2015
International Symposium on
Extreme Ultraviolet Lithography

5-7 October
Maastricht,
The Netherlands

Abstracts of Oral Presentations

Session 1: EUV Insertion in Manufacturing 1

PROGRESS ON ENABLING EUV LITHOGRAPHY FOR HIGH VOLUME MANUFACTURING

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Since multiple production-type scanners NXE3300 have been installed in the field since 2013, tremendous efforts have been made to prove the productivity and reliability of the EUV lithography scanner for high volume manufacturing. Several reports have indicated the progress on the source power up to 80W and thus achieved record of more than a thousand wafers exposed in a day. Gradually, the reliability of the source was improved and we started the marathon test to demonstrated the capability for consecutive 4 weeks, not only productivity but also thorough measurement of CD and overlay. The result was very encouraging. Since scanner capability is moving ahead, the mask defectivity issues popped up. The mask defects, including the mask blank native defect and the fall-on particles, remain to be the biggest question marks. In this presentation, the convincing progress to enable EUVL for high volume manufacturing will be shown.

EUVL READINESS FOR 7NM

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The use of multiple-patterning techniques has allowed extension of 193 immersion lithography far beyond original expectations, but at the cost of significantly increasing the number of processing steps. Insertion of EUV lithography for the 7nm node is desirable to reduce the number of processing steps, but committing a node to EUVL requires confidence in both the cost-of-ownership of EUVL tools in the long term, and in the readiness of EUVL tools and infrastructure to support technology development in the near term.

Several NXE:3300 tools at end users have demonstrated imaging and overlay performance meeting or exceeding expectations. Scanner availability and reliability excluding the source are reasonable for early production tools. Source power in the field is still around one third of that needed for cost-effective production, but this power level has been adequate for short- and medium-term demonstrations of productivity that debunk claims that EUV lithography can never achieve high productivity. Aside from source power, the biggest problems with current system performance are the poor availability and predictability of the source, but there has been solid progress on this front as more tools have come online in the field. Demonstrations of tool performance at customer sites have also reinvigorated efforts to close the remaining gaps in EUV infrastructure, particularly related to masks and resist.

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Session 2: EUV Insertion in Manufacturing 2

INSERTING EUV LITHOGRAPHY AT 7NM

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EUV has made tremendous strides towards insertion at the 7nm Node both commercially and technically. Commercially, the number of announced tool orders has reached 28. Technically, the scanner platform has been robust in terms of CD and overlay. The lens system has maintained its performance and continues to perform within specifications. Mask technology has shown significant progress in terms of mask fabrication while pellicle technology continues to make strides**.** Interim inspections solutions have been established to handle masks adders. Fundamentally, EUV materials have the capability to support the 7nm node resolution requirements. Finally, the first 7nm IC devices have been fabricated leveraging EUV.

There remains critical areas in which progress must continue: Mask technology, (simultaneous) source reliability-power, and resist performance. With the ramp of EUV tools in the fields, the volume of development wafers being exposed per day is increasing which is driving the need to improve mask blank. There is a promising path forward in terms of blank deposition. As in 193nm lithography, the durability of the patterned mask must be thoroughly proven over years and many thousands of exposures. As we detailed previously, source reliability has been shown over the course of months at a power of 40W. However, long term durability of the source needs to be addressed with specific attention to tin mitigation, and droplet generator robustness. IBM’s EUV system has completed the UP2 source upgrade, the next step along that path. We will detail our experience with the upgraded source. Resist performance has continued to improve but lags optical imaging capability. Collectively, the imaging performance of EUV has defined benefits in terms of resolution**,** variation, design, and simplification (relative to a 193i multiple patterning incarnation) that persuade the industry to adopt EUV at the 7nm node.

NXE:3300 INSERTION FOR N7: STATUS AND CHALLENGES

Vicky Philipsen[1], Iacopo Mochi[1], Lieve Van Look[1], Gian Lorusso[1], Kim Vu Luong[1,3], Eric Hendrickx[1], Friso Wittebrood[2], Guido Schiffelers[2], Eelco van Setten[2], Timon Fliervoet[2], Mircea Dusa[2]
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As the design rules for the next technology node - called N7 - are being defined, also the opportunity of EUV insertion into this N7 node is being explored by the industry. The two main patterning paths for N7 include the full adoption of EUV single patterning for the core and EUV insertion for the block layer after ArFi multiple patterning of the core. Meanwhile, state-of-the-art NXE:3300 scanners are being deployed enabling the pitch requirements for the N7 technology node.
In this experimental study we verify the printability limits on a NXE:3300 scanner for EUV single patterning of both 2D and 1D N7 metal-compatible building blocks. We report on the impact of different illumination conditions and resist processes on the resolution pitch of trenches as well as tip-to-tip resolution and 2D constructs. Using process window analysis, we evaluate how Best Focus shifts through a large pitch range (34nm to 88nm) impact the overlapping process window of trenches. We also studied two-bar trench printability for various pitches because of their pattern placement sensitivity to mask 3D effects and scanner settings. These experimental findings have been validated and interpreted using rigorous mask 3D simulations.
In conclusion, we will present experimental printability results from a NXE:3300 scanner in support of the N7 EUV single patterning options, including an assessment of intrinsic EUV effects such as Best Focus shifts and pattern placement through focus.

EDGE PLACEMENT ERROR ANALYSIS FOR N7 LOGIC PATTERNING OPTIONS

Eelco van Setten[1], Eleni Psara[1], Friso Wittebrood[1], Dorothe Oorschot[1], Vicky Philipsen[2], Jo Finders[1], Mircea Dusa[3], Joep van Dijk[1], Guido Schiffelers[1], Eric Hendrickx[2]
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While the 10nm logic node is getting ready for High Volume Manufacturing, the industry has started to make the technology and design choices for the 7nm node. An important question for the industry is whether to make an irreversible choice for EUV, or to keep both EUV and ArFi multi-patterning as options. In the former case, it implies that the design rules of several critical layers will be such that the resulting 2D patterns can only be reliably imaged using EUV. In the latter case, the design rules result in 1D like patterns which are compatible with ArFi multiple patterning, either by application of cut-/block masks or by direct print.

In this presentation we will compare the various patterning options by means of an edge placement error (EPE) based performance analysis. We will explain the advantages and considerations of an EPE budget compared to a traditional CDU budget. The EPE analysis will be applied on imaging results using critical building blocks or constructs taken from 1D and 2D logic designs. These include cut mask, line-ends, 2D patterns and various L/S features. The trade-offs between the different designs in terms of imaging performance will be evaluated, showing the minimum pitch and tip-to-tip or tip-to-line that can be supported based on the required EPE budget. Opportunities for further optimization will be explored by looking at OPC / (source) mask optimization, resist and scanner improvements.
In the end we will summarize the trade-offs for the N7 design choices based on the EPE assessment and its impact on the EUV roadmap.

EXPERIMENTAL VERIFICATION OF PHASE INDUCED MASK 3D EFFECTS IN EUV IMAGING

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EUV lithography is in the qualification phase as next-generation lithography technique for high volume manufacturing of future node semiconductor devices. As EUV will be introduced for highly advanced nodes at low k1 factor, understanding of the interaction between the angular illumination and the EUV reticle is a key enabler to overcome challenges in EUV imaging and to improve imaging quality on wafer.

EUV specific imaging challenges are often referred to as 'mask 3D effects' which include HV bias, best focus shifts through pitch, pattern shift through focus and fading induced contrast loss. Recent publications show the relation between phase shifts in the diffracted orders coming from the EUV mask and effects observed on wafer. Assessments of phase and amplitude of the diffracted orders for illumination with a limited number of angles in combination with simulated mask 3D effects provide insight in the theoretical effects and possible paths towards mitigation of mask 3D effects for EUV lithography.

