Application of the Energetiq EQ-10 Electrodeless Z-Pinch$^{\rm TM}$ EUV Light Source in Outgassing and Exposure of EUV Photoresis

Paul A Blackborow[a], Deborah S Gustafson[a], Donald K Smith[a], Matthew M Besen[a], Stephen F Horne[a], Robert J D'Agostino[a], Youichi Minami[b], Gregory Denbeaux[c]

[a]Energetiq Technology, Inc. Woburn, MA USA;
[b]Litho Tech Japan Corporation, Saitama, Japan;
[c]College of Nanoscale Science and Engineering, SUNY, Albany, NY,USA

ABSTRACT

Formulating high sensitivity and high resolution EUV Resists is a critical issue gating the adoption of EUV lithography. The ability of resist manufacturers to quickly screen outgassing rates and sensitivity of EUV resists will facilitate faster formulation of a production-ready EUV photoresist. The high power and low cost per watt of the Energetiq EQ-10 light source enables relatively simple designs without complex optics to deliver relevant data efficiently. Because the source operates without electrodes, a significant source of contamination is removed, further simplifying the design of exposure systems.

Data will be presented from two prototype exposure systems. The first, in operation at Osaka University, Japan[1] has been used for in-band flood exposure experiments to test resist sensitivity and develop photochemical modeling capability. The second, in operation at SUNY-Albany,[2] integrates exposure/sensitivity with outgassing measurements (GC/MS and RGA) and also allows direct tests of mirror contamination, at power densities near those required for Beta exposure tools. Features of both experiments have been integrated into a commercial device. Details of this tool – the Litho Tech Japan EUVES-7000 system for resist outgassing and exposure – will be presented at this meeting.[3]

Keywords: Z-Pinch, EUV source, resist exposure, resist outgassing

1. INTRODUCTION

The success of EUV lithography in a semiconductor production environment is critically dependent on development of appropriate resist technology. In current high-volume manufacturing, state of the art lithography is based on the ArF laser operating at 193 nm or 6.4 eV per photon. In contrast, the 13.5 nm wavelength selected for EUV lithography delivers 92 eV per photon, many times material ionization potentials. Photosensitivity at these energies relies on interaction of the resist materials with the (multiple) secondary electrons generated by the EUV photon, instead of directly with the DUV photon as in current production technology. While some aspects of resist chemistry can be addressed with generic actinic radiation or with e-beams, in the end there is no substitute for direct experience at the wavelength of ultimate interest. Few tools appropriate for such studies exist, and those that do tend to be large, expensive shared facilities.[4]

In 2005, Energetiq Technology, Inc introduced the EQ-10 EUV source, producing 10 Watts(2π) of 13.5 nm light in-band ($\pm$1%). Since that time, several laboratories have integrated the EQ-10 into facilities specifically to support resist development activities. After a brief review of the unique characteristics of this source (details of which have been previously published[5]), we will describe two of the several currently operating facilities in some detail. Finally, we will mention some more advanced applications for the EQ-10 source which are in various phases of design and construction.

Further author information:
S.F.H.: E-mail: shorne@energetiq.com;
P.A.B.: E-mail: pblackborow@energetiq.com

2. CHARACTERISTICS OF THE INDUCTIVE Z-PINCH

While a detailed description of the physics underlying the source has been published elsewhere,[5] certain of the unique features of the design relate directly to its application and integration as a light source. We will briefly review these below.

The most novel feature of the source compared to previous pinch designs, is that the plasma current appears as closed loops supported by transformer induction, rather than as a current channel supported by electron emission from electrodes.

In a conventional Z-pinch, the pinch current must be extracted from and injected back into metal electrodes. To provide the high currents required (typically tens of kA), the cathode must be both very hot (to provide thermionic emission) and strongly biased negatively. In other words, the cathode presents itself to the plasma as a molten or near-molten metal surface, biased so as to attract heavy (Xenon, typically – 131 AMU) multi-charged (+10, typically) ions. One would be hard pressed to devise a more destructive environment. Evaporation and sputtering reduce electrode lifetime, deposit conducting material on insulating surfaces nearby, and most critically, can contaminate nearby optical elements.

