EBL2: high power EUV exposure facility

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ABSTRACT

TNO is building EBL2: a laboratory EUV exposure system capable of operating at high broad band EUV powers and intensities, in which XPS analysis of exposed samples is possible without breaking vacuum. Its goal is to accelerate the development and testing of EUV optics and components by providing a publicly accessible exposure and analysis facility. The system can accept a range of sample sizes, including standard EUV reticles with or without pellicles. In the beam line, EUV masks and other samples can be exposed to EUV radiation in a controlled environment that is representative of actual operating conditions. This contribution will describe the design of the EUV beam line.

Keywords: EUVL mask, EUV exposure, EUVL pellicle, EUV metrology, lifetime research

1. INTRODUCTION

As EUV lithography progresses from beta testing to the high volume manufacturing phase, reliability, lifetime, and defectivity become more relevant. Further development of both EUV mask and pellicle infrastructure, as well as EUV scanners and inspection tools, is needed to improve in these areas. For all these topics, off-line test infrastructure will enable accelerated development of the required technologies.

TNO International Centre for Contamination Control (ICCC) is dedicated to developing the highest standards and practices in contamination control, for prevention and elimination of both particle contamination and molecular contamination. For over 15 years, we have contributed to the development and validation of optics lifetime strategies[1]. Instrumental in this work was the unique EBL test facility[2], established in Delft with Carl Zeiss SMT GmbH. EBL has been in operation since 2005.

A concept study of a next generation test facility dubbed 'EBL2' was published in 2014[2]. EBL2 is currently under construction as an independent compound facility for EUV exposure and XPS surface analysis. Like its predecessor, it will enable transfer between the two segments without breaking vacuum. The performance of the final system design has been enhanced compared to the earlier concept by entering into two strategic technology partnerships. These partnerships enable Ushio Inc. to supply the EUV source, and ASYS Automatic Systems GmbH & Co. KG to provide the mask handling equipment.

The most common purpose of an EUV exposure is to assess its performance over lifetime by simulating the circumstances that a mask (or pellicle, optics sample, or other component) faces when in use in an EUV system. It is also possible to deliberately vary the conditions to assess the effect of process variability or potential design changes. The in-use circumstances under consideration include EUV irradiation, gas environment, and sample temperature. Each of these parameters must be set and measured to validate the outcome of the exposure.

Correlation of later analysis with the EUV irradiation profile requires adequate sample positioning. Experimental duration and risk can be limited by in-situ sample monitoring, which enables early termination of an exposure.

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The goal of this paper is to provide a system overview and describe the Beam Line in terms of its EUV exposure functionality. The XPS analysis capabilities and sample handling infrastructure of EBL2 have been reported earlier[3]. Current status and project outlook will be discussed in the conclusion.

2. SYSTEM OVERVIEW

An overview drawing of the EBL2 system is shown in Figure 1 below. The main system components are an EUV source (labelled a), a Collector module (b), an Exposure chamber (c), a sample handling system (d), and an XPS analysis system (e). The Beam Line that is the main topic of this contribution consists of sections (a) through (c), and will be described below.