In this study we build a bridge between simulations for simplified illumination settings (limited number of angles) and the mask 3D effects observed on wafers exposed on an NXE:3300 EUV scanner with illumination settings which in general cover a wide range of angles. Lithographic simulations are set up to mimic the conditions of the wafer exposure and to extract the phase and amplitude of the diffracted orders.
The extracted phase and amplitude for the full angular distribution of the illumination setting is linked to simulated through pitch best focus curves and pattern shift. For verification, the simulated effects on wafer are compared to experimental obtained best focus through pitch curves.

IMPLEMENTATION OF MODEL-BASED ASSIST FEATURES IN EUV

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With 18nm line width and 0.33 NA, k1 factor reaches 0.44 in EUV lithography. By comparing with the k1 factor in KrF and ArF lithography, it seems reasonable to consider using sub-resolution assist features (SRAFs) at this point. However, unlike ArF lithography, EUV has its unique characteristics, including the shadowing effects and the through slit effect. These effects may require different SRAF rules for different directions of the edges or corners, and also different rules at different slit locations, under certain printing criterions. Another difficulty in EUV SRAFs comes from the SRAF size. Due to mask manufacturing limit and the small main feature size in the advance nodes, the size of the SRAF is no longer much smaller than the main feature size in EUV. In order to avoid SRAF printing, the SRAF location has to be very sensitive to the change of main feature size and pitch. Hence, generating a good set of rule-based SRAFs is much more difficult in EUV lithography. In this paper, we use different patterns as the test cases, including 1D and 2D features, and investigate if the model-based SRAF solution is easier to use and predicts better printing results than the rule-based SRAF solution.

Abstracts of Oral Presentations

Session 3: EUV Light Source

EUV SOURCES: PROGRESS TOWARDS INDUSTRIALIZATION

Alberto Pirati[1], Sjoerd Lok[1], Rudy Peeters[1], Daniel Smith[1], Arthur Minnaert[1], Martijn van Noordenburg[1], Joerg Mallmann[1], Judon Stoeldraijer[1], Christian Wagner[2], David Brandt[2], Daniel Brown[2], Herman Boom[1], Hans Meiling[1], Roderik van Es[1]
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Significant progress in power extraction from MOPA+PP EUV sources enabled customer device development in the last 12 months.
To enable the use of EUV technology by semiconductor device manufacturers in volume production, improvements in availability, reliability and performance stability of EUV lithography systems, and specifically of EUV sources, are required.
This paper describes the activities on going, and the progress to date, of industrialization activities targeting EUV sources, focusing on the areas of Tin management, CO_2 power and overall system reliability; all these activities require to be planned and executed in parallel with the continuous increases in power required to enable cost effective device shrink at ASML customers.
Field results, particularly in the area of productivity, will be reported and explained.

IN-SITU EUV COLLECTOR CLEANING BY HYDROGEN PLASMA

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Extreme Ultraviolet (EUV) sources produce energetic Sn debris, which subsequently deposits on the collector optic, degrading reflectivity. Debris management (mitigation and cleaning) is essential with increasing demand for EUV power and source availability. This paper presents recent results of next generation techniques for hydrogen plasma cleaning of tin, a technology that has the potential for in-situ implementation addressing two important issues: 1) Sn cleaning and 2) source availability. This technique also has potential usefulness for EUV extension at smaller node sizes.
The fundamental processes behind Sn etching are being studied in order to optimize the Sn removal rate.
Specifically, the etching product SnH_4 is weakly bound and can easily dissociate, causing re-deposition; in order to minimize this effect, the etching, transport, and redeposition processes must be understood. A theoretical framework for Sn removal has been developed, and modeling is being undertaken. Results are presented from experiments designed to yield the previously-unknown probabilities of Sn etching and redeposition. Additionally, a zero-dimensional plasma chemistry model for H_2 has been developed to validate a catalytic radical-probe, which can measure the density of etching radicals anywhere in the plasma. Finally, a discussion of possibilities for cleaning of fuels in the 6.7nm range is presented.

UPDATE OF ONE HUNDRED WATT HVM LPP-EUV SOURCE PERFORMANCE

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, Takashi Saitou
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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 CO2 laser. We have reported engineering data from our resent test such around 118W average clean power, CE=3.7%, with 100kHz operation and other data[1]. We have already finished preparation of higher average power CO2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation[2]. We observed 140W operation with 50% duty cycle during 10 minutes and 2 hours with 100W level operation[3].
Further improvements are underway, we will report the latest challenge to more than one hundred watt stable operation more than several ten hours level, around 4% CE with 20 micron droplet and magnetic mitigation.

References:

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2. Yoichi Tanino et al.:" A Driver CO2 Laser Using Transverse-flow CO2 Laser Amplifiers" EUV Symposium 2013, (Oct.6-10.2013, Toyama)
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LOW-LOSS AND HIGH-GAIN CO2 AMPLIFIERS TO GENERATE EXTREME ULTRAVIOLET (EUV) POWERS OF 250W AND > 500W

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Transverse-gas-flow CO2 lasers are under development to supply low-loss and high-gain amplifiers for laser drivers to generate high-power extreme ultraviolet (EUV) beams. To generate EUV powers of > 250W that are required for wide-acceptance of EUV sources for lithography application, it is calculated that CO_2 laser of >20kW is required with state-of-the-art pre-pulse technology. To generate >20kW without losing the electrical efficiency, the CO_2 amplifiers must be configured based on low-loss and high-gain configuration. After comparing several candidates, we propose transverse-gas-flow CO_2 lasers as the best for the configuration.
We are going to show results on 25kW transverse-gas-flow CO_2 laser drivers analyzing the performances both theoretically and experimentally and also we are going to show theoretical calculations for further enhancements of CO_2 laser powers. We are also going to discuss ecosystems including academic people to enhance the EUV laser powers on the mask by supplying better reflective mirror systems for EUV scanners.

SASE, RAFEL, OSCILLATOR, OR A SELF-SEEDED FREE-ELECTRON LASER SOURCE FOR EUV LITHOGRAPHY

Erik R. Hosler[1], Obert R. Wood II[1], William A. Barletta[2], Moshe Preil[3]
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Free-electron lasers have recently been explored as economic, single-source alternatives to laser-produced plasma sources for powering an entire Fab's EUV lithography program (>500 W per scanner). Successful free-electron laser industrialization will require the best possible choices for facility configuration, type of electron injector, hardware redundancies to ensure maximum availability, and overall efficiency i.e., energy recovery, multipass linac, and undulator tapering. Paramount among these design choices is the choice of the free-electron laser emission mode, specifically, self-amplified spontaneous emission (SASE), an oscillator with resonator mirrors, regenerative amplification (RAFEL), or self-seeding with a second undulator stage. Considering the benefits and complications of each emission mode, the trade-offs between center wavelength, bandwidth, and pulse energy stability vs. industrialization, high-power operation, and coherence are discussed with respect to existing light sources and components as well as future advances and developments.

The outlined emission modes and their respective impact on lithography operations will be discussed using data from previous experimental work carried out at various scientific user facilities and extrapolated from the results of previously published simulation work. A scorecard evaluating each emission mode against fab integration and lithography requirements is prepared as a guide for future research and development. Since each emission modes will drastically alter the cost and complexity of light source operation, there will consequently be a substantial impact on the associated lithography program and ease of tool integration. Free-electron laser emission mode selection will therefore be essential for ultimately evaluating the free-electron laser use case for the semiconductor industry.

CHALLENGES AND OPPORTUNITIES FOR AN INDUSTRIAL EUV FREE ELECTRON LASER

Alex Murokh[1], Aaron Tremaine[2], Tor Raubenheimer[2], Pietro Musumeci[3], Alexander Zholents[4], Patrick Naulleau[5], John Byrd[5], Marco Venturini[5], David Bruhwiler[6], Bob Kephart[7], Stephen Webb[6]
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Free Electron Laser (FEL) is an accelerator driven source of tunable directional light, which principle of action makes it intrinsically immune to key limiting factors of media based sources, such as heat transfer and contamination. As such, FEL technology can be scaled to generate very high output power at 13.5 nm, congruent with the needs of the EUV lithography application in a non-granular configuration. However, developing a viable industrial source for EUVL requires a significant rethinking of the state-of-the-art FEL facilities, including re-optimization of the FEL design, topology, components and operations. This paper presents an overview of the physics and engineering challenges in developing an industrial FEL at 13.5 nm, provides an initial assessment of the industrial FEL road map, and describes relevant ongoing developments under the realm of LCLS-II project in the US.

