Chapter 1

EUV Source Technology: Challenges and Status

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1.1 Introduction

Extreme ultraviolet lithography (EUVL) is the leading technology being considered for printing circuits at the 32-nm node[1] and below in a high-volume manufacturing (HVM) environment fab. In EUVL, a 13.5-nm-radiation wavelength generated by an EUV source is used to print circuits. Because light radiation is strongly absorbed at this wavelength, the entire EUVL scanner system must be in a vacuum environment, and all optics must be reflective, not refractive. Based on the HVM requirements of 100-wafer/h throughput and other system requirements for optics, resist sensitivity, and overhead (Table 1.1), a power requirement of 115 W has been specified for HVM EUVL scanners. Besides power, EUV sources must meet additional specifications. The production-level requirements in Table 1.1 have been jointly agreed upon by major scanner manufacturers.[2,3]

Discharge-produced plasma (DPP) and laser-produced plasma (LPP) are the leading technologies for generating high-power EUV radiation at 13.5 nm. In both technologies, hot plasma of $\approx$20–50 eV of the chosen fuel material is generated, which produces EUV radiation. In DPP, magnetic pinching of low-temperature plasma generates the high-temperature plasma. In LPP, the target material is heated by a laser pulse to generate high-temperature plasma. Xenon, tin, and lithium are the fuel materials of choice for EUV sources.

The cost-effective implementation of EUVL in HVM presents many technical challenges, of which the EUV source power has remained the greatest one until recently. In the fall of 2004, significant progress in EUV source power was reported at the EUVL Symposium in Miyazaki, Japan, making source power a lesser concern. The current challenges for implementing EUVL in HVM are listed in Table 1.2.

Today worldwide, more than eight suppliers and consortia are working to develop high-power EUV sources for EUVL. In addition, some suppliers are working to develop low-power EUV sources that are finding applications in metrology to support EUVL. This chapter presents the status of high-power EUV source technology and summarizes the technical challenges that must be overcome to meet the specifications for high-power EUV sources in HVM.

1.2 Conversion Efficiency of EUV Sources

1.2.1 DPP versus LPP

The conversion efficiency (CE) is the ratio of energy radiated by the EUV source in a 2% bandwidth (BW) around 13.5 nm to the input energy to the EUV source. The CE is used to estimate the utility requirements, choose the fuel, and understand the limits of power scaling. The fundamental CE for a fuel represents the upper limit of CE for that particular fuel.

For DPP, the input energy is the electrical energy consumed by the entire system (energy dissipated in the plasma plus energy lost in the electrical system). However,

Table 1.1 EUV source requirements and technology status.

	Best reported values				Requirements		
EUV source specifications	Xe DPP	Sn DPP	Xe LPP	Sn LPP	Alpha	Beta	Production
Status as of	Q1 2005	Q1 2005	Q1 2005	Q1 2005	2005	2007	2009
Wavelength (nm)	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Throughput (wafers/h)					20	60	100
EUV power at intermediate focus (W)	25	50	2.3	3	10[a]	30[a]	115[b]
Repetition frequency (kHz)	2	6.5	4.5		2[a]	5[a]	7–10[a]
Integrated energy stability (%)	2		5		5[a]	1[a]	0.3[b]
Source cleanliness					TBD	TBD	>30,000 h
Collector lifetime (10^9 pulses)	10	1	5	TBD	1 (1 month)[a]	10 (3 months)[b]	80 (12 months)[c]
Electrode lifetime (10^9 pulses)	0.35	>1	N/A	N/A	1 (1 month)[a]	10 (3 months)[a]	80 (12 months)[b]
Projection optics lifetime (h)							30,000
Etendue of source output (mm^2 sr)			<1		TBD[a]	TBD[a]	<3.3[b]
Max. solid angle to illuminator (sr)					TBD[a]	TBD[a]	0.03–0.2[b]
Spectral purity, 130–400 nm					TBD	TBD	TBD[c]
Spectral purity, >400 nm					TBD	TBD	TBD[c]
Spectral purity, 20–130 nm					TBD	TBD	TBD

[a] No problems.