Some ingenious techniques – particularly, laser triggering of the discharge, combined with rotating electrodes[6]– have been used to ameliorate this and other problems in high power electrode based sources using metal vapor instead of Xenon as the working gas. Tin and lithium in particular have higher efficiency as EUV radiators than has xenon. The cost and engineering complexity of these innovations, however, place them out of reach except for very high power systems. And, of course, introducing a condensible metal vapor into an optical system creates a host of new problems.

Because the inductive Z-pinch has no electrodes, these issues vanish. Power handling becomes a much simpler problem, allowing a source of moderate power (10W, 2π inband) to operate in Xenon continuously and routinely with little routine maintenance and essentially no downtime.[7]

The inductive pinch boasts further advantages over electrode-based systems. In particular, the EUV-emitting region of the plasma naturally displays very high uniformity pulse-to-pulse, both in location and amplitude. In a conventional source, each pulse must be initiated from a zero-current condition; the location and temporal behavior of the initiating current is free to vary across the electrode. In the inductive pinch, the current profile is imposed on the plasma by the induced electric field, whose shape depends only on the geometry of the device. In addition, the magnetic fields produced by the pulsed currents provide essentially perfect centering of the pinched plasma within the bore.

Figure 1 clearly shows the magnetic centering effect in action. From the point of view of any of the six individual plasma loops, the system is very asymmetric, and the current (therefore magnetic field) is only one-sixth of the total pinch current. Nevertheless, each of the six return loops is perfectly centered in its own bore. Figure 2 shows the production version of the source. Our attempts to measure the radial variation of the position of the peak EUV emission on this source have failed to yield any except negative information – we estimate (via statistical analysis of multiple in-band X-ray images) that the radial variation of the position of peak brightness is less than six microns, of which perhaps two microns can be attributed to photon statistics. Our camera pixel size, in the plane of the source, is about 17 microns, which probably is a reasonable overall estimate of the error bar in the six micron “measurement”. The FWHM of the emissive region is less than 500 microns.

Dose reproducibility is critical when resist sensitivity is measured. The dose reproducibility was measured by using an integrating oscilloscope to capture bursts of varying times. The bursts were defined by an inline shutter, to avoid startup transients. Figure 3 shows a typical scope trace. Table 1 gives dose variability data for bursts of between three and sixty seconds.

3. FLOOD EXPOSURE FACILITY AT OSAKA UNIVERSITY

In an earlier paper we described initial experiments with a simple flood exposure device. An engineered version of this system was installed at the University of Osaka in April 2006, and has been operating since then. Figure 4 shows the design of the device.

This system illustrates the simplicity of design enabled by the EQ-10. The 10W inband power and compact design allows use of a single plane multilayer mirror (bandwidth $\approx \pm$ 3%) to give short exposure times. The integrated power diode allows *in situ* dose rate measurements, removing a significant source of uncertainty in exposure experiments. Figure 5 shows the installed device during a training session.

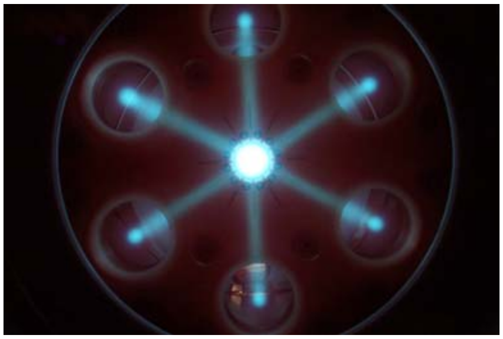

Figure 1: An early prototype (six plasma loops) operating in Argon gas.