Abstracts of Oral Presentations

Session 4: Mask Inspection and Review 1

EUV MASK INFRASTRUCTURE READINESS FOR HVM; DO WE OVERLOOK SOMETHING IMPORTANT?

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EUV mask is one of the key components to realize the EUV lithography for High Volume Manufacturing (HVM). Our industry and global consortia have been developing and industrializing the EUV mask related technologies, such as blank material, mask patterning, quality assurance technologies, mask handling, etc. including the different technologies and tools from current optical masks, for the EUV wavelength and the EUV exposure environment. In recent years, significant progress was made in EUV blank / mask defect inspection and mitigation technologies. This encourages our industry to adopt the EUV lithography for HVM.
In this presentation, readiness, challenges, remaining issues, and prospects of EUV mask related technologies and infrastructures, will be described and compared to optical wavelength technology.

STATUS AND RECENT ACHIEVEMENTS OF THE AIMS™ EUV SYSTEM FOR ACTINIC REVIEW OF EUV MASKS

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For the successful introduction of EUV lithography into volume production, the EUV mask infrastructure needs the capability to provide defect free masks. To achieve this, actinic review of potential defect sites to decide on the need for repair or compensation is required. In a closed loop mask repair solution, the repair or compensation with the **MeRiT®** electron beam repair tool needs actinic verification. ZEISS and the SUNY Poly SEMATECH EUVL Mask Infrastructure consortium started a development program for a EUV aerial image metrology system, the **AIMS™ EUV,** for the realization of actinic mask review.
After providing first aerial image measurements on the prototype and achieving the base capabilities of aerial imaging and EUV mask handling thereafter, the **AIMS™ EUV** development program has now entered the calibration and qualification phase of the prototype. In this paper, we provide an update on the program and qualification status.

EUVL PATTERNED MASK INSPECTION FOR 11 NM HALF-PITCH (HP) GENERATION WITH DEFECT DETECTION CAPABILITY ENHANCEMENT BY A LEARNING SYSTEM

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Patterned mask Inspection (PI) is one of the major issues to realize device fabrication with EUV lithography. EIDEC and EBARA Corporation have been developing a mask inspection system with Projection Electron Microscope (PEM) technology. A learning system has been developed to reduce cost and labor that would be justifiable in attaining a detection capability to meet challenges posed by the newly defined mask defects. The learning system for the PEM consists of a library of registered defects, an image-processing unit exactly equivalent to the image-processing unit in the inspection system, and an engine for optimization. The learning system totally optimizes the detection capability reconciling the previously registered defects and the newly registered defects. The enhancement of the detection capability for the PEM system is easily achieved at the operation site. We have verified the effectiveness of the learning system. We demonstrated the detection capability for hp11nm installed on the PEM inspection system. By this learning system, we can provide a user-friendly mask inspection system with a higher throughput and lower cost of ownership than by the PEM.

This study is supported by New Energy and Industrial Technology Development Organization (NEDO) and Ministry of Economy, Trade and Industry (METI).

DEFECT REVIEW CAPABILITY ON ACTINIC BLANK INSPECTION TOOL

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[1]*Lasertec Corporation, Yokohama;* [2]*EUVL Infrastructure Development Center, Inc. (EIDEC), Tsukuba, Japan*

Actinic blank inspection (ABI) tool have successfully developed in the EIDEC BI program. ABI tool is the only inspection tool that can detect printable phase defect in the multilayer and the tool is used for qualifying the EUV mask blanks. The tool is designed to inspect EUV mask blanks to capture the lithographically significant defects on the blanks. The tool also equips the reviewing function to observe and analyze the captured defects. We confirmed the reviewing function is useful not only for the blank defects but also the mask pattern defects. Using the function, we can clearly identify the defects in the patterned EUV mask. Observing the image including a defect, we can analyze the actinic property of the defect. This is a great advantage of the reviewing function using the EUV light of the lithography wavelength. The observed defect images by the review function on ABI will be reported at the conference to discuss the feasibility of the function to support the mask quality insurance.

This work is supported by NEDO and METI.

ASSESSMENT OF AIMS™ EUV AND SHARP ACTINIC WAVELENGTH MASK DEFECT REVIEW TOOLS FOR THE EVALUATION OF BLANK DEFECT PRINTABILITY

Erik Hosler[1], Erik Verduijn[1], Pawitter J.S. Mangat[1], Obert R. Wood II[1], Renzo Capelli[2], Sascha Perlitz[2], Krister Magnusson[2], Vibhu Jindal[3], Markus P. Benk[4], Antoine Wojdyla[4], Kenneth A. Goldberg[4]
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EUV lithography continues to be a potential patterning option for high volume manufacturing at future patterning nodes. For the more challenging layouts, such as logic, EUV masks will need to have essentially-zero printing defects. Despite a significant improvement in the manufacturing of low defect mask blanks, it is inevitable that some defects will be present and unless these defects are mitigated they may print. Developing viable mitigation strategies will require mask review tools capable of accurately determining defect printability.

In this paper we present a comparison of the AIMS™ EUV (ZEISS) and SHARP (SUNY Poly SEMATECH) actinic wavelength mask review tools for assessing the printability of mask blank defects. We show that these actinic review tools can accurately predict most of the blank defects that will print using an NXE:3300B scanner and help establish ground rules for EUV mask defect repair. Both qualitative comparisons of defect images and quantitative correlations of aerial image profiles measured by the AIMS™ EUV and SHARP actinic review tools will be included in the talk.

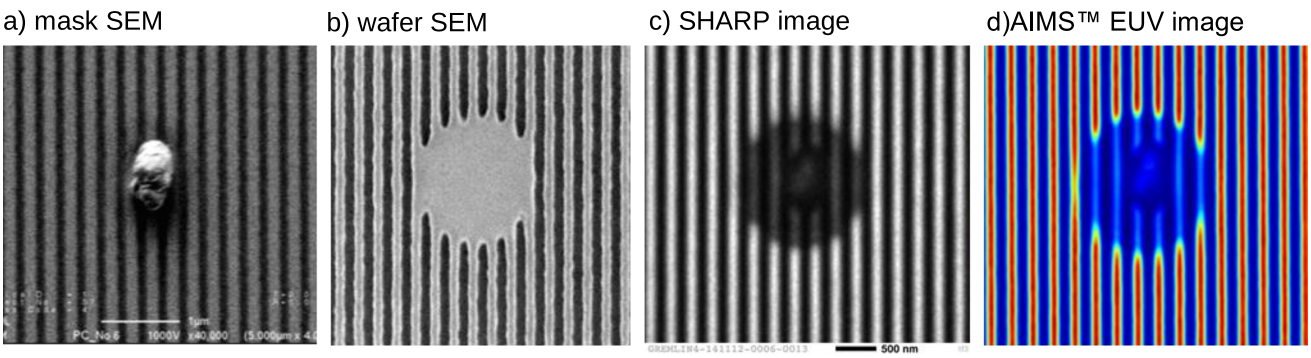

Figure 1 Images of a large blank defect captured with (a) mask SEM, (b) wafer SEM, (c) SHARP actinic microscope, and (d) AIMS™ EUV revealing that the actinic tools capture fine details not seen by a mask SEM.

