2015 International Workshop on EUV Lithography

June 15-19, 2015

Makena Beach & Golf Resort ▪ Maui, Hawaii

Workshop Abstracts

EUV Litho, Inc.

Contents

Organized by:

EUV Litho, Inc.

Welcome

Dear Colleagues;

I would like to welcome you to the 2015 International Workshop on EUV Lithography (EUVL Workshop) in Maui, Hawaii. This workshop, now in its 8th year, focuses on R&D and we have on the agenda, leading researchers from around the world. As we all work to address the remaining technical challenges of EUVL, to allow its insertion in high volume computer chip manufacturing, we look forward to a productive interaction among colleagues to brainstorm technical solutions.

This workshop has been made possible by the support of workshop sponsors, steering committee members, workshop support staff, session chairs and presenters. I would like to thank them for their contributions and for making this workshop a success. I look forward to your participation.

Best Regards

Vivek Bakshi
Chair, 2015 International Workshop on EUVL

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Sergey Zakharov (NAEXTSTREAM)

Workshop Agenda

2015 International Workshop on EUV Lithography

Makena Beach & Golf Resort, Maui, Hawaii, USA

June 15-19, 2015

Workshop Agenda Outline

Monday, June 15, 2015

8:30 AM -5:00 PM
EUV Lithography Short Course (Makena Salon)

Tuesday, June 16, 2015

3:00 PM - 5:00 PM
Registration (Kaeo Ballroom Foyer)
Speaker Prep (Wailea Salon)

6:00 PM - 7:30 PM
Reception (Pacific Lawn)

Wednesday, June 17, 2015

7:30 AM – 8:30 AM Breakfast (Café Kiowai)
8:30 AM – 11:40 AM Oral Presentations (Wailea Salon)
11:40 AM – 1:00 PM Lunch (Molokini Room)
1:00 PM – 4:00 PM Oral Presentations (Wailea Salon)
4:00 PM Afternoon off for Networking

Thursday, June 18, 2015

7:30 AM – 8:30 AM Breakfast (Café Kiowai)
8:30 AM – 12:00 PM Oral Presentations (Wailea Salon)
12:00 PM – 1:00 PM Lunch (Molokini Room)
1:00 PM – 5:00 PM Oral Presentations (Wailea Salon)
5:00 PM - 6:00 PM Poster Session (Wailea Salon Foyer)
6:30 PM – 8:00 PM Dinner (Pacific Lawn)

Friday, June 19, 2015

8:30 AM – 10:00 AM EUVL Workshop Steering Committee Meeting (Café Kiowai)

2015 International Workshop on EUV Lithography

Makena Beach & Golf Resort, Maui, Hawaii, USA
June 15-19, 2015

Workshop Agenda

Monday, June 15, 2015

Short Courses

EUV Lithography
by Vivek Bakshi (EUV Litho, Inc.), Patrick Naulleau (LBNL) and Jinho Ahn (Hanyang University)

8:30 AM -5:00 PM (Makena Salon)

Tuesday, June 16, 2015

Registration and Reception

3:00 PM- 5:00 PM	Registration & Speaker Prep
6:00 PM- 7:30 PM	Reception

Wednesday, June 17, 2015

8:30 AM Welcome and Introduction

Introductions (Intro-1)

Vivek Bakshi
EUV Litho, Inc., Austin, TX, USA

Session 1: Keynote – 1

EUVL for HVM: Progress Update (P1)

Mark Phillips
Intel Corporation, Hillsboro, OR 97124, USA

Challenges of EUV Lithography for HVM (P2)

Takayuki Uchiyama
Lithography Process Development Department, Center for Semiconductor Research and Development, Toshiba Corporation, Japan

Break (20 minutes)

Session 2: Optics and Contamination

Progress with Capping Layer and Optics Refurbishment Development at RIT (Invited Talk) (P72)

Yuriy Platonov[a], Michael Kriese[a], Vladimir Martynov[a], Raymond Crucet[a], Yang Li[a], Steven Grantham[b], Charles Tarrio[b], John Curry[b], Shannon Hill[b], Thomas Lucatorto[b]
[a]*Rigaku Innovative Technologies, 1900 Taylor Rd., Auburn Hills, MI 48326, USA*
[b]*Institute for Standards and Technology, Gaithersburg, MD 20899, USA*

Issues in the Testing of Non-CAR Materials in Hydrogen Atmospheres (Invited Talk) (P73)

C. Tarrio, R. F. Berg, S. B. Hill, and T. B. Lucatorto
Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, MD, 20899, USA

Collector Cleaning and EUV Extendability (Invited Talk) (P74)

David N. Ruzic, Daniel T. Elg, Gianluca A. Panici, Shailendra N. Srivastava
Center for Plasma Material Interactions, Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign

Scintillators and Imaging in EUV/XR Spectral Region (Invited Talk) (P71)

Ladislav Pina
Czech Technical University in Prague (Czech Republic)

Lunch 11:40 AM – 1:00 PM

Session 3: EUV Resists

Recent Progresses in Negative-tone Imaging using EUV Exposure (Invited Talk) (P62)

Toru Fujimori, Toru Tsuchihashi and Toshiro Itani
EUVL Infrastructure Development Center, Inc. (EIDEC), 16-1 Onogawa, Tsukuba-shi, Ibaraki 305-8569, Japan

Novel EUV Resist Development for sub-14 nm Half pitch (Invited Talk) (P64)

Yoshi Hishiro
JSR Micro INC, 1280 N. Mathilda Ave, Sunnyvale, CA 94089, USA

Dissolution Dynamics of Chemically Amplified Resists for Extreme Ultraviolet Lithography Studied by Quartz Crystal Microbalance (Invited Talk) (P65)

Masaki Mitsuyasu, Hiroki Yamamoto and Takahiro Kozawa
The Institute of Scientific and Industrial Research, Osaka University, Address: 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

Characterization of Inorganic Resists Using Temperature Programmed and Electron Stimulated Desorption (P61)

Gregory S. Herman and Ryan Frederick
Oregon State University, School of Chemical, Biological and Environmental Engineering
102 Gleeson Hall, Corvallis, OR USA

EUV Patterning Improvement Toward High-volume Manufacturing (Invited Talk) (P63)

Yuhei Kuwahara [1], Koichi Matsunaga [1], Shinichiro Kawakami [1], Kathleen Nafus [1], Philippe Foubert [2], Anne-Marie Goethals [2]
[1] Tokyo Electron Kyushu Ltd., 1-1 Fukuhara, Koshi city, Kumamoto, 861-1116, Japan
[2] IMEC, Kapeldreef 75, B-3001, Leuven, Belgium

Break 2:40 PM (20 Minutes)

Session 4: EUVL Regional Reviews

Wang Xiangzhao (SIOM, China)

Bob Rollinger (ETHZ, Europe)

Jinho Ahn (Hanyang University, Korea)

Takayuki UCHIYAMA (TOSHIBA, Japan)

Patrick Naulleau (CXRO, USA)

Taiwan (TBD)

Adjourn: Time off for Networking

End Day 1

Thursday, June 18, 2015

Welcome and Announcements (Intro-2)
Vivek Bakshi
EUV Litho, Inc.

