



Title	Robust liquid metal collector mirror for EUV and soft X-ray plasma sources
Authors(s)	Fahy, Kenneth, O'Reilly, Fergal, Scally, Enda, Sheridan, Paul
Publication date	2010-08-02
Publication information	Fahy, Kenneth, Fergal O'Reilly, Enda Scally, and Paul Sheridan. "Robust Liquid Metal Collector Mirror for EUV and Soft X-Ray Plasma Sources." SPIE, August 2, 2010. https://doi.org/10.1117/12.860747 .
Conference details	Advances in X-Ray/EUV Optics and Components V, 2–3 August 2010 San Diego, California, United States
Publisher	SPIE
Item record/more information	http://hdl.handle.net/10197/3752
Publisher's statement	One print or electronic copy may be made for personal use only. Systematic electronic or print reproduction and distribution, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.
Publisher's version (DOI)	10.1117/12.860747

Downloaded 2026-05-01 23:47:26

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

Robust liquid metal collector mirror for EUV and soft X-ray plasma sources

Kenneth Fahy, Fergal O'Reilly, Enda Scally and Paul Sheridan
School of Physics, UCD Dublin, Belfield, Stillorgan Road, Dublin 4, Ireland

ABSTRACT

Recent work in UCD has centred on the development of a liquid metal coating process for EUV and soft X-ray collector optics. The work involves using a room temperature liquid metal coated on a solid metal substrate of the appropriate form. The advances made demonstrate that a stable thin coating film on the interior surface of a rotating optic substrate is possible, and this offers promise as a solution to the problem of producing an atomically flat reflector that remains unspoiled in front of a multi-kilowatt EUV plasma. We report on the results of preliminary EUV tests carried out on a simple focusing liquid metal mirror.

Keywords: collector mirror, liquid metal, extreme-ultraviolet, soft X-ray, semiconductor metrology, EUV lithography

1. INTRODUCTION

Extreme-ultraviolet (EUV) light source technology is a rapidly expanding field mainly driven by the semiconductor industry's activities in the area of EUV lithography [1, 2]. The industry roadmap projects a move from the current deep ultraviolet (DUV) lithography with $\lambda=193$ nm to EUV with a source wavelength of $\lambda=13.5$ nm in order to maintain the trend known as Moore's Law [3, 4]. This 'law' observes that the number density of microprocessors on a silicon wafer should approximately double every 2 years. The industry is approaching the limit of what can be achieved with the current DUV technology, and so the move is on to develop alternative chip patterning technology which will enable smaller, faster and more cost-effective microchip production by 2013. A leading candidate for the realization of this technology is EUV lithography based around a 13.5 nm light source due to the availability of multilayer (Mo/Si) mirrors that reflect this wavelength, since all materials are opaque to light at this energy [2,5]. The EUV source is likely to be a multi-kilowatt laser produced plasma (LPP) or discharge produced plasma (DPP) with tin as the plasma fuel in both cases. In addition to high volume manufacturing (HVM) of silicon microchips, associated EUV lithography infrastructure is required for mask defect inspection and resist test, and development is required by 2013 to support the beta scanners. The mask and resist metrology EUV sources will be tin based LPPs and tin or xenon based DPPs but will be significantly less powerful (~ 1 kW) than the HVM sources (>10 kW). EUV light from the plasma must be collected and brought to an intermediate focus where after the light is further manipulated by additional projection optics depending on the imaging task required. The high temperature nature of EUV plasmas means that energetic ions and particulate debris are emitted from the plasma and therefore any collector optic must be sufficiently robust to withstand this harsh plasma environment. No material is transparent to EUV radiation so that any mirrors used to focus the light (which must be almost atomically flat, because of the short wavelength of the light) are quickly destroyed by the debris, if unprotected. Two plasma fuels are used in commercial systems: xenon plasmas produce fast ions, which sputter the optics; tin plasmas, which are much more efficient EUV light emitters, produce fast ions which sputter the mirrors, and the tin itself also condenses on the mirrors, quickly reducing reflectivity. Typical metrology EUV sources have a 1 kW plasma, which would destroy a mirror in seconds, without debris protection. While debris protection schemes have been developed [2, 6] these are complex and expensive and will inevitably result in a loss of light through the system.