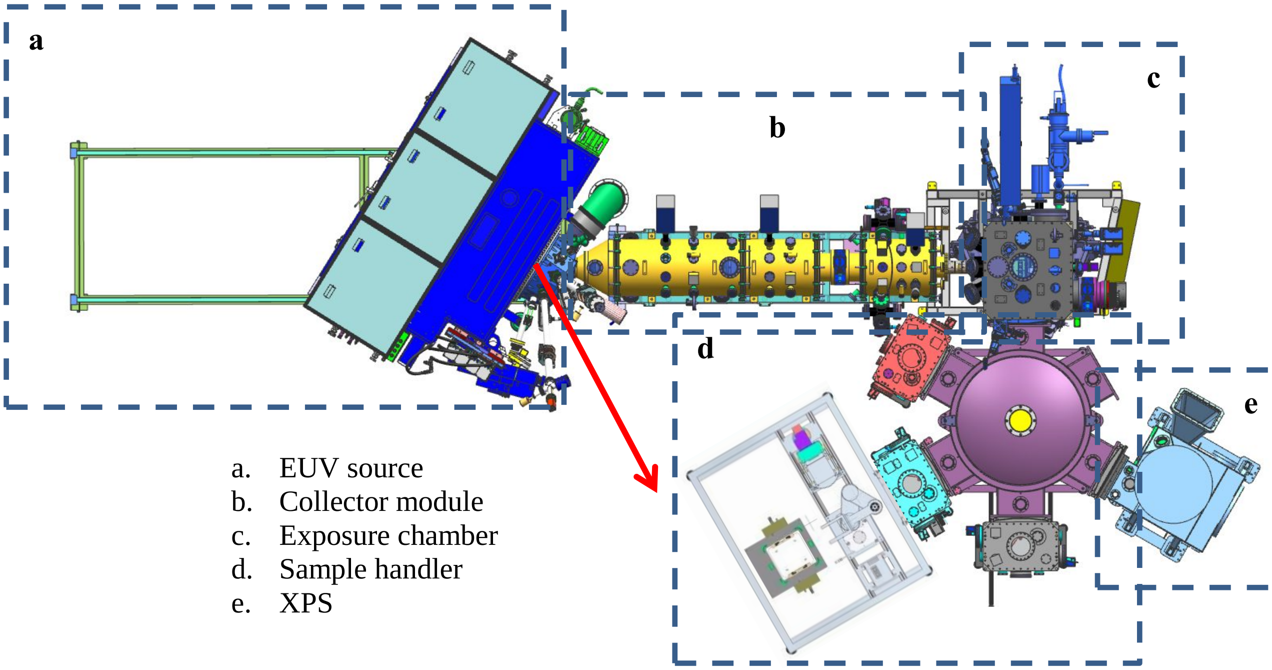

Figure 1: EBL2 CAD design overview. The arrow indicates the beam path out of the Metrology Output Port

The USE-3315E Sn-fueled LDP EUV source (a) is provided by Ushio. Details on the operating principle can be found in Ref. [4]. It provides high power pulsed EUV light to the beam line. Low-power metrology tests are facilitated by a highly flexible metrology output port. The horizontal beam path through this KF40 port is indicated by a red arrow in the schematic drawing. Customized equipment for exposures using the metrology output port can be defined jointly by TNO and users.

The Collector module (b) projects the high power EUV from the source into the Exposure Chamber, while decoupling the two vacuum environments. The collector module consists of two mirrors with an intermediate focus in between to generate a good vacuum separation. Samples are exposed to EUV in a flexible and controlled manner in the Exposure Chamber (c). The sample (mask or other; see below for details) is mounted on a temperature controlled chuck that also contains EUV metrology. The gas environment can be configured using various operating gases and controlled levels of additives and contaminants. The resulting gas mixture can be monitored by a differentially pumped RGA system. In-situ measurements of the optical properties of the sample by ellipsometry will enable real time monitoring of the sample condition. Also, the imaging ellipsometer will serve as an alignment tool, maintaining overlay between sequential EUV exposures and other process steps.

EBL2 will accept EUV masks with or without pellicles, delivered in in SEMI standard dual pods[5]. The handling equipment will handle them on inner pod baseplates (see Fig 2b) as described in Ref. [3]. EBL2 will maintain NXE compatibility of EUV masks. Smaller samples may be handled on custom sample holders using common interfaces indicated in red in Fig. 2a.

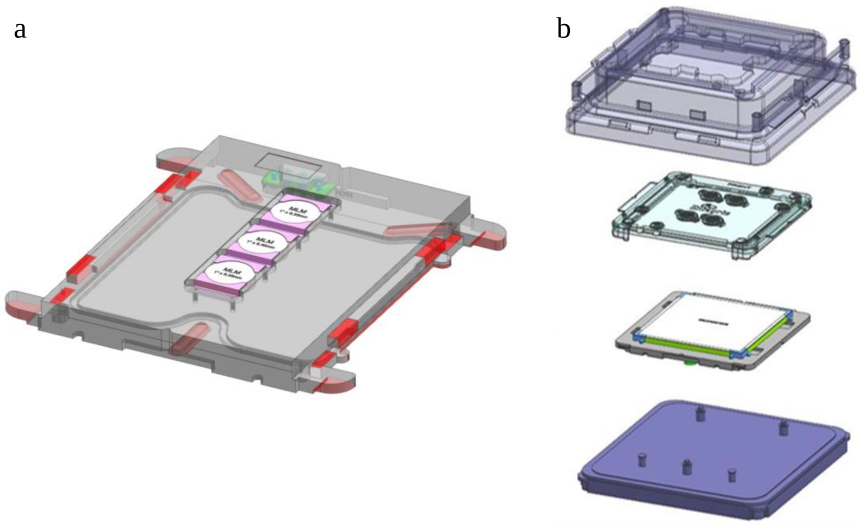

Figure 2: Samples handled in EBL2. a) Custom sample holder for exposure of small samples; b) EUV mask on inner pod base plate.