Session 5: Keynote-2

HVM LPP Light Sources for EUVL (Tentative Title) **(P3)**

Speaker TBA, ASML - San Diego, San Diego, USA

Session 6: EUV Sources

Update of One Hundred Watt HVM LPP-EUV Source (Invited Talk) (P33)

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Takeshi Ohta, Krzysztof M Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada, Taku Yamazaki , Shinji Okazaki and Takashi Saitou
Gigaphoton Inc. Hiratsuka facility: 3-25-1 Shinomiya Hiratsuka Kanagawa,254-8567, JAPAN

States and Prospects of Laser Drivers for 250W and Toward > 500W Extreme ultraviolet (EUV) Generation (Invited Talk) (P35)

Koji Yasui[1] and Jun-ichi Nishimae[2]
[1]*Mitsubishi Electric Corporation, Head quarter, Tokyo, Japan*
[2]*Mitsubishi Electric Corporation, Advanced technology R&D center, Hyogo, Japan*

XUV Research with Compact DPP and LPP Laboratory Sources: Complementary to Beamlines and Large Scale Industrial Tools (Invited Talk) (P31)

Rainer Lebert[1], Christoph Phiesel[1], Thomas Mißalla[1], Christian Piel[1], Klaus Bergmann[2], Alexander von Wezyk[2], Jochen Vieker[2],Serhiy Danylyuk[3], Lukas Bahrenberg[3], Stefan Herbert[3], Larissa Juschkin[4], Aleksey Maryasov[4]
[1] *RI Research Instruments GmbH (RI), 51429 Bergisch-Gladbach, Germany*
[2]*Fraunhofer Institute for Laser Technology (FhG-ILT)*
[3] *Chair for the Technology of Optical Systems*
[4]*Chair for the Experimental Physics of EUV*
[3, 4] *at RWTH Aachen University;*
[2,3,4] *at 52074, Aachen, Germany*

Plasma Design of the EQ-10 EUV Source (Invited Talk) (P34)

Stephen F. Horne, Matthew J. Partlow, Deborah S. Gustafson, Matthew M. Besen, Donald K. Smith, Paul A. Blackborow
Energetiq Technology Inc., 7 Constitution Way, Woburn MA 01801 USA

High Brightness LPP Light Sources for High Volume Inspection (Invited Talk) (P36)

Bob Rollinger
Swiss Federal Institute of Technology, Laboratory for Energy Conversion, ETH Zurich, ML J23, Sonneggstrasse 3, 8092 Zürich, Switzerland

Break (20 Minutes)

Session 7: Panel Discussion (40 Minutes)

Lunch 12:00 PM (60 Minutes)

Session 8: FEL based Sources for EUVL

LCLS-II and Free Electron Laser Drivers for EUV Lithography (Invited Talk) (P44)

Aaron Tremaine
SLAC, 2575 Sand Hill Road, Menlo Park, 94025, USA

An ERL-Based High-Power Free-Electron Laser for EUV Lithography (Invited Talk) (P42)

Norio Nakamura
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

EUV Radiation from a Microbunched Storage Ring (Invited Talk) (P41)

Daniel Ratner, Alex Chao
SLAC, 2575 Sand Hill Road, Menlo Park, 94025, USA

TESSA – a Novel High Efficiency EUV Source (Invited Talk) (P43)

A. Murokh[1], J. Duris[2], P. Musumeci[2]
[1]*RadiaBeam Technologies, USA*
[2]*UCLA, USA*

Simulation of an Electron Gun for ERL-FEL Based EUV Lithography System (Invited Talk) (P45)

Taisuke Kawasaki[1], Makoto Takemura[1], Haruo Miyadera[1],Tsukasa Miyajima[2], Masahiro Yamamoto[2], Yosuke Honda[2], Takashi Uchiyama[2], Xiuguang Jin[2], Yukihide Kamiya[2], Hiroshi Kawata[2], Yukinori Kobayashi[2], Nobuyuki Nishimori[3], Ryoichi Hajima[3]
[1]*TOSHIBA Corporation:8, Shinsugita-Cho, Isogo-Ku, Yokohama 235-8523, Japan*
[2]*High Energy Accelerator Research Organization (KEK): 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[3]*Japan Atomic Energy Agency (JAEA): 4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1184, Japan*

Break 2:40 PM (20 Minutes)

Session 9: EUV Masks

Current Status and Outlook for EUV Mask (Invited Talk) (P52)

Takashi Kamo
Lithography Process Development Department,
Center for Semiconductor Research & Development, TOSHIBA Corporation,
Kanagawa 212-8583, Japan

Progress Towards Actinic Patterned Mask Inspection (Invited Talk) (P51)

Oleg Khodykin
RAPID, KLA-Tencor Inc., USA

Critical Defect Size on the Extreme Ultraviolet (EUV) Mask and Cleaning Process for its Removal (Invited Talk) (P54)

Min-Su Kim[a], Hye-Rim Ji[b], In-Seon Kim[b], Hye-Keun Oh[b], Jin-Ho Ahn[c] and Jin-Goo Park[a†]
[a]*Department of Materials Engineering and Bio-Nano Technology, Hanyang University, Ansan, Korea,*
[b] *Department of Applied Physics, Hanyang University, Ansan, Korea,*
[c]*Department of Materials Science and Engineering, Hanyang University, Seoul, Korea*

Tabletop-Scale EUV Coherent Phase-And-Amplitude Imaging Using High Harmonics (P55)

Daniel E. Adams, Dennis F. Gardner, Elisabeth R. Shanblatt, Christina L. Porter, Robert M. Karl, Michael D. Tanksalvala, Henry C. Kapteyn, Margaret M. Murnane
JILA, University of Colorado, 440 UCB, Boulder, Colorado 80309-0440, USA

Multilayer Mask Roughness: the Relative Importance of Phase and Amplitude (Invited Talk) (P56)

Patrick P. Naulleau[1], Kenneth A. Goldberg[1], Eric Gullikson[1],Rene Claus[2], Henry Wang[2], Andy Neureuther[2]
[1]*Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[2]*University of California at Berkeley, Berkeley, CA 94720*

EUVL Workshop Summary (P90)

Vivek Bakshi
EUV Litho, Inc.

5:00- 6:00 PM Poster Session

6:30 -8:00 PM Dinner

Session 10: Poster Session

Additional Poster Papers To be Announced. The deadline for post deadline poster paper submission is May 29, 2015.

XUV, EUV and Soft-X-Ray Solutions with Compact Laboratory-Sources (P32)

Rainer Lebert[1], Christoph Phiesel[1], Thomas Mißalla[1], Christian Piel[1], Klaus Bergmann[2], Alexander von Wezyk[2], Jochen Vieker[2], Serhiy Danylyuk[3], Lukas Bahrenberg[3], Stefan Herbert[3]
[1] RI Research Instruments GmbH (RI), 51429 Bergisch-Gladbach, Germany
[2]Fraunhofer Institute for Laser Technology (FhG-ILT)
[3] Chair for the Technology of Optical Systems at RWTH Aachen University
[2,3] at 52074, Aachen, Germany

Optimal Shift of Pattern Shifting for Mitigation of Mask Defects in EUV Lithography (P53)

Sikun Li, Xiangzhao Wang, Xiaolei Liu, Heng Zhang
Laboratory of Information Optics and Opto-electronic Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, China, 201800

Title TBA (P75)

Rupert C. C. Perera
EUV Tech, 2840 Howe Road Suite A, Martinez, CA 94553, USA

Friday, June 19, 2015

8:30 AM - 10:00 AM

EUVL Workshop Steering Committee Meeting (Kaeo Ballroom)

8:30 AM - 10:00 AM Breakfast (Café Kiowai)

Abstracts

(Listed by Paper number)

P1

EUVL for HVM: Progress Update

Mark Phillips

Intel Corporation, Hillsboro, OR 97124, USA

Demonstrations of >100W EUV source power on systems in the field, and short-term productivity runs of >1000 wafers in 24 hours, have debunked the notion that EUVL systems can never run at high productivity. While cost-effective HVM still requires more than doubling source power—along with substantial progress on availability and operating cost—two years of solid progress on source power have reestablished the credibility of the technical roadmap to the required power, availability and cost, though some uncertainty remains in the exact schedule. Several NXE:3300 systems are now available at semiconductor manufacturers to run extended performance tests to demonstrate availability, predictability and stability. When this performance is judged sufficient to support technology development, EUVL will be a compelling alternative to further extension of 193 immersion with multiple patterning.

Presenting Author

Mark Phillips is a Senior Principal Engineer in Intel's Logic Technology Development group in Hillsboro, Oregon. After completing a PhD in Physics from the California Institute of Technology, he joined Intel 21 years ago to work on development of the 0.35 micron process node. For the last 12 years, he has been the primary technical interface to Intel's exposure tool suppliers, and has worked on the introduction of every new generation of exposure tool into technology development and manufacturing. In the last few years, Mark has also been responsible for defining the roadmap for the factory automation systems that support Intel's lithography tools, and has worked on introduction of new metrology techniques to support lithography.

