*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-2.072 (2007)*

EUV lithography based on laser-plasma sources and debris mitigation: recent developments at ENEA

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Within a National Project on nanotechnologies (EUVL-FIRB), aimed at developing the Italian know-how in all aspects of EUV lithography, through the realization at the Frascati ENEA Center of a Micro-Exposure Tool (MET) for EUVL with a $<100nm$ resolution, an EUV-Soft X-ray laser plasma source has been realized and a composite Debris Mitigation System (DMS) has been designed and partly implemented. Both the source and the DMS are shortly described.

1. Introduction

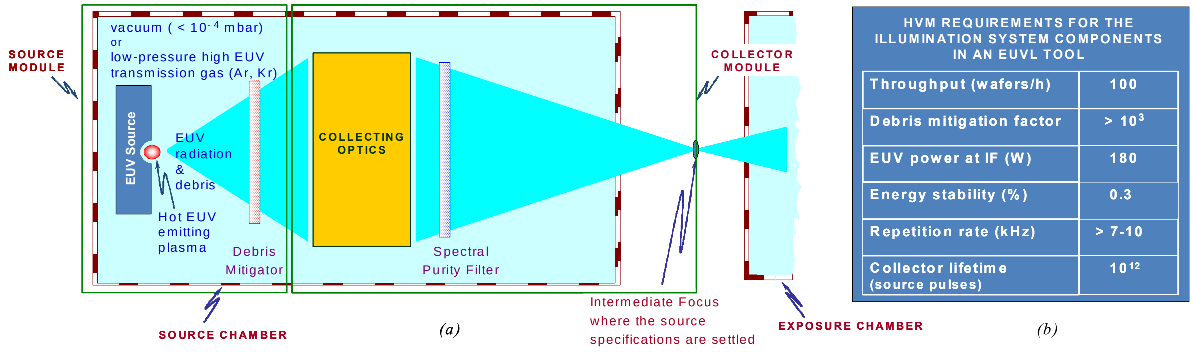
Within the EUVL-FIRB project [1], aimed at implementing a MET for projection EUVL at the Frascati ENEA Center, an appropriate laser plasma source - a tape target irradiated by a properly focused high-power high repetition-rate laser beam - was designed for emission from EUV to Soft X-rays, the specific photon energy range being selectable by adjusting the drive laser intensity hitting the target. It stands now as an EUV-Soft-X-ray laser plasma source facility - named EGERIA (Extreme ultraviolet light Generation for Experimental Research and Industrial Applications) [2]- equipped for a wide range of applications, including microradiography, contact microscopy of biological samples, short-probe research in condensed matter and lithography.

EUV lithography is widely regarded as the most promising patterning technology for the commercial production of advanced microchips in the next decade at the $32nm$ node and below. With a wavelength of $13.5nm$ - basically settled by the multilayer mirror (MLM) technology, presently able to produce highly reflective EUV optics ($R \sim 70\%$) only in the range of $13-15nm$ within a spectral window of $\sim 3\mathring{A}$ around the reflectivity peak, which can be varied by adjusting the multilayer period, and by the past use of lithium, having a very narrow spectral output at $13.5nm$, as a source element -, EUV light could be used to define circuit lines and features much smaller than those being placed on chips today.

The realization of an EUV light source with enough output power and lifetime is one of the critical issues for EUVL technology development. According to the high-volume manufacturing (HVM) requirements as jointly agreed on by the major scanner manufacturers, EUV power of more than $180W$ in the usable bandwidth of 2% at the intermediate focus (IF) is required for $10mJ/cm^2$ photoresist speed to enable better than 100 wafers per hour scanner throughput. Discharge-produced plasma (DPP) and laser-produced plasma (LPP) are the leading technologies for generating high-power EUV radiation. In both, hot plasma of $\sim 20-50eV$ of the chosen fuel material is generated, which produces EUV radiation. Xenon, tin and lithium are the fuel materials of choice for EUV sources [3].

The radiation emitted by the plasma is then collected by a mirror and focused to the IF where it is relayed to the scanner optics and ultimately the wafer. It is here that the source specifications are settled in accord with the joint requirements (Fig. 1.1).

The technical viability of both DPP and LPP source concepts for a HVM tool has been widely investigated. DPP sources have been credited with the capability of producing $10W$ at IF and are expected to be scalable up to $30-50W$. They currently consume less energy and are less expensive than LPP sources, and are being integrated into α-class EUVL scanners. However, the heat and debris resulting from EUV sources, which can



(a)

HVM REQUIREMENTS FOR THE ILLUMINATION SYSTEM COMPONENTS IN AN EUVL TOOL

Throughput (wafers/h)	100
Debris mitigation factor	$> 10^3$
EUV power at IF (W)	180
Energy stability (%)	0.3
Repetition rate (kHz)	> 7-10
Collector lifetime (source pulses)	10^{12}

(b)

Figure 1.1: *(a)* The source and the collector modules in an EUVL tool. *(b)* Inherent HVM requirements.