The sample handler shown in Figure 1d consists of two parts: an atmospheric handler that unloads the mask from the dual pod and places it in a load lock, and a vacuum handler that facilitates transport to and from the Beam Line and XPS segments. Both are provided by technology partner ASYS; See Ref. [3] for more details.

Surface analysis in EBL2 is possible through an XPS system, capable of analyzing elemental composition of the top several nm of a sample[6]. EBL2 contains a customized Kratos Axis Nova XPS system, shown in Figure 1e. It will accept all samples handled by the Sample Handler. EUV masks will be analyzed on their base plates, avoiding physical contact with the XPS system.

3. EUV IRRADIATION

The EUV source can be operated at frequencies from 1 Hz to 10 kHz, resulting in pulsed irradiation of the sample. In the remainder of this paper, the design performance will be listed for operation at 3 kHz. For unfiltered operation, 1.3 W of In-Band EUV radiation will be focused onto a spot with 1.2*0.7 mm FWHM diameter. The resulting peak intensity will be 1.3 W/mm^2, not taking alignment errors into account. The EUV spot can be defocused by moving the collector module and EUV source away from the sample, which will result in a larger spot containing the same power. Numerical simulations of the effect are shown in Fig. below. The maximum achievable spot size on the sample is 30 mm diameter. At this level of defocusing, the spot will have taken on a donut profile reflecting the collector geometry.

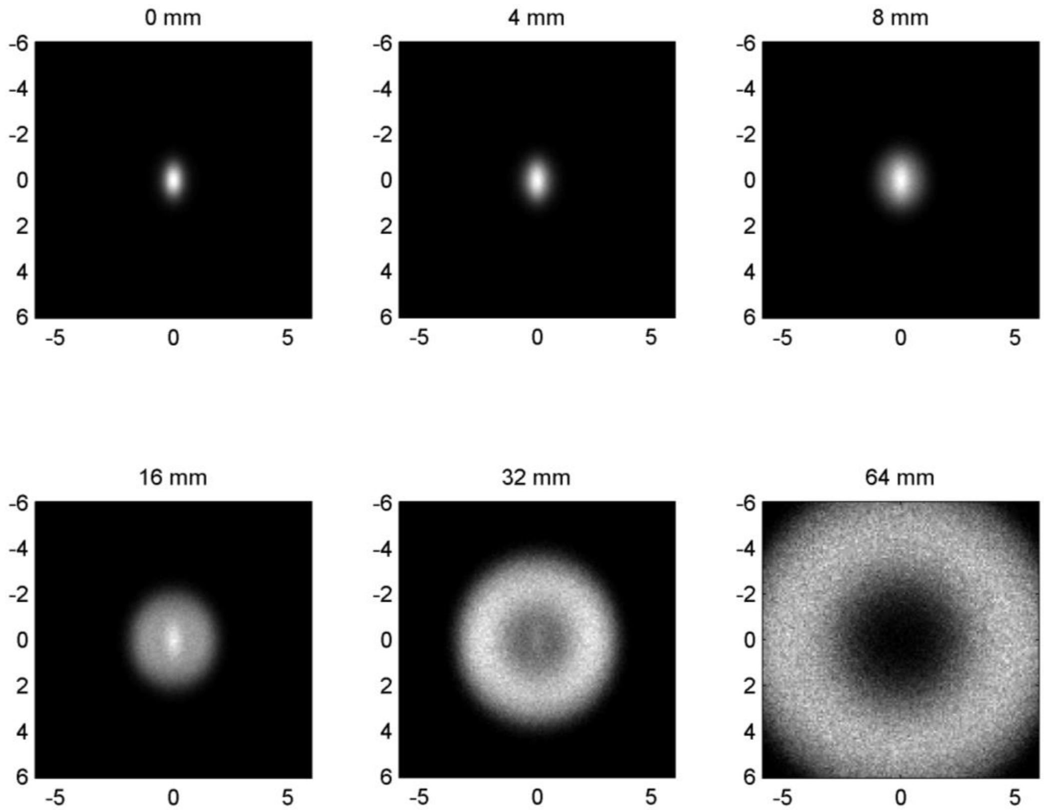

Figure 3: Effect of defocusing the EUV beam.