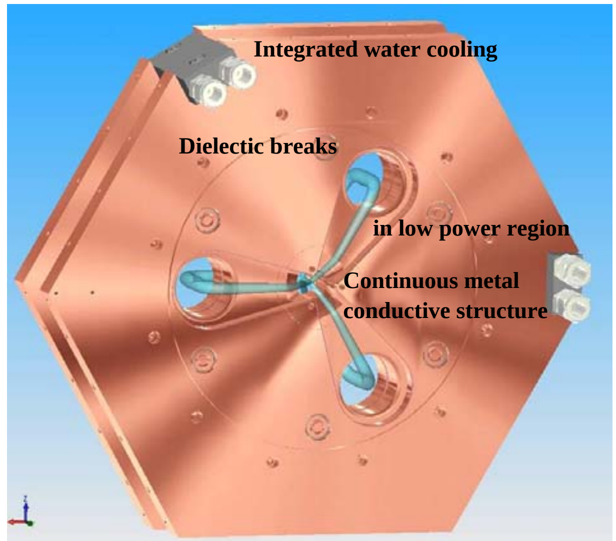

Figure 2: The production version of the EQ-10 uses three plasma loops.

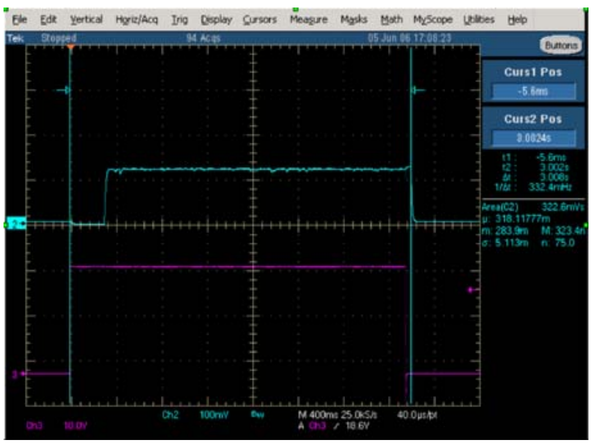

Figure 3: A screen capture of about 2.5 seconds of operation

Seconds	μ=mv-sec	σ	trials	$\sigma/\mu(\%)$
3	318	5.1	75	1.60
5	545	6.7	37	1.23
10	1130	12.3	33	1.09
20	2299	18.4	50	0.80
60	6995	53.3	51	0.76

Table 1: Dose reproducibility for various exposure times

One example of the application of this simple system to resist development is the work of Sekiguchi *et al.*[1] In a series of papers[8–10] Sekiguchi and his colleagues have developed a technique to determine experimentally certain key parameters that characterize resist performance by using flood exposure data, and then by use of those parameters, estimate the detailed performance of the resist. The value of this approach is that it allows sophisticated screening of potential resist formulations without requiring access to a true projection exposure system. They predict,[1] for instance, the performance of particular resists and processing protocols for the Nikon HiNA-3 exposure tool.

Another example of the application of the same exposure system is found in the work of Yamamoto *et al.*[11] This effort is focused on investigating the detailed chemistry of acid generation in chemically amplified resists, comparing EUV and E-beam behavior. Eight different resist formulations were exposed using both E-beam and EUV, at various dose rates. After each exposure, absorption spectra were obtained to quantify acid yields. They conclude that, because the bulk of the acids are generated by the secondary electrons produced by absorption in the polymer, increasing the EUV absorption by the acid generators directly does not significantly increase acid yield.

