Race to EUV Still Depends on Photons:

Review of 2009 International Symposium on EUVL

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The 2009 International Symposium on Extreme Ultraviolet Lithography was held in October in the beautiful city of Prague, Czech Republic. I was looking forward to another Euro trip, where I'd tour fine palaces and sample the local brews while listening to the latest EUVL supplier updates. Alas, I had to settle for reviewing the latest updates using conference proceedings. And after dissecting the presentations, I still see EUV photons as the dominating factor in the race to get EUVL to fabs.

Keynote summary

Jos Benschop, research vice president at toolmaker ASML (Veldhoven, Netherlands), did a good job of summarizing the overall status of EUVL technology. ASML, which has led the industry in its transition to EUVL, revealed roadmaps taking the technology to the 16 nm node. This and two other keynote talks by Tony Yen of Taiwan Semiconductor Manufacturing Co. Ltd. (TSMC, Hsinchu, Taiwan) and Hyeong Soo Kim of Hynix Semiconductor (Icheon, Korea) reiterated the superior pattern fidelity of EUVL compared with 193 nm double patterning. This should come as no surprise, since the EUVL wavelength is effectively 15× shorter than 193 nm.

In a keynote address at the EUVL Symposium, ASML revealed its roadmap for taking lithography technology to the 16 nm node. (Source: ASML)

Lithography has been the key enabler in the semiconductor industry's mostly successful effort to uphold Moore's Law, and has followed a modified Rayleigh criterion in providing the capability to print ever finer features. You could even say that it is Lord Rayleigh who has guided us so far, and continues to do so. Per the modified Rayleigh criterion: Resolution = $k1 \cdot \lambda/NA$

In recent years, resolution improvement has been achieved by reducing k1 value (which denotes lithographic process complexity) or numerical aperture (NA). Now the time has come to step away from twisting 193 nm light around Rayleigh's formula and instead take advantage of the much smaller 13.5 nm wavelength (λ) of EUVL.

Both IMEC (Leuven, Belgium) and GlobalFoundries (jointly with IBM, Toshiba andAMTC) unveiled work showing patterning results at the 22 nm node with functioning devices, and confirmed that it is easier to print with 13.5 nm than with conventional 193 nm lithography. GlobalFoundries' latest patterning results from the University at Albany's NanoTech facility underscored the wisdom of New York's prodigious investment in developing advanced technologies, including EUVL. The Albany NanoTech complex, a worldleading lithography research facility, was key to attracting GlobalFoundries' newest fab to the Albany area, and will continue to lure more leading high-tech businesses as EUVL progresses (congratulations, New York!).

In addition to EUVL's advantages in printing capability, chipmakers are starting to realize that EUVL offers cost advantages as well, a point illustrated by data from TSMC. But mask defects are still a challenge, although defect density continues to go down.

Mask defects are still a challenge, although defect density continues to go down. (Source: ASML)

Critical issues

At the end of the symposium, the customary list of top critical issues for EUVL was issued, with the source collector module (SoCoMo) moving from first to second place. I have to disagree with the assessment, however, that the source/SoCoMo is no longer the top issue. I think source and integrated SoCoMo remain the main challenge, and that continued investment and R&D will deliver the rest of our needs. Sources continue to be the main reason for the delay in EUVL. Some might argue that suppliers are doing as much as possible to deliver EUV sources and that the industry is better off focusing for now on mask defects and metrology; even so, I will explain why I think the industry should keep its focus on EUV sources and SoCoMo.

High-power EUV sources

During the meeting, scanner makers updated their specifications for high-power sources for high-volume manufacturing (HVM) scanners. The power requirements have been increased to 200 W from 180 W, and repetition frequency has been set at >10 kHz. I can't help but wonder why power requirements have gone up, since ASML reported a 30% increase in tool throughput. I keep wishing that source power requirements will someday benefit from advances in other scanner areas. That aside, here's what the suppliers said:

- Cymer (San Diego) reported an estimated source power of 70 W (60% duty cycle, assuming 5 sr collector, 50% collector reflectivity and 90% transmission). Cymer's measurements are not yet at intermediate focus (IF) and are just estimates based on power at the source. However, the company has made good improvements in power at source and source power stability.