[b] Challenges remain.

[c] Potential showstopper; significant technical challenges remain. TBD = to be determined.

Table 1.2 Challenges for Implementation of EUVL in HVM by 2009[a].

Ranked issues	
1	Availability of defect-free masks
2	Lifetime of source components and collectors
3	Resist resolution sensitivity and line edge roughness (LER)
Unranked issues	
	Reticle protection during storage handling and use
	Source power
	Projection and illuminator optics quality and lifetime

[a] List generated by EUVL Symposium Organization Committee, November 2004, Miyazaki, Japan.

sometimes the CE values presented in the literature take into account only the energy deposited in the plasma. In DPP, some of the energy is lost in the electrical components; therefore, the reported CE will depend on system-specific details. Without those details, it is difficult to separate the CE from the fundamental CE limits for a given fuel. Reference 4 gives an example of the CE for the entire system as well as the fundamental CE. For a given fuel, it is possible to optimize the system operation to maximize its CE.[5] One may note that many times the highest CE reported for a fuel and source design combination does not correspond to optimal operating conditions. In this situation, it is best to use the CE for optimal operating conditions to get a realistic utility consumption estimate and understand the limits of power scaling. For the LPP system, the laser power and EUV output in the 2% BW around 13.5 nm is used to estimate the CE. However, for LPP systems, the overall conversion for the entire system is much less than for DPP because of the low wall-plug-to-laser-light CE of a laser system, which is typically less than 10%.

1.2.2 Xe, Sn, and Li conversion efficiency

For Xe plasma, only the Xe^{10+} ionic stage is responsible for the emission in the 13.5-nm radiation bandwidth,[6] which results in a 1% or less CE. Although Xe as a fuel has been favored for being a noble gas, its low CE requires a high energy input to meet HVM EUV source power requirements. Such inputs are prohibitive due to limits on thermal management for DPP, and due to lack of high-power lasers for LPP, precluding Xe as the fuel of choice for high-power EUV sources.

As suppliers learn to optimize their systems, measured CEs have continued to increase. Historical data for such an increase are not given in this section, but can be reviewed in the technology description of various source designs.[7] Although modeling has predicted a wide range of fundamental CE limits for Xe (2–4%),[8] experimentally only a 1% CE has been observed for Xe plasmas.

Today CEs for a Xe DPP system are reported in the ranges of 0.45%,[4] 0.5%,[10] and 1%.[11] One must be cautious in accepting high CE numbers, since (for example) for a given DPP design they may require a source size larger than allowed by the etendue requirements of the system. Therefore, the maximum CE may correspond to the available power at the source and not to the acceptable power at the EUVL scanner.

In the case of LPP, the source size is smaller (on the order of 100 × 100 μm); thus, etendue mismatch is not a concern (see Sec. 1.3.2.5 for details on this topic). For Xe LPP, CEs of 0.7%,[12] 0.8%,[13] and 0.8–1%[11] have been reported. It has been shown that for Xe LPP, the transient nature of the Xe^{+10} population may be limiting the CE, and pulse shaping and pulse trains may help increase it.[14] The above values of the CE are for LPPs produced using Nd:YAG lasers. For LPP systems using pulsed CO_2 lasers, CEs of 0.7%[15] and 0.8%[12] have been reported. For a given system, in the case of LPP, the CE weakly depends on the laser wavelength.[16]

For Sn, multiple ionic stages, Sn^{+8} to Sn^{+12}, contribute to emissions around 13.5 nm, resulting in a higher CE;[17] much higher theoretical estimates for the CE for Sn (4–7.5%) have been reported.[8] Recent work also predicts CEs of 3.5–6% for Sn-based EUV sources.[18] A factor of 3–4 for Sn over Xe is usually quoted in the literature for experimental measurements of the CE.[19,20] For Sn DPP EUV sources, 2% CE has been reported,[10,21] with a goal of 3% CE on the supplier roadmap.[11] Such goals can be achieved by reducing the etendue mismatch and optimizing the system design.[22] Higher CE values have been reported for Sn LPP: 2.5% using Sn-doped droplet targets,[23] and likewise 2.5% using a Sn tape with a 25% Sn concentration.[13,24] Based on current experimental data, a 3% CE can be expected for mass-limited Sn targets.[23] Much higher CEs have been obtained using solid Sn targets (viz., 3%[25] and 5%[23]). Note, however, that solid Sn targets are probably not practical for use as fuel in an EUV source, because they generate large amounts of debris. In fact, for all Sn-based EUV sources, debris mitigation continues to be a serious challenge.

