Distributed EUV Source-Optic Architecture For HVM Using Micro-Plasma Arrays

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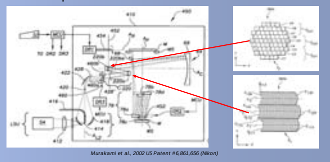
Abstract

In this paper, we present a novel approach to the EUV source-optic architecture using a high-brightness light source array for direct integration with the illumination optical system. By taking advantage of a small plasma emission volume, N light source units can be spatially multiplexed with the etendue envelope of the projection optics. Positioning the array near the location of a conventional fly's-eye optical integrator in the Illuminator, spatial uniformity and Köhler illumination can be achieved with a reduction of 4 mirror elements. This significantly increases the illuminator throughput by >75%. Additional optical rastering and assay illumination greyscaling can further improve system efficiency leading to a viable HVM solution. Thermal and material constraints are also overcome by distributing power and particle loadings over a large N unit area—providing system scalability.

This paper presents the results of recent experimental testing and optical design showing a clear development pathway and high probability for success. No fundamental show stoppers have been found. Starfire Industries is looking for interested parties to further R&D and industrial prototyping.

Motivation

The key motivation for this work is to improve the efficiency of the collective EUV source and optical train. For many years, the source and optics system have been considered disparate entities. As a result, very high lamp powers are required due to mirror complexity and associated power loss.

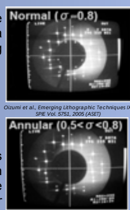

Murakami et al, 2002 US Patent #6,861,656 (Nikon)

An 8-mirror illumination system from in a conventional EUVL scanner system is shown. Incoming light is planarized and directed through a preferred aperture for desired illumination of the mask. Only a few 2-5% of the incoming light makes it to the entrance pupil of the projection optics—poor throughput.

Fly's Eye Optical Integrators

Since a single EUV light source is used with some variation in output, spatial uniformity, and focus, the optical system needs to improve light uniformity. This is achieved by breaking up the incoming light into discrete light bundles by using a fly's eye optical element. The light is then spatially averaged for uniformity and recombined at the reticle, achieving the desired intensity and coherence for Kohler and/or critical illumination.

The fly's eye breaks up the incoming light and forms a secondary image plane consisting of a 2D array of point-like sources.

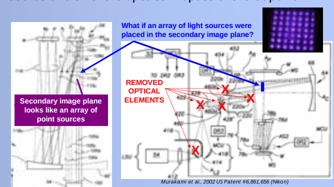


Oizumi et al, Emerging Lithographic Techniques IX, SPIE Vol. 5751, 2005 (ASET)

Here is a good example of this effect is visualized at the projection optics entrance pupil from the HiNA experiment at ASET for different partial coherence values.

Simulate Image Plane?

At the 2006 EUV Source Workshop, Starfire Industries presented the question: Could a 2D array of micro-plasma light sources be placed at the fly's eye location in the Illuminator to **simulate** a single high-power light source and all of the upstream optics until that point?



Murakami et al, 2002 US Patent #6,861,656 (Nikon)

This could lead to the elimination of up to four (4) mirror elements **after** the intermediate focus! This could increase the illuminator efficiency by:

$$\eta_{gain} = \left(R_{reflectivity}\right)^{-N_{mirrors}} = (0.65)^{-4} = 5.6x$$

Micro-Plasma Arrays

Microdischarge devices are readily fabricated with a variety of possible electrode configurations, including hollow cathode, capillary, z-pinch, etc., with 1-1000µm characteristic dimensions and high areal density arrays.

Laser produced plasmas can also be used to create an arrayed patter with low-power, high-brightness amplifiers directed onto a surface.

These are ideal for light source applications:

- No fast ion generation (in some configurations)
- Spatial source distribution defined by geometry
- Excellent shot-to-shot repeatability
- Low debris generation (in some configurations)
- Low voltages required due to small size (< 1200V)

Individual "pixels" can be switched on/off by controlling the capacitor recharge with external circuitry. An addressable array could simulate different illumination apertures (annular, special oblique, etc.) without the need for a beam-chopping aperture wheel. Depending on the illumination and relay optics, this could provide additional power savings (20-40%).

