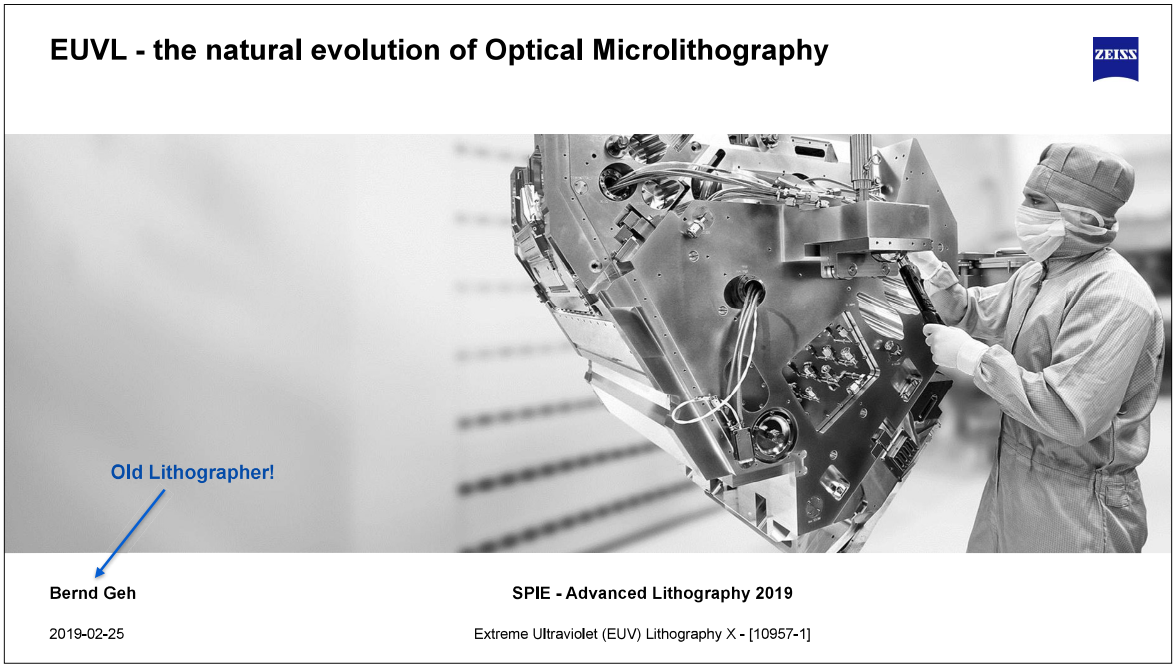


EUVL - the natural evolution of Optical Microlithography

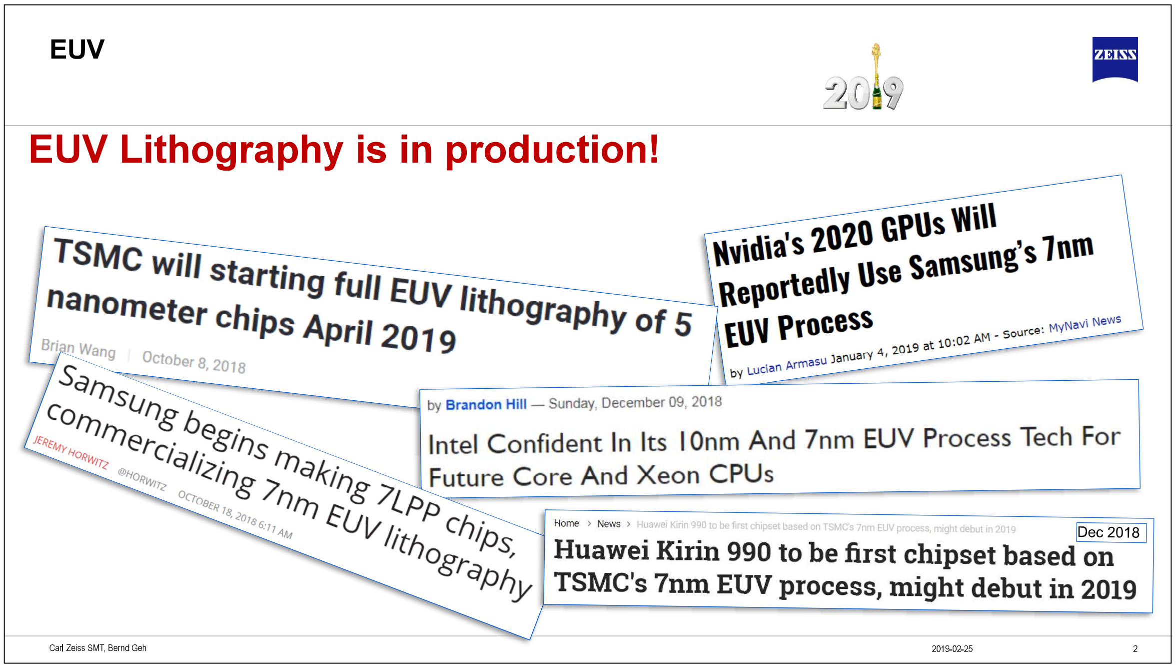
Old Lithographer!

Bernd Geh

2019-02-25

SPIE - Advanced Lithography 2019

Extreme Ultraviolet (EUV) Lithography X - [10957-1]



EUV

2019

EUV Lithography is in production!

TSMC will starting full EUV lithography of 5 nanometer chips April 2019

Brian Wang | October 8, 2018

Nvidia's 2020 GPUs Will Reportedly Use Samsung's 7nm EUV Process

by Lucian Armasu January 4, 2019 at 10:02 AM - Source: MyNavi News

by Brandon Hill — Sunday, December 09, 2018

Intel Confident In Its 10nm And 7nm EUV Process Tech For Future Core And Xeon CPUs

Samsung begins making 7LPP chips, commercializing 7nm EUV lithography

JEREMY HORWITZ @HORWITZ OCTOBER 18, 2018 6:11 AM

Home > News > Huawei Kirin 990 to be first chipset based on TSMC's 7nm EUV process, might debut in 2019

Dec 2018

Huawei Kirin 990 to be first chipset based on TSMC's 7nm EUV process, might debut in 2019

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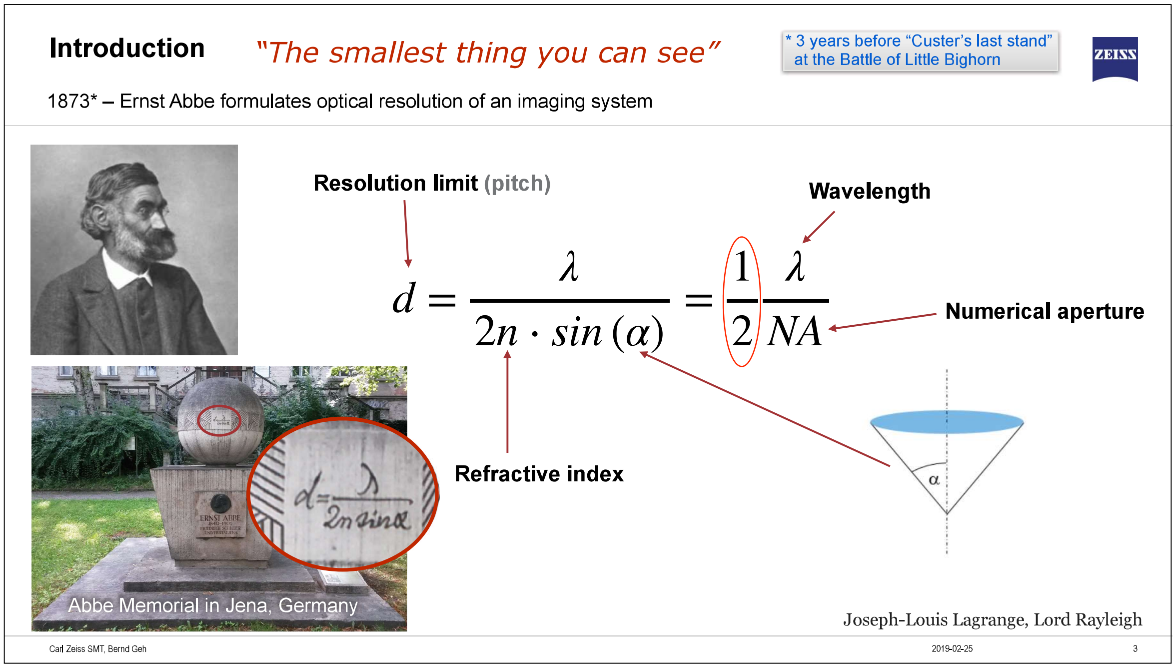
Extreme Ultraviolet (EUV) Lithography X, edited by Kenneth A. Goldberg, Proc. of SPIE Vol. 10957, 1095705 · © 2019 SPIE · CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2515791



Introduction *"The smallest thing you can see"*

* 3 years before "Custer's last stand" at the Battle of Little Bighorn

1873* – Ernst Abbe formulates optical resolution of an imaging system

Resolution limit (pitch)

Wavelength

$$d = \frac{\lambda}{2n \cdot \sin(\alpha)} = \frac{1}{2}\frac{\lambda}{NA}$$

Numerical aperture

Refractive index

Abbe Memorial in Jena, Germany

Joseph-Louis Lagrange, Lord Rayleigh

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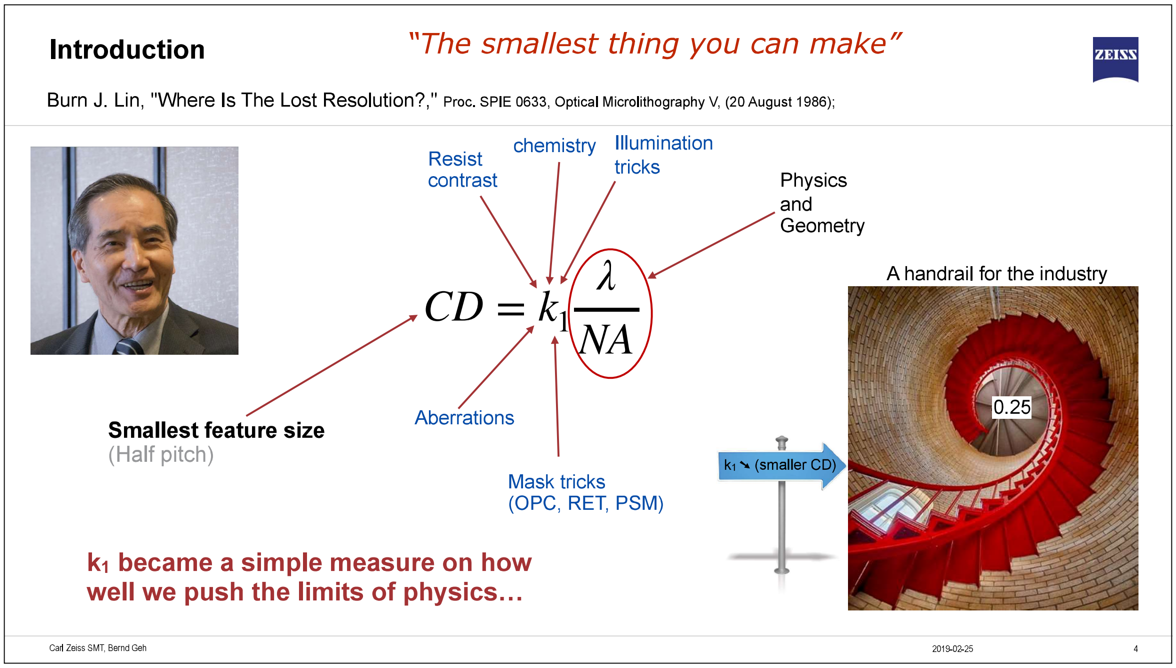

Introduction *"The smallest thing you can make"*

Burn J. Lin, "Where Is The Lost Resolution?," Proc. SPIE 0633, Optical Microlithography V, (20 August 1986);

Resist contrast

chemistry

Illumination tricks

Physics and Geometry

$$CD = k_1 \frac{\lambda}{NA}$$

Smallest feature size
(Half pitch)

Aberrations

Mask tricks
(OPC, RET, PSM)