The beam line can be operated without filter, resulting in a typical Sn EUV spectrum produced shown in Figure 4 below. The spectrum was generated using a typical spectrum measured on the EUV source and the calculated performance of the collector mirrors. The in-band content of the EUV light transmitted by the collector module is 14 %. The grazing incidence collector design only marginally affects the spectrum as it is transmitted from the EUV source to the sample. The resulting broad band EUV power onto the sample is 9 W at standard operation.

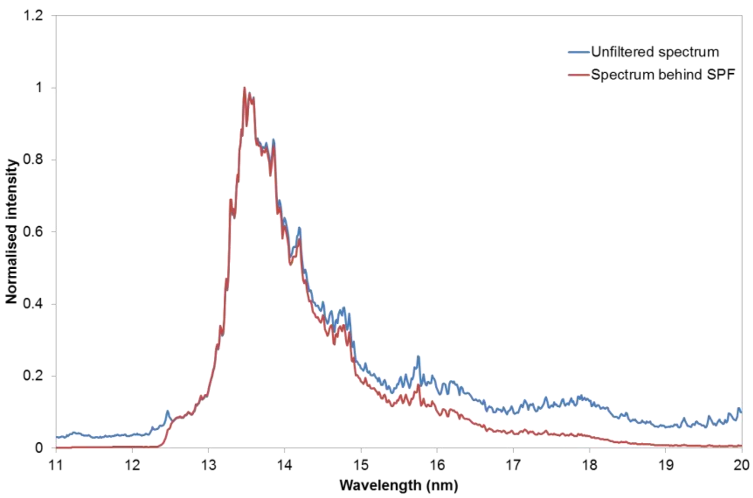

Figure 4: Unfiltered spectrum, and spectrum behind SPF.

A spectral purity filter can be added at two closely spaced locations between the first collector mirror and the intermediate focus to modify the spectral content of the EUV light. The filter must have a clear aperture of 40 mm; a commercially available mount such as Luxel TF140[7] can be accepted without problems. Any filter membrane can be mounted. Filters can be loaded or unloaded without venting the beam line. The irradiation pupil and intensity can be modified by loading apertures or meshes at the same positions.

As an example of spectral filtering, we use a simulated membrane consisting of 50 nm Zr, 200 nm Si, and 30 nm Mo. This filter transmits 50% at 13.5 nm, but effectively blocks all light below 12.4 nm and above 20 nm. Total calculated transmitted power is 3.5 W for this filter, using IMD. In the VUV and DUV range, the calculated filter transmission is less than 10^{-10} for wavelengths from 100 nm to 300 nm. With this filter, the calculated in band content is increased from 14 % of total power to 18% of total power. 90% of light is now between 12.5 nm and 16.0 nm, and 99% of light is in the range from 12.5 nm to 18.5 nm.

Controlled EUV exposure requires measuring the EUV performance of the system. EUV light is measured at 3 locations in the beam line:

1. The EUV source has an internal in-band power sensor;
2. A coated photodiode is present in DPA-1; and
3. The sample stage contains a scintillator and two photodiodes.

The SXUV photodiodes at sample stage and in DPA1 are Zr coated to filter out non-EUV radiation, and calibrated to absolute standards. The in-band power fraction of the light emitted by the source plasma can be measured by comparing the signals of the DPA1 photodiode and the in band power sensor. The fixed photodiode in DPA-1 monitors every pulse, providing a continuous check on the EUV power.

The photodiode on the sample stage registers the EUV intensity at a position defined by an orifice. As both photodiodes have the same (measured) spectral response, and the spectral profile hardly changes from source to sample for unfiltered operation, the unfiltered in-band content and power may be assessed using the same in-band to broad band ratio. A spare photodiode is available on the sample stage for periodic internal recalibration. A coated scintillator screen is present on the sample stage to map out the EUV spot profile. A mesh is used to limit the EUV intensity on the scintillator. The fluorescence from the scintillator screen is analyzed using a camera outside the vacuum system.