P2

Challenges of EUV lithography for HVM

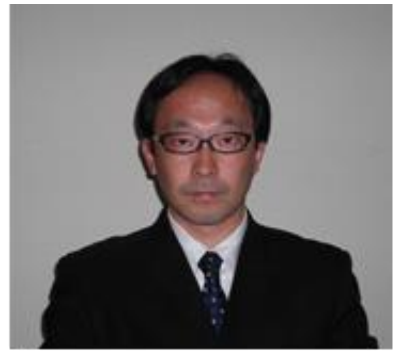
Takayuki UCHIYAMA

Lithography Process Development Department, Center for Semiconductor Research and Development, TOSHIBA Corporation

To keep the device scaling, the multiple patterning with ArF immersion lithography is applied for HVM (high volume manufacturing). It requires very complicated process control and long process steps. Therefore, practical application of NGL (the Next Generation Lithography) has been desired. EUV lithography is one of the strongest candidates of NGL. It has high resolution which can provide very simple process. But EUV lithography has many difficult technical challenges must be overcome. Furthermore, CoO and the timing are very important for implementation. EUV source is the most critical issue. The target is 250 W with high availability in 2016 which corresponds to 125 WPH. However, the current power level of LPP source is low, less than half of the target, and the availability is too low to apply for HVM.

In the future, higher NA EUV lithography will require higher power due to resist shot noise issue for sub-10nm patterning. XFEL(X-ray Free Electron Laser)is one of the candidates for next generation EUV source with high power. There are many challenges for XFEL with the wavelength of 13.5 nm, such as full-time stable operation (365 D/24 H) for semiconductor manufacturing, suppression of speckle noise due to high coherence, and reduction of optics damage due to high peak power. In this paper, challenges of EUV lithography for HVM of future devices will be mentioned.

Presenting Author



Takayuki UCHIYAMA is Chief Specialist of Lithography Process Technology Department, Center For Semiconductor Research & Development, TOSHIBA Corporation. He joined TOSHIBA Corporation in 2012 and has been involved in the research and development of the next generation lithography. He has 25 years of experience in lithography process development. He received his B.E. and M.E. degrees in mechanical engineering from Tohoku University in 1987 and 1989, respectively. After graduation, he joined NEC Corporation, where his experience includes the production engineering of lithography process and the development of KrF, ArF and ArF immersion lithography. He has published numerous technical journal papers.

P3

HVM LPP Light Sources for EUVL (Tentative Title)

Igor Femenkov

ASML, San Diego, CA

Presenting Author

P31

XUV Research with Compact DPP and LPP Laboratory Sources: Complementary to Beamlines and Large Scale Industrial Tools

Rainer Lebert[1], Christoph Phiesel[1], Thomas Mißalla[1], Christian Piel[1],
Klaus Bergmann[2], Alexander von Wezyk[2], Jochen Vieker[2]
Serhiy Danylyuk[3], Lukas Bahrenberg[3], Stefan Herbert[3],
Larissa Juschkin[4], Aleksey Maryasov[4]

[1] RI Research Instruments GmbH (RI), 51429 Bergisch-Gladbach, Germany
[2]Fraunhofer Institute for Laser Technology (FhG-ILT)
[3] Chair for the Technology of Optical Systems
[4]Chair for the Experimental Physics of EUV
[3, 4] at RWTH Aachen University; [2,3,4] at 52074, Aachen, Germany

The consortium of the authors, i.e. of the company RI[1], the FhG-ILT and the university chairs of the RWTH Aachen is involved in developing EUV sources and tools and is doing research with XUV radiation since 1997.

Our common approach of R&D is analyzing requirements in EUV, XUV and soft x-ray applications and suggesting the most suitable and simultaneously most economical solution fulfilling the top-level specifications. Such solutions are found selecting and integrating the full chain of components, including various XUV sources, optical schemes, high precision optical elements and suitable detectors – ideally from our own portfolio combined with proven design concepts and supported by solid fundamental studies.
We are always active in supplementing our scope by, e.g., extension of available source features towards higher power, brightness, other wavelengths or shorter pulses. With these laboratory XUV-sources such experiments are fully stand-alone and can be set-up for different ranges of XUV radiation, e.g. soft x-ray (2-5 nm), EUV (10-20 nm) and VUV (20-50 nm).

We present some recent progress in source technology and examples on successful application of our concepts to

- EUV source characterization metrology
- Actinic mask metrology (reflectometry, defect inspection)
- Actinic EUV and grazing incidence structural analysis
- Nano-layer thin film spectrophotometry
- Scatterometry
- High intensity EUV irradiation of materials
- Interferometric lithography and
- Nanoscopy (microscopy with sub 100 nm resolution)

[1] Originating from former ACCEL GmbH, Bruker ASC and AIXUV activities

Paths towards achieving demanded properties on wavelength calibration, measurement reproducibility, accuracy, sensitivity, and resolution are discussed. While repeatability is largely an issue of source monitoring, accuracy is highly demanding. With our plasma based sources, we have demonstrated to achieve outstanding spectral precision and accuracy of up to > 10,000 (sub-pm for EUV at 13.5 nm) exploiting tool internal calibration with plasma emission lines.

[1] Originating from former ACCEL GmbH, Bruker ASC and AIXUV activities

Presenting Author

Rainer Lebert was born in 1956 and graduated from TH Darmstadt, Germany, in 1984. He received his PhD from RWTH Aachen university for his thesis "Pinchplasmen als Röntgenquellen hoher spektraler Strahldichte" with Summa Cum Laude grade in 1990.

Theoretical and experimental investigations on tailoring of emission from dense and hot plasmas has always been in his focus. During the diploma studies it was the infrared originating from magnetically dominated instabilities. During his Ph.D. studies optimizing the soft-x-ray for developing plasma based X-ray sources for x-ray microscopy and proximity x-ray lithography were the issues.

As a post-doc and during the work as an assistant professor at the RWTH Aachen, he chaired the department for plasma technology at the „Lehrstuhl für Lasertechnik. Investigations on EUV emission at 13 nm from laser produced plasmas, Metrology with pulsed plasma based sources, e.g. x-ray microscopy, XPS, XANES etc., basic investigation of the physics of pinch plasmas, high power and high current switches, diode-pumped fs-Lasers and the invention of the compact EUV-lamp based on the "Hollow Cathode Triggered Pinch" concept were some achievements.

R&D for tailoring emission from plasmas has always been in the focus of his work. While being assistant professor, he chaired the department for plasma technology where basic investigations on EUV and soft x-ray emission from laser produced and pinch plasmas and concepts for EUV and X-ray applications of such sources were achieved in his group.

In September 2000 Dr. Rainer Lebert founded the AIXUV GmbH with the mission to commercialize the "HCTP"-Lamp for low-power industrial metrology in developing EUV-Technology. He has been managing director of AIXUV until merging into Bruker ASC in 2010 for joining competencies on EUV lab sources and tools with the existing BASC business on synchrotron instrumentation. These activities are continued after merging of BASC into RI Research Instruments GmbH in 2015.

P32

XUV, EUV and Soft-X-Ray Solutions with Compact Laboratory-Sources

Rainer Lebert[1], Christoph Phiesel[1], Thomas Mißalla[1], Christian Piel[1], Klaus Bergmann[2], Alexander von Wezyk[2], Jochen Vieker[2] Serhiy Danylyuk[3], Lukas Bahrenberg[3], Stefan Herbert[3]

[1] *RI Research Instruments GmbH (RI), 51429 Bergisch-Gladbach, Germany*
[2]*Fraunhofer Institute for Laser Technology (FhG-ILT)*
[3] *Chair for the Technology of Optical Systems at RWTH Aachen University*
[2,3] *at 52074, Aachen, Germany*

The Photon Instrumentation group at RI (Originating from former ACCEL, Bruker ASC and AIXUV activities) is developing and producing tools for metrology in the spectral range of 1 -50 nm (XUV) for both synchrotron beamline and laboratory use in close cooperation with our research partners from e.g. RWTH Aachen.

