Evolving Source Demands and Requirements for EUV Lithography in Manufacturing

Steven L Carson
Outline

▪ Current state of the EUV exposure source
▪ Current state of EUV metrology sources
▪ Potential challenges for scanner sources
▪ Potential challenges for metrology sources
Current State of the Exposure Source
Exposure source has achieved 250W roadmap

NXE:3400 baseline exposure source power demonstrated repeatably in the field

Focus moves to ensuring sufficient power overhead to enable predictable throughput and dose quality
Intel NXE combined scanner/source availability

- Annualized availability continues to improve
- Increased fleet size enables faster information turns
- Extended period with large perturbations
- Improvements continue to release to the field
- Focus remains on system availability

Last 4 years
Intel NXE system availability limited by source

Last 2 years

Source availability lagging scanner availability

Not surprising source contains more significant technology inventions and innovations

Schedule maintenance durations reaching a floor

Technology changes needed to take next step in availability
NXE:3400C reduces source scheduled maintenance

- Newest ASML scanner platform offers paradigm shifts in serviceability of NXE source
- Inline refill completely eliminates a significant scheduled maintenance
- Droplet generator modifications enable more rapid swaps
- New collector mounting technology enables quicker collector swaps
- NXE:3400C source technology improvements focused on availability
  - Many days of availability regained each year

E. Verhoeven, ASML (EUVL Symposium, 2020)
Initial systems confirm improved availability

E. Verhoeven, ASML (EUVL Symposium, 2020)
Collector lifetime improvement continues

Decreasing CDR (collector degradation rate) increases the time between collector swaps

Increased collector lifetime along with reduced swap time on NXE:3400C significantly reduces the biggest G2G duration of scheduled maintenance DT

Continued reduction in CDR further improves availability

E. Verhoeven, ASML (EUVL Symposium, 2020)
Exposure source meets initial HVM requirements

- Power consistently meets the initial HVM roadmap
- Availability showing dramatic improvement over past couple of years
- NXE:3400C source vessel enable further reductions in maintenance durations scheduled and unscheduled
- Collector contamination rates meeting swap frequency targets
Current State of the Metrology source
EUV AIMS High-NA proof of concept

The proof of concept for a 0.55 NA emulation within AIMS™ EUV has been successfully demonstrated:

**IMAGING OF ANAMORPHIC STRUCTURES**

- **Mask design**
  - CD<sub>x</sub>=64nm  CD<sub>y</sub>=128nm
  - As available on AIMS™ EUV calibration mask

- **Current AIMS imaging (0.33NA)**

- **High-NA anamorphic emulation**

Same physical structure on the mask

EUV AIMS solution for high-NA emulation successfully demonstrated

EUV AIMS Production Availability

~70% uptime with pre-production SW/FW release

Full production SW/FW upgrade Q1’20 improving availability by addressing several error mechanisms

Through pellicle measurement capability will be implemented

Slide courtesy
LTD-IMO: Nathan Wilcox
APMI operational for full mask inspection

- Full-mask inspection successful
- Captured expected defects
- Resolved defect details

Defect map

7nm/5nm mask

Defect samples

Ref  Defect  Difference

Partially blocked via

Missing OPC

EUV actinic

DUV optical

Images rotated 90°

Slide courtesy LTD-IMO: T. Liang
APMI operational for full mask inspection

Defect map

Defect samples

Ref

Defect

Difference

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- Captured expected defects
- Resolved defect details

EUV actinic

DUV optical

7nm/5nm mask

APMI extendable to high-NA through enhancements

- Captured expected defects
- Resolved defect details

Slide courtesy LTD-IMO: T. Liang
APMI detects ML phase defects

APMI captures ML phase defects in mask inspection
APMI is the only solution to find all mask defects that impact wafer print and plays a critical role as the last step to ensure defect free mask before releasing to wafer fab.
High-brightness LDP source for actinic patterned mask inspection

- ✔ High brightness
- ✔ Stable: no spatial and timing synchronization needed
- ✔ Reliable: 24/7 operation
- ✔ Clean: multi-stage debris shield is used
Robust platform - Already exemplifying ~80% of the POR Optical platforms

Two key failure modes are fixed in a relatively short period of time.