A handrail for the industry

k_1 became a simple measure on how well we push the limits of physics…

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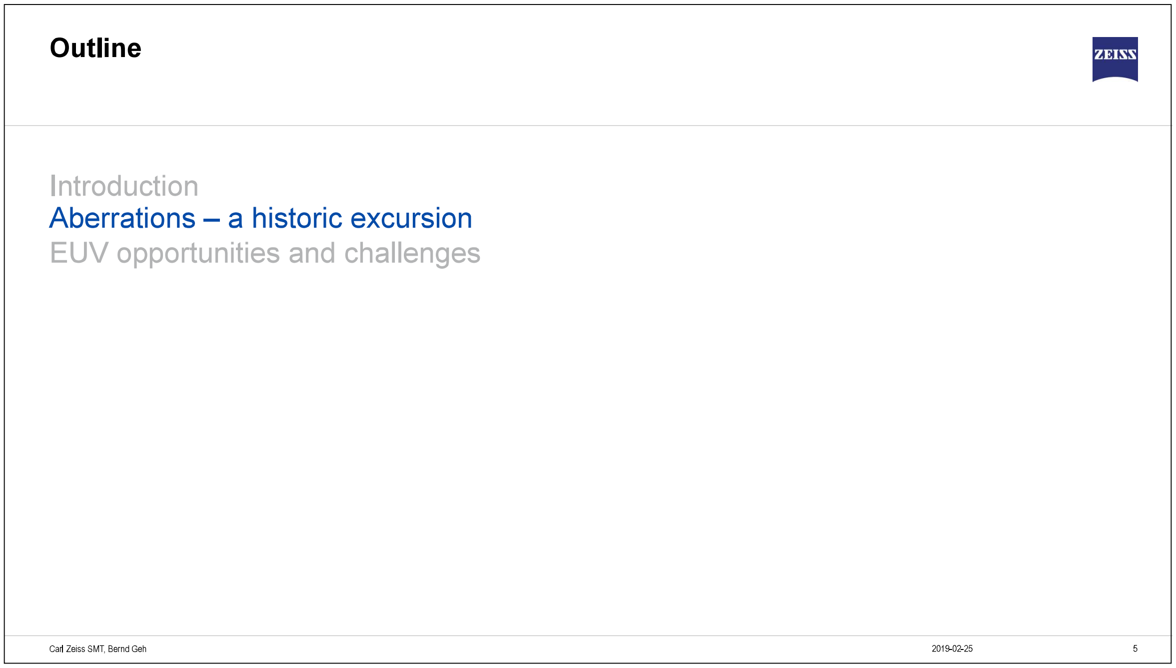
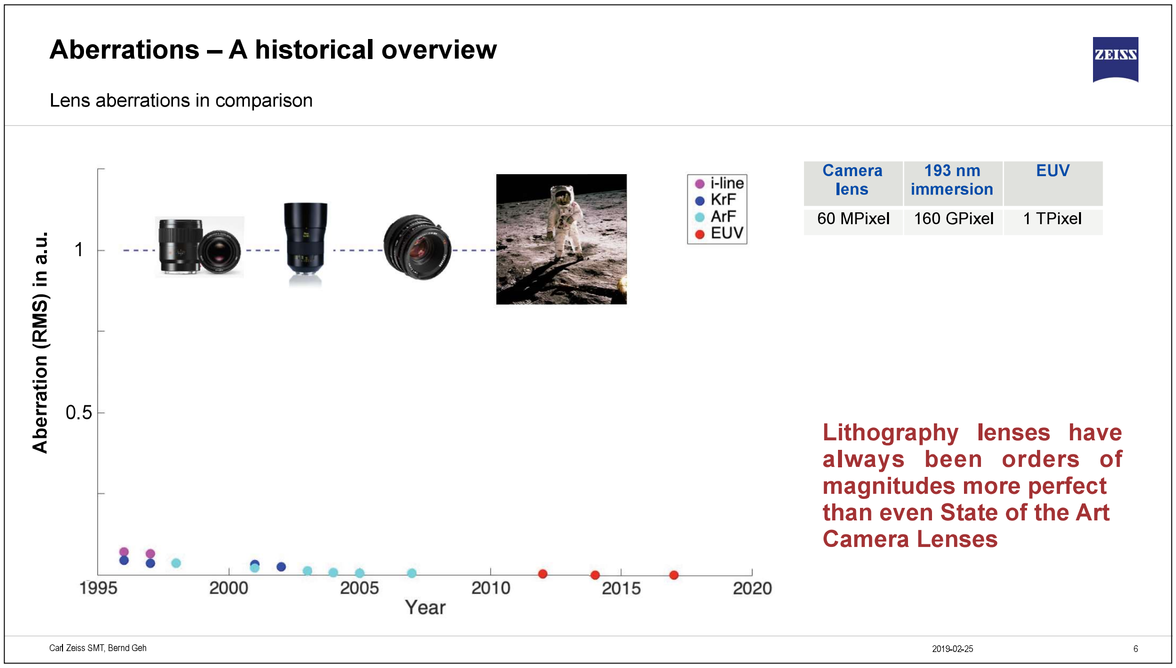


Outline

Introduction

Aberrations – a historic excursion

EUV opportunities and challenges

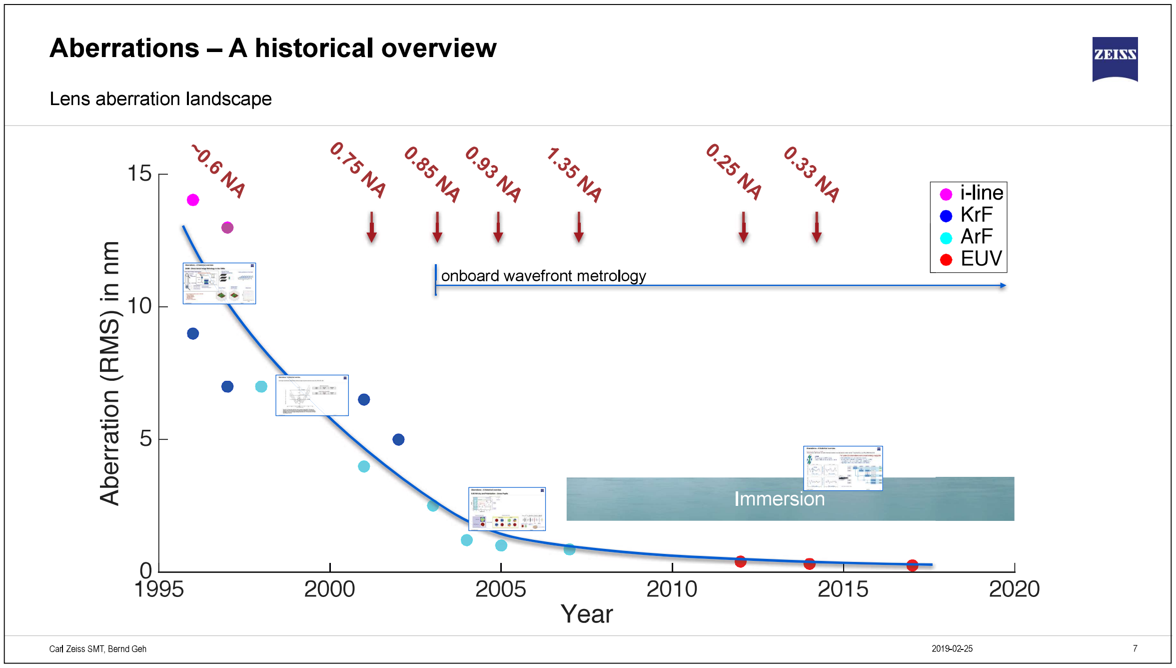


Aberrations – A historical overview

Lens aberrations in comparison

Camera lens	193 nm immersion	EUV
60 MPixel	160 GPixel	1 TPixel

Lithography lenses have always been orders of magnitudes more perfect than even State of the Art Camera Lenses



Aberrations – A historical overview

Lens aberration landscape

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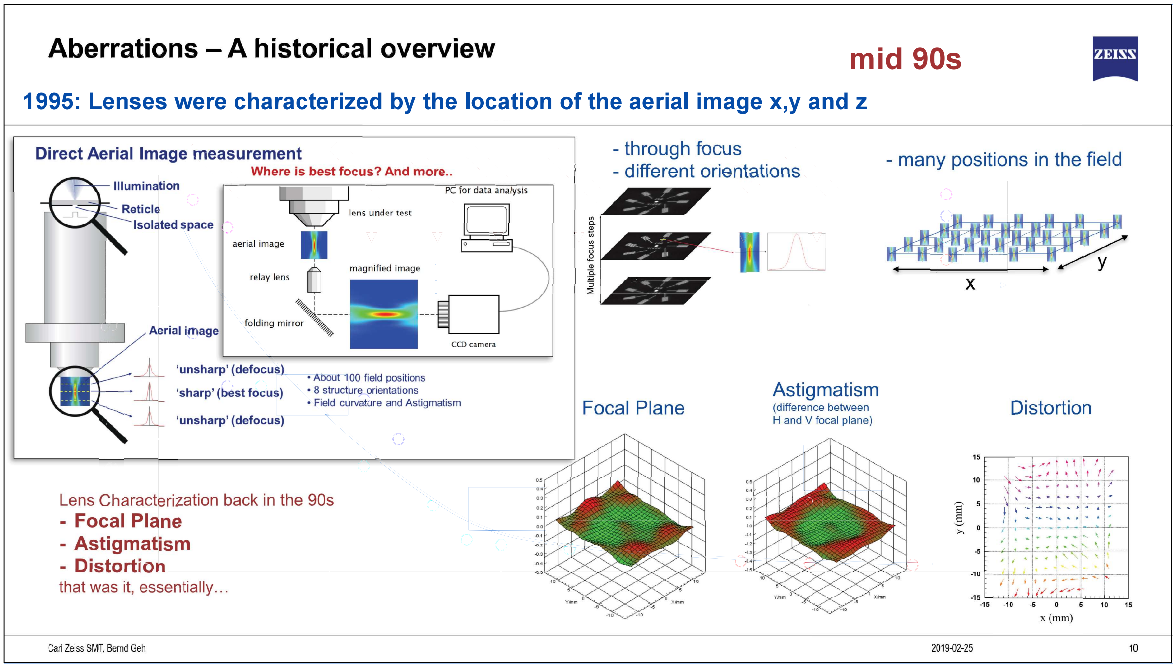

Aberrations – A historical overview

mid 90s

1995: Lenses were characterized by the location of the aerial image x,y and z

Direct Aerial Image measurement

Where is best focus? And more..

- About 100 field positions
- 8 structure orientations
- Field curvature and Astigmatism

- through focus
- different orientations

- many positions in the field

Focal Plane

Astigmatism
(difference between H and V focal plane)

Distortion

Lens Characterization back in the 90s
- **Focal Plane**
- **Astigmatism**
- **Distortion**

that was it, essentially…

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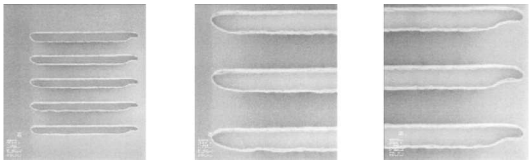
Aberrations – A historical overview

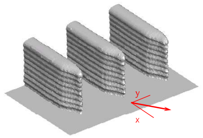
mid 90s

Customers finding strange things on wafers - Mouse biting

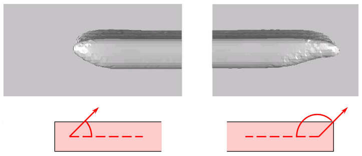
SEM images top-down



Simulation with Lens Coma



assumed values:
coma$_x$ = 0.075 λ
coma$_y$ = 0.055 λ
defocus = 0.9 um*
* from top of resist