Our approaches is analyzing user requirements in EUV, XUV and soft x-ray metrology and suggest the most suitable and simultaneously most economic solution for best fulfilling of the top-level specifications. With our laboratory stand-alone XUV-sources such systems are fully autarkic and can be set-up for different ranges of XUV radiation, e.g. soft x-ray (2-5 nm: 250-600 eV), EUV (10-20 nm: 60 – 125 eV) and VUV (20-50 nm: 25-60 eV).

When developing and building our fully autarkic stand-alone laboratory tools we are relying on our broad scope of laboratory XUV-sources of which we know how to tailor towards desired working wavelength, spectral distribution, brightness or power for most efficiently meeting user demands in EUV, XUV and soft x-ray metrology. Starting from experienced design concepts and sub-unit options, we integrate the components XUV-source, sample stages, optics (lenses, mirrors, gratings, and filters) and detectors as to realize the most suitable and simultaneously most economic solution for fulfilling the top-level specifications. Hence, dedicated variants for specific tasks are easily tailored and may be extremely compact and economic.

We present some resent progress in source technology and examples on successful applying our concepts to Lab Instrumentation.

Presenting Author

P33

Update of One Hundred Watt HVM LPP-EUV Source

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Takeshi Ohta, Krzysztof M Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada, Taku Yamazaki, Shinji Okazaki and Takashi Saitou

Gigaphoton Inc., Hiratsuka facility: 3-25-1 Shinomiya Hiratsuka Kanagawa,254-8567, JAPAN

We have been developing CO_2-Sn-LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique and original technologies such as; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses shooting and mitigation with magnetic field have been developed in Gigaphoton Inc. The theoretical and experimental data have clearly showed the advantage of our proposed strategy. Based on these data we are developing first practical source for HVM; "GL200E". This data means 250W EUV power will be able to realize around 20kW level pulsed CO_2 laser. We have reported engineering data from our resent test such around 43W average clean power, CE=2.0%, with 100kHz operation and other data [1).

We have already finished preparation of higher average power CO_2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation[2). Recently we achieved 140W with 50kHz, 50% duty cycle operation and two hours operation at one hundred watt power range[3). Further improvements are underway, we will report the latest challenge to more than one hundred watt stable operation, around 4% CE with 20 micron droplet and magnetic mitigation.

1) Hakaru Mizoguchi, et. al.: "Sub-hundred Watt operation demonstration of HVM LPP-EUV source", Proc. SPIE 9048, (2014) [9048-12]
2) Yoichi Tanino et.al.:" A Driver CO2 Laser Using Transverse-flow CO2 Laser Amplifiers" (EUV Symposium 2013, Oct.6-10.2013, Toyama)
3) Hakaru Mizoguchi et al.:" Performance of one hundred watt HVM LPP-EUV Source " Proc. SPIE 9422 , (2015) [9422-11]

Presenting Author

Hakaru Mizoguchi is Executive Vice President and CTO of Gigaphoton Inc.

He is a member of The International Society of Optical Engineering, The Laser Society of Japan and The Japan Society of Applied Physics. He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu Ltd. He joined CO_2 laser development program in Komatsu for 6 years. After that he was guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F_2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got PhD degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development under his present position.

P34

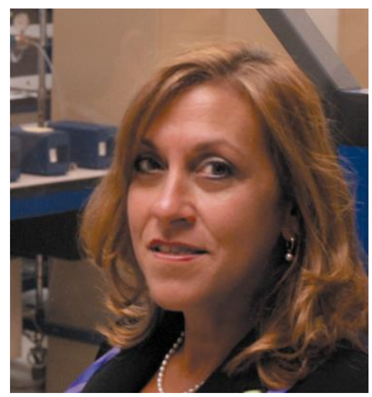
Plasma Design of the EQ-10 EUV Source

Stephen F. Horne, Matthew J. Partlow, Deborah S. Gustafson, Matthew M. Besen, Donald K. Smith, Paul A. Blackborow

Energetiq Technology Inc.
7 Constitution Way, Woburn MA 01801 USA

As the actinic inspection tools for mask blanks, and aerial image analysis of patterned masks are being developed, challenges in source design is being identified. The key critical parameters are brightness, stability (spatial and temporal), and etendue. As inspection tools are now operating, other parameters are being discussed such as lifetime of the consumables and shape of the EUV plasma. Energetiq has done some recent work on identifying areas of the EUV source that can be designed for these critical parameters.

Presenting Author



Debbie Gustafson is an industry veteran for over 20 years and has held various management positions in technical Sales and Marketing in the Semiconductor Equipment Industry. Her focus has been on component and subsystem equipment and service. Ms. Gustafson's is a senior manager at Energetiq Technology, Inc. in Woburn, Massachusetts as their Vice President of Marketing and Sales. Her responsibility also includes marketing and the management of manufacturing and finance. She has successfully driven the company to become the leading supplier of EUV sources globally. Ms. Gustafson has vast knowledge in the international markets with a focus on Asia. She has managed the opening of a subsidiary in Japan and a joint venture sales and service organization in Korea. She also has extensive experience in negotiating multimillion dollar contracts and supplier agreements.

Currently Ms. Gustafson is the past chairperson of the SEMI New England Committee. She holds a BS in Mechanical Engineering and an MBA in Management from Bentley College.

P35

States and prospects of laser drivers for 250W and toward > 500W extreme ultraviolet (EUV) generation

Koji Yasui[1] and Jun-ichi Nishimae[2]

[1]Mitsubishi Electric Corporation, Head quarter, Tokyo, Japan
[2]Mitsubishi Electric Corporation, Advanced technology R&D center, Hyogo, Japan

Laser drivers based on commercially available transverse-gas-flow CO_2 lasers are described. With the pre-pulse scheme configuration, 250W extreme ultraviolet (EUV) generation is expected by using 25kW CO_2 lasers consisted of one oscillator and four amplifiers. The performances of transverse-gas-flow CO_2 lasers are investigated so that they have better beam quality and higher gains to ensure compact and efficient laser drivers for EUV generations.

Requirements for further EUV powers > 500W are also going to be investigated in this talk. Since 25kW is generated only by using four amplifiers, further enhancement of driver power is possible by simply adding more amplifiers. Therefore we consider that we must share roadmaps toward > 500W and even >1kW EUV generations, for instance, by using better reflective mirrors, better materials to complete EUV lithography processes and so on.

We are also constructing ecosystem including academic people so that best practices are adapted to our systems and technological matters are solved most effectively by most talented engineers, researchers, and professors.

Presenting Author

Koji Yasui received B.S. and Ph. D. degrees from the University of Tokyo in 1982 and 1989 respectively. He was a visiting scientist at the Stanford University in 1989. He joined Mitsubishi Electric Corporation in 1982, where he has developed high-power CO_2 lasers, high-power solid-state lasers, high-power green lasers, high-power UV lasers and laser processing machines using those laser sources. He is now in charge of laser technology, EDM technology, CNC technology and e-beam technology and related businesses.

P36

High Brightness LPP Light Sources for High Volume Inspection

Bob Rollinger

Swiss Federal Institute of Technology, Laboratory for Energy Conversion
ETH Zurich, ML J23, Sonneggstrasse 3, 8092 Zürich, Switzerland

Progress in the development and prototype testing of Laser Produced Plasma (LPP) light sources for actinic inspection over the last 8 years will be presented. The sources are based on 30 to 50 micrometer-sized droplets that are irradiated by a high repetition rate (kHz) Nd:YAG laser. Current systems are designed for application that require high brightness, high stability sources for EUV photomask inspection, such as AIMS™, actinic blank and pattern inspection. Recent achievements cover source stability, life-time and cleanliness after IF. The latest source performance results related to EUV emission at the source and IF, as well as cleanliness will be presented. Details about the extension of the source operating time to 24/7 with high availability (>90%), including aspects of life-time management of the EUV collection optics will be also discussed in this presentation. Extensions of the LPP source to other applications will be detailed. Technology for this light source has been developed at ETH Zurich and exclusively licensed to Adlyte corporation which is commercializing a range of products with its partners. An overall source roadmap will be presented.