In addition to the EUV high volume manufacturing and metrology applications outlined, small simple soft x-ray radiation collectors could find important uses more generally in soft x-ray imaging and microscopy in the biomedical, materials and physical sciences. Liquid metal thin films have been proposed as a grazing incident mirror for robust final optics in a laser inertial fusion energy power plant [7]. It has been known for several centuries that the surface of a spinning liquid takes the shape of a paraboloid and this is being exploited to make the primary mirror for astronomical telescopes [8].

In this paper we discuss a potential solution to the problem of maintaining a stable, atomically flat surface just centimeters away from a hot plasma. A thin coating (tens of microns) of a liquid metal is applied to the interior of an EUV collector shell of suitable figure, since the surface of clean liquid metal is known to be atomically flat [9]. This metal is chosen as a compromise between EUV reflectivity and low melting point. Initially we have chosen a room temperature liquid metal – an alloy of gallium (68.5%), indium (21.5%) and tin (10%), known commercially as galinstan. Other liquid metals such as indium/bismuth/tin alloys which have higher EUV reflectivity over a broader range of grazing incidence angles (Figure 1) will be investigated in the future [10].

Since the liquid metal is a tin alloy, particles or ions impinging on the liquid surface will become absorbed in the liquid mix, thus maintaining the ultrapolished finish required for efficient EUV collection. This mirror will provide significantly longer lifetimes than the current state of the art solid solutions and will remove or reduce the need for debris mitigation. The challenge is to find a flow regime in which the surface is stable enough to deliver the required mirror figure.

In this paper we report on our first EUV tests of a simple hollow cylinder coated with galinstan. We present also the results of some preliminary EUV modeling of this optic using the commercial ray-tracing package ZEMAX [11]. Work is underway to develop single shell liquid coated ellipsoid sections which will ensure much higher EUV collection efficiencies as well as tighter focused spot sizes, compared to the simple cylinder discussed here.

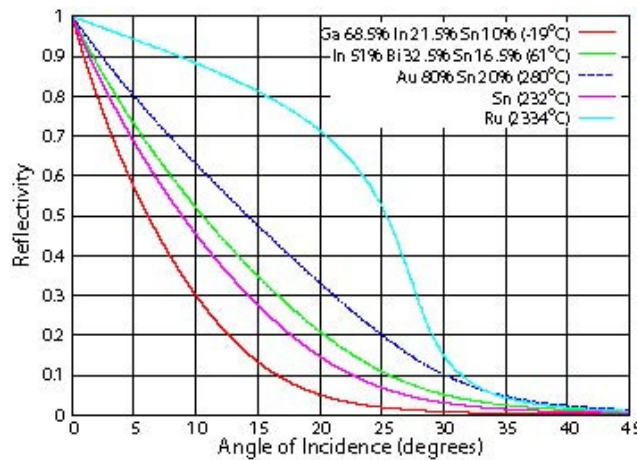


Figure 1. Theoretical reflectivity of various liquid metals as a function of grazing angle at 13.5 nm [10]. The quoted temperature corresponds to the melting point.

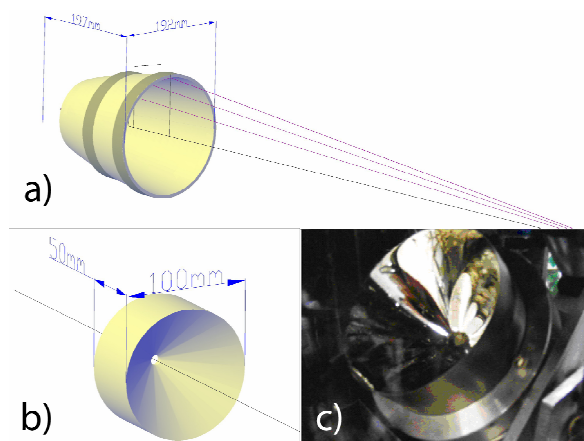


Figure 2. a) Example of a prototype ellipsoidal EUV liquid coated collector mirror currently in development; b) Schematic of our first rotating (conical) liquid mirror prototype; c) Photo of our conical prototype rotating collector mirror specified in b) coated with galinstan.