4. GAS ENVIRONMENT

EUV exposure testing under controlled circumstances requires a clean background environment. The base pressure of the EBL2 exposure chamber will be below 10^{-8} mbar, and is expected to be dominated by residual water and hydrogen. During EUV irradiation, a small amount of the source operating gas will leak into the exposure chamber, resulting in an additional pressure of 10^{-7} mbar of Ar.

The operating gases can be added using flow controllers. Standard operating gases available are Ar, He, and H_2. All operating gases are purified by point-of-use filters. The system can operate at full pump speed with pressures up to 0.1 mbar, and at reduced pump speed up to 4 mbar.

For some applications, it is of interest to simulate conditions with residual outgassing or air leaks. Various contaminants can be added in a controlled manner by five separate gas inlets. Standard contaminants include N_2, O_2, XCDA, and water. Dedicated model hydrocarbons or organic mixtures can also be added under certain restrictions to simulate outgassing of organic materials. It will be possible to add these contaminants at partial pressures up to 1E-4 mbar. To ensure cleanliness of the chamber, all flanges are metal sealed and the system can be baked up to 150 °C to remove contaminants from previous experiments.

Monitoring of this gas environment is possible using a differentially pumped RGA system. The system has an automated valve system that enables operation at a wide range of pressures. By inserting orifices into the connecting vacuum tube it is possible to measure the gas composition in the Exposure Chamber from high vacuum to 4 mbar total pressure. The Pfeiffer QMA400 RGA operates at a working pressure of $<5*10^{-6}$ mbar and has a base pressure of $<5*10^{-10}$ mbar. The detection limit of the RGA is $<1*10^{-15}$ mbar and it has a dynamic range of 9 decades. At an operating pressure of 0.1 mbar of the exposure chamber and a pressure of $5*10^{-6}$ mbar in the RGA chamber due to the inflow of gas from the exposure chamber the system can still detect partial pressures in the exposure chamber of $1*10^{-10}$ mbar.

5. SAMPLE LOADING AND THERMAL CONTROL

Masks are loaded into the exposure chamber through the vacuum handler. The mask is offered on its inner pod base plate by the vacuum handler robot, and picked up by the Sample Rotation Unit (SRU) inside the Exposure Chamber. The vacuum handler then removes the Inner Pod Base Plate from the Exposure Chamber. Subsequently, the SRU rotates the mask to a vertical position, and offers it to the chuck. Once the chuck has taken over the mask, it applies thermal control, and the mask is ready to be exposed, as shown in Figure 5.

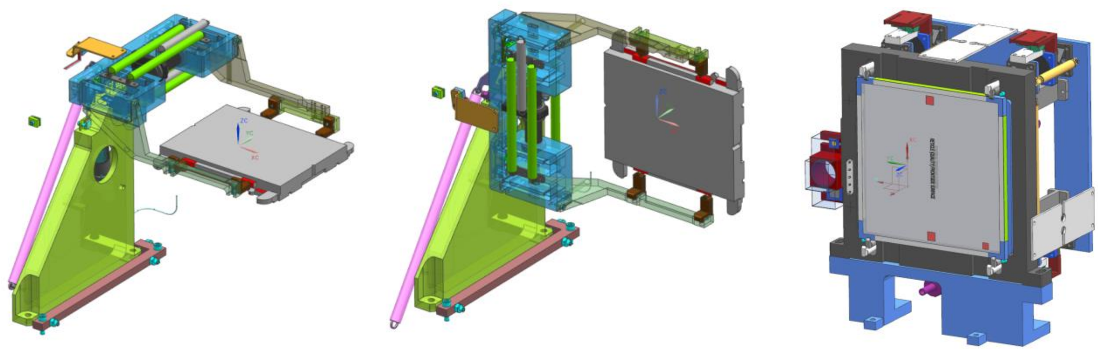

Figure 5: Left: Sample rotation unit accepts sample holder horizontally from vacuum handler. Center: sample rotation unit offers sample holder vertically to chuck. Right: Chuck holds photomask ready for exposure.

For non-photomask sample holders, the procedure is similar. The SRU now rotates the sample holder, and the chuck clamps it onto a different contact area than the one used for photomasks. To the left of the mask in Figure 5, five electrical contacts can be seen that can be used by appropriately designed sample holders. The EUV metrology is shown in red mounted to the left of the contacts.