HIGH-RADIANCE LDP SOURCE FOR MASK INSPECTION

Yusuke Teramoto, Bárbara Santos, Guido Mertens, Ralf Kops, Margarete Kops, Alexander von Wezyk, Klaus Bergmann, Hironobu Yabuta, Akihisa Nagano, Noritaka Ashizawa, Takahiro Shirai, Kiyotada Nakamura, Hitoshi Katsuyama, Kunihiko Kasama
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High-throughput actinic mask inspection tools are needed as EUVL begins to enter into volume production phase. One of the key technologies to realize such inspection tools is a high-radiance EUV source of which radiance is supposed to be as high as 100 W/mm2/sr. Ushio is continuously developing laser-assisted discharge-produced plasma (LDP) sources. Ushio's LDP source is able to provide sufficient radiance as well as cleanliness, stability and reliability. Radiance was confirmed to be 120 W/mm2/sr behind the debris mitigation system and peak radiance at the plasma can be as high as 180 W/mm2/sr. One of the unique features of Ushio's LDP source is cleanliness despite liquid tin as fuel material. Source cleanliness was evaluated by placing Ru mirror samples behind the debris shield. Samples were exposed for at least 100 Mpulse and surface of each sample was analyzed with XRF and SEM. Deposition of tin was negligible and sputter rate of ruthenium was a few nm per Gpulse. Collector lifetime is therefore considered to be sufficiently long. Days-long non-interruption runs were also carried out to address system reliability and long-term stability. A prototype source has been successfully assembled and has begun its test programs.

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Session 5: EUV Resist 1

THE ROAD TOWARDS SINGLE DIGIT NANOMETER RESOLUTION PATTERNING IN MASS PRODUCTION: STATE-OF-THE-ART EUV RESISTS PLATFORMS COMPARED

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It is with no doubt that extreme ultraviolet lithography (EUVL) at 13.5 nm still stands as the main candidate for patterning for sub-10 nm technology nodes in the semiconductor industry. Yet, it is still unclear which resist platform will be favored once this wavelength driven lithography shift (from λ = 193 nm deep UV immersion lithography) occurs and which might dominate the industry even further in the future (sub-5 nm technology nodes). Here, we present a comparative study among three distinct and highly performing state-of-the-art resist platforms, namely an organic chemically amplified resist (CAR), a negative tone chemically amplified molecular resist and a Sn-based metal organic resist as they compete and undoubtedly complement each other (depending on the resolution and material properties needed) in the race towards single-digit nanometer resolution patterning in high volume manufacturing (HVM) of semiconductor devices.

A thorough characterization of their resolution, line-edge roughness (LER), sensitivity-dose to size- and exposure latitude (EL) when exposed under the same conditions using EUV interference lithography at the Swiss Light Source in the Paul Scherrer Institute is presented with the goal to resolve sub-10 nm line/space patterns as it relates to HVM needs. Our results confirm the feasibility of EUV lithography in high volume manufacturing from the resist material performance point of view.

NOVEL EUV RESIST DEVELOPMENT FOR 13 NM HALF PITCH

Satoshi Dei[1], Masafumi Hori[1], Motohiro Shiratani[2], Takehiko Naruoka[2], Tomoki Nagai[2], Motoyuki Shima[2]
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Extreme ultraviolet (EUV) lithography is a promising candidate for the manufacturing of semiconductor devices at the sub-13nm 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. It is well-known that the key challenge for EUV resist is the simultaneous requirement of ultrahigh resolution (R), low line edge roughness (L) and high sensitivity (S). In this paper, we will report the recent progress of resolution and sensitivity for sub-13nm half pitch LS pattern and beyond.

STUDY ON DEFECT CONTROL OF RESIST PROCESS FOR PRODUCTION READY EUV LITHOGRAPHY

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Although many competing technologies have developed, Extreme ultraviolet (EUV) is the most powerful candidate for post ArF immersion lithography. Since the introduction of the latest NXE3300, many significant results have been reported. Especially recent throughput increase by 80W source power is most remarkable. It is thought to be quite sufficient to encourage EUV community to accelerate preparations for high volume manufacturing.

For the implementation of EUV lithography to HVM, we need to overcome a lot of challenges such as higher source power, mask defectivity and resist trade- off and so on. In addition, suppression of resist defect on process becomes another important requirement because infinitesimal change in material or process can be easily turned into defect and this tiny defect can degrade productivity.

In this paper, the overall-control-method of EUV resist defect was investigated. First, patterned wafers were prepared using NXE3300 and the latest TEL track. In order to examine resist defects, pattern wafer inspection tool and CDSEM are used for defect classification and repeating mask defects are excluded carefully. We tried to explain the root causes of various kind of defect in classified defect types. Experimental to reduce EUV defects by proper arrangement of materials and process were followed and the results will be presented.

SUB-50 NM METROLOGY ON EUV CHEMICALLY AMPLIFIED RESIST – A SYSTEMATIC ASSESSMENT

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With EUVL lithographic patterning dimensions decreasing far below 50 nm, it is of high importance to understand metrology at such small scales. In order to determine the differences between various (local) Critical Dimension (CD) metrology techniques we conducted an experiment using scatterometry, CD-Scanning Electron Microscopy (CD-SEM), Helium-ion Microscopy (HIM) and Atomic Force Microscopy (AFM).
We present metrology results obtained from dense arrays of contact holes with various CDs (15 – 50 nm) patterned in a chemically amplified resist (CAR) using an ASML EUV scanner and measured at ASML and TNO. We discuss the observed similarities and differences between the various techniques. To this end, we assessed the spatial frequency content in SEM, HIM and AFM images. Furthermore, we analyzed SEM, HIM and AFM waveforms in detail. HIM and AFM resolve the highest spatial frequencies, which is attributed to the more localized probe-sample interaction for these techniques. CD-SEM requires advanced beam scan strategies to mitigate sample charging. All techniques show good correlation albeit the reported CD values systematically differ significantly. A significant speed boost for HIM (10x) and AFM (1000x) would be required before these techniques are to capable of serving the demanding industrial metrology applications like OCD and CD-SEM do nowadays.

A DEFECTIVITY STUDY ON DRY DEVELOPMENT RINSE PROCESS (DDRP)

Harold Stokes[1], Yan Thouroude[1], Dieter Van Den Heuvel[3], Safak Sayan[2,3], Philippe Foubert[3], Danilo De Simone[3]
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Pattern collapse currently limits the achievable resolution of the highest resolving EUV photoresists available. The causes of pattern collapse include surface tension during the rinse process and resist pattern shrinkage during the drying step[1].
To overcome this issue, the dry development rinse material (DDRM) was developed for both positive and negative tone process schemes[2].
In this contribution, we will report defect reduction studies focusing on defects and associated root causes to achieve improved understanding for the dry development rinse process (DDRP) on 300mm blanket and patterned silicon wafers. This work identifies DDRM as an acceptable patterning material from a defectivity perspective in addition to enabling improved resolution via pattern collapse mitigation as reported in ref[1].

References:

1. Safak Sayan et al., Proc. SPIE 9425, Advances in Patterning Materials and Processes XXXII, 942516, (April 1, 2015); doi:10.1117/12.2086486
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Abstracts of Oral Presentations

Session 6: Mask Inspection and Review 2

RECENT PROGRESS OF EUV BLANKS DEVELOPMENT

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Extreme Ultra Violet Lithography (EUVL) mask blanks are one of the key enabling technologies for EUVL implementation for the 16nmhp (7nm node) and beyond. Low defect density EUVL mask blanks have consistently been one of the critical technology gaps identified as a gating technology for EUVL commercialization. To help bridge this gap, precise defect control during the Mo/Si multilayer deposition process and on the Low Thermal Expansion (LTE) substrate are essential to achieving zero killer defects and to controlling defects below the mitigatable number. Additional key technology gaps such as substrate flatness, bow, etc. have to be met to support key lithography criteria. In this presentation, the recent development progress of EUVL mask blanks at HOYA Corporation will be introduced and the overall readiness of EUVL blanks to ramp for commercialization of EUVL will be reviewed.

