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EUVL: the natural evolution of optical microlithography

Bernd Geh

Bernd Geh, "EUVL: the natural evolution of optical microlithography," Proc. SPIE 10957, Extreme Ultraviolet (EUV) Lithography X, 1095705 (18 October 2019); doi: 10.1117/12.2515791

SPIE.

Event: SPIE Advanced Lithography, 2019, San Jose, California, United States

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

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

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

by Brandon Hill — Sunday, December 09, 2018

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

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

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

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Resolution limit (pitch)

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

Wavelength

Numerical aperture

Refractive index

Joseph-Louis Lagrange, Lord Rayleigh

2019-02-25

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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

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

Aberrations

Mask tricks (OPC, RET, PSM)

$k_1 \propto$ (smaller CD)

Smallest feature size (Half pitch)

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

A handrail for the industry

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Outline

Introduction

Aberrations – a historic excursion

EUV opportunities and challenges

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Aberrations – A historical overview

Lens aberrations in comparison

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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

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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

source: Rudi v. Buena

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

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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

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Aberrations – A historical overview

Lens aberration landscape

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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 RMS 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 horizontal axis are Progler Lens Olympic levels [2].

Progler Lens Olympic

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Aberrations – A historical overview

Lens aberration landscape

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Outline

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

Carl Zeiss SMT GmbH, Winfried Kaiser

2018-11-07

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High NA EUV

Construction status ZEISS Oberkochen in Nov 2018

Carl Zeiss SMT GmbH, Winfried Kaiser

2018-11-07

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What does 50pm surface deviation mean?

Zugspitze* (2962 m)

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

~ 0.05 nm single mirror surface accuracy

source: Winfried Kaiser

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

2011 2012 2013 2014 2015 2016 2017 2018
Year

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ZEISS EUV infrastructure support

ZEISS ForTune™ Process EUV-ArFi Overlay matching improvement

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

Carl Zeiss SMT, Bernd Geh

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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 et 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 Kersten, 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

imec

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 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-exposure 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, Myoung 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

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 Schiffrers, Felix Wahlsch, Gijbert Rispens, Bram Slachter, ASML Netherlands B.V. (Netherlands); Katsuke Yoshida, Arisa Hara, Noriaki Okawa, 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 Vanderbergh, IMEC (Belgium) [10957-14]

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

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EUVL - Photon statistics

Wrapping the head around LER and LCDU

unit: [Energy*Length³] unit: [Length³] unit: [Length²] unit: [Energy/Length²]

Z-factor = HP³ · LER² · sensitivity

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

unit: [Length] unit: [Length^{1/2}] unit: [Length³]

LCDU = a · ILS^b

Steve Hansen, JMI 2016 Vol. 17

unit: [Length] unit: [Energy^{1/2}] unit: [Energy^{1/2}·Length] unit: [1]

Resist Dose Contrast

$$\sqrt{\frac{h\nu}{\alpha} \left(1 + \frac{1}{QE}\right)}$$

$$\sqrt{\frac{1}{Dose}}$$

$$\frac{1}{NILS}$$

Jan van Schoot, EUVL Conference 2017, Monterey

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Proc. of SPIE Vol. 10957 1095705-11

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Photon statistics - revisited

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

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Photon statistics - revisited

How Dose fluctuation turns into edge placement

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Photon statistics - revisited

A more detailed “sing along” version - FOR HANDOUT

$$\Delta CD = 2\Delta x$$

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

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

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

will make this 1/NILS

Units suck !!! try $\hbar = c = \pi = \sqrt{-1} = 1$?

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Photon statistics - revisited

How Dose fluctuation turns into edge placement

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

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

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

Image Log Slope

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

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

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

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

Example:
Dose = 20 mJ/cm²,
 $h\nu = 92\text{eV}$ (EUV),
NILS = 2.5

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

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Photon statistics - revisited

How Dose fluctuation turns into edge placement

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

EUV - Stochastics

Following Burn Lin's footsteps

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

$$DoF = k_2 \frac{\lambda}{NA^2}$$

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

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

EUV - Stochastics

Following Burn Lin's footsteps

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

$$DoF = k_2 \frac{\lambda}{NA^2}$$

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

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

chemistry
 resist stochastic
 molecule size
 accounts for statistical nature of photons (unit: 1)
 blur
 new ideas
 3D mask
 Illumination
 NA, Aberrations, flare, MSD, OoB
 Pitch/CD

Today at NILS = 2.5, $h\nu=92\text{eV}$ and reported LCDU values around 3-4 nm $\Rightarrow k_4$ is between 4 and 8.

The photon field itself would have k_4 of 0.75

2 beam imaging (small features):

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

36% gain

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k_4 - landscape 2018

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

data source: Gijsbert Rispen

k_4 values for contacts

LCDU for 2 different CAR resists

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EUV - missing contacts

Local effects "beyond dose"

Prolith stochastic resist model simulations - Steve Hansen

Results of 10000 calculations each

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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

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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," JM³ 16(4), 041013 (2017)

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]

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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...

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2019-02-25

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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

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There's always new things to discover

SPIE - Advanced Lithography 2019

Extreme Ultraviolet (EUV) Lithography X

Acknowledgements

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