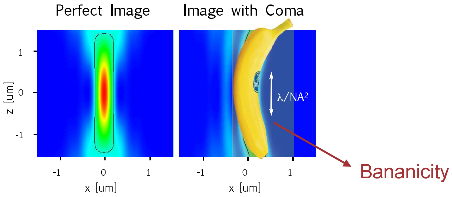


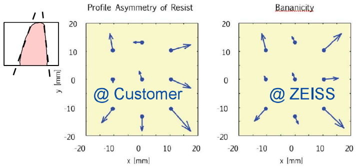
Coma$_x$ = 0.07 λ, Coma$_y$ = 0.07 λ

Coma$_x$ = 0.07 λ, Coma$_y$ = 0.07 λ

source: Rudi v. Buenau

It became clear that the standard lens characterization was no longer adequate





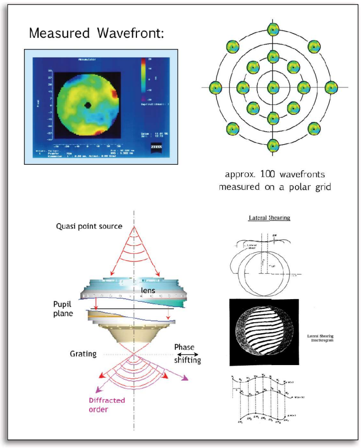
Aberrations – A historical overview

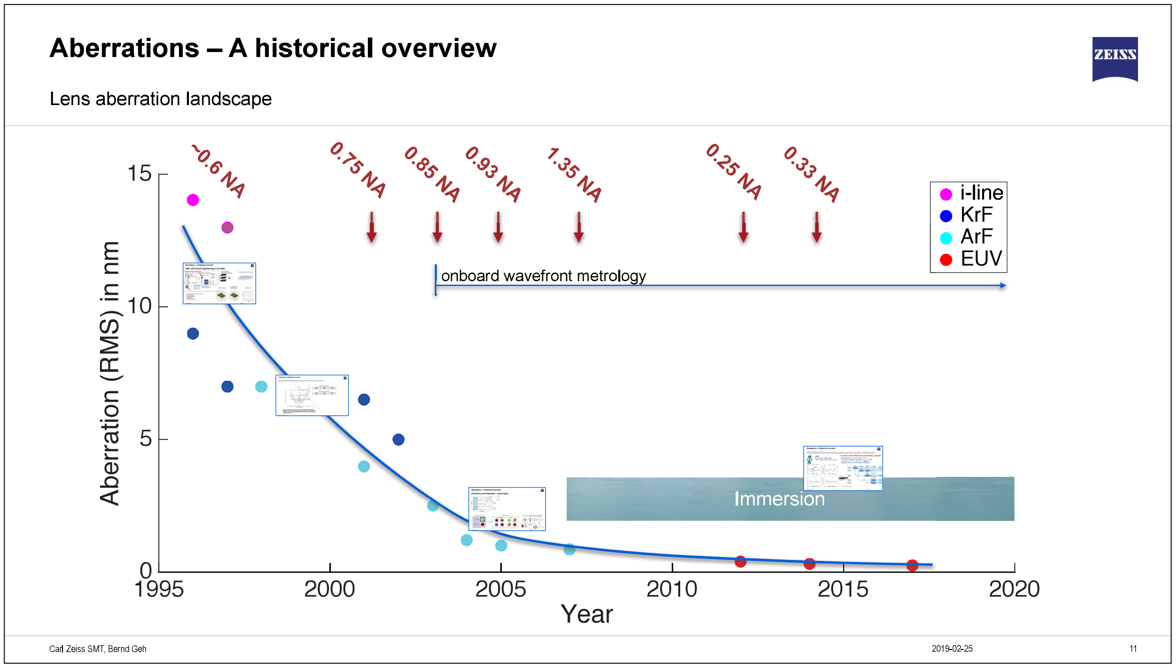
mid 90s

Push towards actinic through-the-lens aberration measurements

Both internal and also external…

Full wavefront based characterization of lenses

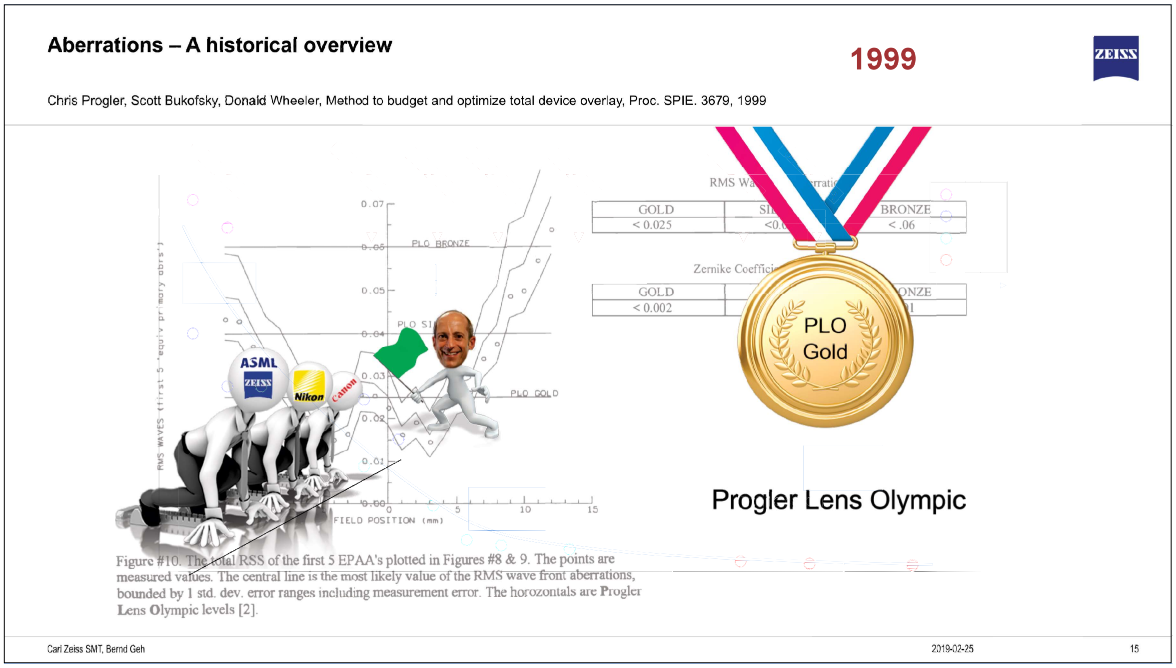




Aberrations – A historical overview

Lens aberration landscape

Carl Zeiss SMT, Bernd Geh 2019-02-25 11



Aberrations – A historical overview

1999

Chris Progler, Scott Bukofsky, Donald Wheeler, Method to budget and optimize total device overlay, Proc. SPIE. 3679, 1999

Figure #10. The total RSS of the first 5 EPAA's plotted in Figures #8 & 9. The points are measured values. The central line is the most likely value of the RMS wave front aberrations, bounded by 1 std. dev. error ranges including measurement error. The horozontals are Progler Lens Olympic levels [2].

Progler Lens Olympic

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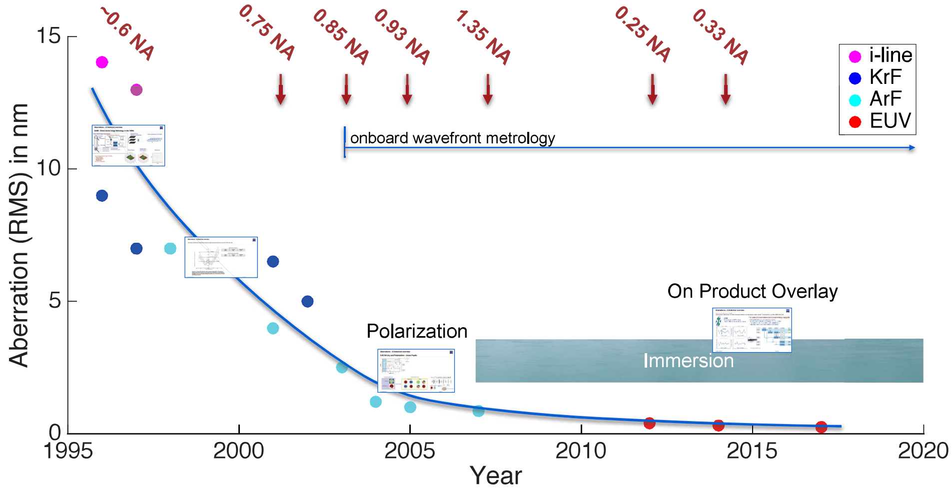
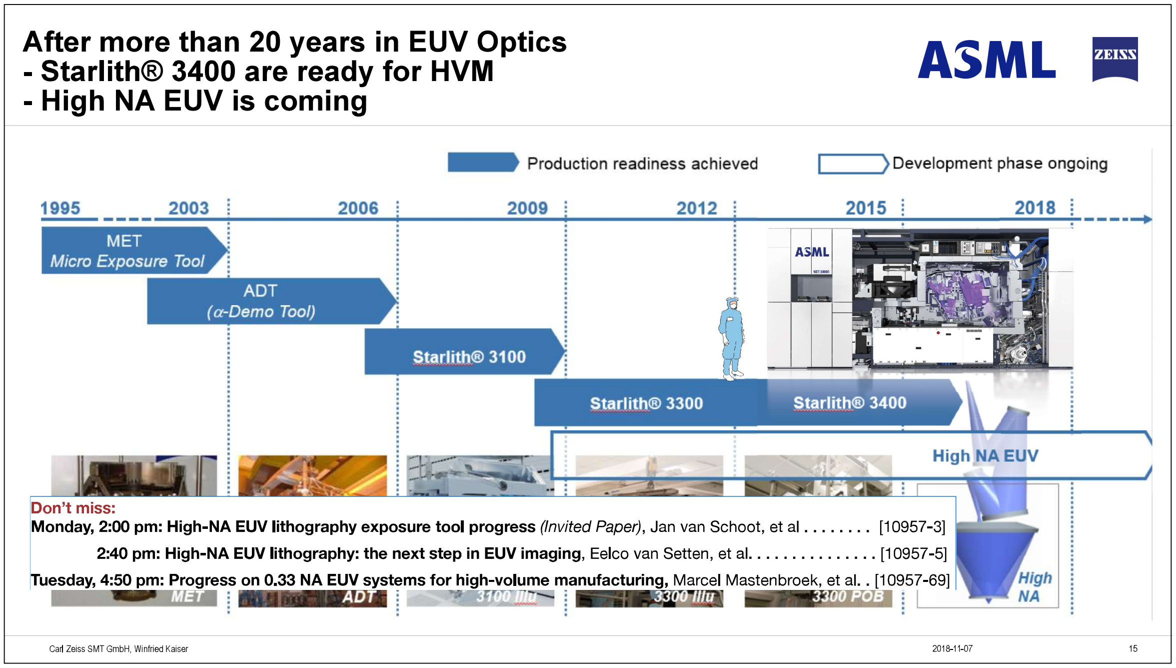
Aberrations – A historical overview

Lens aberration landscape



Outline

Introduction
Aberrations – a historic excursion
EUV opportunities and challenges



After more than 20 years in EUV Optics
- Starlith® 3400 are ready for HVM
- High NA EUV is coming

Don't miss:

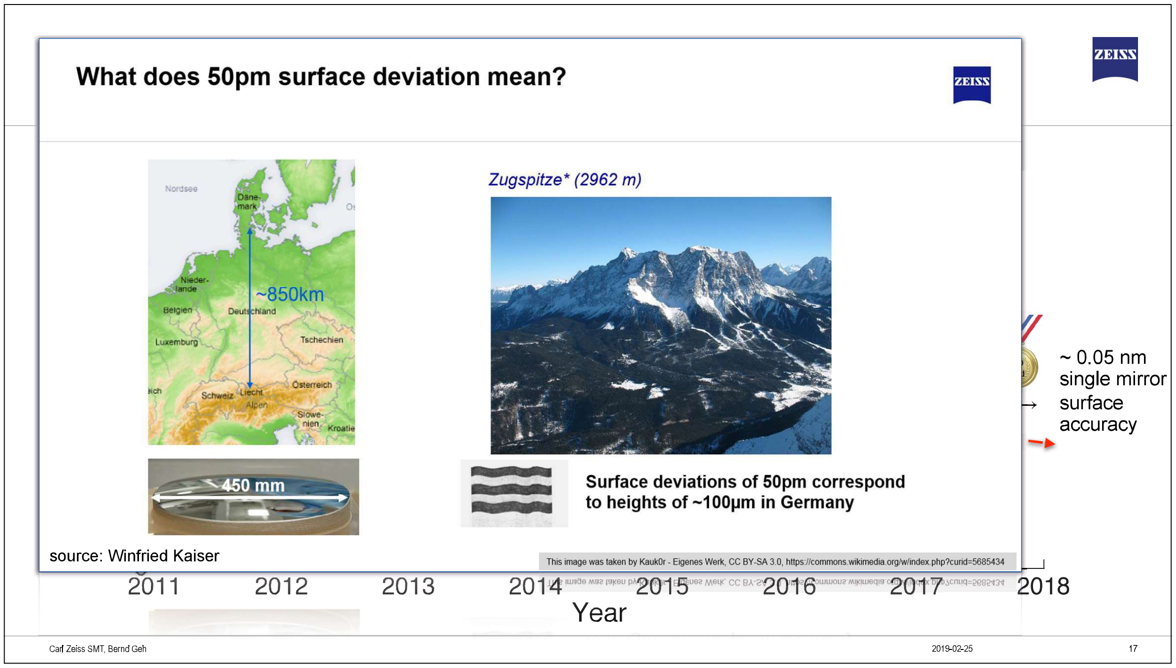
Monday, 2:00 pm: High-NA EUV lithography exposure tool progress *(Invited Paper)*, Jan van Schoot, et al . . . . [10957-3]

2:40 pm: High-NA EUV lithography: the next step in EUV imaging, Eelco van Setten, et al. . . . . [10957-5]

Tuesday, 4:50 pm: Progress on 0.33 NA EUV systems for high-volume manufacturing, Marcel Mastenbroek, et al. . [10957-69]

High NA EUV

Construction status ZEISS Oberkochen in Nov 2018



What does 50pm surface deviation mean?