ABI TOOL PERFORMANCE CONFIRMATION BY NXE3300 PRINTING RESULTS FOR NATIVE EUV BLANK DEFECTS

Rik Jonckheere[1], Hidehiro Watanabe[2], Noriaki Takagi[2], Dieter Van de Heuvel[1], Takeshi Yamane[2], Emily Gallagher[1]
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EIDEC and imec jointly report the results of their collaboration on ML-defects, the EUV-specific type of defect relating to the multilayer (ML) mirror on the mask. Successful correlation is demonstrated between actinic blank inspection on the ABI tool under development at EIDEC, in collaboration with Lasertec, and a wafer printing evaluation by imec on the ASML NXE3300 EUV scanner. At 27nm and 22nm half-pitch both forward correlation, from blank inspection to on-wafer review, as well as backward correlation, from wafer inspection to blank inspection, were successfully executed. We could determine a printability threshold based on ABI detection intensity, and we could confirm that ABI had detected all ML-defects on the blank that could be revealed by the repeating defects found during inspection of the printed wafer. A major contribution in the forward correlation was obtained by application of the high magnification review capability of the ABI tool, intended for blank review with the higher position resolution, to assess whether a ML-defect detected on the blank became covered by the absorber pattern of the mask, or not. The present publication will focus on the 22nm hp results and give an outlook on the extended collaboration towards 16nm hp.

ACTINIC MASK IMAGING: TAKING A SHARP LOOK AT NEXT GENERATION PHOTOMASKS

Markus Benk, Antoine Wojdyla, Kenneth Goldberg, Patrick Naulleau
Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, USA

The Semiconductor High Numerical Aperture Actinic Reticle review Project (SHARP) is a synchrotron-based, extreme ultraviolet (EUV) microscope dedicated to advanced photomask research. SHARP flexibly emulates the specifications of current lithography tools and several generations into the future. SHARP now contributes photomask research in defect detection, printability and repair; substrate and pattern roughness; optical proximity correction and mask architecture. Future directions in EUVL include optimized freeform pupil fills (i.e. source-mask optimization) and higher mask-side NA values, including anamorphic imaging.

With its fully programmable angular source spectrum and coherence control, SHARP can study imaging with conventional and arbitrary source profiles today. The tool emulates both pixelated and continuous sources with either binary or continuous angular flux densities. SHARP now includes high-NA imaging optics at mask-side NAs of 0.125 (0.5 4x) and 0.156 (0.625 4x), and will soon include emulation of an anamorphic projection optic at approximately 0.55 NA.

We will present our recent demonstration of real-space imaging of 22-nm half-pitch mask features (5.5-nm wafer equivalent), aerial image metrics with freeform sources, and general imaging at higher mask-side NA values.

ENHANCED DEFECT SENSITIVITY BY ZERNIKE PHASE CONTRACT FOR ACTINIC BLANK INSPECTION

Yow-Gwo Wang[1], Rene Claus[1], Ryan Miyakawa[2], Weilun Chao[2], Kenneth Goldberg[2], Andy Neureuther[2], Ted Liang[2], Patrick Naulleau[2]

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Efficient detection of multilayer defects on EUV mask blanks is one of the critical challenges facing high-volume manufacturing. In this paper, we will cover both simulation study and the experimental demonstration of Zernike phase contract microscope using the SHARP EUV microscope at LBNL.

First, we will explain the theory of Zernike phase contrast microscopy and show that this method is an efficient way to identify multilayer defects. Using phase shift and apodization to suppress the speckle noise induced by mask surface roughness, Zernike phase contrast shows the improvement on defect signal-to-noise ratio (SNR). Also, with simulations on different heights and widths, the data shows a good correlation between the defect size and the signal strength. Such correlation enables effective defect dispositioning without the use of complex computational algorithm.

By using Fresnel zoneplates with various phases and attenuation design, the experiment has been conducted using the SHARP EUV microscope. Using a programmed defect mask, the strong enhancement of defect signal and the suppression of noise have been verified experimentally. Showing that the Zernike phase contrast microscopy is a promising technique for EUV multilayer defect inspection.

DEFECTIVITY STUDY ON EXTREME ULTRAVIOLET MASK

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One of the biggest challenges facing manufacturers of EUV (Extreme Ultraviolet) masks today is the defectivity of EUV blanks. Defect levels on EUV blanks are improving, however, a considerable number of detectable defects still exist. These defects must be mitigated through pattern shift or repair if they affect wafer imaging. However, neither approach is fully mature, as current pattern shift technology has limitations, and defect repair (especially for buried defects) is still under development.

This paper will focus on the characteristics, detectability, and printability of EUV mask defects which are detectable by conventional blank and mask inspection tools. Defect inspection sensitivities are compared among different inspection method, correlated to physical characteristics, and the sensitivity are evaluated using wafer printability data. This paper will also include defect analysis of the defectivity of the Black Border region, augmented by assessing the defect printability through simulation. Finally, we will discuss the required defect specification for EUV masks based on those analyses.

A NOVEL METHOD IN EUV MASK REPAIR

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Taiwan Semiconductor Manufacturing Company, Ltd., Hsinchu County, Taiwan

Mask technology is an important component of EUV lithography, whereas mask repair is a critical step in mask making. Challenges for repairing EUV masks over traditional optical masks involve not only fixing the top absorber layer but also not damaging the underneath Ru capping layer during the repair process. Some research has reported using H_2O as a passivation gas to adjust the etching selectivity and further prevent spontaneous reaction between the absorber layer and the etching gas XeF_2. However, this method has been beset by several side-effects, such as oxidation of the underneath Ru capping layer by H_2O, which causes the Ru layer to be easily damaged by the reactive XeF_2 gas in absorber etching and the halo removal process of Cr deposition. Since durability of the absorber layer is highly correlated with the amount of H_2O, the repair strategy of the EUV mask has faced a dilemma. In light of the issue, trends toward using new gas chemistry with a low amount of H_2O and reduced accelerating voltage of electron beam during the repair process have been proposed. In this study, we examine the repair capability of the EUV masks by applying the concepts. Encouraging results confirmed by SEM, TEM, AIMS EUV and wafer printing showed both the etching selectivity of absorber layer and the repair yield were doubled. The new technique not only solves the issue of Ru capping layer damage but also proves to be a promising concept for next generation mask repair.

Abstracts of Oral Presentations

Session 7: EUV Resist 2

THE MULTIVARIATE POISSON PROPAGATION MODEL AND RESIST STOCHASTICS

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As we push resist resolution beyond 16 nm half pitch and strive for high sensitivity, stochastic limits are of increasing concern. To provide help assess stochastic limits in EUV resists the Multivariate Poisson Propagation Model (MPPM) [1-3] has been developed enabling rapid conversion of a two dimensional aerial image into a stochastic resist image. Here we report on the use of the MPPM in the performance assessment of a variety of leading 16-nm resist both with and without chemical amplification as compared to stochastic limits.

We compare the resist performance from a variety of perspectives including the Z-factor and two new metrics: dose to requirement (DTR) and the stochastic limit multiplier (SLM). Dose to requirement can be expressed as $DTR = S_m(L_p/L_t)^2$, where S_m is the measured sensitivity, L_m is the estimated photon-limited LWR using the MPPM, and L_p is the target LWR. This metric effectively removes resolution from the equation noting that resolution is in fact an inflexible requirement RLS tradeoff. The resulting number is an estimate of the best dose that could be achieved in the resist while meeting the LWR requirements assuming the material LWR terms are ignored. SLM on the other hand is quite similar to Nano-Z factor in that it is a ratio of the measured Z-factor to an ideal Z-factor, however, the ideal is determined through the MPPM instead of the ITRS roadmap. Since the model will through fitting force a fit to resolution and sensitivity, SLM simply becomes the ratio of the measured LWR to the stochastic model limit.

The results show that the best materials are nearing stochastic performance limits. Moreover we find all but one resist to be clearly dominated by material limits, be they stochastic material limits predicted by the MPPM or residual material limits due to terms not captured by the model.