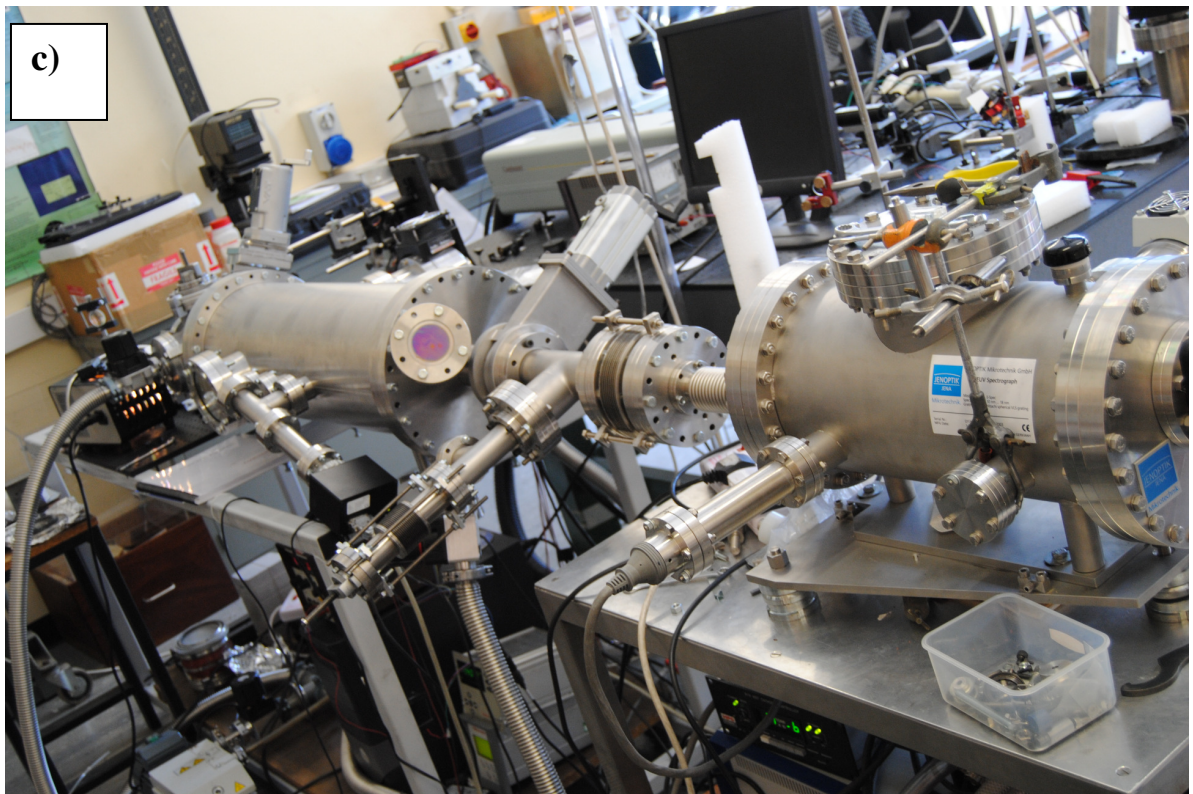
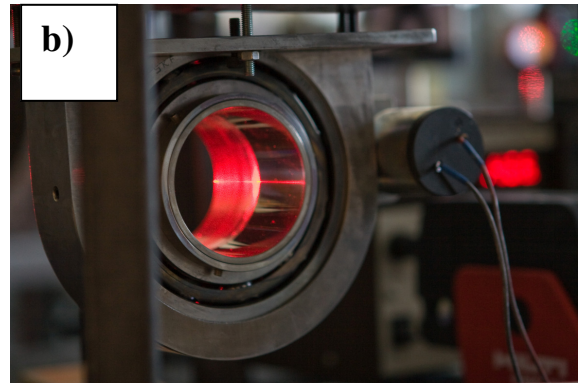
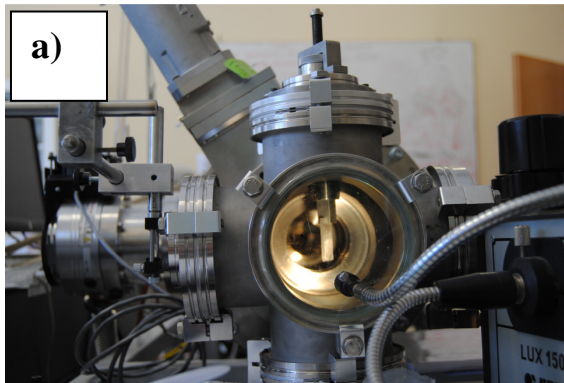