Li is a third material of choice that was recently revisited by EUV source suppliers for both LPP[9] and DPP systems.[26] In the past, very low CEs of 0.1% for capillary discharges[27] and 0.23% for dense plasma focus (DPF) systems[28] were reported. However, recently much higher CE measurements of 2.5–3% have been reported for Li-based LPP EUV sources,[9] and 2.5% CE is expected for Li-based DPP EUV sources.[26]

1.2.3 Utility requirements

Utility requirements for EUV sources and for a wafer manufacturing fab in general should be considered, since these requirements allow an understanding of why some potential EUV source technologies may not be cost-effective. Although firm numbers are not available for laser utility requirements and full-scale scanners, utility consumption estimates can still point out potential issues.

EUVL is expected to be implemented in a 300-mm HVM fab. Based on current data, the utility requirements in 300-mm fabs have been estimated.[29,30] In a

Chapter 2

EUV Source Requirements for EUV Lithography

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2.1 Introduction and Background

2.1.1 Joint specifications

Joint specifications for EUV sources were first presented by ASML, Canon, and Nikon in February 2002 to accelerate source development by source suppliers, and the joint specifications have been updated periodically. The latest requirements are shown in Table 2.1, which was presented at the EUV Source Workshop in Miyazaki (Japan) on November 5, 2004.[1]

These specifications are defined at/after the intermediate focus (IF), which is explained in the next subsection. Table 2.2 shows how major requirements changed from 2002 to 2004. Requirements for wavelength, EUV inband power, and etendue

Table 2.1 Joint requirements for EUV sources (February 2004).

Source characteristics	Requirements
Wavelength (nm)	13.5
EUV power (inband) (W)	115*
Repetition frequency (kHz)	>7–10‡
Integrated energy stability (%)	±0.3, 3σ over 50 pulses
Source cleanliness (hours)	>30,000†
Etendue of source output (mm^2 sr)	<3.3‡
Max. solid angle input to illuminator (sr)	0.03–0.2‡
Spectral purity:	
130–400 nm (DUV/UV) (%)	<3–7‡
>400 nm (IR/visible) at wafer (%)	TBD‡

*At intermediate focus (IF).
†After IF.
‡Design dependent.

Table 2.2 Changes in joint requirements.

Source characteristics	Feb. 2002	Oct. 2002	Feb. 2003	Sept. 2003	Feb. 2004	Nov. 2004
Wavelength (nm)	13–14	13.5	13.5	13.5	13.5	13.5
EUV power (inband) (W)	47–120	80–120	115	115	115	115
Repetition frequency (kHz)	5	6	7–10	7–10	7–10	7–10
Etendue of source output (mm^2 sr)	1	1–3.3	1–3.3	1–3.3	1–3.3	3.3
Max. solid angle input to illuminator (sr)	0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2

of source output were agreed on at the workshop, but requirements for repetition frequency and maximum solid angle input to illuminator are not yet agreed on, because they depend on the tool design.

2.1.2 Definition of EUV source

Two kinds of plasmas emit EUV light: laser-produced plasma (LPP) and gas-discharge plasma (GDP). There are various types of GDPs according to the arrangement of the electrodes. Furthermore, several materials (Xe, Sn, etc.) are used for the plasma. Thus, even if only the plasma is considered, there are many potential candidates for the EUV source to be used for high-volume manufacturing (HVM). Collector optics is used to collect EUV light that radiates from the plasma and to focus the light at the IF. There are two kinds of mirror for the collector: the normal-incidence multilayer mirror and the grazing-incidence total-reflection mirror. Furthermore, there are many types of collector that are being developed.