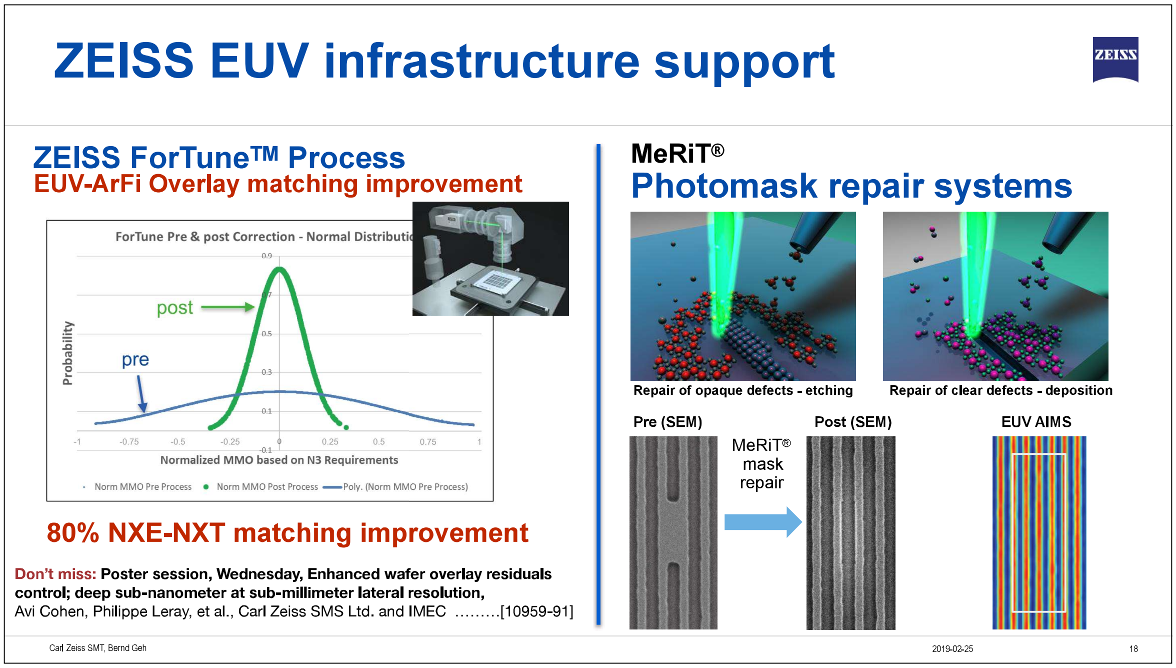
Zugspitze (2962 m)*

Surface deviations of 50pm correspond to heights of ~100µm in Germany

source: Winfried Kaiser

This image was taken by Kauk0r - Eigenes Werk, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=5685434

~ 0.05 nm single mirror surface accuracy



ZEISS EUV infrastructure support

ZEISS ForTune™ Process

EUV-ArFi Overlay matching improvement

ForTune Pre & post Correction - Normal Distributio

80% NXE-NXT matching improvement

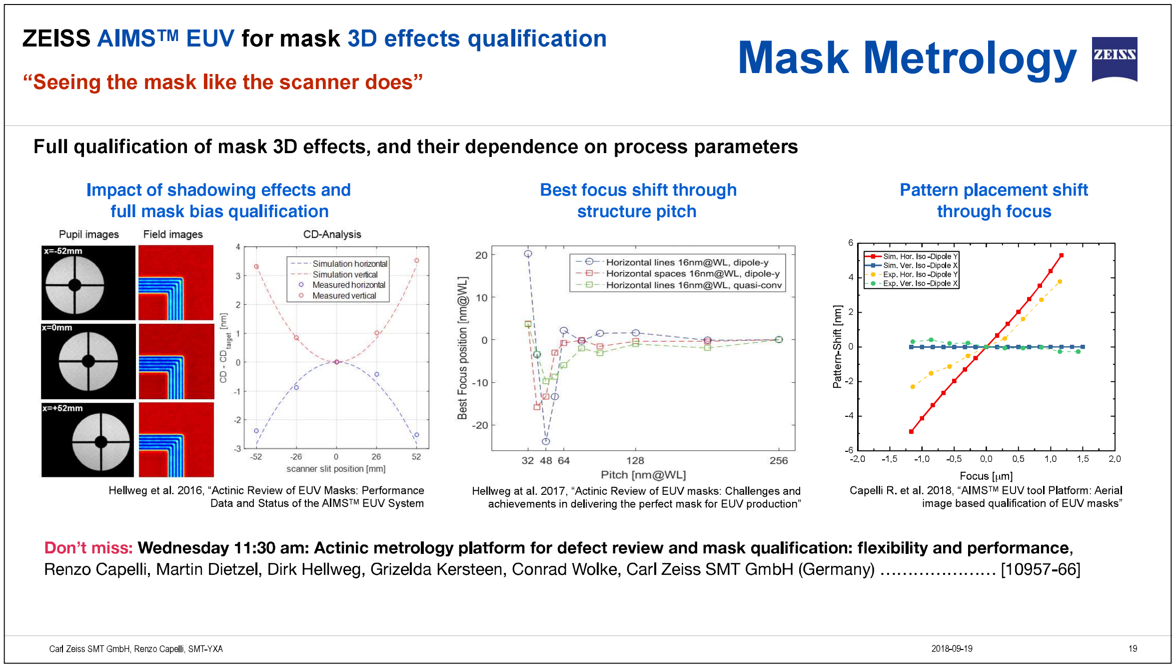
Don't miss: Poster session, Wednesday, Enhanced wafer overlay residuals control; deep sub-nanometer at sub-millimeter lateral resolution,
Avi Cohen, Philippe Leray, et al., Carl Zeiss SMS Ltd. and IMEC ....[10959-91]

MeRiT®

Photomask repair systems

Repair of opaque defects - etching

Repair of clear defects - deposition



ZEISS AIMS™ EUV for mask 3D effects qualification

"Seeing the mask like the scanner does"

Mask Metrology

Full qualification of mask 3D effects, and their dependence on process parameters

Impact of shadowing effects and full mask bias qualification

Hellweg et al. 2016, "Actinic Review of EUV Masks: Performance Data and Status of the AIMS™ EUV System

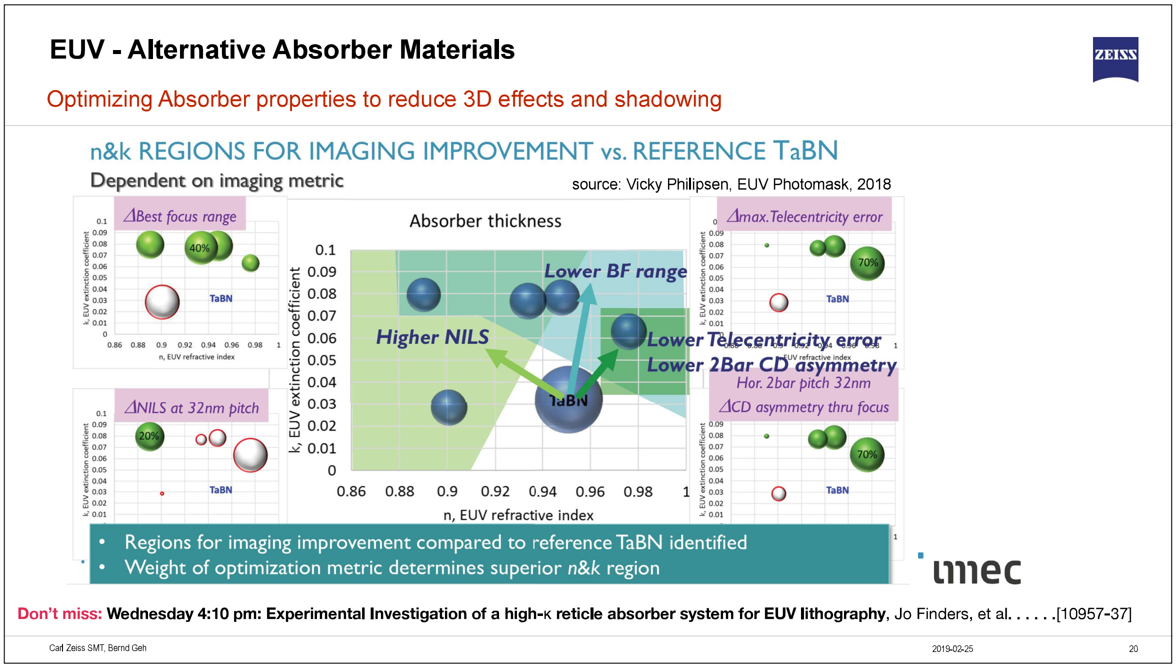
Best focus shift through structure pitch

Hellweg at al. 2017, "Actinic Review of EUV masks: Challenges and achievements in delivering the perfect mask for EUV production"

Pattern placement shift through focus

Capelli R. et al. 2018, "AIMS™ EUV tool Platform: Aerial image based qualification of EUV masks"

Don't miss: **Wednesday 11:30 am: Actinic metrology platform for defect review and mask qualification: flexibility and performance,** Renzo Capelli, Martin Dietzel, Dirk Hellweg, Grizelda Kersteen, Conrad Wolke, Carl Zeiss SMT GmbH (Germany) ………………… [10957-66]



EUV - Alternative Absorber Materials

Optimizing Absorber properties to reduce 3D effects and shadowing

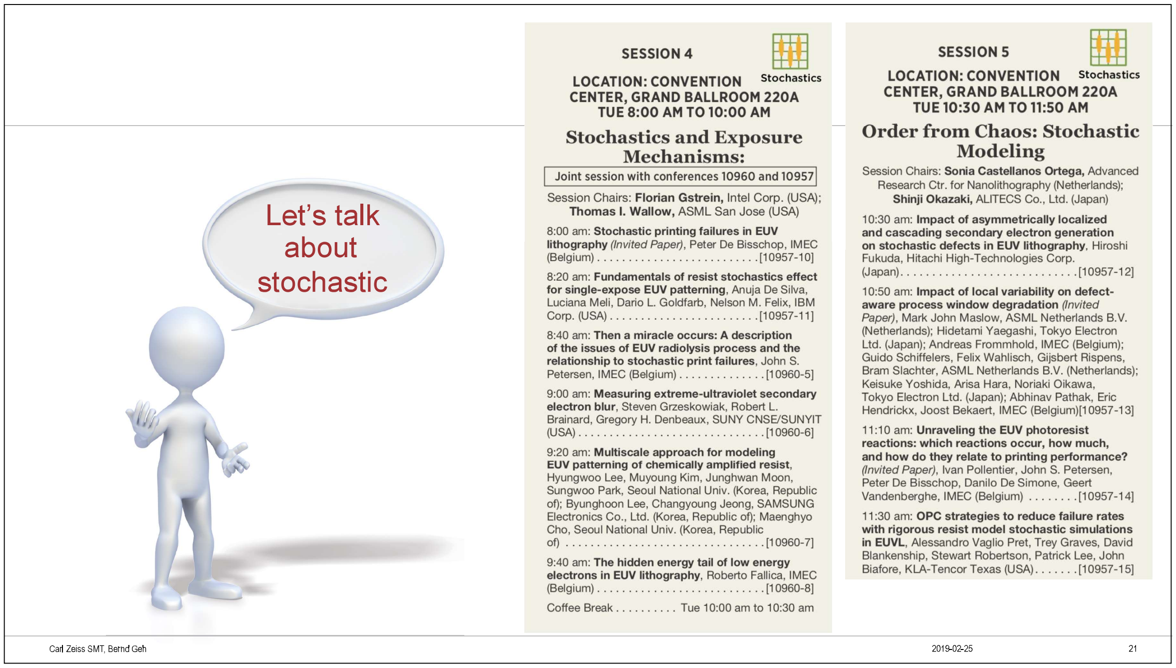
n&k REGIONS FOR IMAGING IMPROVEMENT vs. REFERENCE TaBN