Current focus is to further improve reliability and availability.

Safak Sayan, Kishore K. Chakravorty, Yusuke Teramoto
“Laser-assisted Discharge Produced Plasma (LDP) EUV Source for Actinic Pattern Mask Inspection”
Upcoming Invited Talk at SPIE-2021
✔ Compact Design
✔ Brightness is scalable, and Stable operation is demonstrated up to 11 kHz
✔ >200 W/mm²/sr obtained at the source level
✔ Hours of continuous operation can be sustained

Yusuke Teramoto, Safak Sayan, Kishore K. Chakravorty
"High-brightness LDP source for actinic patterned mask inspection" S23 on 11/04/2020 Session.5
Metrology source meets initial HVM requirements

- Brightness meets the initial HVM needs
- Source performance meets the technical requirements of the metrology technology
- Availability lagging POR optical platforms – improvement observed
- MTBF meeting expectations for initial systems
- Brightness scaling demonstrated towards evolving throughput improvements
Challenges for Exposure Sources
Resist resolution limited by stochastic defects

CAR pushing resolution limits

CAR resists currently not able to resolve 24 nm pitch

Charles Wallace

SPIE Advanced Lithography, EUV, Feb. 24, 2020

Resist resolution limited by stochastic defects

LWR decreasing with increasing dose

**New chemistries need to provide differentiation in RLS (Resolution, Sensitivity and LWR) and improved stochastic control**

Charles Wallace

SPIE Advanced Lithography, EUV,  Feb. 24, 2020

LWR decreasing with increasing dose

High doses will become necessary:
- resolve tight pitches
- reduce LER
- prevent stochastic defects

New chemistries need to provide differentiation in RLS (Resolution, Sensitivity and LWR) and improved stochastic control

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SPIE Advanced Lithography, EUV, Feb. 24, 2020
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- resolve tight pitches
- reduce LER
- prevent stochastic defects

Economics require that TPT is not sacrificed for those higher doses
Full-field TPT more than doubling in 5yrs

- **NXE:3400B TPT spec**
  - 125WPH @20mJ

- **NXE NEXT >220WPH**
  - @ 30mJ

- **EXE:5200 >220WPH**
  - @ 30mJ and half-field scan-lengths

**EUV product roadmap**

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>NA, Half pitch</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
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<td>135 wph²</td>
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<td>160 wph</td>
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<td>NEXT</td>
<td>&lt;1.1 nm</td>
<td>&gt;220 wph</td>
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<tr>
<td>EXE:5000</td>
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<td>185 wph¹</td>
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</tr>
<tr>
<td>EXE:5200</td>
<td>&lt;1.1 nm</td>
<td>&gt;220 wph¹</td>
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</tbody>
</table>

wafer/ horas/ h (s) are based on 50m²/cm²
10m²/cm²/10m²/cm²/10m²/cm²
10m²/cm²/10m²/cm²/10m²/cm²
Throughput upgrade

E. Verhoeven, ASML (EUVL Symposium, 2020)

\[
\text{TPT} \propto \frac{\text{POWER}}{\text{DOSE}} \quad \rightarrow \quad \text{Wafer plane power will roughly double in 5yrs}
\]
Increasing source power drives need for higher doses

- Throughput is a function of EUV power at the wafer plane and the applied dose
  \[ \text{Dose/Power} = \frac{J}{W} = \text{time} \]
- For a constant dose, as the power is increased, the exposure time is decreased

- Source power is delivered by pulses, so for a constant rep rate
  - as source power increases, the pulse energy increases
  - as exposure time decreases, fewer pulses are required to meet dose