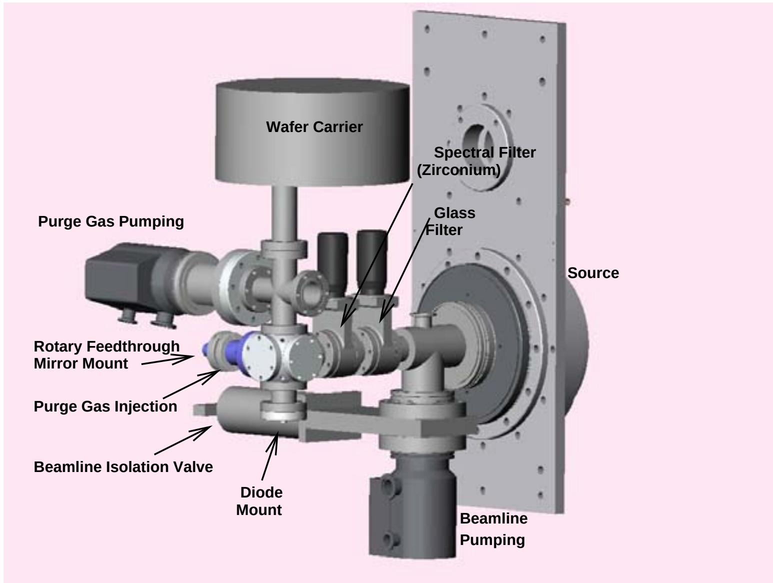

Figure 4: A simple flood exposure system

Figure 5: Training at Osaka University

4. EXPOSURE AND OUTGASSING MEASUREMENTS AT U. ALBANY

This program began in 2005[12] and concentrates on understanding outgassing and contamination issues relevant to EUV exposure systems.[2] Figure 6 shows the installed system.

The experiment uses four complementary techniques to measure resist outgassing. The simplest technique is simply to observe the pressure rise with an ion gauge. Since some of the outgassed species consist of complex (presumably "sticky") hydrocarbons, this method is not particularly accurate and probably gives only a lower bound. However, by depositing the photoresist on a quartz microbalance and measuring the mass loss rate during exposure, a direct measure of mass loss