Distributed array allows excellent electrode cooling and power dissipation into the 10s kW range without need for exotic materials. Also the source array can be covered with a micro-foil debris catcher and spectral purity filter.

Experimental Testing

Starfire's micro-plasma thruster facility was utilized for preliminary experiments.

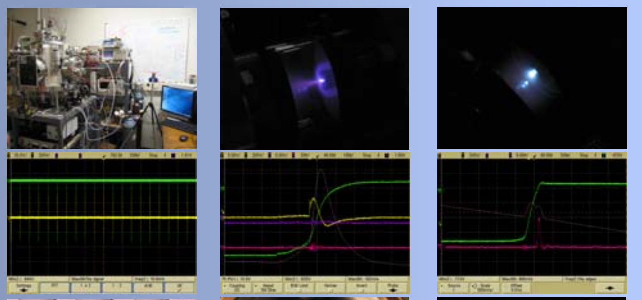
Microdischarge operation was achieved at 1-10kHz operation in the laboratory with argon and xenon gases. Plasma source diameters of 100-400µm were tested at moderate voltages 600-1000V.

Current pulse times on the order of 75-100nsec observed with peak currents in the 100s of amps through a small constriction.

EUV signals were measured on an IRD Si/Zr filtered photo diode after a single bounce on a Ru-capped Mo/Si MLM with 40 bilayers. Measurements at the UIUC Sn Xtreme source with this detector showed signals in the ~300mV, so we are observing a good signal in the 5-10mV range for the small microdischarge source. Only signals were detected with xenon, not argon.

A 5 x 5 array was constructed and operated to test out independent switching, addressability, and cross-talk concerns.

Fast ion generation and debris generation have not been tested with the current arrangement, but will be forthcoming.

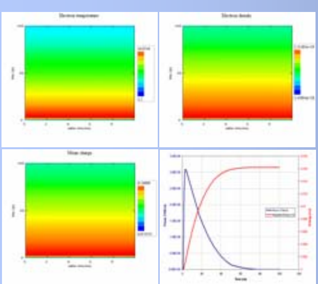


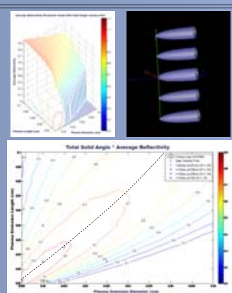
Helios CR Plasma Simulations

Starfire has utilized the PrismCS Helios 1D collisional radiative MHD plasma model to estimate the light output intensity and conversion efficiency for a given set of parameters.

Starfire contacted the University of Illinois and they simulated a range of operating conditions and dimensions to map out a parameter space for microdischarge plasma operation.

Helios code simulations show microdischarge plasma sources can reach >1.2% CE in 2π sr for xenon over a wide range of conditions (voltage, pressure, geometry, etc.). Thus, optimal conditions can be tailored for different input parameters. The figures to the left show a sample simulation for a 200µm diameter .





Integrated Collection Optics

Based on feedback from the 2006 Vancouver Source, one question was: what is the collection angle and efficiency reasonably achievable with an collection optic array?

Starfire Industries examined the effective collection angle for a simple parabolic grazing-incidence collector optic that is integrated with a micro-plasma source. There are a series of contour plots showing the region of maximum solid angle x average reflectivity for a given plasma emission volume. A uniform cylindrical profile was assumed for these calculations and integrated as a function of angle and reflectivity.

There is a maximum value along the dashed line representing the optimum trade-off between capturable solid angle and reflectivity. A optimal value of plasma diameter-to-length is ~42.5% including opacity effects as calculated with the Helios-CR code for representative conditions with a xenon fill gas. In addition, one advantage of the integrated collection optics is alignment right at the source.

Hyperion Development Review

Based on feedback from the 2006 Vancouver Source Workshop, Starfire contacted Hyperion to examine the technical merits of the proposed distributed source-optic architecture. Preliminary analysis indicates that there is substantial merit in this approach and a potential for improving illuminator efficiency and source power scaling for HVM.

N Source Etendue

One main question from the Vancouver Source Workshop was related to etendue, namely how could a system of N sources be able to meet the etendue limitation of the projection optics?