- Gigaphoton (Oyama, Japan) reported estimated power of 2.5 W (7.5 W at source with 10% duty cycle for 3 hours continuous run).
- Philips Xtreme (Jena, Germany) showed 100% duty cycle runs for its discharge-produced plasma (DPP) sources with measurements at IF, but the company's power results were not estimated. Philips measured 14 W with a three-shell collector and hopes to increase that figure to 34 W with a nine-shell collector (after demonstrating 19 W for nine shells). Since the company's results are for integrated measurements and a 100% duty cycle, Philips offers the most reliable data, since estimated measurements cannot readily be compared with integrated measurements.

Although there have been reports of 50 W and even 100 W at IF, my review of the presentations did not produce figures to support these claims. It's important to remember that suppliers have made headway in the difficult task of increasing power and stability at source, and this should be noted with great appreciation. Nevertheless, we need to get real data on what can be delivered from the source to IF over a long period.

Laser-produced plasma (LPP) sources still need to show long-term integrated results — and I am sure suppliers are working hard to achieve this goal. Integrated SoCoMo and debris mitigation are still potential showstoppers for LPP. The good news is that abundant research continues to shed light on debris production in LPP, which hopefully will improve mitigation. I realize that some people now think the source issue is being sufficiently addressed, while others point out that the lack of an integrated performance solution means LPP cannot deliver enough photons to the wafer. I prefer to take the middle road on this issue: We just need to wait for the results of integrated performance measurements.

Last spring, I predicted that 100 W sources would not be ready this year, and this now seems to be the case. If 40 W fully integrated LPP sources are in place by 2010, I will be extremely delighted and will consider it a wonderful achievement for the industry. Also, the debate over LPP vs. DPP appears to have taken a positive turn. A few years ago, when there were almost a dozen suppliers, we needed to narrow down options and pick a winning source technology. Now there are essentially three suppliers, and DPP offers another good option for EUVL scanners. I expect DPP to be able to supply 40 W sources (integrated performance, 100% duty cycle) in 2010. So overall this is good news for the industry, whichever way we go. Remember, all we need in 2010 is a beta-level EUVL scanner and 40 W to help us print 40 wph — enough to keep any development line humming.

Potential solutions for LPP integration troubles

In my opinion, the key reasons for LPP SoCoMo integration delay, which is related to debris mitigation, are the fundamental flaws in how tin is delivered via a droplet-based delivery system and the collection approach in today's LPP systems. The droplet system was first used for xenon, a noble gas, and this method was simply replicated for tin. DPP has already moved away from droplet delivery, producing better results in debris mitigation and thermal load management. The DPP collector, which sits behind the debris mitigation device foil trap, offers additional protection.

Droplet delivery treats tin as fuel instead of just a means of converting laser pulse energy to EUV photons. It does not have to be this way, and I hope suppliers will think of out-of-the-box solutions for using tin for energy conversion without creating all the debris, which is a nightmare to control. Only a small amount of tin is needed per pulse and there may be more than one way to collect EUV photons. Of course, this may involve some redesign of scanners, but it cannot be more difficult than keeping the collector clean for LPP sources.

Mask infrastructure

In my opinion, mask infrastructure is not the leading potential showstopper for the timely insertion of EUVL in HVM; integrated EUV source is. However, computer chip manufacturers can't do much for high-power source technology since the ball is in the suppliers' court, and they are working hard. But chipmakers can do something about mask infrastructure, which makes it a good focus area.

Essentially, there are five components of mask infrastructure: defect-free substrates, defect-free mask blanks, repair, optical proximity correction (OPC) and handling without adding defects. The battle to control defect introduction during handling basically has been won, there are good options available for mask repair, and OPC will be dealt with.