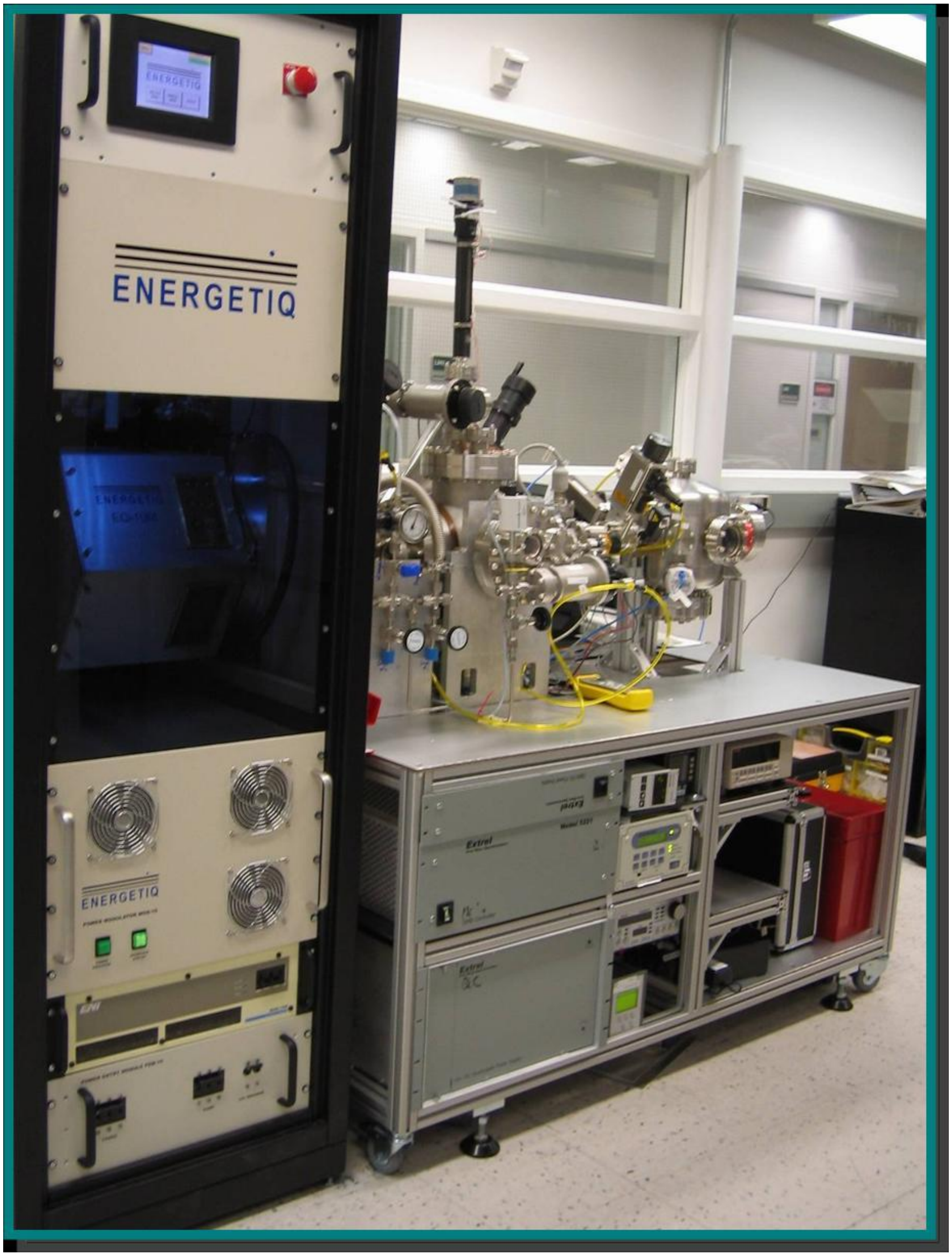

Figure 6: Source installation at U. Albany

can be obtained. The microbalance yields accurate mass loss, but gives no species data. A quadrupole mass spectrometer integrated into the experiment gives real-time mass spectra of outgassed species, but these spectra require a certain amount of interpretation due to fragmentation of the original molecules during ionization within the mass spectrometer itself. By also integrating a thermal desorption tube into the system, this last issue can be addressed directly, through use of off-line GC/MS. The combination of these techniques enables a detailed quantitative analysis.[7] Figure 7 shows a photograph of