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3. P. Naulleau, C. Anderson, W. Chao, S. Bhattarai, A. Neureuther, K. Cummings, S. Jen, M. Neisser, B. Thomas “EUV resists: pushing to the extreme,” J. Photopolym. Sci. Technol. 27, 725-730 (2014).

ADVANCES IN EUV NANOPARTICLE PHOTORESIST DEVELOPMENT

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Resist performance remains a significant challenge to the realization of EUV lithography for future technology nodes. Requirements for EUVL manufacturing require simultaneous delivery of high resolution, sensitivity, and low line width roughness (LWR) on commercial grade hardware. The ultimate resolution of organic-based chemically amplified resists (CARs) is currently limited by pattern collapse and/or acid blur below 12-14nm half-pitch[1] and requires higher doses than would be necessary for HVM. Inorganic-based nanoparticle photoresists have the potential to surpass CARs in future technology nodes because of their theoretically higher mechanical stability, non-acid-catalyzed mechanism, and increased EUV absorbance.
However, little is known about the reactivity of these novel materials compared to the extensive mechanistic knowledge of CARs. As such, only minimal structure-activity relationships have been observed. We present a detailed study of the photopatterning chemistry of metal oxide nanoparticle-based photoresists. Using spectroscopic analysis techniques and lithographic experiments, key insights into the patterning mechanism have been discovered, as well as factors affecting the resist stability. Using these results, we have made significant strides in simultaneously improving stability, contrast, dose and resolution of nanoparticle resists, illustrated in Figure 1. These process, structural and formulation improvements based on improved understanding of the nature of these materials will be discussed.

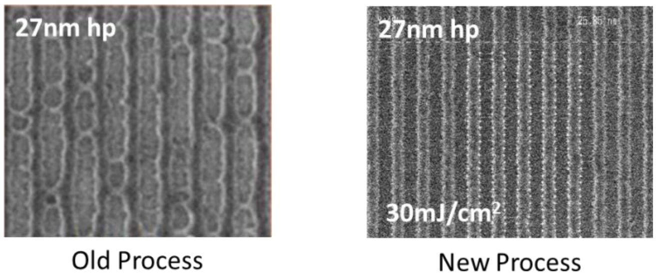

Figure 1 Process improvements of a nanoparticle resist at 27nm half-pitch using an NXE3300

Reference:

1. Kulmala, T., et.al. "Towards 10nm half-pitch in EUV lithography: results on resist screening and pattern collapse mitigation techniques," Proc. SPIE, 9422, EUV Lithography VI, 942204, 2015.

COMBINED EXPERIMENTAL AND THEORETICAL INVESTIGATION OF EUVL RADIATION CHEMISTRY FUNDAMENTALS

Frank Ogletree, Bo Xu, Kristina Closser, Oleg Kostko, Musahid Ahmed, Paul Ashby, Suchit Bhattarai, Yi Liu, Patrick Naulleau, Deirdre Olynick, David Prendergast
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EUVL radiation chemistry differs significantly from both deep UV and electron-beam lithography, and a fundamental understanding is required to guide the development of high-performance resist systems. Molecules with *4d* and *5d* elements (Sn, I, etc) have much higher x-ray absorption cross-sections than those with light elements (C, H, O) alone. Ionization of the semi-core levels, followed by Auger relaxation results in multiple secondary electrons and highly-ionized molecules, which can then fragment into radicals and ions.
We are bringing new experimental and theoretical methods to bear on EUVL. Energy-dependent secondary-electron distributions and molecular fragmentation patterns are experimentally measured for gas-phase resist component molecules exposed to variable-energy beams from either a synchrotron or an electron gun. Later the condensed-phase processes that follow the primary events will be analyzed using similar methods on aerodynamic beams of resist-coated nanoparticles.
In parallel, electronic structure tools are being used to calculate the photoionization contributions of different molecular orbitals and subsequent Auger relaxation branching ratios. Then *ab-initio* molecular dynamics are used to predict molecular fragmentation patterns. Once validated by comparison with experiment, predictive tools will be able to guide resist material development. We will describe our approach and present initial results.

IMPROVING EUV RESIST PERFORMANCE THROUGH MATERIAL DESIGNS

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The advancement of EUV lithography strongly depends on material performance. Chemically amplified resists have shown progress in improving resolution; however, it is still challenging to incorporate low-dose and line edge roughness (LER) requirements within the same resist. A method for achieving the resist performance targets is to decouple 1 or 2 of the 3 required properties ("Resolution, LER, and Sensitivity (*RLS*) tradeoff") from the resist. Brewer Science is designing underlayers that have been shown to induce dose reduction in resists and is exploring post-processing methods for lowering LER in positive- and negative-tone development (PTD and NTD) resists.

Another patterning option is to utilize inorganic resists. These have shown promise for achieving the required resolution and LER. Dose performance has decreased in recent months, but how these materials perform on substrates other than silicon is not well understood. It is also not known how chemical effects can affect the performance of inorganic resists when they are coated over spin-on carbon (SOC) layers. We will present preliminary work on performance of inorganic resists on SOC layers.

NOVEL ULTRA-HIGH SENSITIVE NON-CAR MATERIALS USING EUV EXPOSURE

Toru Fujimori, Toru Tsuchihashi and Toshiro Itani
EUVL Infrastructure Development Center, Inc. (EIDEC), Tsukuba, Japan

Extreme ultraviolet (EUV) lithography is considered to be the most effective strategy for realize sub-10 nm manufacturing and beyond. A key factor for the realization of EUV lithography is the choice of EUV resist material that is capable of resolving below 20-nm half pitch with high sensitivity. Recently, some researchers have reported concerns on the limitations in the performance of positive-tone chemically amplified resist (CAR). Consequently, there is a critical need for new chemistry and development of new resist materials.

This study describes novel ultra-high-sensitive non-CAR materials using EUV exposure for sub-10 nm manufacturing. Herein, the developments of novel non-CAR materials have been just started for improvement of sensitivity using ‘metal containing non-CAR materials’, called ‘EIDEC standard metal EUV resist (ESMR)’. The preliminary results of novel non-CAR materials indicate ultra-high sensitivity using EB lithography will be shown. In addition, the latest EUV exposure results will be presented in the symposium.

SUPPRESSION OF STOCHASTIC EFFECTS IN CHEMICALLY AMPLIFIED RESIST PROCESSES FOR EXTREME ULTRAVIOLET LITHOGRAPHY

Takahiro Kozawa[1], Julius Joseph Santillan[2], Toshiro Itani[2]
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Line edge roughness (LER) rapidly increases in the sub-10-nm-half-pitch region of resist processes used for the fabrication of semiconductor devices. Also, the stochastic defect (pinching and bridges) generation is a significant concern for the high resolution patterning with high throughput. In this study, the stochastic effects were investigated using a model resist with disclosed contents. The backbone polymer was a random hybrid polymer with methacrylate monomers and phenol monomers. Using the model resist, line-and-space patterns with 20-60 nm half-pitch were fabricated in the exposure dose range of 15-25 mJ cm-2. On the basis of the analysis of exposure results, the suppression of stochastic effects is discussed from the viewpoint of material design.

Abstracts of Oral Presentations

Session 8: EUV Resist 3

METAL OXIDE PHOTORESISTS: UNLOCKING THE FULL POTENTIAL OF EUV PATTERNING

Michael Kocsis[1], Andrew Grenville[1], Ben Clark[1], Jason Stowers[1], Peter De Schepper[1], Geert Vandenberghe[2], Danilo De Simone[2]
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Inpria is developing directly patternable, metal oxide hardmasks as robust, high-resolution photoresists for EUV lithography. Targeted formulations have achieved 13nm half-pitch resolution on an ASML NXE:3300B scanner. These materials are capable of substantially higher resolution by EUV patterning, having achieved 10nm lines on a 20nm pitch with 1.7nm LWR on the PSI EUV exposure tool. Inpria's second-generation materials have an absorbance of 20/µm, thereby enabling an equivalent photon shot noise compared to conventional resists at a dose lower by a factor of 4X. These photoresists have ~40:1 etch selectivity into a typical carbon underlayer, so ultrathin 20nm films are possible, mitigating pattern collapse. In addition to updates on lithographic performance, we review progress in parallel advances required to enable the transition from lab to fab for such a metal oxide photoresist. This includes considerations and data related to: metals cross-contamination, coat uniformity, stability, outgassing, etch, and rework.