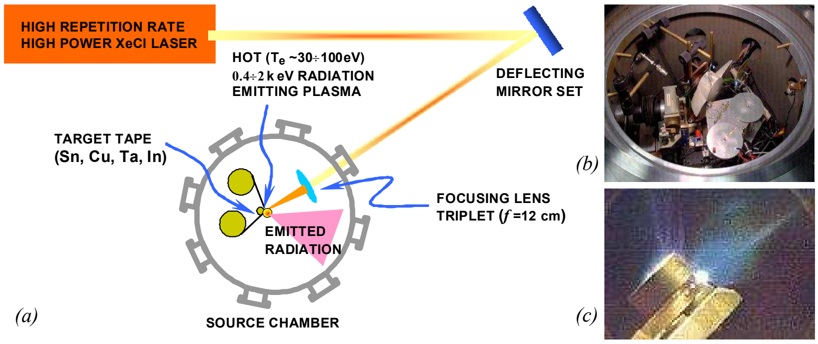
seriously damage EUVL scanner components, are more difficult to control in DPP-based systems. These disadvantages and the recent progress in high power lasers are increasing the feasibility of LPP-based systems. As emerged at the recent SEMATECH EUV source workshop [4], high-power (e.g. pulsed CO_2, Nd:YAG and fiber-based) laser driven Sn-LPP sources can now produce up to $130W$ of power for short periods, which could result in more than $40W$ of power at IF using highly efficient collectors. Multiplexing less powerful sources could produce the necessary wattage for a HVM tool. So, only the technology problems of a smaller power source should be solved for LPP-based systems.

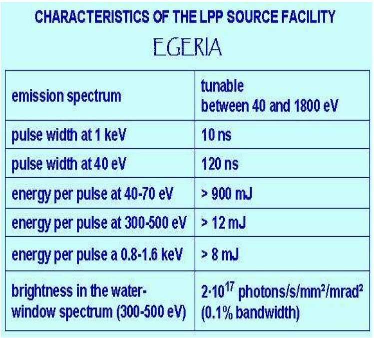
The lifetime of the source components, including the collector optic, is an important factor in the cost of ownership of an EUV source. Debris severely shortens the lifetime of the collector, one of the single most costly element in an EUV source. Its performance can be degraded by deposition of the source element and debris, diffusion of these materials in the MLM structure and fast ion sputtering of the MLM coating. Without protection, collector lifetime would be limited to just a few million pulses. At expected repetition rates $\geq 10kHz$, this would correspond to just minutes of production time. Presently, the lifetime of a collector optic in an EUVL α-class tool is $\sim 10^8 - 10^9$ source pulses, whilst the lifetime specification in a HVM tool is $\sim 10^{12}$ source pulses. Various methods for controlling the debris from plasma have been proposed: application of electric and/or magnetic fields for deflection or speed reduction, use of ambient gas for speed moderation or of foil traps for particle capture or also of mass-limited (e.g. porous) targets for reducing debris emission without affecting the conversion efficiency. The material, size and state (ion, neutral or particulate) of the debris depend evidently on the method of generating the plasma and on its material. Hence, the structure of the DMS, which appears as an indispensable component of any EUV litho equip, must be optimized for each EUV source.

In this paper, we briefly describe the EGERIA facility and report on the design and performance of the inherent DMS in relation to the EUVL-prototype development status.

2. EGERIA: the EUV-Soft-X-ray LPP source facility at ENEA

EGERIA is a LPP solid-tape-target source facility emitting over a tunable range from $40eV$ to $\sim 2keV$. It presents unique features among similar source-based devices in Europe as to the pulse energy and width. The characteristics of the emitted radiation such as spectral range and purity, peak intensity, pulse width, conversion efficiency can be controlled by the drive laser intensity, pulse duration and repetition rate and by the





CHARACTERISTICS OF THE LPP SOURCE FACILITY

EGERIA

emission spectrum	tunable between 40 and 1800 eV
pulse width at 1 keV	10 ns
pulse width at 40 eV	120 ns
energy per pulse at 40-70 eV	> 900 mJ
energy per pulse at 300-500 eV	> 12 mJ
energy per pulse a 0.8-1.6 keV	> 8 mJ
brightness in the water-window spectrum (300-500 eV)	$2 \cdot 10^{17}$ photons/s/mm²/mrad² (0.1% bandwidth)

Figure 2.1: *(a)* EGERIA layout showing the drive laser, the deflecting optics and the source chamber, which houses *(b)* the focusing optics and the tape target. *(c)* Emission of radiation and plasma plume.

target material. In fact, the EGERIA LPP source can alternatively be driven by two different high-power high-repetition rate XeCl lasers ($\lambda = 308nm$); precisely, the laser facility Hercules (developed by ENEA Frascati) whose pulse energy, width and repetition rate are respectively $E_L = 6J$, $\tau_L = 120ns$ and $p.r.r. \leq 5Hz$ or the commercial Lambda-Physik LPX-305 laser having $E_L = 0.5J$, $\tau_L = 30ns$ and $p.r.r. \leq 50Hz$. Target materials such as Sn, Cu, Ta and In are available for different applications. For instance, Sn and In are appropriate for lithographic processing at respectively $13.5nm$ and $14.4nm$.