Figure 3. a) On axis view through the test chamber from the target side. The solid tin slab is visible at the centre of the hexagonal chamber. b) Mirror substrate mounted on the bearing. This bearing hangs from a sliding rail running through the central axis of the chamber allowing for external control of the mirror position. c) View of system from the detector end. Here the Jenoptik E-Spec grazing incidence EUV spectrograph is attached.

2. EXPERIMENTAL SETUP AND RESULTS

2.1 Experimental arrangement

The experimental setup is shown in Figure 3. The basic arrangement consists of the solid tin source, liquid coated mirror (mounted in a rotating bearing) and a EUV sensitive CCD detector housed in vacuum. The source is mounted in a separate hexagonal chamber which can be isolated from the main mirror chamber by means of a gate valve. This allows replacement of the tin target without disrupting the mirror chamber vacuum. The detector is a thermoelectrically cooled Princeton Instruments CCD camera with a 20 mm² sensor containing a 1024 x 1024 pixel array. Likewise this is also housed in a separate compartment with a gate valve opening to the main chamber. The system reaches a pressure of 1x10⁻⁶ mbar with all valves open. The laser is a pulsed Continuum Surelite Nd:YAG 1064 nm, 800 mJ, 7 ns, 7 mm diameter pulse focused onto the target using a spherical lens with f=150 mm. The laser beam is manipulated through a periscope mounted on micrometer slides allowing X-Y adjustment of the laser spot on the target. The lens is also attached to the periscope arrangement meaning we can translate the beam on the target (in order to find the optical axis of the cylinder) without changing the focus conditions. The focused spot size is estimated to be in the region of 50 μm and with a laser input energy 30 mJ this yields a peak power density on the tin target of $\sim 2 \times 10^{11}$ Wcm⁻². Tin is well known to emit strongly in the EUV region of the spectrum at these power densities [2]. EUV emission from the plasma will be confirmed by attaching a Jenoptik E-spec EUV grazing incidence spectrograph to the end of the main chamber. The mirror bearing assembly is mounted on a slide in the main chamber and can be translated along the optical axis by means of an externally controlled rotary actuator. A polyamide/ zirconium EUV filter is placed along the optical axis between the mirror and CCD. The thickness of the polyamide is 100 nm on top of 976 nm of zirconium. The EUV transmission of this arrangement is shown in Figure 4.

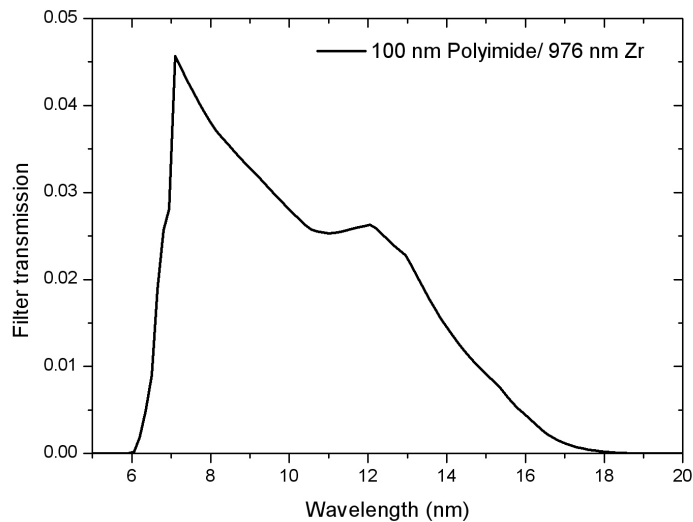


Figure 4. Theoretical polyimide/Zr filter transmission from 5 to 20 nm [10].