Presenting Author

P41

EUV Radiation from a Microbunched Storage Ring

Daniel Ratner, Alex Chao

SLAC, 2575 Sand Hill Road, Menlo Park, 94025

Particle accelerators are promising sources of short wavelength radiation due to the ease of wavelength tuning and the potential for high average power. To capture the full potential, it is crucial to separate the electrons into microbunches separated by the target wavelength, for example by the free electron laser (FEL) process. However, while FELs can produce very high peak power, they are based on linear accelerators in which each electron bunch is only used once before being dumped. By contrast, the bunches stored in a ring can radiate on every pass, in total nearly a billion times per second. To combine the peak power of an FEL with the near continuous repetition rate of a storage ring, we propose a new mechanism called steady-state microbunching (SSMB), in which an external optical laser forces the electrons to an equilibrium state that maintains microbunching on every turn. In this talk we describe the basics of the mechanism, the potential peak powers achievable, and the steps required to turn SSMB into reality.

Presenting Author

Daniel Ratner is a staff scientist in the laser department of the SLAC National Accelerator Laboratory. His research focus is on free electron lasers, electron-laser interactions, and collective effects in accelerators.

P42

An ERL-Based High-Power Free-Electron Laser for EUV Lithography

Norio Nakamura

High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

Energy recovery linac (ERL)-based free electron lasers (FELs) are promising candidates for high-power EUV sources of lithography. They can recover most acceleration energy from the electron beams and greatly reduce the dumped beam power and activation compared with those based on ordinary linear accelerators. A possible design and construction plan of a 10-kW class ERL-based FEL operated at 13.5 nm were investigated for EUV lithography applications [1][2]. We have studied designs of the injector, main superconducting linac and arc sections of the ERL-based EUV-FEL in more detail and also performed simulations of the bunch compression to optimize the beam parameters for the FEL performance. In this talk, we will present the updated EUV-FEL design with the optimized beam parameters to discuss the properties and performance of the EUV-FEL and mention the status of the on-going ERL project in Japan, the Compact ERL (cERL), which is a basis for designing the EUV-FEL.

[1] R. Hajima et al., 2014 EUV Source Workshop, November 4, 2014, Dublin, Ireland.
[2] E. Kako et al., 2014 EUV Source Workshop, November 4, 2014, Dublin, Ireland.

Presenting Author

Norio Nakamura is a professor of accelerator science at KEK. He received his Ph. D in Physics from the University of Tokyo in 1987. He first worked for operation and development of the Photon Factory storage ring at KEK and then he was an associate professor at the University of Tokyo from 1996 to 2011. Since 2011, he has been a group leader of the beam dynamics and magnet group in Accelerator Division VII (light source division) of the Accelerator Laboratory at KEK.

P43

TESSA – a Novel High Efficiency EUV Source

A. Murokh[1], J. Duris[2], P. Musumeci[2]

[1]*RadiaBeam Technologies*
[2]*UCLA*

We propose a new source concept, termed Tapering Enhanced Stimulated Superradiant Amplifier (TESSA), to generate > 10 kW EUV radiation at 13.5 nm. Just like in a Free Electron Laser (FEL), TESSA uses relativistic electron beam and magnetic undulator to transfer the energy from an electron beam to the radiation. However, in TESSA the beam-laser interaction is much stronger, and the beam undergoes rapid deceleration in a relatively short strongly tapered undulator. Initial simulations demonstrated possibility of transferring as much as 50% of electron beam energy to the radiation field in a 15 meters long TESSA undulator. A development and demonstration plans for TESSA are discussed in the context of the potential application to EUV lithography.

Presenting Author

P44

LCLS-II and Free Electron Laser Drivers for EUV Lithography

Aaron Tremaine

SLAC, 2575 Sand Hill Road, Menlo Park, CA 94025

LCLS-II, currently under construction, will be an X-ray Free Electron Laser (FEL) facility based on a versatile 4 GeV CW superconducting RF (SCRF) linac and two undulators for delivering high average power, coherent x-rays for fundamental research. This facility will integrate technologies from SLAC, LBNL, Jefferson Lab, Fermilab and Cornell University, in which the 1.3 GHz SCRF linac is based heavily on the technology developed for the EuFEL and the International Linear Collider modified to operate with 100% duty cycle. LCLS-II technology can be scaled to generate a >10kW, ~800 MeV EUV FEL at 13.5nm for driving the multiple steppers in a semiconductor fabrication facility. A consortium of US National Laboratories, academia and private industry is investigating different 13.5 nm FEL EUV light source configurations that could support semiconductor high volume manufacturing.

Presenting Author

Aaron Tremaine is a Senior Scientist at SLAC National Accelerator Laboratory and the Work for Others Program Manager in the Technology and Innovation Directorate. Prior to SLAC, he was the Technical Director of the 150 MeV Accelerator/Laser Facility at LLNL and PI of the facility Strategic Mission Support focused on national security. Tremaine was competitively selected as a University of California Discovery Fellow where he was the Director of Business Development for the California NanoSystems Institute and co-founded a VC funded start-up. He was instrumental in many of the early SASE high gain FEL experiments at UCLA, LANL and the project manager of the VISA FEL at BNL. Tremaine received is PhD in Physics from UCLA and an MBA from the Haas School of Business at UC Berkeley.

P45

Simulation of an Electron gun for ERL-FEL based EUV Lithography System

Taisuke Kawasaki[1], Makoto Takemura[1], Haruo Miyadera[1]
Tsukasa Miyajima[2], Masahiro Yamamoto[2], Yosuke Honda[2], Takashi Uchiyama[2], Xiuguang Jin[2], Yukihide Kamiya[2], Hiroshi Kawata[2], Yukinori Kobayashi[2]
Nobuyuki Nishimori[3], Ryoichi Hajima[3]

[1]TOSHIBA Corporation:8,Shinsugita-Cho, Isogo-Ku, Yokohama 235-8523,Japan
[2]High Energy Accelerator Research Organization (KEK): 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[3]Japan Atomic Energy Agency (JAEA): 4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1184, Japan

Free electron laser (FEL) and energy recovery linac (ERL) are promising combination for the next generation high-power EUV lithography. In collaboration with KEK and JAEA, Toshiba is designing such a FEL-based light source for EUV lithography where a goal is set at developing a 30-kW-class FEL capable of supplying 1-kW EUV to 10 lithography lines. Advantages of ERL-based system are: high beam quality, high energy efficiency, and less radioactive. One of the major challenges is development of high-current low-emittance electron gun. We worked on feasibility study of such an electron gun using simulation codes: Poison/Superfish for 2-D electrostatic field and General Particle Tracer for 3-D electron trajectory calculations.

Presenting Author

Taisuke Kawasaki is a scientist of TOSHIBA Corporation. He received MS degree in physics for a study on an ultrafast laser to drive electron gun for ERL in 2009 from University of Tokyo. After that, he joined TOSHIBA and developed laser application technology. His research interest includes spectroscopy, analytical technology using laser and light source for processing and analysis of power plant and social infrastructure.

P51

Progress towards Actinic Patterned Mask Inspection

Oleg Khodykin

RAPID, KLA-Tencor Inc.

Significant progress has been reported by EUV scanner supplier towards delivering productivity, availability and operational expenses consistent with cost-effective HVM, the semiconductor industry needs to work on a well-known list of supporting technologies like bright, stable EUV sources for actinic mask metrology tools as well as development of mask inspection tools (blanks, aerial image, and pattern).

RAPID division of KLA-Tencor has been providing patterned mask inspection tools for semiconductor industry for more than 30 years and has been working on EUV actinic patterned mask inspection solution since late 2008.

In this presentation, we are going to present overview of latest progress in developing critical subsystems: EUV optics degradation and mitigation, particle control and mitigation inside of mask inspector as well as bright and stable EUV source.

Presenting Author

Oleg Khodykin is a Manager of EUV source development in KLA-Tencor's RAPID division in Milpitas, California. Prior joining KLA-Tencor in 2011, he worked at CYMER (now ASML company) for 10 year as senior scientist and EUV collector group leader on different concepts of EUV source (both discharge and LPP, lithium, xenon and Sn based). Dr. Khodykin received his Ph.D. from Moscow Physical-Technical Institute in 1998 and did postdoctoral training at Bayreuth University and at the University of Southern California.