The lab space for this facility houses the two drive lasers, the beam directing optics - needed for laser safety reasons - and the source vacuum chamber in which the EUV/Soft-X-ray radiation is generated and to which several diagnostics and/or devices can be coupled to make experimental observations or develop specific tools (Fig. 2.1).

Presently, the EGERIA source chamber is coupled to an exposure vacuum chamber, in which, as a final step of the aforementioned project, mask patterns will soon be imaged on photoresists or photonic materials with a $< 100nm$ resolution. For such applications, the Hercules driven EUV emission has been optimised with a laser intensity $I_L = 10^{10} W/cm^2$, resulting in a $\cos(\theta)$-distributed emission over a 2π solid angle with an $E \approx 20mJ/shot$ in 1 sr and 2.5% bandwidth from a $500\mu m$-wide and $100ns$-emitting source.

3. Towards a clean EUV source: the EGERIA DMS

In general, debris in LPP systems include fast source element ions and neutrals and source element particles. Of course, atomic and particulate debris behave differently; hence, an efficient DMS must embed different tools to effectively affect both kinds of debris.

An accurate speed-size characterization of atomic and particulate debris, emitted by the source, has been performed. Also, the mitigating power of various tools: ambient gas (Ar and Kr), mechanical interdicting device (fans with different numbers of blades and speeds) and magnetic field has been tested by observing the plasma debris contamination of glass plates, exposed - under different enviromental conditions and laser shot numbers - to the radiation from Cu tape, after being irradiated by the Lambda-Physik laser.

As a result, the EGERIA DMS combines a gas filter for continuous gas cleaning with a velocity moderating and a mechanical interdicting device (Fig. 3.1a). The former, by use of Kr as ambient gas at a pressure $\leq 1mbar$ allowing for EUV transmission $\sim 86\%$ through the overall target-to-collector distance ($\sim 10cm$), greatly reduces the range of flight of atomic debris. The mechanical device interdicts the arrival on the collector of

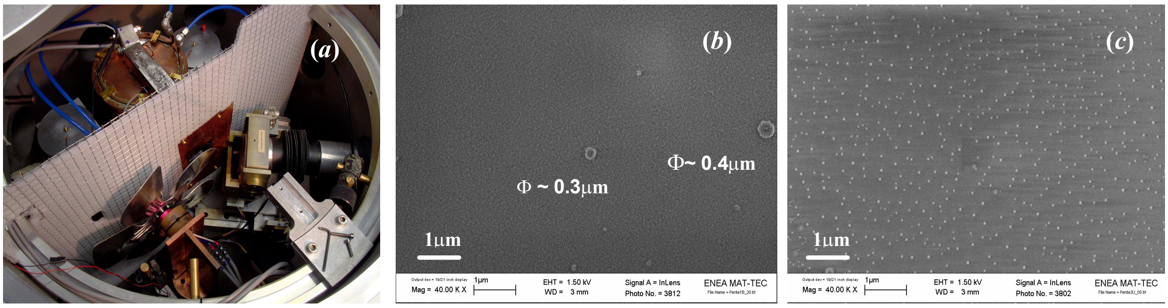


Figure 3.1: *(a)* EGERIA source chamber with the gas filter and the 5 blade aluminum alloy fan used for preliminary DM tests. SEM images of glass plates exposed in *(b)* vacuum + fan and *(c)* Kr + fan.

the particulates which, due to their quite varied sizes ($\Phi \sim 1-10\mu m$) and the mechanism of their formation, are scarcely moderated by the gas. The use of Kr requires to shift the operating wavelength to values $> 13.8nm$; in particular, at the chosen value of $14.4nm$ the Mo-Si MLMs maintain the same integrated reflectivity also after eight reflections.

Observation of the exposed plates by both the optical microscope and the microdensitometer resulted in very encouraging values of the debris mitigation factor (DMf) for both atomic and particulate debris. However, as expected, the mitigating power of Kr is markedly superior with respect to that of Ar.

Values up to 800 for the DMf of atomic debris - which is in the fore-front of the matter - resulted from the optical density measurements by a microdensitometer. An infinite DMf resulted for large size particulate debris ($\Phi > 1\mu m$) in both Ar and Kr. An inverse scaling law of the DMf vs. the fan cutting time was observed for small particulates ($\Phi < 1\mu m$), for which a $DMf > 600$ was obtained in Kr with a $0.5ms$ fan cutting time.

4. Outlook

Even better results are expected by implementation of the definitive patented fan - specifically designed for a maximum interdicting action, whose completion is imminent. It will have, for instance, a cutting time of $90\mu s$.

The formation of submicrometer presumably Cu-compounds clusters powder was also observed due to a homogeneos nucleation-like mechanism favored by the cooling action of the ambient gas (Fig. 3.1c). The dependence of such a powder formation on the ambient gas and its pressure as well as on the magnetic field, having seemingly an inhibiting action on it, will be investigated in order to devise an effective filtering or inhibiting mechanism.

The authors thank Dr. T. Dikonimos and Dr. N. Lisi for SEM analysis and comments.

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