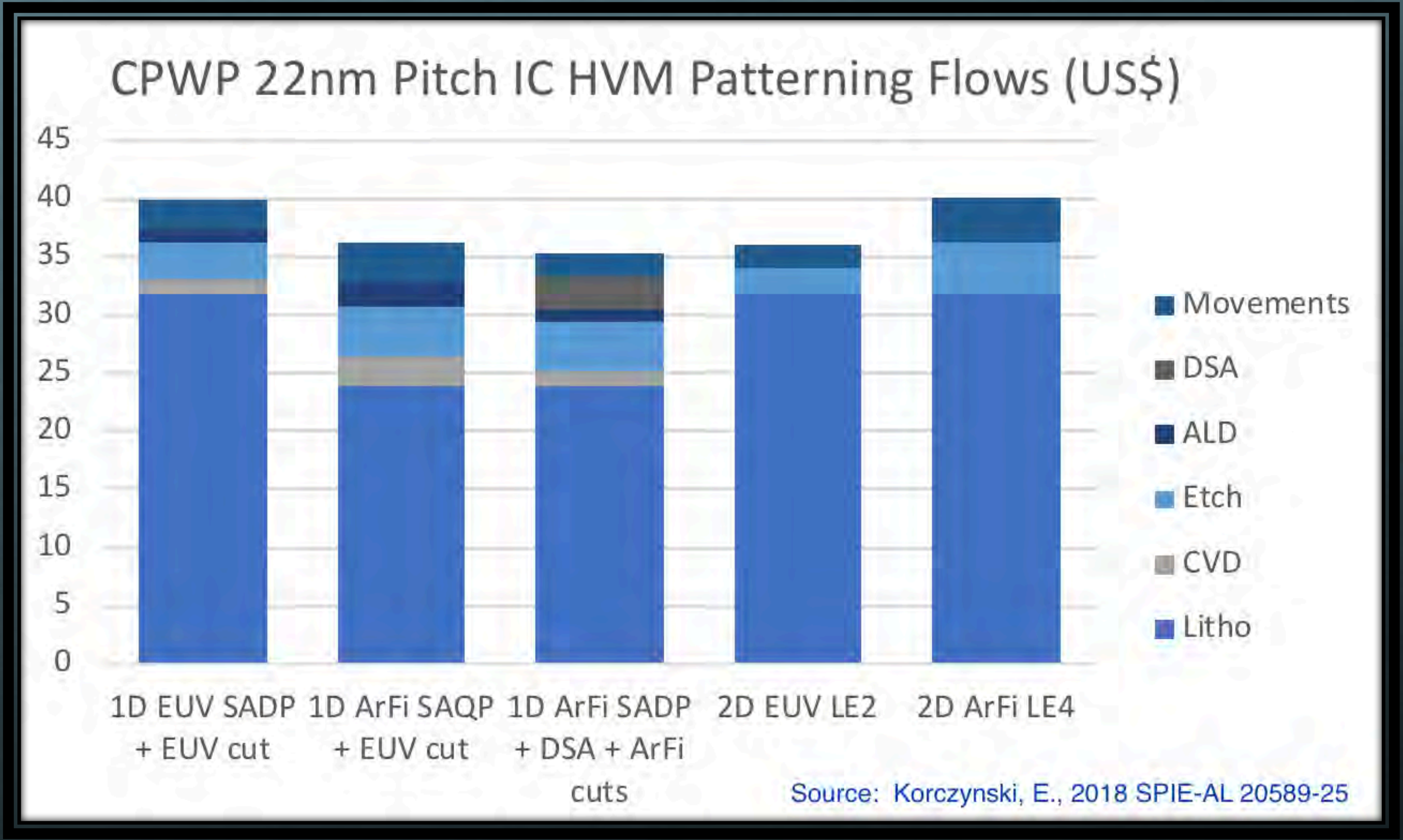
Cost Per Wafer Pass – Adv. Litho

- "Movements"= $0.50 per transfer between cluster tools
- Deposition and etch costs relatively small
- Not including EDA nor masks nor test
- Assumes 100% yield



CPWP integrating DSA

- Assumption here is only 2 or 3 ”bottom-up” DSA pitch divisions can be controlled so have to do one SADP to create grapho-template lines
  - R&D shows 4-6 pitch divisions possible but unsure if controllable in HVM
  - Likely trade-off with self-assembly time on hot-plate
- Assumes most expensive litho materials – may need 3 spins with special ambient controlled hot-plates in track tool
  - High-Chi material
  - “Aligning” material
  - “Blocking” material

CPWP 22nm Pitch - Analysis

- Of the many multi-patterning options, just considering CPWP it seems that EUV saves money over only using ArFi
- EUV masks may cost 3-5 times one advanced ArFi mask
- EUV EDA will save cost over more pattern fractioning ‘colors’ with ArFi
- EUV systemic-yield-losses will be lower than with ArFi – reduced EPE within one layer for example
- EUV will save fab space and turn-around time (TAT)

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Thank you!

http://techcet.com/product/photoresists-and-photoresist-ancillaries/

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