Dependent on imaging metric

source: Vicky Philipsen, EUV Photomask, 2018

- Regions for imaging improvement compared to reference TaBN identified
- Weight of optimization metric determines superior *n&k* region

Don't miss: **Wednesday 4:10 pm: Experimental Investigation of a high-κ reticle absorber system for EUV lithography**, Jo Finders, et al. . . . . .[10957-37]



Let's talk about stochastic

SESSION 4

LOCATION: CONVENTION CENTER, GRAND BALLROOM 220A
TUE 8:00 AM TO 10:00 AM

Stochastics

Stochastics and Exposure Mechanisms:

Joint session with conferences 10960 and 10957

Session Chairs: **Florian Gstrein,** Intel Corp. (USA); **Thomas I. Wallow,** ASML San Jose (USA)

8:00 am: **Stochastic printing failures in EUV lithography** *(Invited Paper)*, Peter De Bisschop, IMEC (Belgium) . . . .[10957-10]

8:20 am: **Fundamentals of resist stochastics effect for single-expose EUV patterning**, Anuja De Silva, Luciana Meli, Dario L. Goldfarb, Nelson M. Felix, IBM Corp. (USA) . . . .[10957-11]

8:40 am: **Then a miracle occurs: A description of the issues of EUV radiolysis process and the relationship to stochastic print failures**, John S. Petersen, IMEC (Belgium) . . . .[10960-5]

9:00 am: **Measuring extreme-ultraviolet secondary electron blur**, Steven Grzeskowiak, Robert L. Brainard, Gregory H. Denbeaux, SUNY CNSE/SUNYIT (USA) . . . .[10960-6]

9:20 am: **Multiscale approach for modeling EUV patterning of chemically amplified resist**, Hyungwoo Lee, Muyoung Kim, Junghwan Moon, Sungwoo Park, Seoul National Univ. (Korea, Republic of); Byunghoon Lee, Changyoung Jeong, SAMSUNG Electronics Co., Ltd. (Korea, Republic of); Maenghyo Cho, Seoul National Univ. (Korea, Republic of) . . . .[10960-7]

9:40 am: **The hidden energy tail of low energy electrons in EUV lithography**, Roberto Fallica, IMEC (Belgium) . . . .[10960-8]

Coffee Break . . . . Tue 10:00 am to 10:30 am

SESSION 5

LOCATION: CONVENTION CENTER, GRAND BALLROOM 220A
TUE 10:30 AM TO 11:50 AM

Stochastics

Order from Chaos: Stochastic Modeling

Session Chairs: **Sonia Castellanos Ortega,** Advanced Research Ctr. for Nanolithography (Netherlands); **Shinji Okazaki,** ALITECS Co., Ltd. (Japan)

10:30 am: **Impact of asymmetrically localized and cascading secondary electron generation on stochastic defects in EUV lithography**, Hiroshi Fukuda, Hitachi High-Technologies Corp. (Japan). . . . .[10957-12]

10:50 am: **Impact of local variability on defect-aware process window degradation** *(Invited Paper)*, Mark John Maslow, ASML Netherlands B.V. (Netherlands); Hidetami Yaegashi, Tokyo Electron Ltd. (Japan); Andreas Frommhold, IMEC (Belgium); Guido Schiffelers, Felix Wahlisch, Gijsbert Rispens, Bram Slachter, ASML Netherlands B.V. (Netherlands); Keisuke Yoshida, Arisa Hara, Noriaki Oikawa, Tokyo Electron Ltd. (Japan); Abhinav Pathak, Eric Hendrickx, Joost Bekaert, IMEC (Belgium)[10957-13]

11:10 am: **Unraveling the EUV photoresist reactions: which reactions occur, how much, and how do they relate to printing performance?** *(Invited Paper)*, Ivan Pollentier, John S. Petersen, Peter De Bisschop, Danilo De Simone, Geert Vandenberghe, IMEC (Belgium) . . . .[10957-14]

11:30 am: **OPC strategies to reduce failure rates with rigorous resist model stochastic simulations in EUVL**, Alessandro Vaglio Pret, Trey Graves, David Blankenship, Stewart Robertson, Patrick Lee, John Biafore, KLA-Tencor Texas (USA). . . . .[10957-15]

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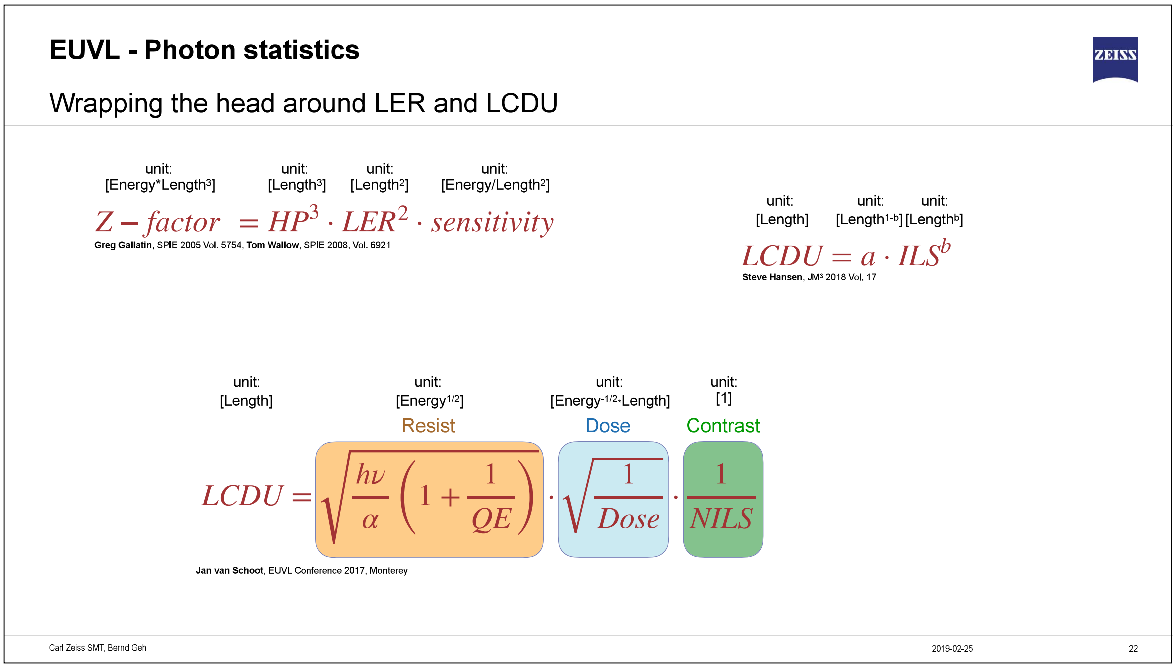

EUVL - Photon statistics

Wrapping the head around LER and LCDU

ZEISS

unit: [Energy*Length^3] unit: [Length^3] unit: [Length^2] unit: [Energy/Length^2]

$$Z-factor = HP^3 \cdot LER^2 \cdot sensitivity$$

Greg Gallatin, SPIE 2005 Vol. 5754, **Tom Wallow**, SPIE 2008, Vol. 6921

unit: [Length] unit: [Length^{1-b}] unit: [Length^b]

$$LCDU = a \cdot ILS^b$$

Steve Hansen, JM^3 2018 Vol. 17

unit: [Length] unit: [Energy$^{1/2}$] unit: [Energy$^{-1/2}$*Length] unit: [1]

Resist Dose Contrast

$$LCDU = \boxed{\sqrt{\frac{h\nu}{\alpha}\left(1+\frac{1}{QE}\right)}} \cdot \boxed{\sqrt{\frac{1}{Dose}}} \cdot \boxed{\frac{1}{NILS}}$$

Jan van Schoot, EUVL Conference 2017, Monterey

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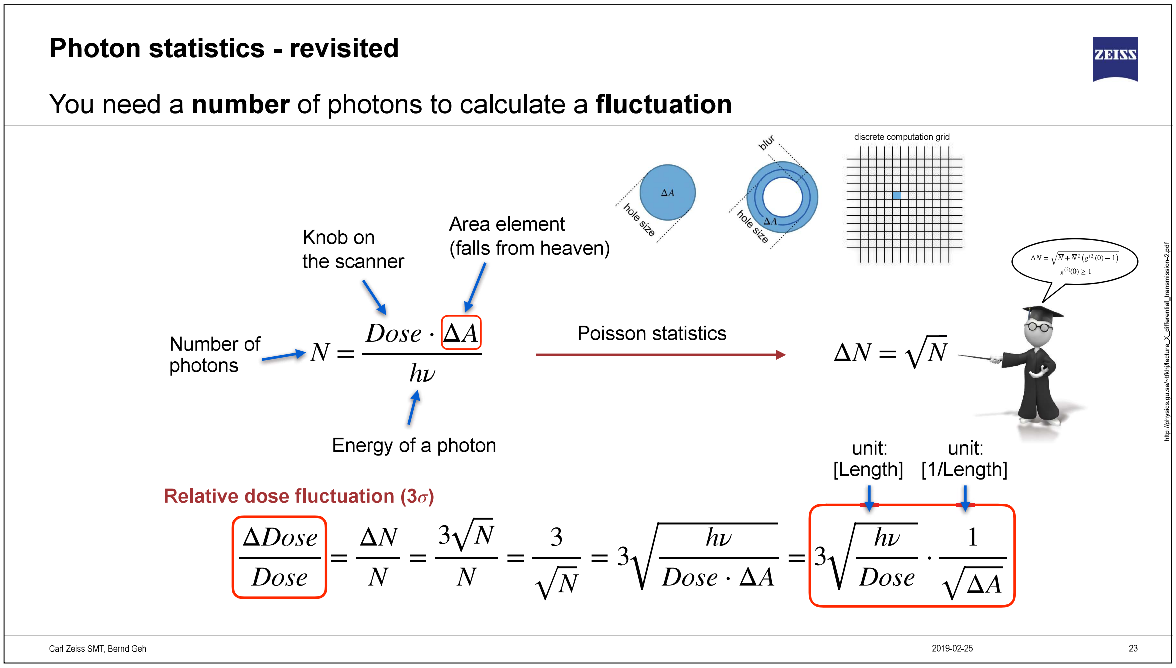


Photon statistics - revisited

You need a **number** of photons to calculate a **fluctuation**

Knob on the scanner

Area element (falls from heaven)

Number of photons

$$N = \frac{Dose \cdot \boxed{\Delta A}}{h\nu}$$

Energy of a photon

Poisson statistics

$$\Delta N = \sqrt{N}$$

$$\Delta N = \sqrt{\overline{N} + \overline{N}^2 \left(g^{(2)}(0) - 1\right)}$$

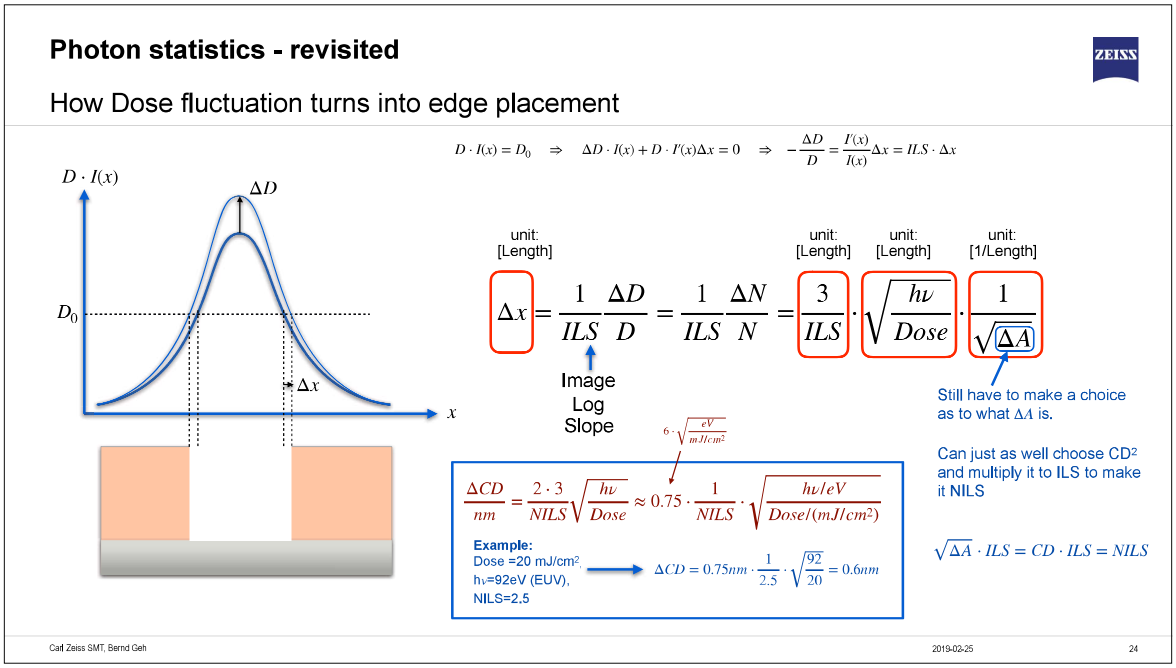
$$g^{(2)}(0) \geq 1$$

unit: [Length]

unit: [1/Length]

