2019 Source Workshop

Highlights

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The 2019 Source Workshop was held November 4-6, 2019 at Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, The Netherlands. In this blog, I will first present highlights and then cover additional topics of interest. Proceedings for the workshop are available on our website www.euvlitho.com.

Highlights

As 250 W sources are operational in fabs and 500 W sources look feasible to support high NA EUV scanners, the main focus in the high power source area is on technology options for >500 W. Current options are limited to increasing CO_2 laser power to support High NA EUVL and then High NA EUVL MP. However, now is the time to ask whether alternate drive-lasers will be more effective. How will we continue to increase conversion efficiency (CE) and reduce debris? And last, if we decide to go with the option of shorter wavelengths, what will be the best LPP sources and with what laser drivers? We got information in the workshop on these topics and more, outlined below.

First, it is clear that the fundamental work in the area of sources and metrology remains a key enabler for extension of Moore's Law. We will need source power beyond 500 W to support k1 extension for a high NA EUV scanner, while keeping the throughput. To enable such sources, we need to look at topics like CE, debris mitigation and alternate high-power laser drivers. ARCNL is doing this work by looking into the fundamentals of plasma generation and debris generation. They are going deeper into fluid dynamics of tin and laser interaction, and studying complex plasma emissions of Sn LPP, which so far has been sort of "swept under the rug" by the general term of unidentified transition array (UTA). For now, we are relying on plasma modeling to answer some of our questions. Modeling is cheaper and faster than experimental work alone.

Another point I noted during the workshop is that the LPP Source R&D community is benefitting from the expertise and fundamental data available at U.S. national labs, as well as vast experience from the worldwide plasma fusion community. Such collaborations are of value to us, as significant expertise with LPP plasmas (experimental and theoretical) exists at national labs.

There are several important questions on continued power scaling beyond 500 W as we look into alternatives to Sn LPP driven by CO2 lasers at 10. At which wavelength is the peak value for CE for drive lasers? Currently no experimental data exists between 1 and 10. During the modeling of Sn LPP at 2 thulium lasers, another interesting question has been put forward: what is the best way to characterize an EUV LPP system – via the current definition of CE, which is EUV energy per incident laser energy, or by EUV energy per microgram of tin consumed, which may be more relevant to cost of ownership? (Please see the LLNL papers for details.)

EUVL Scanner Update

ASML in their keynote gave an update on the status of EUVL scanners. There are 38 NXE:3400B scanners in field with 125 WPH throughput, while the latest version of NXE:3400C with throughput of 170 WPH is being shipped now. NXE:3400B versions have 80% uptime, and with various improvements 3400C is supposed to be better. Mask pellicles are robust for up to 10,000 wafers at 250 W with 83% transmission. By mid-2020, we expect to have pellicles with 88% transmission.

250 W sources have availability of >85% with very small power variation, which is corrected by scanner dose control so that dose variation at the wafer is less than 0.01%. Although high NA scanner (EXE) will take over at the 3 nm node from current NXE versions, power requirements are not known yet. I expect it to be >500 W and supported by scaling of Sn LPP. How far this can be done is still to be seen, although >500 W data in the burst mode was presented to demonstrate the feasibility of such sources. An increase in power essentially comes from the addition of additional power amplifier stage for CO2 lasers. CE is already at 6%, so it will take lot more work to squeeze out more EUV photons per pulse at a higher CE. Throughput for EXE scanners is projected to >185 WPH for half fields (or only half of the wafer will be printed).

Among several updates, some caught my attention: from 2013 to today, droplet generator availability has gone from 60% to 99% while runtime has increased from 80 hours to 1500 hours. By next year, we can expect 99.5% uptime with 4000 hours runtime. Also, over the last several years we have eliminated the need to refill the droplet generator reservoir, and collector lifetime is now 100 gigapulses from the 4x reduction in degradation at 3x higher power. All of these have increased source uptime to almost 90%. While in the area for the Source Workshop, I also toured ASML's EUVL factory. My impressions appear in my blog.

Blue-X – extension of EUVL beyond High NA option

Blue-X is the option of extension beyond high NA multiple patterning (MP). High NA EUV MP probably will continue into the near future, but now is the time to start looking at alternatives to assess their technical and economic feasibility. Options including change of drive lasers, wavelength, optics and optical design. There were several sessions on this topic and here I will present the highlights.

In terms of transitioning the drive laser away from CO2 lasers, one option is the thulium laser at 2. In the workshop, we had a modeling session where several groups presented their CE modeling results as well as plasma parameters for Sn LPP driven by 2 lasers. Next year, we hope to have experimental data for comparison. Modeling is a cost effective and efficient way to assess new technology options. In our efforts, we have been recruiting experts in fundamental data, experimental expertise and modeling in the area of fusion, as could be noted from the background of several speakers in the workshop.