- This would be true for all the plasma-based scanner sources that have been investigated (LPP, DPP, LDPP)
Source Power Budget (for some nominal dose)
Source Power Budget (for some nominal dose)
Source Power Delivered Discretely by Pulse
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Source Power Delivered Discretely by Pulse

OPEN LOOP POWER

DOSE ERROR
Source Power Delivered Discretely by Pulse

OPEN LOOP

DOSE ERROR

DOSE CONTROL
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CLOSED LOOP POWER
Source Power Delivered Discretely by Pulse

OPEN LOOP POWER

DOSE ERROR

DOSE CONTROL

CLOSED LOOP POWER
Closed Loop Power May Not Scale With Pulse Energy

- Continuous Energy Budget
- Discrete Pulse Budget
- Pulse Energy 20% Higher

OPEN LOOP POWER

CLOSED LOOP POWER

CLOSED LOOP POWER

CLOSED LOOP POWER
Building a model source

Start with a Wafers/Hour (WPH) value at a particular dose, number of fields/wafer, and a field size

Convert WPH to Time/Wafer → Time/Field

Select a pulse (repetition) rate for the source → Pulses/Field

Calculate total dose (energy) in field → Field Size Area * Dose

Divide total energy in field by pulses in field → Energy/Pulse at wafer level

With energy/pulse, for any dose and field size, can calculate # pulses to deliver dose
Pulses to meet dose decrease as power increases
Introduce Pulse Energy Variation 🡪 # Pulses Vary

Scan time has to account for the maximum number of pulses needed to supply the requested dose.

Most scans will not use that maximum number of pulses 🡪 example of power margin.
Fewer pulses needed to achieve dose as power goes up
Fewer pulses needed to achieve dose as power goes up

- 20mJ at 1st source config
- 20mJ at 2nd power config

Increasing power
Fewer pulses needed to achieve dose as power goes up

40% fewer pulses
Higher dose retains pulse count as Power goes up.

- Same pulse count at 2nd power config.
- Increasing power.
- 20mJ at 1st source config.
Higher dose retains pulse count as Power goes up
**Control System Works in Time, not Energy**

- Increasing pulse energy → more energy per unit time → more power
- That increased power delivered in less time and fewer discretized intervals
- If control scheme or repetition rate unchanged, decreasing ability to control energy through scan as power increases
Dose Error Margin Calculated as Pulses

- Model accumulated pulses in field “window”
- Energy applied in that window needs to meet dose error requirement defined by process
- At current power, determine pulses needed to maintain dose stability
- As pulse energy (source power) increases, if controls don’t improve □ still need same time (number of pulses) to maintain stability
Power Margin Decreases as Power Increases
Power Margin Decreases as Power Increases

- Select a dose at lower power → follow that dose to higher power
- The pulse difference between those points is the change in available power margin
- Is the control system capable of providing stable dose with that reduced number of pulses to integrate through the dose error margin?
Power Margin Decreases as Power Increases

- In this case, the dose error margin is reduced by more than 40%
- If the control system is unchanged, part of the dose control margin may have to be used to manage dose errors
- The dose control margin would likely be tuned to be minimized to maximize system power
Maintain Pulse Margin by Increasing Dose

- Select a dose at lower power followed by that pulse count to higher power.
- The difference between those points is the change in dose to maintain dose error pulse margin.
Maintain Pulse Margin by Increasing Dose

- Select a dose at lower power → follow that pulse count to higher power
- The difference between those points is the change in dose to maintain dose error pulse margin
- The dose increase necessary to maintain that pulse dose margin is >60%
Considerations on increasing source power

- EUV scanner throughput scales with source power at constant dose
- Dose stability and control does not scale at same rate (without improvements)
- Trade-offs
  - Increase TPT but at risk of reduced dose stability through scan
  - Increase dose in order to maintain dose stability but reduce the TPT gain
  - Increase power margin in order to maintain dose stability but reduce TPT gain
Repetition Rate to Improve Power

- Source power scales linearly with repetition rate (frequency) and with pulse energy

![Graph showing the relationship between relative wafer plane power and normalized repetition rate.](image)
Repetition Rate to Improve Power

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- Expecting source power to roughly double in next 5 years.
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- Doubling of rep rate at same pulse energy will double power.