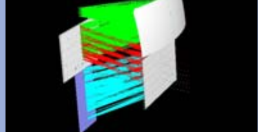
Since the EUV light is collected at each individual source location and then relayed into the illuminator, the total etendue of the system is a simple summation:

$$\varepsilon_{etendue} = \sum_{N} \varepsilon_{source} = \sum_{N} A_{source}\Omega_{capturable}$$

Thus, a system of N sources with a collectable solid angle Ω and effective source area A can be matched to the etendue of the projection optics box by selecting appropriate micro-plasma geometry and parameters.

Case #1: Conventional Fly-Eye Solution

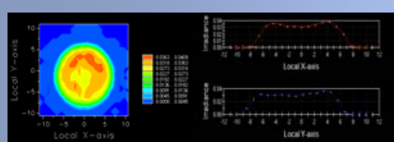
- Multiplex N sources and adapt to a conventional illumination system.
- Collect light at each micro-plasma source with a standard grazing-incidence collection element.
- Spatial averaging and uniformity mixing is achieved with a standard set of two fly's-eye mirrors.
- Use two field shaping optics to transform and relay light beam into the required rectangular slit at the reticle.
- Total of four (4) optical elements vs. six-to-eight (6-8) for a conventional HVM illuminator system.

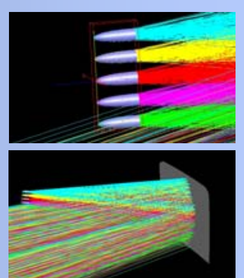


Customization of the plasma emission area into a slit or arcurate segment may allow the reduction in one field shaping element leading to a three (3) element system.

Case #2: Direct Multiplex Solution

- Multiplex N sources and create a customized illumination system that further reduces the number of optical elements.
- Collect light at the micro-plasma source via CPC or non-traditional integrated reflector.
- Overlap sources to create uniform pupil fill and spatial uniformity, mimicking effects of fly's-eye mirrors.
- Utilize unique collector/source/plasma parameters to provide homogenization at each source.
- Require one-to-two (1-2) field shaping optics to transform and relay light beam into the reticle slit geometry, depending on source area customization.
- Total of only one-to-two (1-2) optical elements in the illuminator for a four-to-seven (4-7) reduction vs. the current SOTA!





Beam irradiance and uniformity across the pupil fill will depend on a variety of factors in the source/optic system. Further R&D is required to determine what direct multiplex solutions are possible.

Clear Pathway Forward

There is a development roadmap for investigating the optical system leading to an optimization for an illuminator system based on an array of Starfire Industries micro-plasma sources.

•Etendue Matching	See Solution
•Spatial Uniformity	See Solution
•Kohler Illumination	See Solution
•Minimizing Bounces	Have Multiple Options
•Eliminating Fly-Eye's	Need More Development

Likewise, there is a developmental roadmap for investigating the micro-plasma sources themselves leading to high-efficiency light generation for a high-output array of Starfire Industries micro-plasma sources.

•High Rep Rate Operation	See Solution
•Thermal Management	See Solution
•Source Debris/Lifetime	See Solution
•Source Geometry	Have Multiple Options
•EUV CE%	Need More Development

Next Steps

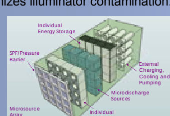
- Perform in-band diagnostic source imaging with calibrated Flying Circus instrumentation for basic comparative measurements.
- Expand optical illumination system design leading to a point design for 1-2 different concepts.
- Expand experimental micro-plasma source development to investigate CE% optimization in concert with illumination system needs.
- Perform more detailed thermal, engineering and manufacturing analysis to see what will and will not work for an HVM system.
- Work with external developers for prototype feasibility.

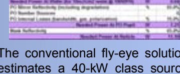
The goal of this work is to:

- **Reduce EUV power requirements**
- **Make spatial and temporal multiplexing easier**
- **Reduce overall CoO for the scanner tool**
- **Provide lithographic capability & value to end-user**

HVM Estimations

An HVM source array system can be completely sealed and integrated with collectors, SPF material, energy storage, and circuit switching. The enclosure also minimizes illuminator contamination.





The conventional fly-eye solution estimates a 40-kW class source array, assuming three illuminator mirror bounces and assumptions on the source collection, absorption and spectral purity. The direct multiplexing solution results in a 17-kW class source array with only one illuminator bounce. Note these estimates are for xenon, not Sn or Li.

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