Back to the discussion of modeling results. Although initial results show that CE from CO2 and thulium lasers are comparable, with one from thulium on the lower side by up to 1%. Although Cymer showed results on 1D simulation which revealed much lower numbers (8.5% at 10 vs 5.5% at 2) from a commercial package, I have a lot more confidence in LLNL simulations. Their simulations show that the maximum CE that one can achieve for Sn LPP will be from a drive laser between 5 and 10. We also learned that pulse length of 2 nm may not be optimum for 2 thulium lasers, and optimal value will depend on drive lasers. There is a good case for looking into thulium lasers for many reasons – they are solid state lasers, making them lot more efficient (wall plug to laser light) than CO2 laser, and they can be pulse shaped to further increase CE. Most importantly is they can be scaled up to deliver 100 kW and more of laser power, although this needs to be demonstrated.

ARCNL Program Showcase

This year we added a half day of additional program to showcase ARCNL programs and projects. Part of the workshop included a tour of ARCNL's new lab and office building. It is an impressive facility and I look forward to their contribution in source as well as metrology, resist and material. With the total number of graduate students and staff approaching 100, they are now the leader in EUV source R&D. There were several papers from ARCNL, which you can review in the proceedings.

One project from ARCNL caught my attention: "Detection of Gratings Buried Underneath Optically Opaque Metal/Dielectric Layers through its Acoustic Signal." They formed a grating underneath a flat layer of Au and Ni. The grating underneath samples were similar to a 3D NAND structure. As the multiple dielectric layers have very little effect on the shape and strength of diffracted signal, this technique has a potential of being a very useful technique for advanced semiconductor manufacturing.

Lifetime Achievement Award

A Lifetime Achievement Award was given to Steve Horn of Energetiq during the 2019 Source Workshop. Energetiq's metrology source has been a key enabler of EUVL since early 2000, and as EUVL moves into HVM, we have several HVM metrology tools in field and labs that are using Energetiq' s source. Steve has been the technical lead at Energetiq, always working to improve the sources. Steve has also been the "Technical Face" of Energetiq in the Source Workshop and other conferences for a long time. It was a very well deserved award. Congratulations!

Poster Session Awards

- First Place: "Towards High-Resolution Imaging at 13.5 nm using a Fiber Laser Driven High-order Harmonic Source (S36)"; Wilhelm Eschen, HelmholtzInstitute Jena and Institute of Applied Physics, Jena.
- Second Place: "Playing with the Temporal-shape of a High-power Nanosecond 1064 nm Laser Pulse to Explore EUV Generation and Different Droplet-deformation Regimes (S74)"; Zeudi Mazzotta, ARCNL.
- Third Place: "Towards High Harmonic Generation in Laser-Produced Tin Plasma (S56)"; Jan Mathijssen (ARCNL).

Additional Highlights

- Gigaphoton in their keynote talk presented results from their Sn LPP source powered by an upgraded CO2 laser, with power of 27 kW and improved beam uniformity. > 350 W operation is now successfully demonstrated at Pilot #1 system in the short-term, and it will be demonstrated fully by Q4 2019.
- Different lasers may be needed for Sn LPP drivers for scanner and metrology tools. There is a need to include Doppler effect in modeling Sn LPP, as that improves the comparison between modeling and experimental data. (V. Ivanov, ISAN and EUV Labs)
- Significant work has been done by Hanneke Gelderblom Eindhoven University of Technology with ARCNL to study the fluid dynamics that cause breakup of tin droplets and subsequent solidification.