Increasing pulse energy range ~±100%
Repetition Rate to Improve Power

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- Doubling of rep rate at same pulse energy will double power
Addressing dose control concerns

Increasing source power (pulse energy) will drive up TPT

Reduced pulse count for a given dose (especially lower doses) may increase likelihood of dose-driven CD errors (increased dose instability)

Improved control schemes can mitigate some of that risk, but source drifts and stochastics, available pulses, and pulse energies will constrain level of improvement

Increasing source pulse rate (even at the cost of pulse energy) could overcome current constraints needs to be considered for future high power sources

As sources increase power, dose stability issues can also be addressed by increasing dose or power margin both offset effective TPT gain of power improvement
Challenges for Metrology Sources
Scanner source lagged collaterals

200W (2010) delivered 6 years later

100W (2011) never delivered on initial platform, eventually, on 0.33NA, 5yrs later

250W (2013) delivered 5yrs later

Rest of EUV scanner tech initially ready ~2010

Reticle materials developed/delivered WELL ahead of source power
EUV technology collaterals at high power

- Optics, reticles, stages, and resists were all “ready” well ahead of the source exception: pellicle
- These collateral technologies are only recently getting stressed at high powers (2yrs at most)
- Opportunity for high power sources to provide lower cost test vehicles to stress these collaterals
- Metrology needed for reticle and through pellicle reticle inspection
- Illumination for metrology (spot) very different than for scanner (slit)
- Brightness (power) improvement will drive TPT improvement (economics)
- Possible that power density from metrology sources on substrate exceeds power density from scanner source key concerns: reticle and pellicle
- How can you predict whether metrology source power is compatible with the scanner ecosystem?
Wafer Plane Power Scales with Pulse Energy

- Pulse energies at wafer plane scale with increasing TPT
- 0.33NA tools will lead the scaling of wafer plane power
- Estimates that wafer plane power at least doubles in 5yrs
Reticle Plane Power Similarly Scales

- Pulse energies at wafer plane scale with increasing TPT
- 0.33NA tools will lead the scaling of reticle plane power
- Reticles on 0.55NA tools will experience ~half power density
  - area scaling wafer to reticle
Challenge & Opportunity

- If metrology source power density exceeds scanner levels, impact to reticle is unknown

- Scaling brightness as scanner reticle plane power scales should ensure safe operation
  - if collaterals can’t operate at scanner powers, bigger problem

- Scanner power density will double in next five years — opportunity for metrology sources to drive dramatic improvement in TPT

- Novel mask absorber materials will be introduced in next five years — need rapid understanding of resilience to EUV and power
Summary
Summary

- Scanner exposure source is in good shape for initial HVM insertion
  - Power can be consistently achieved
  - Availability and maintenance durations are rapidly improving
- Sources are meeting the needs for the initial HVM mask metrology tools
  - Brightness meeting the current technology needs
  - Availability is meeting expectations and demonstrates improvements
Summary

▪ Increasing exposure source power levels while maintaining constant exposure doses introduce heightened risk of dose errors
  • Increasing the process dose is favorable to source capability and to photoresist performance but results in reduced TPT benefit

▪ Metrology sources will strive to increase brightness to improve TPT
  • Learnings on the effects of scanner collaterals and reticles at high source powers are only recently available
  • Metrology sources need to be careful in exceeding the reticle plane power density of the scanner
  • Novel absorber stacks will be introduced resilience to EUV power density needs to be comprehended for all sources
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