2.2 Optical modeling with ZEMAX

Preliminary optical modeling of the cylindrical optic has been carried out using the powerful commercial ray-tracing package ZEMAX® [11]. Zemax is a program which can model, analyse and assist in the design of optical systems. The cylinder shape is a predefined object in Zemax and we define the coating by supplying a file containing the real and imaginary parts of the refractive index appropriate to 13.5 nm light on galinstan. Although we are imaging a continuous wavelength band between 6 and 18 nm, initial polarization dependant modeling has been performed for a single

wavelength. Tin emits most strongly at 13.5 nm [2] and the reflectivity curve as a function of wavelength for galinstan does not vary significantly across the wavelength range detected here. Zemax will be used continuously throughout this research to define optimal mirror shape and size for particular EUV sources and particular EUV output powers depending on the application.

2.3 Results

Figure 5a shows the CCD image obtained with the liquid coated cylindrical mirror placed midway between source and detector (optimum focus) at a distance of 800 mm along the axis. A cross section of this spot is shown in Figure 5b. The focused spot size for this work is taken to be the full width at half maximum (fwhm) of a Gaussian fit to the cross section. The measured spot diameter is 279 μm . Zemax simulations have been performed for the same cylinder size and source-detector distance. A detector area of 4 mm X 4 mm with 200 pixels in each dimension is used for the simulations. A source size of 100 μm is assumed. The fwhm of the simulated cross section yields a spot diameter of 130 μm . Work is ongoing to establish more precisely our experimental source size and subsequently the ratio increase in collected EUV power compared to the background ($1/r^2$ distribution from the plasma) over the fwhm spot area from experimental data, and this will be compared with Zemax predictions.

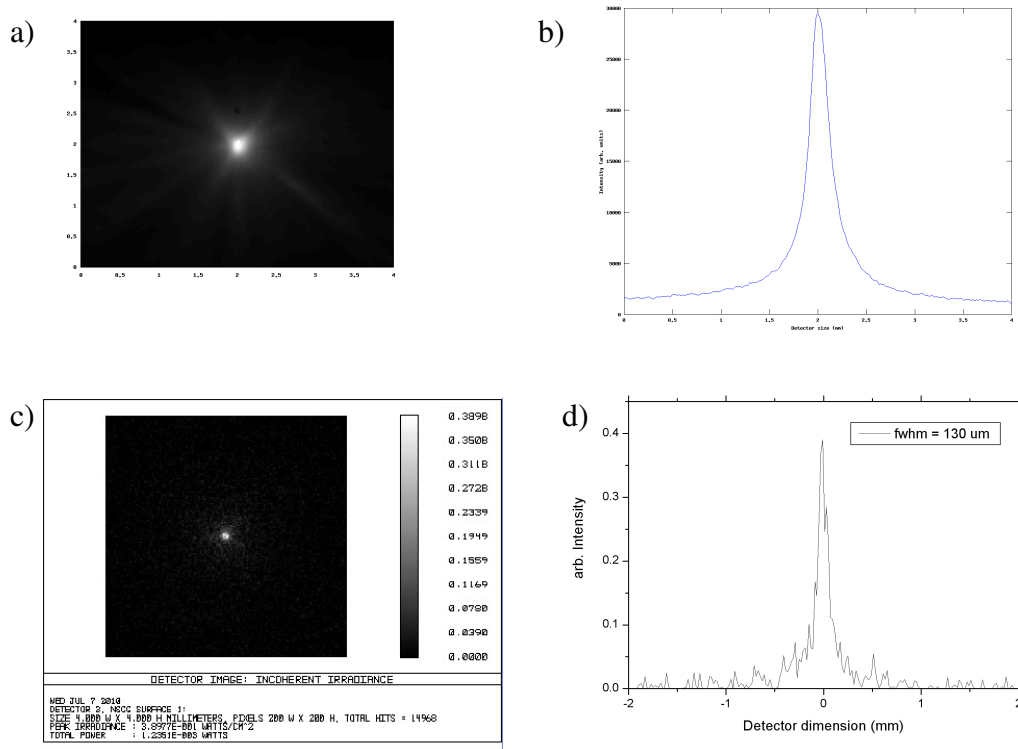


Figure 5. Experimental and simulated EUV images from the liquid coated cylinder. a) is the measured EUV spot as seen on a 4 mm X 4 mm region of the CCD detector. The associated cross section displayed in b) has fwhm = 279 μm . Image c) is the Zemax simulated image for 13.5 nm light on a 4 mm X 4 mm (200 X 200 pixel) detector area. A spherical uniform source of 100 μm diameter is used for these simulations yielding a focused spot diameter (fwhm) of 130 μm , shown in d).