- A sheet with thickness of several 10 nm is formed after a laser pulse hits a tin droplet. Mass in the target sheet is less than half. Rim of droplet after impact and fragments account for 10% and 40% amount of the initial tin, respectively (Bob Liu, ARCNL).
- EUV collectors should be cooled to a lower temperature to mitigate tin contamination (Norbert Bowering, Bielefeld University).
- The EUV brightness at plasma of about 100 W/mm2 sr has been demonstrated via a tin LPP metrology source at 60 kHz driven with a low power (30 W) IPG fiber laser. Brightness can increase 3x with a 400 W laser. Presenters noted 5% degradation in about seven weeks for the carbon nanotube (CNT) which was used to mitigate tin debris from droplet (Alexander Vinokhodov, EUV Labs).
- Brightness of Sn-LDP (Laser driven DPP) source is sufficiently high for enabling EUV actinic mask inspections (ABI, API and AIMS). Current development is focusing on stability, reliability and robustness through multiple long-term tests. Availability of these sources is >80 %. Also, LPP metrology sources show the brightness of approximately 150 W/mm2/sr 28 kHz for a drive laser of 220 W (Y. Teramoto, Ushio).
- Laser heated discharge plasma can increase EUV output up to 7 times (Florian Melsheimer, RWTH Aachen University). • Investigation on 20 nm - 50 nm emission of different gases in a ~2 J discharge plasma (neon, argon, krypton, xenon) was presented. Highest conversion efficiency for neon is ~100 mJ/2psr (~4 %/2sr) (Klaus Bergamann, ILT - Fraunhofer).
- Progress was shown on unraveling fundamental atomic physics aspects on the topics of atomic structure line identifications, 13.5-nm in band EUV light, line shapes and opacity, Sn ion-solid interactions and Sn ions traversing H2 gas. See presentation for details (Ronnie Hoekstra, ARCNL).
- Multiple excited states contribute to Sn LPP even at moderate densities, hence calculation of spectra is very difficult. Work continues with predictive sets of opacities and emissivities (J. Colgan, LANL).
- A study of plasma emission between 3-9 nm for strontium plasma and comparison of theoretical and experimental work were described (P. Dunne, UCD).
- EUVL extension beyond “High NA MP” will be needed in ~ 10 years. We need to start evaluating various options now and develop community consensus on those options, so that we can focus on fewer options and evaluate them in depth. A list of questions (source, drive lasers, optics, optical design, resist) has been proposed, along with groups for evaluation. Community consensus will be reported in coming workshops (Vivek Bakshi, EUV Litho, Inc.).

- Design data was presented for Tm:YLF-EUV lasers for EUVL applications, along with important questions about power scaling. Where is the peak wavelength for drive lasers for maximum CE, as currently no experimental data exists between 1 and 10 microns? What is the best way to characterize an EUV LPP system – via current definition of CE (EUV energy per incident laser energy) or EUV energy per microgram of tin consumed? There's a lot more interesting information in the presentation (Craig Siders, LLNL).
- There's a huge difference between ideal and experimental reflectance at 6.7 nm wavelength from reflection losses due to roughness, intermixing and chemical reactions at the interfaces. Current championship data: R = 64.1 % using La/LaN/B. Target for HVM will be R > 70 % . To achieve this, we need lower chemical reactivity and optimized barrier layers (Torsten Feigl, optiXfab). • EBL2 is a unique facility, accessible to third parties, that enables EUV lifetime research with ASML EUV scanner relevant conditions and up to EUV mask sample size (Norbert Koster, TNO). • EUV/BEUV/SXR/XR grazing incidence mirrors have been studied and analyzed. Selected applications of EUV/BEUV/SXR/XR mirrors were presented (Ladislav Pina, Rigaku).
- Reconstruction of silicon nanostructures via (grazing incidence small angle scattering and XUV scatterometry (GISAXS) (Frank Scholze, PTB).
- Successful design, fabrication and verification was reported for Holographic Masks for Proximity Lithography with EUV radiation. Similar printing results occurred from exposure at PSI and ILT (Larissa Jushkin, RWTH Aachen University).
- Computational imaging is a powerful method that can extend the capabilities of microscopy. Broadband HHG sources may provide the means for imaging nanostructures with spectral resolution. Ptychography can be used to characterize complex light fields, in parallel with imaging and metrology (Stefan Witte, ARCNL).
- High harmonics are a compact source of femtosecond pulses at EUV wavelengths. Magnetic imaging with HHG reaches sub-wavelength resolution, at a large field-of-view (Ofer Kfir, University of Göttingen).
- Thin-disk lasers operational at 550 W, 92 kHz, 6 mJ, <2ps. >1 kW power will be available soon with laser wavelengths from 206 nm up to 3.2 (Martin Smrž, HiLASE).
- Constructing mid-IR FEL (MIR-FEL) for 1-100 W. MIR-FEL can demonstrate many of the challenges for realizing EUV-FEL which is planned (Hiroshi Kawata, KEK).

- Steady state microbunching (SSMB) has been proposed as a mechanism for EUV-FEL. Preliminary experimental work is in progress in Berlin (Xiujie Deng, Tsinghua University).
- As we look at shorter wavelengths for potential extension of EUVL, we need to think about angular bandwidth as well as peak reflectivity of ML optics. Also, if the industry switches to FEL for high power sources for scanners, Mo/Si at 12.6 nm has been proposed as a better choice for several reasons. Reflectivity of the reflectivity of 66.5% at 6.7 nm was reported by Andrey Yakshin and >70% is possible! (A. Yakshin, University of Twente).