Relative dose fluctuation (3σ)

$$\boxed{\frac{\Delta Dose}{Dose}} = \frac{\Delta N}{N} = \frac{3\sqrt{N}}{N} = \frac{3}{\sqrt{N}} = 3\sqrt{\frac{h\nu}{Dose \cdot \Delta A}} = \boxed{3\sqrt{\frac{h\nu}{Dose}} \cdot \frac{1}{\sqrt{\Delta A}}}$$



Photon statistics - revisited

How Dose fluctuation turns into edge placement

$$D \cdot I(x) = D_0 \quad \Rightarrow \quad \Delta D \cdot I(x) + D \cdot I'(x)\Delta x = 0 \quad \Rightarrow \quad -\frac{\Delta D}{D} = \frac{I'(x)}{I(x)}\Delta x = ILS \cdot \Delta x$$

unit: [Length]

unit: [Length]

unit: [Length]

unit: [1/Length]

$$\boxed{\Delta x} = \frac{1}{ILS}\frac{\Delta D}{D} = \frac{1}{ILS}\frac{\Delta N}{N} = \boxed{\frac{3}{ILS}} \cdot \boxed{\sqrt{\frac{h\nu}{Dose}}} \cdot \boxed{\frac{1}{\sqrt{\boxed{\Delta A}}}}$$

Image Log Slope

Still have to make a choice as to what ΔA is.

Can just as well choose CD^2 and multiply it to ILS to make it NILS

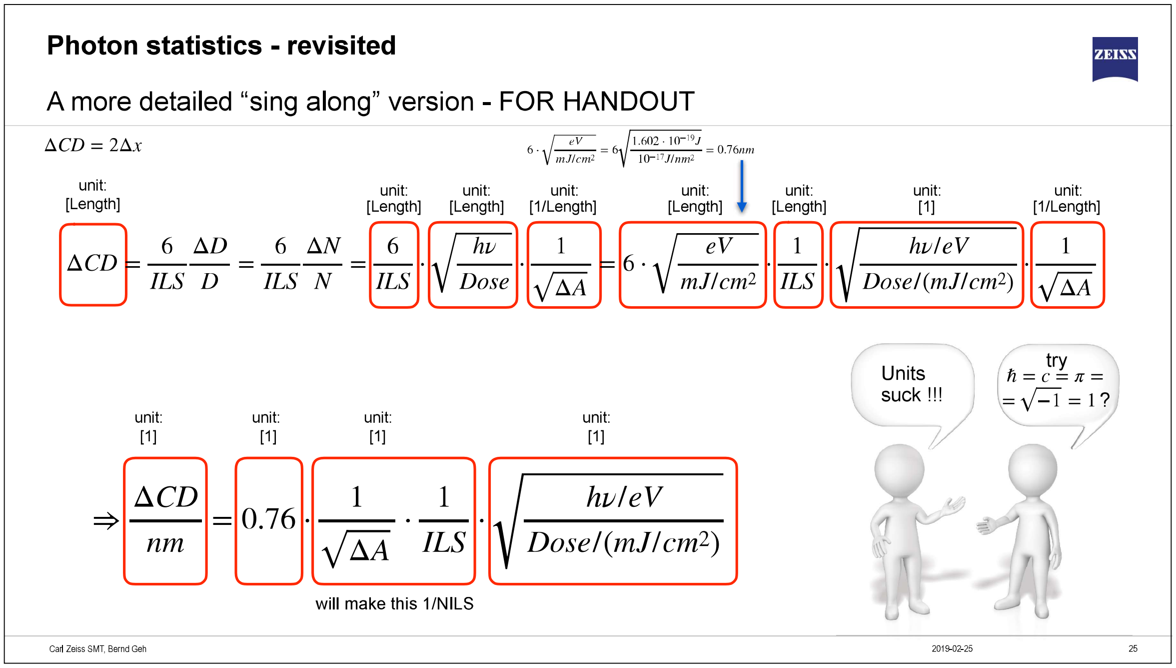
$$\sqrt{\Delta A} \cdot ILS = CD \cdot ILS = NILS$$

$$6 \cdot \sqrt{\frac{eV}{mJ/cm^2}}$$

$$\frac{\Delta CD}{nm} = \frac{2 \cdot 3}{NILS}\sqrt{\frac{h\nu}{Dose}} \approx 0.75 \cdot \frac{1}{NILS} \cdot \sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$

Example:
Dose =20 mJ/cm^2,
hν=92eV (EUV),
NILS=2.5

$$\longrightarrow \quad \Delta CD = 0.75nm \cdot \frac{1}{2.5} \cdot \sqrt{\frac{92}{20}} = 0.6nm$$



Photon statistics - revisited

A more detailed “sing along” version - FOR HANDOUT

$\Delta CD = 2\Delta x$

$$6\cdot\sqrt{\frac{eV}{mJ/cm^2}} = 6\sqrt{\frac{1.602\cdot 10^{-19}J}{10^{-17}J/nm^2}} = 0.76nm$$

unit: [Length] — unit: [Length] — unit: [Length] — unit: [1/Length] — unit: [Length] — unit: [Length] — unit: [1] — unit: [1/Length]

$$\boxed{\Delta CD} = \frac{6}{ILS}\frac{\Delta D}{D} = \frac{6}{ILS}\frac{\Delta N}{N} = \boxed{\frac{6}{ILS}}\cdot\boxed{\sqrt{\frac{h\nu}{Dose}}}\cdot\boxed{\frac{1}{\sqrt{\Delta A}}} = \boxed{6\cdot\sqrt{\frac{eV}{mJ/cm^2}}}\cdot\boxed{\frac{1}{ILS}}\cdot\boxed{\sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}}\cdot\boxed{\frac{1}{\sqrt{\Delta A}}}$$

unit: [1] — unit: [1] — unit: [1] — unit: [1]

$$\Rightarrow \boxed{\frac{\Delta CD}{nm}} = \boxed{0.76}\cdot\boxed{\frac{1}{\sqrt{\Delta A}}\cdot\frac{1}{ILS}}\cdot\boxed{\sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}}$$

will make this 1/NILS

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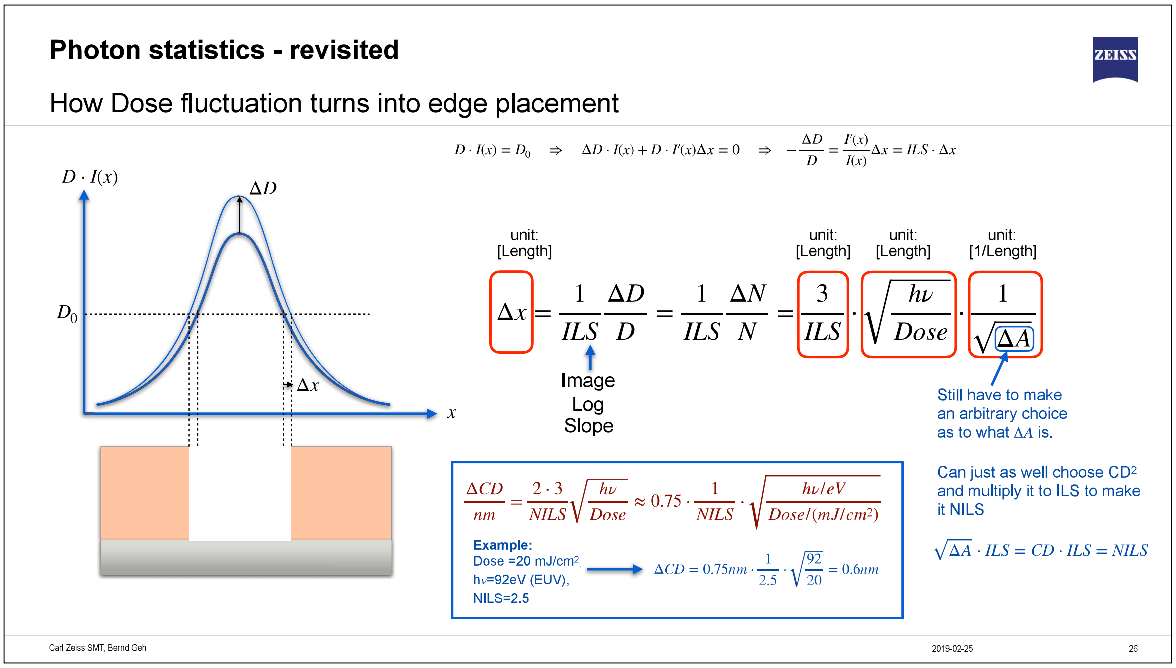

Photon statistics - revisited

How Dose fluctuation turns into edge placement

$$D\cdot I(x) = D_0 \quad\Rightarrow\quad \Delta D\cdot I(x) + D\cdot I'(x)\Delta x = 0 \quad\Rightarrow\quad -\frac{\Delta D}{D} = \frac{I'(x)}{I(x)}\Delta x = ILS\cdot\Delta x$$

unit: [Length] — unit: [Length] — unit: [Length] — unit: [1/Length]

$$\boxed{\Delta x} = \frac{1}{ILS}\frac{\Delta D}{D} = \frac{1}{ILS}\frac{\Delta N}{N} = \boxed{\frac{3}{ILS}}\cdot\boxed{\sqrt{\frac{h\nu}{Dose}}}\cdot\boxed{\frac{1}{\sqrt{\boxed{\Delta A}}}}$$

Image Log Slope

Still have to make an arbitrary choice as to what ΔA is.

$$\frac{\Delta CD}{nm} = \frac{2\cdot 3}{NILS}\sqrt{\frac{h\nu}{Dose}} \approx 0.75\cdot\frac{1}{NILS}\cdot\sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$

Example:
Dose =20 mJ/cm², hν=92eV (EUV), NILS=2.5 → $\Delta CD = 0.75nm\cdot\frac{1}{2.5}\cdot\sqrt{\frac{92}{20}} = 0.6nm$