3. DISCUSSION AND FUTURE WORK

The work carried out to date on a simple cylinder mirror geometry suggests that a stable thin film of liquid metal can be applied to the interior surface of a rotating optic of appropriate form assuming sufficiently slow rotation rates are employed (~1rpm). The effect of increasing the rotation rate to ~4 rpm has been observed qualitatively and further analysis will be carried out to determine the optimum rate. EUV images of a laser plasma have been acquired using this simple arrangement and work is underway to quantify the amount of reflected EUV. This will be done by measuring the EUV from the plasma using the absolutely calibrated Jenoptik EUV spectrograph.

An ellipsoid is currently being machined and which will yield significantly higher EUV collection efficiencies, smaller focused spot sizes and thus higher brightness images compared to the cylinder. The ray tracing code Zemax will be used to find the optimum ellipsoid parameters which will yield maximum brightness as required by the EUV metrology community. Other mirror figures such as Wolter type optics as well as multishell arrangements will also be investigated in the future. The ellipsoid mirror system will be tested for overall 'figure' (shape) optically using a CCD camera and laser and LED light sources. The light source will be placed at one ellipse focus and the CCD camera will be moved through the other focus along the optic axis. The resulting CCD images will be analysed to quantify the mirror figure.

Lifetime monitoring of the liquid optic will be performed by measuring the output power stability from a commercial high power EUV plasma.

We have developed a coating method using Galinstan (a room temperature liquid metal) to coat complex optics. While the EUV reflectivity of this metal may be useful for some applications (particularly for 'water window' biomicroscopes at 2-5 nm), it is advantageous to use other tin alloys, such as an indium/bismuth/tin alloy, which has a melting point of 62°C and significantly higher reflectivity at 13.5 nm. We will develop our coating techniques to include these very low melting point alloys, in order to benefit from this higher reflectivity.

ACKNOWLEDGEMENTS

This work is funded by Enterprise Ireland under grant number TD-2009-0346, and Science Foundation Ireland under grant number 07/IN.1/1771. The authors would like to thank the technicians of the UCD School of Physics mechanical workshop for their invaluable assistance throughout this project to date. Thanks also to Intel Ireland for their support.

REFERENCES

- [1] <http://www.semtech.org/research/litho/index.htm>
- [2] Bakshi, V, ed, "EUV sources for lithography", SPIE Press, Bellingham, WA 98227-0100, USA, 2006
- [3] <http://www.itrs.net/>
- [4] Moore, GE, "Cramming more components onto integrated circuits", Electronics 38(8) (1965)
- [5] Atwood, D, "Soft X-rays and Extreme Ultraviolet Radiation Principles and Applications", Cambridge University Press (1999)
- [6] Jurczyk, B.E., Vargas-Lopez, E., Neumann, M.N. and Ruzic, D.N. "Illinois debris mitigation EUV applications laboratory", Microelectronic Engineering, 77(2) (2005)
- [7] Moir, R.W., "Grazing incidence liquid metal mirrors (GILMM) for radiation hardened final optics for laser inertial fusion energy power plants", Fusion Engineering and Design, 51-52, 1121-1128 (2000)
- [8] Borra E.F., Brousseau, D., Gagne, G., Faucher, L., and Ritcey, A.M. "Nanoengineered parabolic liquid mirrors", in Optomechanical Technologies for Astronomy", Proc. SPIE 6273, (2006)
- [9] Regan, M.J, *et al*, "Surface layering in liquid gallium: An X-ray reflectivity study", Physical Review Letters, 75(13), 2498-2501 (1995)
- [10] http://henke.lbl.gov/optical_constants/mirror2.html
- [11] <http://www.zemax.com/>