Sematech's Mask Blank Development Center (MBDC) in Albany has done an excellent job of driving down mask defectivity. As defects become fewer and smaller, R&D involving new physics is needed - but academia and research labs don't seem to be actively working on this topic. This should continue to be an important area of research, since defectivity still needs to be reduced by 100× and the problem will become more difficult as we move to smaller nodes. Mask defectivity reduction cannot be addressed simply as an engineering problem. However, it has been getting harder to make further progress in reducing mask defects, especially without the help of mask metrology tools. It also has become apparent that manufacturing and handling processes may add defects, which in the end must be repaired. For repairs to occur in HVM, an aerial imaging measurement system (AIMS) tool is a must.

To fully comprehend the mask infrastructure issue, it's helpful to understand why metrology tools are not available today, and what needs to be done to bring them forward. There are two reasons for the lack of an actinic mask metrology tool: First, a Sematech program to produce such a tool folded when supplier Exitech (which also produced EUV micro-exposure tools) went out of business; second, no consensus had emerged until recently on whether actinic tools were needed for EUVL.

At the symposium, KLA-Tencor (Milpitas, Calif.) showed that its non-actinic inspection tool can detect all defects up to the 22 nm node, but actinic inspection will be needed below the 20 nm node. Clearly, now is the time to prepare actinic inspection tools for sub-20 nm nodes.

In addition, metrology tool specs (especially source specs) have not been widely agreed upon, as they have been for highvolume EUV sources, thanks to the efforts of scanner makers. Specs for EUV metrology tools were proposed at the 2009 EUVL Workshop in July, and it is clear that the main challenge will come from a familiar area — EUV sources. One cannot expect suppliers to invest in new equipment development until there is clear agreement on what is needed for EUV metrology tools.

Constructing an actinic mask metrology tool is much simpler than building an EUVL scanner. I hope scanner makers will share their hard-earned learning — because they won't sell many HVM EUVL scanners unless the mask infrastructure is ready. I also hope no wheels will be reinvented in the development of EUVL mask metrology.

Much as been learned in contamination, optics and defect control since the last time a consortium took a shot at making an EUV AIMS tool. We'll probably still use spectral purity filter (SPF) films to separate the source environment from the rest of the tool, and we only have to deal with a few mirrors, and no resist. In the end, whoever gets this job should be able to put together a system (minus source) fairly quickly. However, because of the small etendue, sources need to be brighter than they are today. So the main challenge once again will arise from EUV sources.

Considering all the facts, a consortium seems like a good approach for addressing technical challenges and sharing the risks of developing EUV metrology, and the industry would do well to organize one. Such a consortium could very much help the cause of getting EUV sources for metrology, and here is a suggested list of ways:

- Develop metrology source specs and obtain industry consensus.
- Organize another Flying Circus to independently measure source brightness and performance (rather than just taking data from supplier presentations).
- Assess alternative source technologies, including EUV lasers (metrology tools do not have to be exactly 13.5 nm).
- Assess critical risks for scaling of a particular type of source technology.
- Support R&D to address critical roadblocks.

Resist and LER

Line-edge roughness (LER) is still the leading challenge for EUV resists. Intel demonstrated 22 nm half-pitch resolution with 4.3 nm LER for a 12.8 mJ resist. Intel is engaging effectively with consortia and academia and continuing to test new possibilities; suppliers are engaged and new materials are being tested. This is certainly the right way to solve the problem.

Summary

As predicted last spring, DPP power has more than doubled since SPIE 2009, while LPP has made good progress but is not yet at 100 W. Patterning at the 22 nm node continues to show the advantages of EUVL over 193 nm lithography. Now is the time to get mask inspection tools ready for HVM.

In my opinion, the top EUVL challenges are:

1. SoCoMo (power scaling and demonstration of integrated system by LPP-based sources)
2. Mask (metrology tool and defectivity)
3. Resist (LER)
4. Continued R&D and investment (keep developing new ideas for addressing critical challenges via industry engagement with academia and national labs)

At times, the race to get EUVL to HVM seems more like a marathon than a track run. Perhaps we should think of EUVL research as an obstacle course, where we make great leaps or disappointing stumbles — but keep on moving forward.