Can just as well choose CD² and multiply it to ILS to make it NILS

$\sqrt{\Delta A}\cdot ILS = CD\cdot ILS = NILS$

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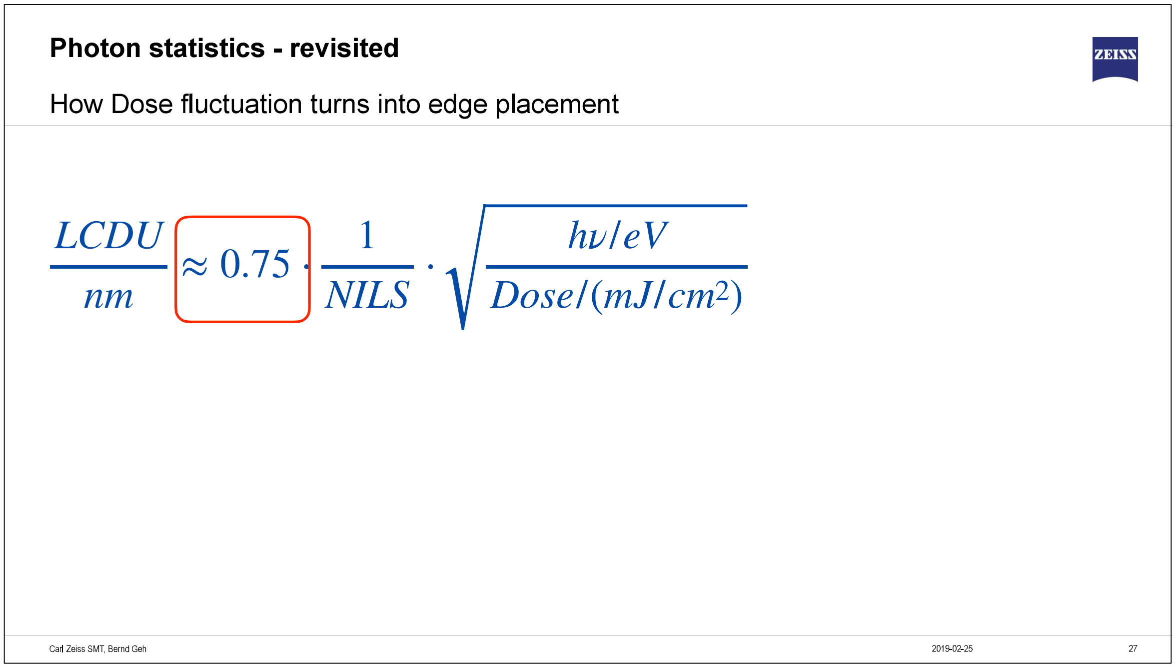
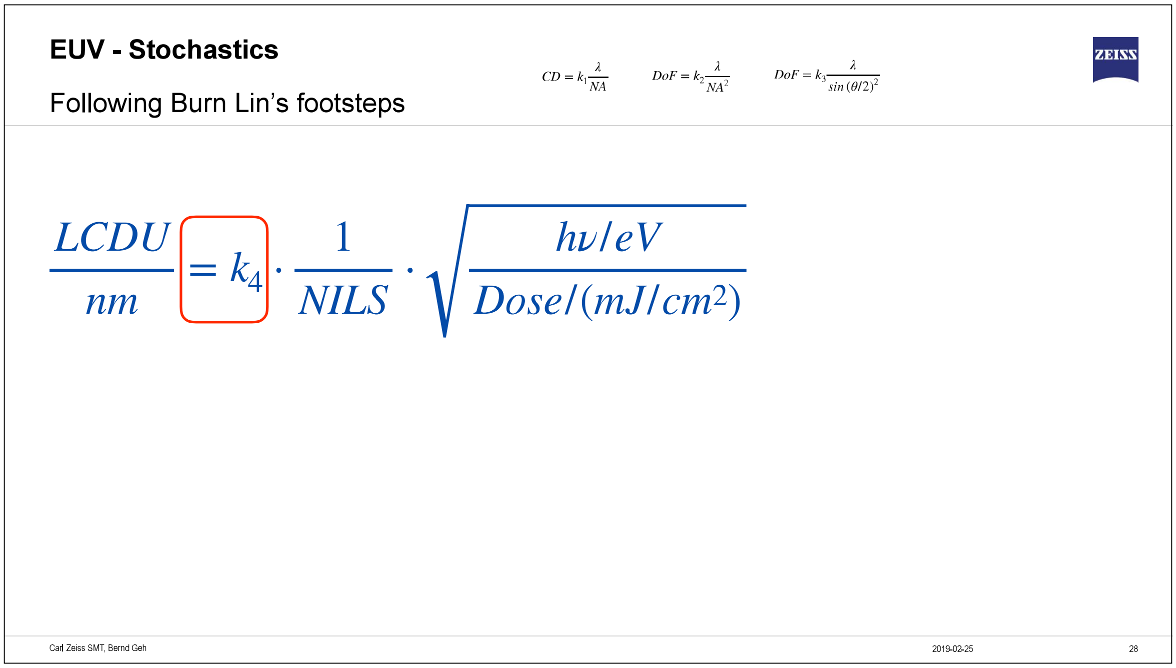


Photon statistics - revisited

How Dose fluctuation turns into edge placement

$$\frac{LCDU}{nm}\boxed{\approx 0.75\cdot}\frac{1}{NILS}\cdot\sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$

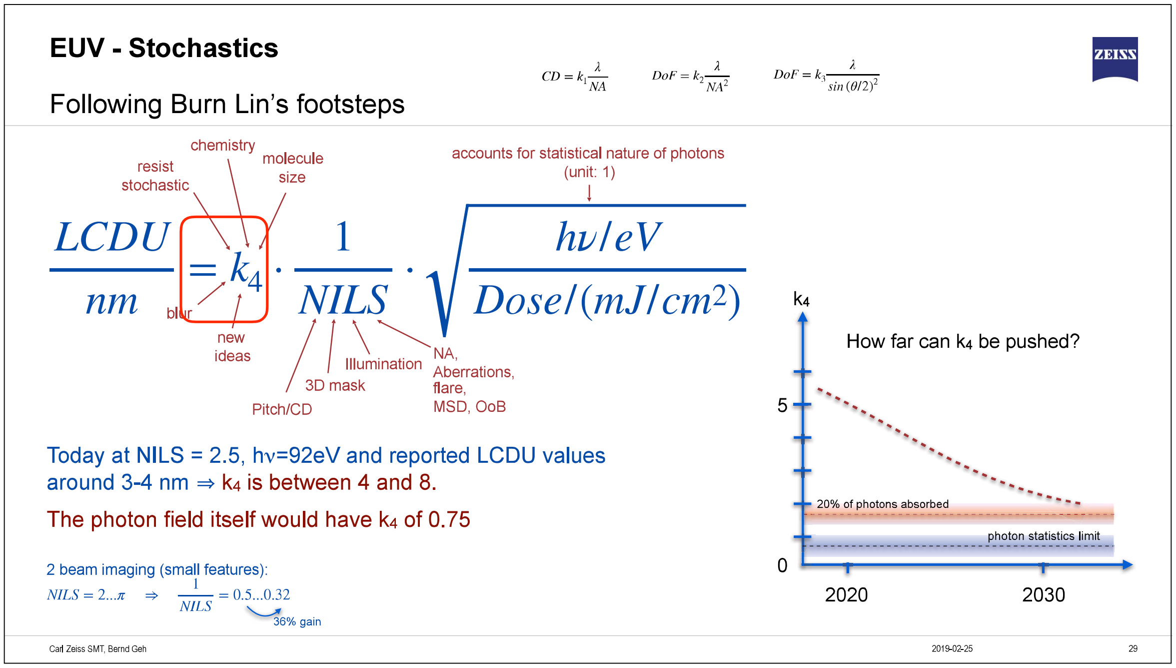


EUV - Stochastics

Following Burn Lin's footsteps

$CD = k_1\frac{\lambda}{NA}$ $DoF = k_2\frac{\lambda}{NA^2}$ $DoF = k_3\frac{\lambda}{sin(\theta/2)^2}$

$$\frac{LCDU}{nm}\boxed{=k_4}\cdot\frac{1}{NILS}\cdot\sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$



EUV - Stochastics

Following Burn Lin’s footsteps

$$CD = k_1 \frac{\lambda}{NA} \qquad DoF = k_2 \frac{\lambda}{NA^2} \qquad DoF = k_3 \frac{\lambda}{sin(\theta/2)^2}$$

$$\frac{LCDU}{nm} \boxed{= k_4} \cdot \frac{1}{NILS} \cdot \sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$

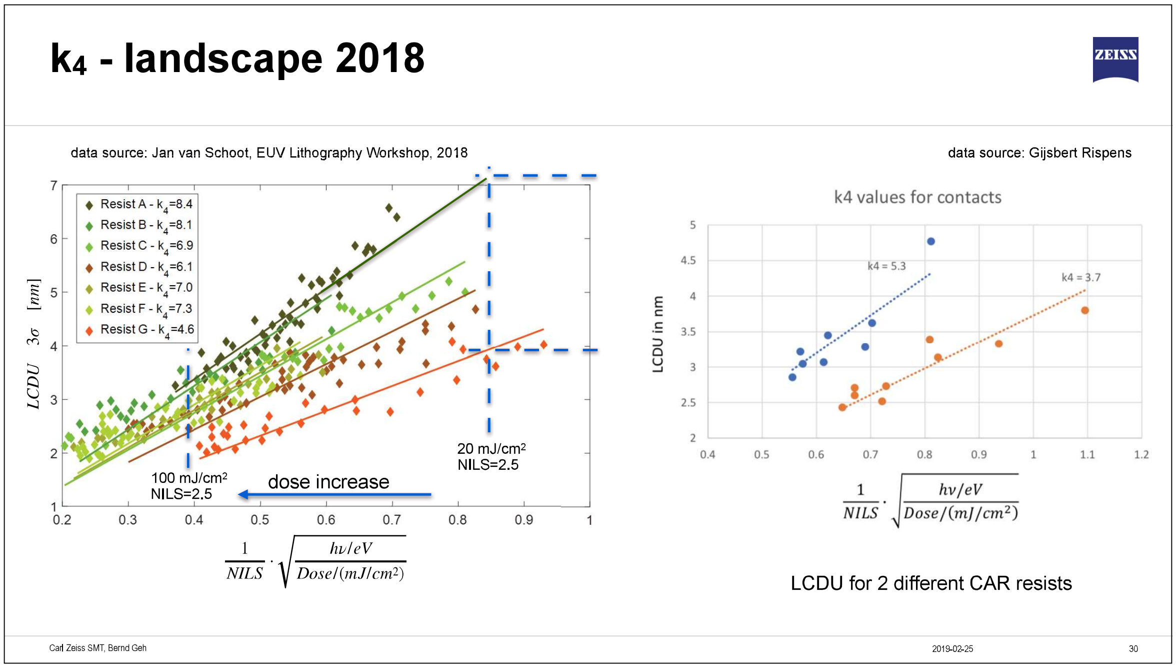
Today at NILS = 2.5, hν=92eV and reported LCDU values around 3-4 nm ⇒ k_4 is between 4 and 8.

The photon field itself would have k_4 of 0.75

2 beam imaging (small features):

$$NILS = 2 \ldots \pi \quad \Rightarrow \quad \frac{1}{NILS} = 0.5 \ldots 0.32$$

36% gain



k_4 - landscape 2018

data source: Jan van Schoot, EUV Lithography Workshop, 2018

$$\frac{1}{NILS} \cdot \sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$

data source: Gijsbert Rispens

k4 values for contacts

$$\frac{1}{NILS} \cdot \sqrt{\frac{h\nu/eV}{Dose/(mJ/cm^2)}}$$

LCDU for 2 different CAR resists

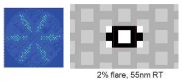
EUV - missing contacts

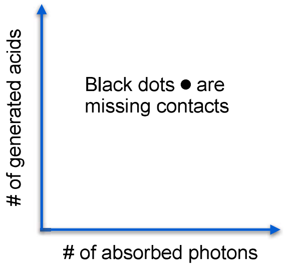
Local effects “beyond dose”

Prolith stochastic resist model simulations - Steve Hansen

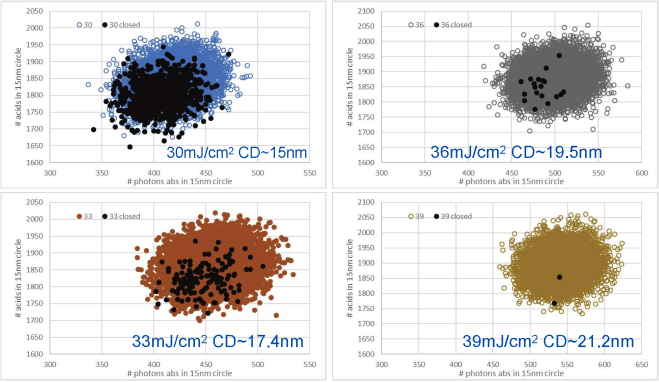
Results of 10000 calculations each

Weak correlation of closed holes to either:
# of absorbed photons
# of photo acids


2% flare, 55nm RT



Black dots ● are missing contacts

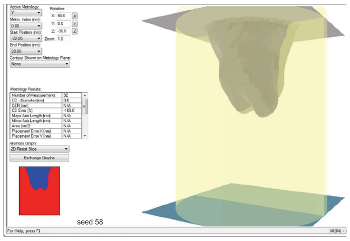


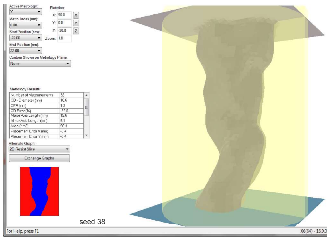
EUV - missing contacts

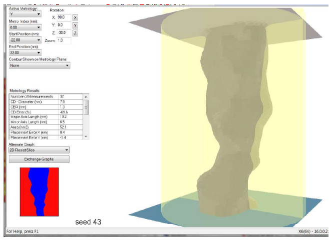
Local effects “beyond dose”