P52

Current Status and Outlook for EUV mask

Takashi Kamo

Lithography Process Development Department,
Center for Semiconductor Research & Development, TOSHIBA Corporation,
Kanagawa 212-8583, Japan

One of the key challenges before EUVL production is to achieve defect-free masks. There are three main categories of mask defects: substrate or multilayer defects which cause phase defects, absorber pattern defects, and particles during blank/mask fabrication or mask handling after its mask fabrication. It is important to manage these defects including development of EUV mask infrastructure in order to realize cost-effective defect-free masks. EUV mask is also required to exhibit high lithographic performances, such as higher image contrast, smaller shadowing effect caused by oblique illumination, better flatness control, etc. As target patterns shrink, the hurdles induced by mask 3D topology go higher in 0.33NA EUVL system. Moreover, in high-NA (>0.5) EUVL, mask induced effects impact the lithographic performance. Therefore, high-NA system is currently proposed that CRA should be lower than 8 degree and mask magnification should be larger than 4x instead.

In this paper, we present current development status of EUV mask including EUV mask infrastructure for cost-effective defect-free masks. Next we show capability of new EUV mask structure: etched multilayer mask. And outlook for etched multilayer mask with 4x full-field & 6 inch size will also be presented.

Presenting Author

Takashi Kamo is Senior Specialist of Lithography Process Technology Department, Center For Semiconductor Research & Development, TOSHIBA Corporation. He received his BE and MS degrees in pure and applied physics from Waseda University in 1989 and 1991, respectively. In 1991, he joined the ULSI research center, TOSHIBA Corporation and he carried out the development of phase-shifting mask. He has been involved in EUV lithography since 2006 when he was assigned to the EUVL mask program in Semiconductor Leading Edge Technologies, Inc. (SELETE). He received PhD from the University of Tokyo in 2012.

P53

Optimal Shift of Pattern Shifting for Mitigation of Mask Defects in EUV Lithography

Sikun Li, Xiangzhao Wang, Xiaolei Liu, Heng Zhang

Laboratory of Information Optics and Opto-electronic Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, China, 201800

Mask blank fabrication is usually concerned with defect problems in EUV lithography. Pattern shifting method and its combinations with other methods are the most promising methods for defect mitigation. Two methods, namely, minimum impact method and maximum number method, are proposed for determining the optimal shift of pattern shifting. A function is proposed to describe the impact of defect. The defect heights at different locations in the defect region are introduced to determine the impact. The minimum impact of all defects and the maximum number of covered defects after pattern shifting are considered as merit functions in the two methods, respectively. In addition, the error tolerance and mask writer error are also considered in the merit functions. Neglecting complexity, the minimum impact method is more likely to succeed in the mitigation of defects than the maximum number method. Finally, the two methods are compared. Based on the comparisons of those methods with different defect sizes and amounts, the reduction of defects with large FWHM in the blank is essential for successful defect mitigation.

Presenting Author

Sikun Li received his Ph.D in optical engineering from Sichuan University, China, in 2011. Now he is an Associate professor at the Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences. His research interests include lithography simulation, optical information processing and machine vision.

P54

Critical Defect Size on the Extreme ultraviolet (EUV) Mask and Cleaning Process for its Removal

Min-Su Kim[a], Hye-Rim Ji[b], In-Seon Kim[b], Hye-Keun Oh[b], Jin-Ho Ahn[c] and Jin-Goo Park[a†]

[a]*Department of Materials Engineering and Bio-Nano Technology, Hanyang University, Ansan, Korea,*
[b] *Department of Applied Physics, Hanyang University, Ansan, Korea,*
[c]*Department of Materials Science and Engineering, Hanyang University, Seoul, Korea*

Extreme ultraviolet lithography (EUVL) is the most promising lithography technique for the 22 nm half-pitch and beyond. EUV patterned masks work in a reflective mode. EUV mask does not yet have a pellicle which protects mask surface from contaminants. Therefore, EUV mask is more vulnerable to particle contamination during lithography processing which is a major yield loss in device fabrication. No study has been reported on effect of particle size on CD variation if they exist on EUV mask. The critical defect size, which can cause 10 % CD error, has to be removed from the mask surface. When the defect is located between line and space patterns on the mask, the reflectivity will be reduced due to defect absorption. Simulation predicted that 30 nm sized silica particle can cause 10 % CD error on 16 nm line and space pattern. Thus, 30 nm silica particle has to be removed from EUV mask surface for preventing CD variation. However, these fine particles are not easy to remove when compared with large particles. In this paper, we will discuss the effect of critical defect size on CD change and its removal process without causing materials loss and pattern damages.

Presenting Author

Jin-Goo Park received B.S degree in metallurgy and materials engineering from Hanyang University, Korea in 1984 and the M.S. and Ph.D. in materials science and engineering from University of Arizona in 1988 and 1993, respectively. From 1992 to 1994, he was with Texas Instruments, Dallas, TX, where he was responsible for microcontamination control in semiconductor wet processing and DMD development. In 1994, he joined Hanyang University at Ansan, where he is now a professor in the Department of Materials Engineering as well as Directors of Micro Biochip Center and Nano-bio Electronic Materials and Processing Lab. (NEMPL). His research interests include wafer cleanings and chemical mechanical polishing as well as nano-bio MEMS

P55

Tabletop-Scale EUV Coherent Phase-And-Amplitude Imaging Using High Harmonics

Daniel E. Adams, Dennis F. Gardner, Elisabeth R. Shanblatt, Christina L. Porter, Robert M. Karl, Michael D. Tanksalvala, Henry C. Kapteyn, Margaret M. Murnane

JILA, University of Colorado, 440 UCB, Boulder, Colorado 80309-0440, USA

The need for defect-free masks has been recognized as a potential roadblock to broad adoption of EUVL. A viable method for through-pellicle inspection and microscopy with the required <50 nm resolution can play an important role in development and production. SEM and AFM require removal of the pellicle, and suffer from surface charging and deposition, slow measurement speed, and/or potential for damage. This lead to the development of actinic inspection tools like the Zeiss AIMS. However, tools such as these use reflective or diffractive optics that are expensive, and difficult to manufacture, align, and limit the NA.

Here we demonstrate EUV coherent diffraction imaging (CDI) using a tabletop high-harmonic (HHG) coherent light source. CDI enables quantitative, full-field imaging with higher contrast than SEM. Using 29 nm illumination, we demonstrate 45x80 nm lateral resolution, and ultrahigh 0.6 nm axial (i.e. topographic) resolution. EUV CDI can also allow for through-pellicle imaging, elemental sensitivity, and ultimately full three-dimensional characterization including buried layers. In this work, we scan a ~10 μm beam over a 40μm x 70 μm area, acquiring ~200 scattered light patterns in an exposure time of <1 minute. Ongoing work using 13 nm with higher NA can push resolution to ~10-nm.

Presenting Author

Dr. Daniel Adams received his PhD from the Colorado School of Mines in 2010 specializing in ultrafast spatio-temporal dynamics. His interests range from perturbative nonlinear optics and high harmonic generation to phase retrieval with application to coherent diffraction imaging. Dr. Adams and his team currently hold the world record resolution of ~ 22nm using a tabletop high harmonic source, in any imaging modality. Future work will include extension of coherent diffraction imaging to three-dimensional studies of defect inspection in next generation storage devices, time-resolved nano-scale acoustic propagation and ultrafast magnetization dynamics.

P56

Multilayer Mask Roughness: The Relative Importance of Phase and Amplitude

Patrick P. Naulleau[1], Kenneth A. Goldberg[1], Eric Gullikson[1], Rene Claus[2], Henry Wang[2] and Andy Neureuther[2]

[1]*Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

[2]*University of California at Berkeley, Berkeley, CA 94720*

It is now well established that extremely ultraviolet (EUV) mask multilayer roughness leads to wafer-plane line-width roughness (LWR) in the lithography process [1-4]. Analysis and modeling done to date has assumed, however, that the roughness leading to scatter is primarily a phase effect and that the amplitude can be ignored [1]. Under this assumption, simple scattering measurements can be used to characterize the statistical properties of the mask roughness [5]. In this presentation we explore the implications of this simplifying assumption by modeling the imaging impacts of the roughness amplitude component as a function of the balance between amplitude and phase induced scatter.