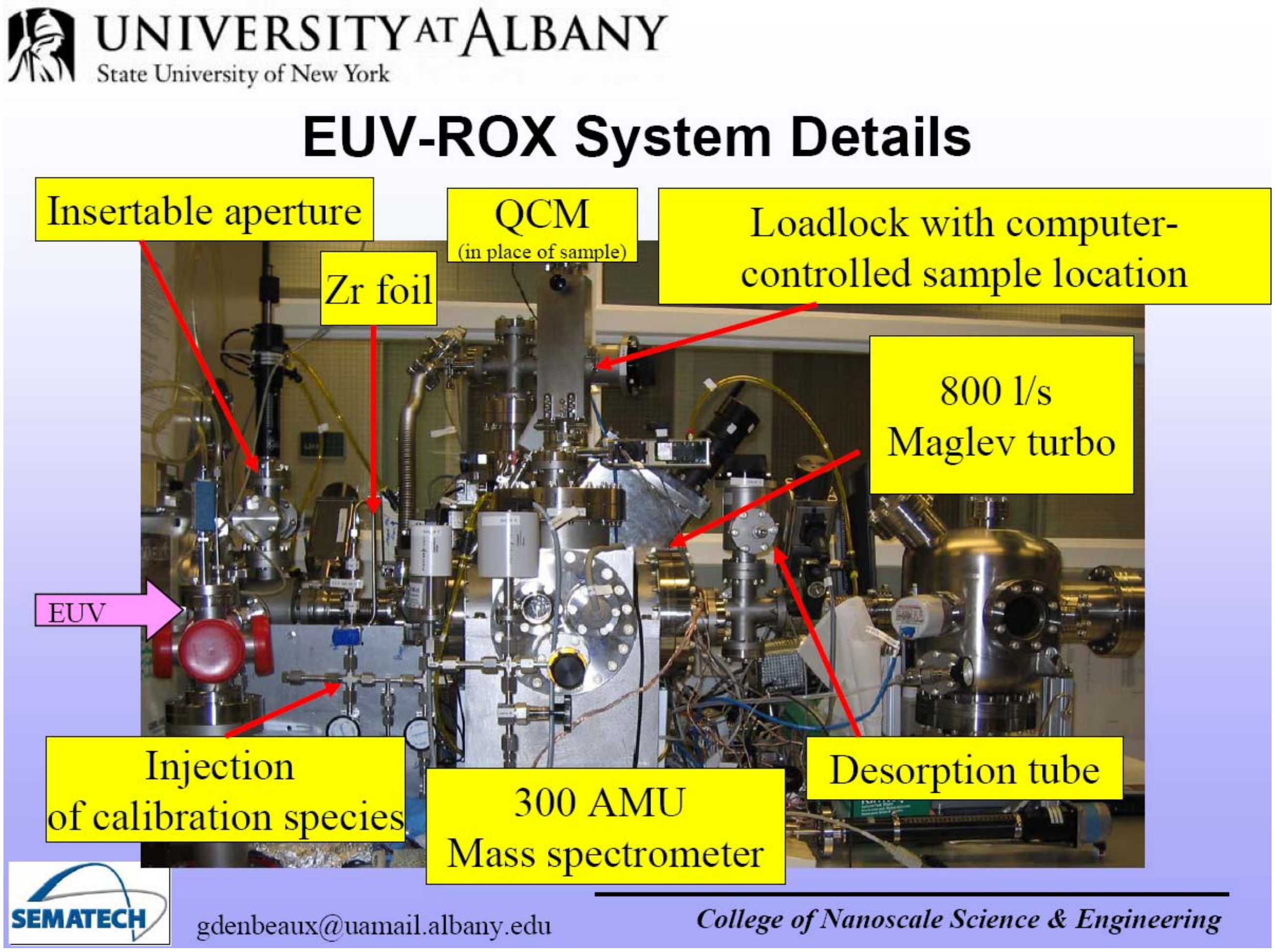

Figure 7: Diagnostic chamber at U. Albany (courtesy Greg Denbeaux)

the diagnostic chamber.

One feature of this experiment is that the wide-band EUV output of the EQ-10 is used, by simply filtering the source output through a zirconium foil and forgoing the use of a mirror. Because of the dominant role played by secondary electrons in exposures with 92 eV photons (as distinct from the DUV case, with 6.4 eV photons) it is presumed that the extra bandwidth will simply increase the dose rate, with no other change to the chemistry – thus allowing a more realistic simulation of dose rates relevant to production.

An additional feature of this experiment is the ability to perform realistic tests of mirror contamination, by exposing a sample multilayer to both resist outgassing products and EUV flux. This approach has allowed a direct measure of the reflectivity loss of a multilayer mirror sample due to full exposure of one-quarter of a 300 mm wafer, including the effects of EUV exposure of the mirror.[13]

5. LETI

Another experiment reporting results recently is installed at the Laboratory d'Electronique de Technologie de l'Information (CEA,France).[14] This experiment (in contrast to the experiment at U. Albany) uses a near-normal multi-layer mirror to expose the resist to in-band radiation only. The primary diagnostic is a mass spectrometer. A photograph of the system

Figure 8: The LETI resist exposure system. Photograph courtesy of Philippe Michallon.

is shown in figure 8. The remote head version of the EQ-10 is used, which allows installing the light source itself some distance from the ancillary subsystems.

Plans for this program include measurement of outgassing of commercial resists, characterization of the impact of the various components, direct measurement of mirror contamination due to broadband EUV and possibly development of mirror cleaning techniques. The system has been used to compare outgassing results using continuous radiation (from the Elettra synchrotron) to pulse radiation (from the EQ-10). Preliminary results were inconclusive, due to large differences in the diagnostics in the two facilities;[14] for more recent data, see these proceedings.

6. ADVANCED CONCEPTS – INTERFERENCE PRINTING TOOL

While much useful preliminary screening data on resist performance may be gained through flood exposure systems, these methods cannot accurately benchmark the imaging behavior of a candidate resist. In the end one must actually print small features and measure performance parameters such as CD and LER. Projection systems with appropriate capability require complex optical systems and are enormously expensive. Techniques based on interference, on the other hand, allow printing of small features with relevant geometry - lines and spaces – without requiring a full-fledged projection system.

While the broad-band nature of EUV emission from a plasma is not convenient for an interference device, various techniques have been developed to produce interference fringes with broad-band light. Figure 9 shows one interesting configuration which uses two gratings of different pitch, in series.