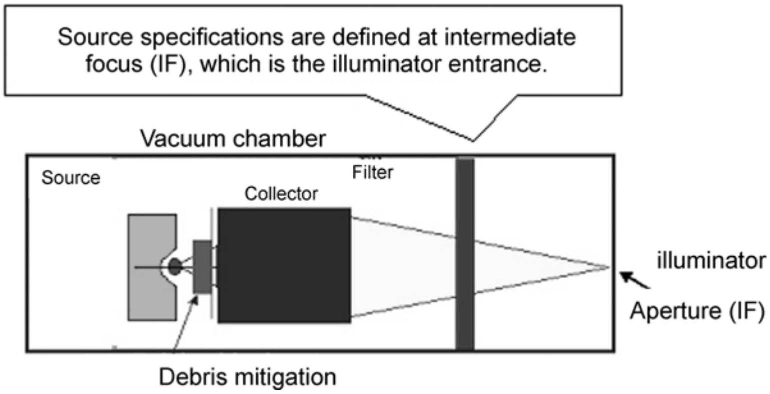

Figure 2.1 Definition of EUV source.

The EUV source is defined as the IF where the EUV light is focused, so that the appropriate exposure tool, and particularly its illuminator, does not depend on the variety of EUV source as described above. The IF is the illuminator entrance (see Fig. 2.1). The characteristics of EUV light at the IF should not depend on the method of generating the plasma or on its material, but must satisfy the overall joint requirements.

The lifetime of the source components, including the collector optics, is an important factor in the cost of ownership (CoO) of the EUV source. Debris shortens the lifetime of the collector. The material, size, energy, and state of the debris depend on the method of generating the plasma and on its material. Therefore, a debris mitigation system is an indispensable component, and its structure must be optimized for each EUV source.

Light emitted from a plasma has a wide-ranging spectrum, from EUV to IR. A spectral filter may be needed for the EUV source to satisfy the requirement of spectral purity for its application. It is known that the spectra of light from LPPs and GDPs are different. The spectral filters for LPP and GDP may therefore differ because they must be optimized.

2.2 Source Requirements

2.2.1 Choice of wavelength

The optics used in the EUVL tools is based on multilayer mirrors (MLMs). Different combinations of multilayer pairs are possible. The most common for the EUV region are Mo/Si and Mo/Be pairs. The Mo/Be mirrors' spectral range is larger than that of the Mo/Si mirrors. The cutoff wavelength for Mo/Si mirrors is about 12.5 nm in the shortwave region. No source, though, has been found so far that can make effective use of this fact. Strong emission in the 11-nm region has been demonstrated for LPP Xe sources; see Fig. 2.2. Nevertheless, because the spectral width of the ML mirror in the shorter wavelength region is narrower than in the longer wavelength region, the total power at the wafer for Mo/Be mirrors does not exceed that of Mo/Si mirrors. Coupled with the manufacturing and safety problems of Mo/Be mirrors, that has led to a choice of wavelength in favor of Mo/Si mirrors.

A more quantitative choice relates to the final adjustment of the system wavelength within a given spectral window of the Mo/Si mirror. The source emission characteristics play a major role in that choice.

A number of sources have potential for EUVL.[2–7] Due to their emission characteristics, the working materials that are used in those sources are usually Xe, Sn, and Li. Li, being a line emitter,[7,8] is the most sensitive to the choice of operating wavelength of the lithographic tool. Li radiates at 13.50 nm with a linewidth of 0.03 nm. The choice of a central wavelength differing from 13.50 nm by even a small amount can eliminate the possibility of using Li as a working material in the source for EUVL. On the other hand, a nonoptimal choice of the wavelength of the sources with other radiators means loss of power as well. The amount of energy lost due to nonoptimal spectral alignment can be evaluated. This type of analysis has been done for a white-light source with a wavelength-independent spectrum.[9] In this case, the integrated reflectivity of the system, with 10 mirrors, is only 5% lower for 13.5 nm than for 14.4 nm, as mentioned by Stuik et al. in Ref. 9. However, the final analysis has been done with a combination of the optical throughput and the light-source spectrum in Ref. 10.