In addition to model-based analysis, we also use the SHARP EUV microscope [6] to compare experimental through focus data to modeling in order to assess the actual amount of amplitude roughness on a typical EUV multilayer mask.

Finally, we consider stochastic modeling of the multilayer stack to numerically study the potential ratio between phase and amplitude roughness in an EUV multilayer.

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4. E. Gallagher,et al., "EUV masks under exposure: practical considerations," Proc. SPIE 7969, 79690W (2011)
5. Rikon Chao, et al., "EUV scatterometry-based measurement method for the determination of phase roughness," Proc. SPIE. 8880, 88801B ; (2013)
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Presenting Author

P61

Characterization of Inorganic Resists Using Temperature Programmed and Electron Stimulated Desorption

Gregory S. Herman and Ryan Frederick

Oregon State University, School of Chemical, Biological and Environmental Engineering, 102 Gleeson Hall, Corvallis, OR USA

Inorganic resists are of interest for nano manufacturing due their high resolution, low line width roughness, and high sensitivity. The combination of high absorption coefficient elements and radiation sensitive ligands can improve inorganic resist sensitivity while still allowing high contrast. As an example of this concept, is the inorganic resist with the general formula, $Hf(OH)_{4-2x-2y}(O_2)_x(SO_4)_y{\cdot}qH_2O$ (HafSOx). HafSOx has both high absorption coefficient elements (Hf) and radiation sensitive ligands (peroxides). In this presentation we discuss the characterization of HafSOx dehydration using temperature programmed desorption (TPD) and the interaction of low energy electrons with HafSOx using electron stimulated desorption (ESD). Both TPD and ESD allow us to characterize the key desorption species through thermal and radiative processes that occur while patterning. ESD results indicate that the peroxo species are very radiation sensitive, even for low energy electrons that approximate secondary electrons from EUV exposures. The primary desorption products from HafSOx are O_2 and H_2O, and the time evolution suggest much faster kinetics for O_2 desorption. These data provide insight into the radiation-induced changes responsible for the solubility transition upon exposure and patternability during development, and the role of secondary electrons in these processes.

Presenting Author

GREGORY S. HERMAN received his B.S. degree in Chemistry at the University of Wisconsin-Parkside in 1985 and his PhD. in Physical Chemistry at the University of Hawaii at Manoa in 1992. Gregory has had permanent positions at Pacific Northwest National Laboratory, Hewlett-Packard Corporation, and Sharp Laboratories of America. In 2009 he joined the School of Chemical, Biological and Environmental Engineering at Oregon State University (OSU) as an Associate Professor. Gregory has a broad background covering surface science, thin film growth, device physics, and nanotechnology.

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Recent Progresses in Negative-tone Imaging using EUV Exposure

Toru Fujimori, Toru Tsuchihashi and Toshiro Itani

EUVL Infrastructure Development Center, inc. (EIDEC)
16-1 Onogawa, Tsukuba-shi, Ibaraki 305-8569, Japan

Chemical Amplified Resist (CAR) using positive-tone development (PTD) is still one of the strongest candidates for EUV lithography realization for sub-10 nm generation. However, some researchers have reported concerns on the limitations in the performance of PTD-CAR. Consequently, there is critical need for new chemistry and development of new resist materials. Negative-tone imaging (NTI), which uses organic solvent-based developer, results in low swelling and smooth-dissolving behavior. Accordingly, NTI using EUV exposure (EUV-NTI) is considered to have several advantages in terms of performance, especially for improving LWR. Further, organic solvent-based developer was useful for development of new resist materials due to their wide variety of solubility.

This study describes the recent progresses in negative-tone imaging using EUV exposure (EUV-NTI) compared with PTD. Herein, novel chemical amplified resist materials for EUV-NTI are investigated to improve LWR and sensitivity. Results indicate that the EUV-NTI has better performance than PTD, with 'single digit mJ/cm^2', while maintaining the LWR performance. In addition, the developments of new resist materials have been just started to study for improvement of sensitivity using 'metal containing non-CAR materials'. The preliminary results of new resist materials indicate ultra-high sensitivity using EB lithography will be shown.

Presenting Author

Toru Fujimori, is a senior researcher in the Advanced Resist Research Department / Resist Outgas Research Department of EUVL Infrastructure Development Center, Inc. (EIDEC).

Toru Fujimori received B.S. and M.S. degrees in organic chemistry from Saitama University, Japan, in 1989 and 1991, respectively. In 1991, he has joined FUJIFILM Corporation as a researcher in synthetic organic chemistry laboratories. He has been studying for synthesizing new materials for photo films for 3 years. Since 1994, he has been studying for synthesizing new materials for semiconductor materials (photo resist materials) for 8 years. In 2002, he has moved to electronic materials research laboratories to study color resist materials for image sensor for 6 years. In 2006, he has promoted to be a research manager. Since 2008, he has been studying photo resist materials for semiconductor for 5 years; research manager of resist materials for KrF/ArF lithography in 2008-2011, project manager of all materials for Taiwan market in 2012 and project manager of resist materials for EUV lithography in 2013. He is currently senior researcher at EIDEC (EUVL Infrastructure Development Center, Inc.) as an assignee from FUJIFILM to study “Advanced resist materials” and “Resist outgas” in 2014. He has filed over 200 patents in this field.

P63

EUV Patterning Improvement toward High-volume Manufacturing

Yuhei Kuwahara[1], Koichi Matsunaga [1], Shinichiro Kawakami [1], Kathleen Nafus [1], Philippe Foubert [2], Anne-Marie Goethals [2]

[1] Tokyo Electron Kyushu Ltd., 1-1 Fukuhara, Koshi city, Kumamoto, 861-1116, Japan
[2] imec, Kapeldreef 75, B-3001, Leuven, Belgium

Extreme ultraviolet lithography (EUVL) technology is a promising candidate for a semiconductor process for 18nm half pitch and beyond. So far, the studies of EUV for manufacturability have been focused on particular aspects. It still requires fine resolution, uniform and smooth patterns, and low defectivity, not only after lithography but also after the etch process.

Tokyo Electron Limited and imec are continuously collaborating to improve manufacturing quality of the process of record (POR) on a CLEAN TRACK™ LITHIUS Pro™Z-EUV. This next generation coating/developing system has been upgraded with defectivity reduction enhancements which are applied along with TEL™ best known methods. We have evaluated process defectivity post lithography and post etch. Apart from defectivity, FIRM™ rinse material and application compatibility with sub 18nm patterning is improved to prevent line pattern collapse and increase process window on next generation resist materials.

This paper reports on the progress of defectivity and patterning performance optimization towards the NXE:3300 POR.

Presenting Author

Yuhei Kuwahara is current a TEL resident at imec, Leuven. He is in charge of TEL's Lithius ProZ for EUV. Through collaborations with the imec consortium members and access to NXE3100 and NXE3300 scanners, Kuwahara is working on the readiness of EUV coat and develop processes with low defect counts.

Previous he was a member of TEL's patterning group in Yamanashi R&D site. He developed the SADP process and investigated its scaling limits. Kuwahara started his career at DNP as mask writing production engineer. He graduated from Osaka University with a masters in semiconductor physics.

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Novel EUV resist development for sub-14 nm half pitch

Yoshi Hishiro

JSR Micro INC, 1280 N. Mathilda Ave, Sunnyvale, CA 94089, USA

Extreme ultraviolet (EUV) lithography is a promising candidate for the manufacturing of semiconductor devices at the sub-14nm half pitch lines and spaces (LS) pattern for 7nm node and beyond. For the high volume manufacturing of semiconductor devices, significant improvement of resolution and sensitivity is required for EUV resist. The key challenge for EUV resist is simultaneous achievement of low line edge roughness (LER), high sensitivity, and ultrahigh resolution for lines and spaces features. We have already reported that better LER and Z-factor were obtained with higher Tg polymer, thus in shorter acid diffusion length system. In this paper, we will report the recent progress of resolution and sensitivity improvement of JSR novel EUV resist.