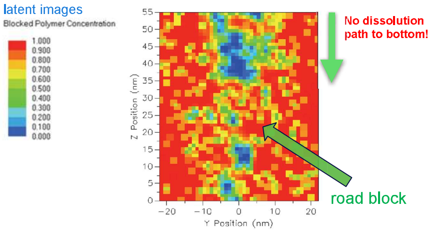
Prolith stochastic resist model simulations - Steve Hansen

nearly same # of photons and same # of acids in all 3 cases

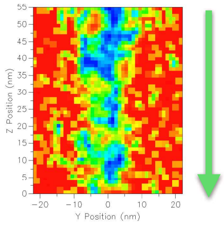




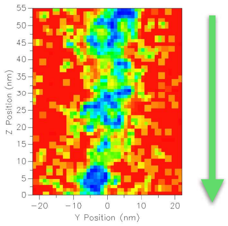


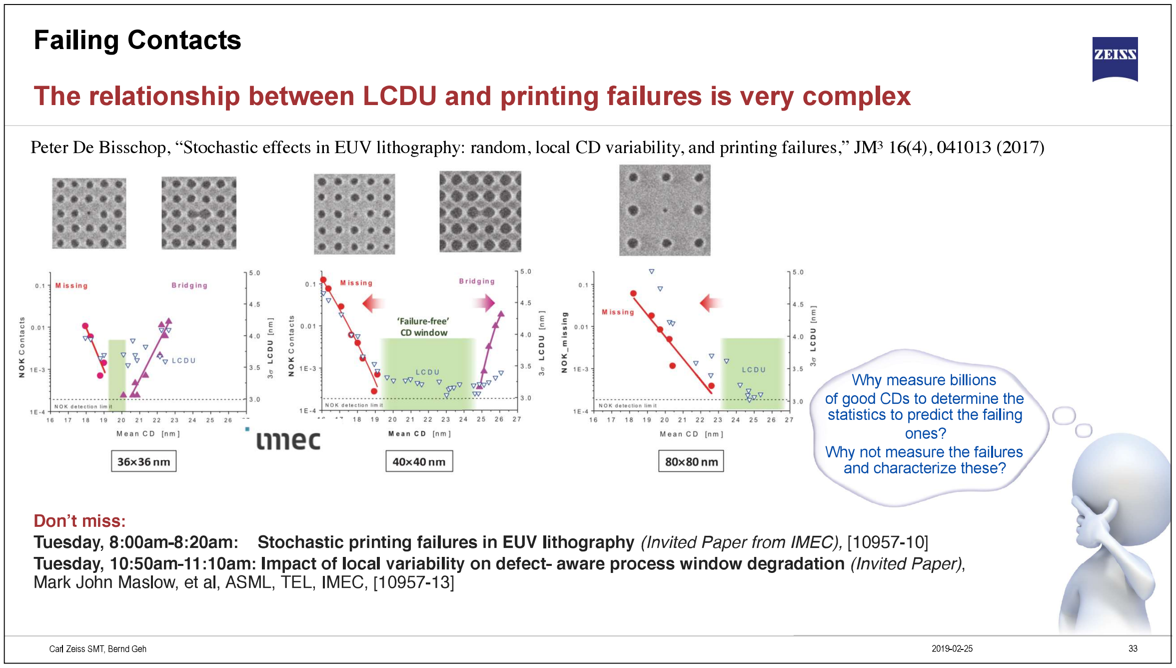


No dissolution path to bottom!



De-blocked polymer profile gives dissolution path to bottom





Failing Contacts

The relationship between LCDU and printing failures is very complex

Peter De Bisschop, “Stochastic effects in EUV lithography: random, local CD variability, and printing failures,” JM^3 16(4), 041013 (2017)

36×36 nm

40×40 nm

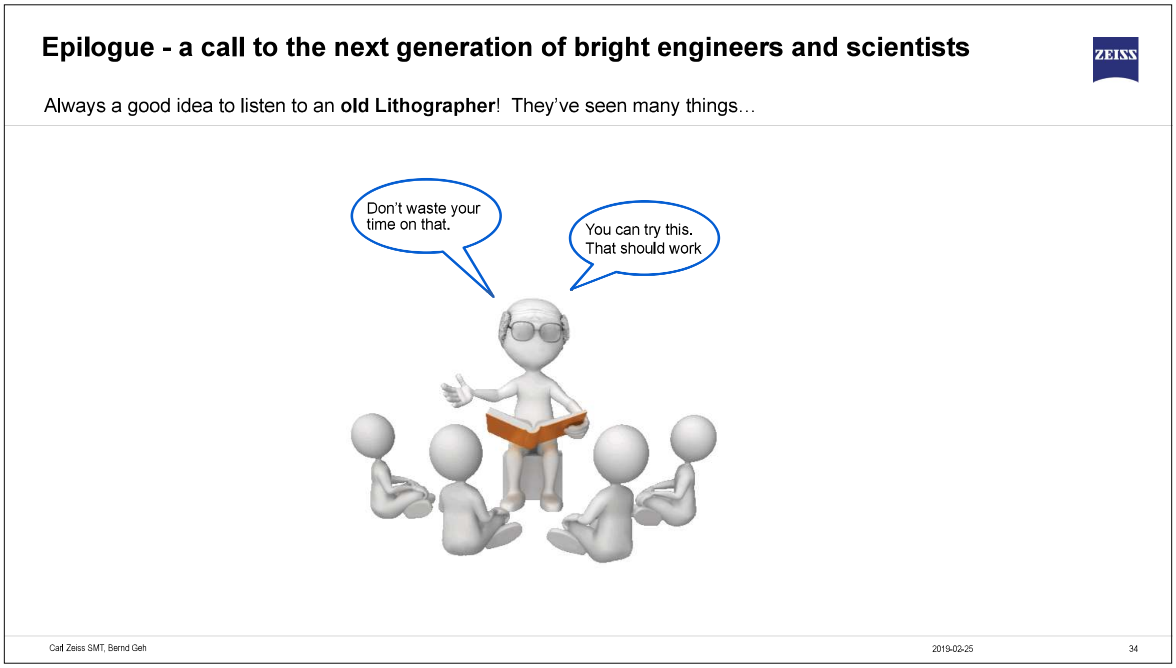
80×80 nm

Why measure billions of good CDs to determine the statistics to predict the failing ones?
Why not measure the failures and characterize these?

Don’t miss:

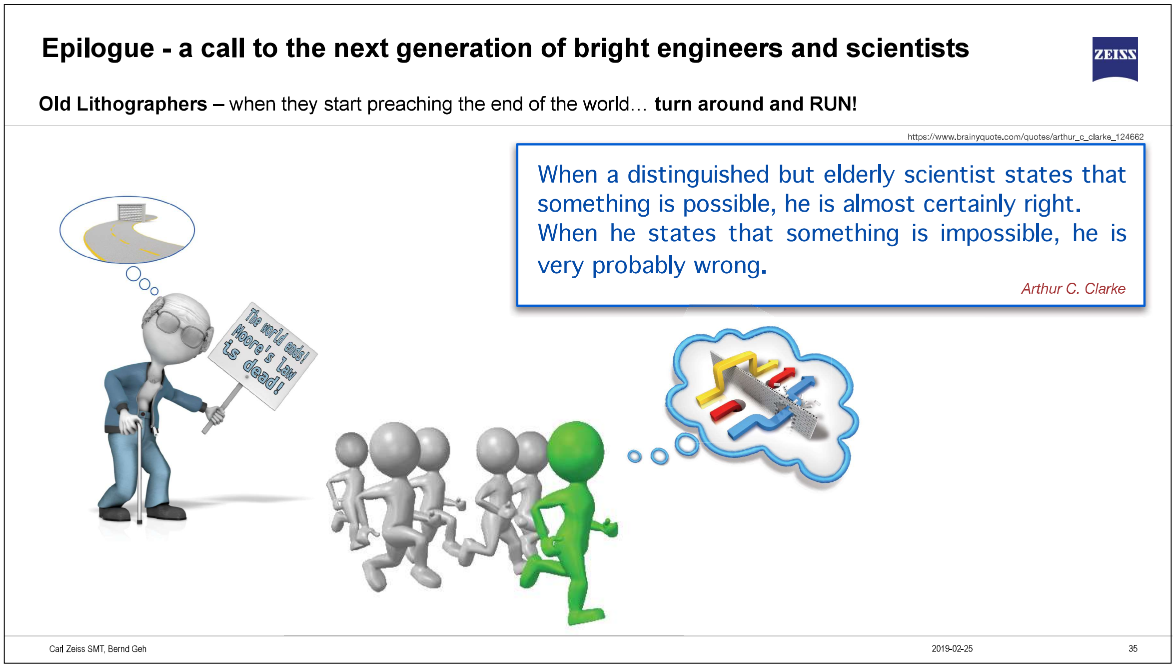
Tuesday, 8:00am-8:20am: Stochastic printing failures in EUV lithography *(Invited Paper from IMEC)*, [10957-10]

Tuesday, 10:50am-11:10am: Impact of local variability on defect- aware process window degradation *(Invited Paper)*, Mark John Maslow, et al, ASML, TEL, IMEC, [10957-13]



Epilogue - a call to the next generation of bright engineers and scientists

Always a good idea to listen to an **old Lithographer**! They’ve seen many things…

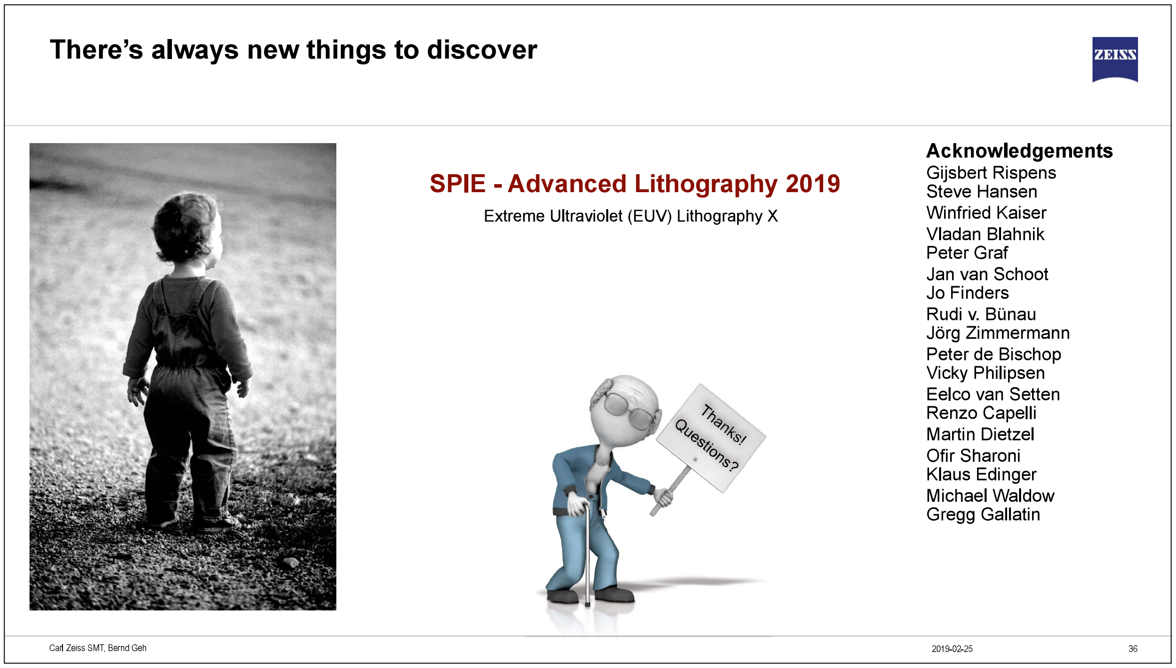


Epilogue - a call to the next generation of bright engineers and scientists

Old Lithographers – when they start preaching the end of the world… **turn around and RUN!**

https://www.brainyquote.com/quotes/arthur_c_clarke_124662

> When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.
>
> *Arthur C. Clarke*



There's always new things to discover

SPIE - Advanced Lithography 2019

Extreme Ultraviolet (EUV) Lithography X

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