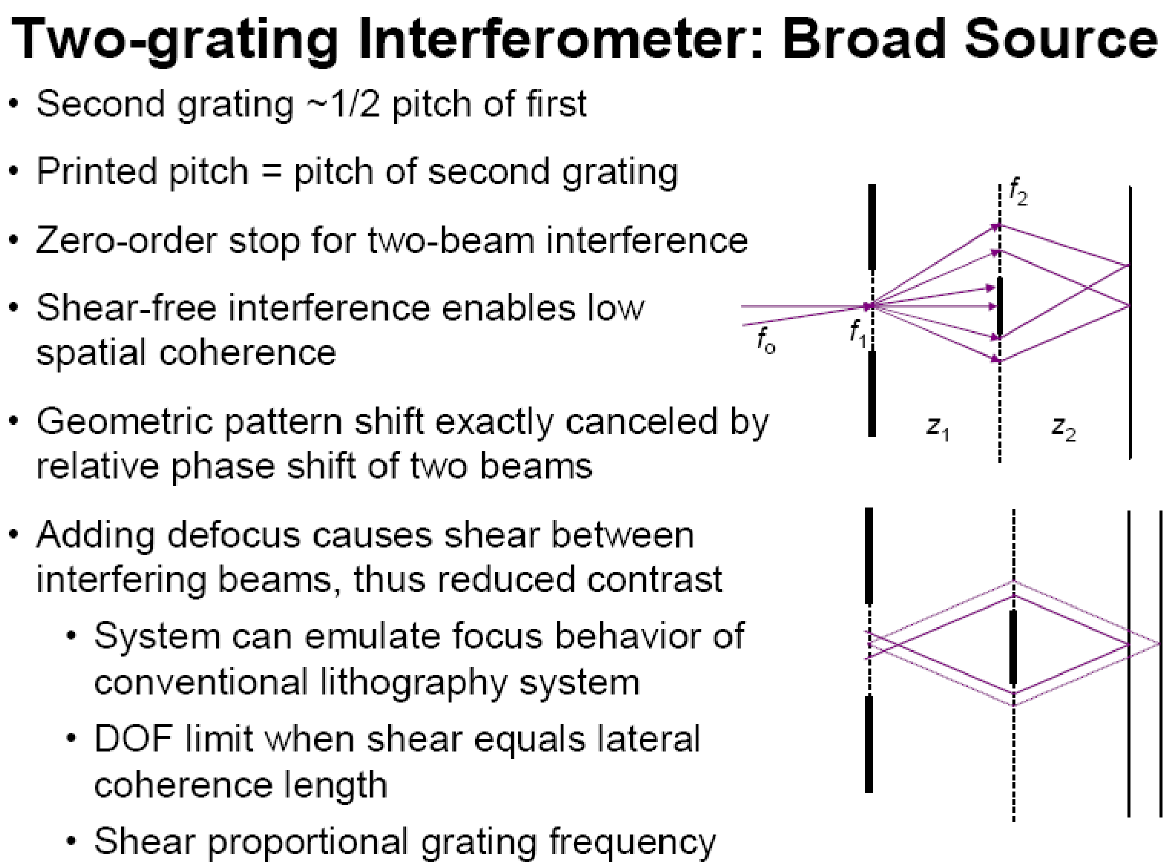

Figure 9: A two-grating broad-band interference device. (Courtesy Patrick Naulleau)

The goals of this design are to enable printing of multiple pitches down to 15 nm lines and spaces, with a field size greater than 1 mm square. There is an interesting cost trade-off between source power and system mechanical stability which leads one to consider a source power moderately in excess of the 10 watt EQ-10 specification. An in-band power of 15 watts would give exposure times of less than 5 seconds for one design currently being considered.[15]

The engineering safety margins for the EQ-10 are probably adequate to support a 15 W inband output; however a program of optimization and reliability testing would be required before a 15 W version would be commercially available.

7. CONCLUSIONS

Three currently operating resist development systems have been described; each design boasts a different collection of features and diagnostics. (A fourth system is just beginning operation;[3] preliminary results are expected for this meeting.) Two of these systems have been used as part of the "EUV Resist Outgassing Round Robin" program. (A third result within that program was obtained using a prototype system at Energetiq.[16,17] As of October 2006, all of the data obtained within that program used either synchrotron radiation, or the EQ-10 source.) The compact source enables simple and economical mechanical and optical designs and has demonstrated good reliability in operation. A 15 Watt version is being considered to enable an advanced interference printing tool, which will allow economical access to the next stage of EUV resist development.

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