CHALLENGE FOR 10NM RESOLUTION BY APPLYING DRY DEVELOPMENT RINSE PROCESS (DDRP) AND MATERIALS (DDRM)

Wataru Shibayama, Shuhei Shigaki, Makoto Nakajima, Ryuji Onishi, Rikimaru Sakamoto
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EUV lithography has been desired as the leading technology for single nm half-pitch patterning. However, the source power, masks and resist materials still have critical issues for mass production. Especially in resist materials, RLS trade-off is the key issue. To overcome this issue, we are suggesting Dry development rinse process (DDRP) & materials (DDRM) as the pattern collapse mitigation approach. This DDRM can perform not only as pattern collapse free materials for fine pitch, but also as the etching hard mask against bottom layer (spin on carbon: SOC). In this presentation, we especially propose new approaches to achieve high resolution around hp10nm. The key points of our concepts are 100% water solvent system and PR smoothing. This new DDR technology can be the promising approach for Hp10 level patterning in N7/N5 and beyond.

NOVEL MATERIALS BASED ON NEGATIVE-TONE IMAGING FOR EUVL

Hideaki Tsubaki, Wataru Nihashi, Toru Tsuchihashi, Takahiro Goto
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Negative-tone imaging (NTI), containing radiation-sensitive resist and organic solvent developer, is important lithographic process which contributes to shrinkage in various semiconductor devices. In NTI process, both resist and organic solvent play important roles in determining lithography performance not only resolution, but also line-width roughness (LWR) and sensitivity. However, these chemicals must be designed to satisfy numerous demanding requirements which are becoming more and more stringent as the minimum feature size continues to shrink.

Manipulation of dissolution properties by changing organic solvent developer and rinse solvent provides a novel NTI process designed for EUVL to obtain fine pattern beyond the limitation of imaging system based on alkaline developer. We report herein novel materials design to overcome resolution, LWR and sensitivity requirements.

A wide variety of resist, developer, and rinse solvents have been designed and evaluated to investigate their impacts on lithographic performances. A key finding here is to achieve high contrast and low swelling character during development step by manipulating solubility parameter of resist, developer, and rinse solvents. Lithographic performances of newly developed NTI process using a NXE:3300 will be also described in this paper in comparison with both traditional NTI process and positive-tone process.

IDENTIFYING EUV RESIST MATERIALS FOR SUB-10 NM NODES

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One of the main challenges in EUV lithography is the development of EUV resists fulfilling the strict sensitivity, resolution and line-edge roughness (LER) requirements. EUV interference lithography (EUV-IL) combines the simplicity of IL and the short wavelength advantage of EUV light, being an effective method for resist screening beyond the resolution capabilities of scanners. The EUV-IL tool at PSI has demonstrated world-leading resolution down to 7 nm half-pitch.

Here, we report our results on extensive screening of chemically amplified resists (CARs) and novel inorganic resists with high EUV absorption with the main focus on identifying the most promising materials when moving towards 10 nm HP resolution and beyond. Furthermore, we have optimized the processing parameters (such as developing, bake conditions, underlayers) for the most promising materials, yielding significant improvements in their performance. We report our results and provide extensive comparison of the performance (resolution, sensitivity, LER) of different resists and processing parameters. Finally, novel rinsing and pattern freezing methods that prevent pattern collapse as the resolution approaches 10 nm HP are discussed.

2015
International Symposium on
Extreme Ultraviolet Lithography

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Session 9: EUV Lithography Extendibility

ANAMORPHIC HIGH NA OPTICS ENABLING EUV LITHOGRAPHY WITH SUB 8 NM RESOLUTION

Bernhard Kneer[1], Sascha Migura[1], Johannes Ruoff[1], Matthias Rösch[1], Tilmann Heil[1], Winfried Kaiser[1], Jan van Schoot[2]
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Anamorphic high-NA EUV lithography is the most promising high-volume chip manufacturing solution for single shot patterning with sub 8 nm resolution. The titular anamorphic high-NA optics concept is at the heart of this system. It features a direction dependent, so called anamorphic magnification. This anamorphic optics allows to drive the numerical aperture (NA) beyond 0.5 enabling sub 8 nm resolution imaging without performance degradation via mask shadowing effects. Furthermore, it enables a 26 x 16.5 mm half-field imaging still using 6'' mask technology. Accordingly, the anamorphic high-NA EUV optics simultaneously allows for superior imaging performance and productivity.

In this paper, we report on most recent design progress of the anamorphic high-NA optics, and discuss selected system features. Furthermore, we present detailed studies of anamorphic imaging behavior assessing the performance of relevant sub 8 nm applications.

EUV HIGH-NA SCANNER AND MASK FOR SUB 8 NM RESOLUTION

Jan van Schoot[1], Koen van Ingen Schenau[1], Kars Troost[1], John Zimmerman[2], Sascha Migura[3], Jens-Timo Neumann[3], Bernhard Kneer[3], Winfried Kaiser[3]
[1]ASML, Veldhoven, The Netherlands; [2]ASML, Wilton, USA; [3]Carl Zeiss SMT GmbH, Oberkochen, Germany

EUV lithography for resolutions at 8 nm half pitch and below requires the numerical aperture (NA) of the projection lens to be significantly larger than the current state-of-the-art 0.33NA. In order to be economically viable, a throughput above 100 wafers per hour is needed.
As a result of the increased NA, the incidence angles of the light rays at the reticle increase significantly. Consequently the shadowing deteriorates the aerial image contrast to unacceptably low values.
As shown before[1], the only solution to reduce the angular range at the reticle is to increase the magnification in the scanning direction. Simulations show that this can be done with an anamorphic 4/8x step and scan system. Fields are printed that are half the size of the current full field, where the main assumption is that we keep the current 6” mask size. By increasing the transmission of the optics and by increasing the acceleration of the wafer- and reticle stage we can enable a throughput in excess of 150 wafers per hour, making this an economically viable lithography solution.
In this paper we will show how we can further optimize throughput, CDU and overlay by optimizing the main system and mask design parameters.

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CURRENT STATUS AND OUTLOOK OF ETCHED MULTILAYER MASK FOR EUV EXTENSION

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With shrinking pattern size at 0.33 NA EUV lithography system, mask 3D effects are estimated to become stronger, such as horizontal/vertical shadowing, best focus shifts through pitch and pattern shift through focus. Also at high-NA (>0.4) EUV lithography whose chief-ray-angle (CRA) is 8 degree and whose mask magnification is 4x, conventional absorber stacked EUV mask 3D 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, which leads to half-field exposure system. On the other hand, etched multilayer type mask structures have been proposed in order to reduce mask 3D effects at 0.33NA extension, and at high-NA under the condition that CRA is 8 degree with full-field exposure. And recently, it is also demonstrated that etched multilayer mask is effective in reducing mask 3D effects with 0.33NA exposure tool.

In this paper, we present process integration results of etched multilayer mask such as resist patterning process, etch process, and cleaning durability, including etched multilayer pattern collapse by mask pattern inspection tool. And we will show outlook for etched multilayer mask targeting 0.33NA EUV extension.