Presenting Author

Yoshi Hishiro is Director of Research, JSR Micro Inc. He is responsible for Lithography research including advanced patterning like EUV and DSA as well as CMP research. He is responsible for joint development programs and joint research programs of lithography and CMP. He holds various patents in the US and Japan. Before JSR, he worked for Sumitomo Chemical as product manager for electronic materials then Micron Technology as Advanced lithography group supervisor. He was engaged in various advanced patterning projects and responsible for materials development at Micron such as 95nm KrF lithography development with initial SMO, KrF double patterning development, ArF lithography introduction, ArF advanced patterning with SMO, ArF double patterning development, new litho materials introduction into patterning integration, and initial ArF immersion lithography development. He has been in the semiconductor industry for more than 20 years.

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Dissolution Dynamics of Chemically Amplified Resists for Extreme Ultraviolet Lithography Studied by Quartz Crystal Microbalance

Masaki Mitsuyasu, Hiroki Yamamoto, and Takahiro Kozawa

The Institute of Scientific and Industrial Research, Osaka University, Osaka, Japan

Owing to the world-wide efforts, the resolution of EUV lithography with chemically amplified resist processes has already reached sub-16 nm region. With the progress in the resolution, the feasibility of sub-10 nm half-pitch has, recently, attracted much attention from the viewpoint of the extendibility of EUV lithography. For the development of high resolution resist materials, it is important to understand the dissolution behavior of the resist film into alkaline developer. In particular, the dissolution in partially exposed area of resist films is one of most critical issues. However, the details in dissolution process of EUV resist have not been investigated thus far. In this study, the dissolution of poly(4-hydroxystyrene) (PHS) polymer and PHS partially-protected with t-butoxycarbonyl group (t-BOC-PHS) with and without additives such as acid generator and amines was studied by using the quartz crystal microbalance (QCM) method. The effects of each components on the dissolution dynamics are discussed.

Presenting Author

P71

Scintillators and Imaging in EUV/XR Spectral region

Ladislav Pina

Czech Technical University in Prague, Czech Republic

Imaging in EUV and X-ray region plays important role in radiography, tomography, spectroscopy and lithography. Direct detection with use of CCD back illuminated detectors features high sensitivity and relatively low optical resolution given by minimum available pixel size. Detection using small crystals scintillators placed as a thin layer on fibre optic plate or directly on CCD sensor has still relatively high sensitivity and low resolution. Monocrystal scintillators have advantage of continuous homogeneous structure resulting in high resolution. However, they usually require an additional magnifying optical system in front of CCD detector. Overall sensitivity is low due to scintillator quantum efficiency and throughput of the optical system. All above mentioned methods of detection are widely used according to required parameters. Comparison of cameras using different scintillators and optical systems is presented together with measurement of monocrystal scintillator quantum efficiency in EUV and X-ray region.

Presenting Author

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Progress with Capping layer and Optics Refurbishment Development at RIT

Yuriy Platonov[a], Michael Kriese[a], Vladimir Martynov[a], Raymond Crucet[a], Yang Li[a], Steven Grantham[b], Charles Tarrio[b], John Curry[b], Shannon Hill[b], Thomas Lucatorto[b]

[a]*Rigaku Innovative Technologies, 1900 Taylor Rd., Auburn Hills, MI 48326, USA*
[b]*Institute for Standards and Technology, Gaithersburg, MD 20899, USA*

Results on developing reactively-sputtered oxide capping layers such as SiO_2, TiO_2 and ZrO_2 will be presented. Mo/Si multilayers with the capping layers were deposited in a dual process chamber inline magnetron system designed for coating a large EUV mirrors. The coated structures were EUV exposed in the presence of water vapor at the NIST Physical Laboratory. Oxidation and EUV reflectivity loss due to the exposure will be reported. Results on refurbishment of multilayer EUV optics will also be presented. The refurbishment process is being developed for recovery of multilayers deposited on metal substrates typically used for collector optics. Surface roughness and EUV reflectivity after multilayer stripping and re-deposition will be discussed.

Presenting Author

Yuriy Platonov received MS degree in physics in 1977 from Moscow State University and PhD degree from Nizhny Novgorod State University in 1989. From 1978 to 1991 he worked at the Institute of Applied Physics of Russian Academy of Sciences (RAS) and his activities were focused on laser produced plasma diagnostics, pulsed laser deposition technology and multilayer X-ray optics. From 1991 to 1995 he ran the X-ray Optics Laboratory at the Institute for Physics of Microstructures of RAS. Since 1995 he is Director, Coatings and Senior Science Adviser at Rigaku Innovative Technologies, formerly Osmic. His field of scientific interests includes physics of artificial thin film structures, design and deposition of x-ray multilayer optical elements, X-ray analytical instrumentation, and multilayer neutron optics.

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Issues in the Testing of Non-CAR Materials in Hydrogen Atmospheres

C. Tarrio, R. F. Berg, S. B. Hill, and T. B. Lucatorto

Sensor Science Division, National Institute of Standards and Technology, Gaithersburg MD 20899 USA

With the increasing likelihood that EUVL will rely on non-traditional resists, interest in testing of standard chemically amplified resists is waning. Limited testing has been done on non-CAR materials, with good results. However little is known about the behaviors of such materials under intense EUV irradiation in the presence of large pressures of hydrogen. We are developing a program to carry out such tests at the NIST SURF III storage ring, however there are many technical hurdles to be overcome. Exposures must be carried out in atmospheres of up to 1 mbar of hydrogen. However since hydrogen contamination is perilous to ion-pumped systems, virtually complete isolation between the sample chamber and upstream vacuum pipes must be achieved. We will discuss techniques used to achieve this and progress toward our beamline upgrade.

Presenting Author

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Collector Cleaning and EUV Extendability

David N. Ruzic, Daniel T. Elg, Gianluca A. Panici, Shailendra N. Srivastava

Center for Plasma Material Interactions, Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign

EUV lithography sources expel high-energy Sn debris, which can deposit on the collector optic and lower reflectivity. This necessitates collector cleaning. To minimize cleaning-related downtime, it is desirable to perform the cleaning *in-situ* by using hydrogen radicals to etch Sn. An ideal way to carry this out is to drive a hydrogen plasma by using the collector as an antenna, creating radicals at the collector surface, eliminating the need for any sort of radical delivery system, and allowing cleaning to occur during EUV production. Such a reduction of downtime is crucial to the use of EUV in high-volume manufacturing systems. This cleaning method has been demonstrated to remove Sn and restore EUV reflectivity to multilayer mirrors. The latest developments in understanding the fundamental physics behind this method are presented. In addition, any hydrogen-based cleaning technique will have to deal with the etching product SnH_4, which is an unstable molecule that can easily re-deposit on surfaces. Since the removal of SnH_4 with minimal redeposition is crucial to hydrogen plasma cleaning, relevant processes and physics behind SnH_4 removal and dissociation are discussed.

Finally, with an eye to the continuation of Moore's Law and lithography in the EUV region, issues affecting 6.7nm lithography are discussed. It is possible for 6.7nm optics to overcome their small bandwidth by achieving high peak reflectivity if research into deposition techniques continues. Additionally, conversion efficiency can possibly be raised by means of a proposed method of synthesizing Gd-rich particles.

Presenting Author

Dr. David N. Ruzic is the Director of the Center for Plasma Material Interactions at the University of Illinois at Urbana-Champaign. He is a full professor in the Department of Nuclear, Plasma, and Radiological Engineering and affiliated with the Department of Electrical and Computer Engineering and the Department of Physics, having joined the faculty in 1984. His current research interests center on plasma processing for the microelectronics industry (deposition, etching, EUV lithography and particle removal) and on fusion energy research. Prof. Ruzic is a Micron Professor at Illinois and a Fellow of the American Nuclear Society and of the American Vacuum Society. He is the author of the AVS monograph, *Electric Probes for Low Temperature Plasmas*, numerous book chapters, patents, and over 100 refereed journal articles. He obtained his PhD and MS in Physics from Princeton University, and his BS degree in Physics and Applied Math from Purdue University. He really enjoys teaching and tries to blow something up during every lecture.

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