Figure 2.2 presents a calculated near-normal-incidence reflectivity, based on the model of Ref. 11, for an 11-mirror reflective system. In contrast with a white spectrum, real Xe-, Sn-, and Li-based sources[8] have a maximum near 13.5 nm. Alteration of the peak wavelength by 0.5 nm might cause light losses of 60%–100%. The light loss induced by placing the tool wavelength at 13.5 nm for Xe and Sn emitters does not exceed 5%–10%.

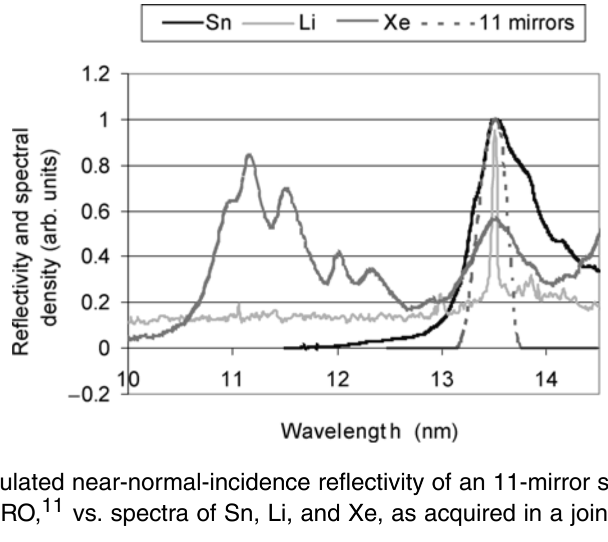

Figure 2.2 Calculated near-normal-incidence reflectivity of an 11-mirror system, based on the model of CXRO,[11] vs. spectra of Sn, Li, and Xe, as acquired in a joint investigation by ASML-ISAN.[8]

Thus, depending on the type of light source, it is possible to achieve only a 5%–10% increase in the optical throughput of a system by accurate spectral matching for emitters other than Li. The same shift for a Li-based source would make its use in EUVL impossible. That is not desirable at this early stage of development of EUVL. Currently, therefore, 13.5 nm is the wavelength of choice for EUVL.

2.2.2 Source power

The output power is the most important characteristic for EUV sources, because it affects the wafer throughput of EUV exposure tools directly. A typical EUV wafer throughput model is shown in Table 2.3. The energy required for exposing a wafer is obtained from field and wafer parameters. Assuming a field size of 25 mm × 25 mm and 89 fields in a wafer, 78.7% of the wafer area is exposed. A 25-mm field height is formed by masking a 26-mm field with an aperture, so 3.8% (= 1/26) of the light power is blocked. Assuming the resist sensitivity to be 5.0 $\mathrm{mJ/cm^2}$, the energy needed to expose all fields in a wafer is 2.9 J.

On the other hand, the power at the wafer is obtained from the source power, illuminator conditions, reticle conditions, and projection optics (PO) box conditions.

Table 2.3 Typical wafer throughput model.

Throughput	wafers/h	100
Time per item		
Total time per wafer	sec	36.0
Stage overhead	sec	27.0
Exposure time	sec	9.0
Field and wafer parameters		
Wafer diameter	mm	300
Fraction of wafer exposed	%	78.7
Penalty for not using full field height	%	96.2
Resist sensitivity	$\mathrm{mJ/cm^2}$	5.0
Intermediate derivatives at wafer		
Total energy per wafer	J	2.9
Power at wafer	W	0.321
PO box		
Reflectivity, mirror	%	67.5
Number of near-normal mirrors		6
Bandwidth mismatch loss	%	5.0
Polarization loss	%	5.0
Gas absorption PO	%	5.0
Total transmission PO	%	8.1
Reticle		
Reflectivity reticle	%	65.0
Power at reticle	W	6.1
Illuminator		
Total transmission	%	8.4
General		
Overall component degradation	%	37.0
Power: captured clean inband photons	W	115.2