IMPACT OF CONDUCTIVE LAYER FOR ETCHED MULTILAYER EUV MASK ON THE SENSITIVITY OF PATTERNED MASK INSPECTION

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An etched multilayer (ML) mask is a candidate for high-NA EUV lithography due to less shadowing effect. Patterned mask inspection for this type of mask is one of the issues to be solved. We developed a projection electron microscope (PEM) for patterned mask inspection for EUV mask with considerably high throughput. We had already reported that > 16 nm sized defects were detected on hp 64 nm L/S patterned EUV mask by this inspection system. In this paper, the patterned mask inspection for an etched ML EUV mask was investigated. We propose the optimal structure using B_4C based conductive layer between 20-pair-ML and SiO_2 substrate from the standpoint of not only a pattern inspection using PEM, but also considering other fabrication processes using EB technique such as CD metrology and mask repair. This structure gives high durability for cleaning, high conductivity, and high defect detection capability. The simulation results show 16 nm sized extrusion and intrusion defects can be detectable on hp 40 nm L/S pattern (10 nm node) in both case with as-etched and refilled structure, and also shows the surface structure of the residual-type defect (etching residue) affects its detectability.

MODELING EUV MASK USING ALTERNATIVE MATERIALS FOR MASK 3D EFFECT COMPENSATION

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Extreme ultraviolet (EUV) lithographic patterning has the potential to enable 7nm node technology in an affordable way. Moreover, we can optimize the EUV mask stack to improve the imaging performance and to compensate for mask 3D effects, such as the CD dependency on feature orientation, pattern placement errors through focus, and the best focus shift through pitch.

State-of-the-art EUV mask stack has a binary architecture, consisting of a Mo/Si multilayer (ML) mirror overcoated with a patterned Ta-based absorbing layer. In this study, we investigate the imaging impact when using alternative materials for both the ML mirror and the absorber. Initial samples of a Ru/Si ML mirror stack and a Ni-based absorber stack are deposited separately on wafers and characterized by EUV reflectometry.

The experimental results are used to calibrate a mask model using rigorous mask 3D simulations. Based on this model, the imaging characteristics of representative patterns at the N7 technology node (e.g. lines, contact holes, etc.) are simulated through-pitch starting from the resolution limit at the current NA 0.33 with 4x reduction and at a future NA 0.52 with anamorphic scanning (4x/8x reduction for V/H lines).

We show an improvement of best focus shift through pitch, while simultaneously reducing the absorber thickness by exploring alternative materials other than Ta. Thinner mask topography additionally leads to reductions in the shadowing effect and telecentricity error. The latter is also sensitive to the ML mirror and can be reduced by a uniform angular EUV reflectivity spectrum. This can be achieved by reducing the intermixing between the Ru/Si bilayers. In conclusion, we have identified alternative materials as tuning knobs to optimize the EUV mask stack, based on experimental characterization of multilayer deposition on wafer and on the results of rigorous simulations.

Abstracts of Oral Presentations

Session 10: Pellicle, Mask Cleaning and Thermal Expansion

AN EUV PELLICLE SOLUTION FOR DEFECTIVITY CONTROL

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EUV is approaching high volume manufacturing today with many advances and improvements to previously identified challenges. Reticle front side defectivity control is a highly relevant topic requiring further investigation. The NXE platform has made significant progress in design, manufacturing, and operating improvements to achieve orders of magnitude defectivity reduction in the past five years. In order to further improve reticle front side particle adders for high volume manufacturing, a EUV pellicle is being actively investigated and developed at ASML.

In this presentation, we will provide an update on our progress on free standing pellicle development. We will present experimental results from our prototype full size films, including material properties, imaging capabilities, scalability and manufacturability. Further, provide insights into our recent developments of an interchangeable NXE pellicle concept and practical implementation flows into the existing EUV reticle flow at a mask shop.

PROPERTIES AND PERFORMANCE OF EUVL PELLICLE MEMBRANES

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EUV mask protection during handling and exposure remains a challenge for high volume manufacturing using EUV scanners. A thin, transparent membrane can be mounted above the mask pattern so that any particle that falls onto the front of the mask is held out of focus and does not image. The fluoropolymer membranes that are compatible with 193nm lithography absorb too strongly at the 13.5nm EUV exposure wavelength to be considered. Initially, the industry planned to expose EUV masks without any pellicle; however, the time and cost of fabricating and qualifying an EUV mask is simply too high to risk decimating wafer yield each time a particle falls onto the mask pattern. Despite the challenges of identifying a membrane for EUV, the industry has returned to the pellicle concept for protection. EUVL pellicles have been in development for more than a decade and reasonable options exist. The danger is that high volume manufacturing conditions have not yet been tested, so establishing alternative membrane options is an important risk mitigation effort. This paper first reviews the desired membrane properties for EUVL pellicles.
Next, candidate materials are introduced based on reported properties and compatibility with fabrication.
Finally a set of candidate membranes are fabricated. These membranes are screened using a simplified set of tests to assess their suitability as an EUV pellicle. EUV transmission, film stress, and film durability data are included. The results are presented along with general guidelines for pellicle membrane properties for EUV manufacturing.

THERMAL LIMITATION OF SILICON EUV PELLICLE AND POSSIBLE IMPROVEMENTS FOR MASS PRODUCTION OF EUV LITHOGRAPHY

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EUV lithography reveals that there are many serious issues to be overcome for its successful application towards sub-10nm node production although it is definitely promising technology for the future of semiconductor industry. Many progresses have been made especially in EUV mask, EUV scanner source power, and scanner defects in recent several years. Still, EUV scanner defect levels are much severe that what is acceptable for mass production while further reduction is not realistic, which makes pellicle technology necessary for EUV lithography.
One of the most promising and actively developed candidates for EUV pellicle is poly-silicon (pSi) pellicle; pSi pellicle membrane shows enough structural and mechanical stability as free-standing pellicle but has not yet proved compatible thermal stability during EUV exposure. In this study, we demonstrate that pSi pellicle has definitely insufficient thermal resistance against EUV exposure using Finite Elements Method (FEM) simulations and actual simulated experiments. Also various capping materials are investigated from perspectives of optical, mechanical, chemical, and thermal properties, suggesting better candidates as capping layer to improve intrinsic thermal limitation of Si membrane. Finally alternative materials/structures of EUV pellicle are proposed to confirm that they have better heat resistance thereby longer lifetime during EUV exposure compared to current EUV pellicle of SiN/pSi/SiN.

PLASMA-ASSISTED CLEANING TO ENHANCE EUV MASK CLEANLINESS AND DURABILITY

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Challenges in EUV mask cleaning are surface cleanliness and multiple-cleaning durability to satisfy mask high-frequency cleaning requirement for high volume manufacturing. To remove carbon and resist without surface oxidation, a plasma process is proposed to produce hydroxyl radicals for resist ashing. Rather than oxygen radicals, hydroxyl radicals with smaller amount of hydrogen radicals were initiated for surface deoxidization and wettability enhancement which is a key parameter for wet-cleaning performance. After the plasma treatment, particle removal efficiency of wet cleaning increases by 15% while the contact angle on EUV mask patterning decreases from 80 to 5 degree as the result of good wettability. Mask surface characterization by XPS and TOF-SIMS measurements showed no substantial ruthenium damage after 100 cleaning cycles. An improved plasma-assisted EUV mask cleaning can achieve the surface cleanliness and minimize variations in lithographic performance.

CONSIDERATIONS ON THERMAL EXPANSION SPECIFICATION FOR EUV MASK SUBSTRATES

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Impressive progress has been made towards implementation of EUV Lithography in manufacturing over the last 12 to18 months. A key factor has been significant improvements in light source power, enabling machines with high production throughput for the first time. Industry-wide mask blank substrate specifications still current today were codified nearly a decade ago, before all operational trade-offs were as well understood as they are today. We believe that the current specifications are adequate for relatively low power levels, but that they would preclude the realization of EUVL's full potential unless they are revised in the near future. We present simplified calculations which demonstrate that an increase in the specified zero-crossover temperature, Tzc, for the material CTE(T) would yield significantly improved performance compared to current specifications. In view of the long production cycle for EUV masks, revised specifications ought to be phased-in in the near future to enable optimum masks to be available as EUVL is more widely deployed.