When exposing a sample to high EUV loads, adequate thermal control becomes critical to the success of the experiment. The sample is mounted on a temperature controlled block, and backfill gas is applied to maintain thermal contact to this block. The backfill gas is either H_2 or He, depending on the operating gas. Some of the backfill gas will leak out into the vacuum chamber; it will add less than 10^{-6} mbar of backfill gas partial pressure to the total gas environment.

With this architecture, sufficient thermal contact is established with the back side of the sample holder to enable temperature control of thermally conducting samples over a range from -20°C to +150°C. For small samples, irradiating at full power may result in temperature transient of 1-10°C/s. Fast feedback is possible using an additional heater and sensor in the sample holder.

For photomask exposures, the mask substrate has a low thermal conductivity and it is only possible to control the temperature of the mounting block. The thermal resistance of the backfill gas is less than that of the photomask substrate, meaning that exposure settings will be limited by the mask rather than the chuck.

6. SAMPLE POSITIONING AND MONITORING

The sample holder or mask is mechanically clamped on the chuck. In addition to the sample, the chuck also contains a temperature controlled block and the EUV metrology equipment. The chuck is rigidly connected to the bottom flange of the system. A vacuum bellows enables movement of the bottom flange relative to the exposure chamber, as shown in Figure 6 a. The flange and hence the chuck and sample are actuated by a hexapod outside the vacuum system. This design keeps all outgassing and maintenance sensitive components outside the vacuum system

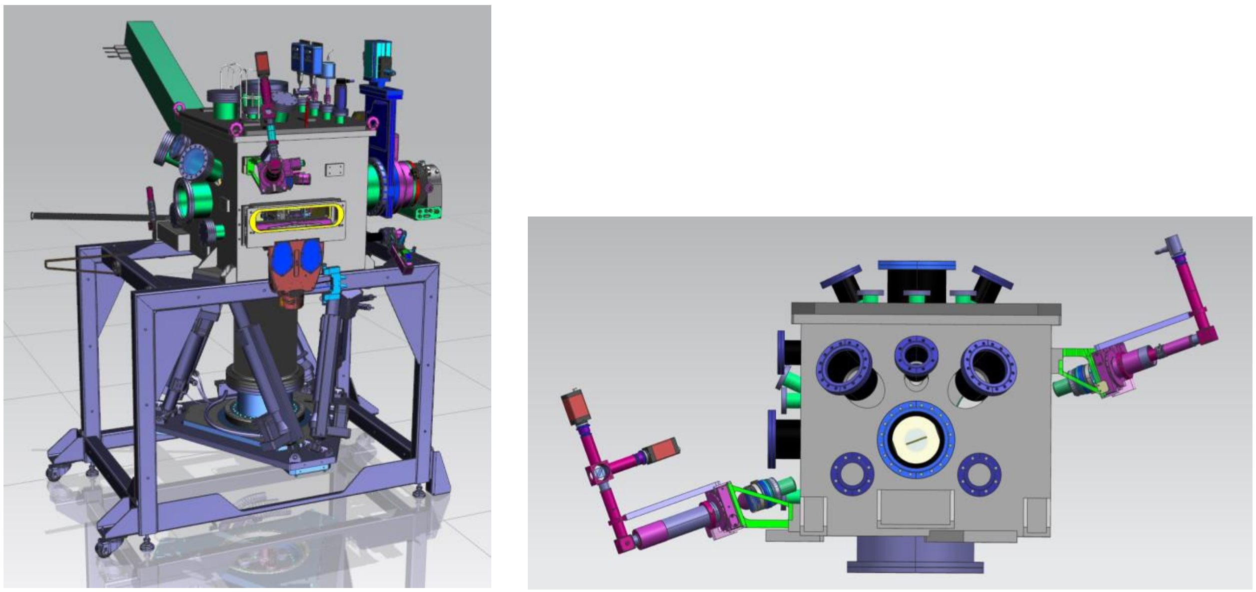

Figure 6: Left: exposure chamber, with bellows and hexapod at the bottom. Right: ellipsometer mounted on exposure chamber.

The mechanical strokes of the system are ±125 mm in both axes of the mask surface; a limited perpendicular stroke is available for alignment. The sample can be tilted upwards with respect to the EUV optical axis by up to 10 degrees.

The sample condition can be monitored in real time during exposure using an in-situ Mueller matrix imaging ellipsometer developed in-house. It is attached to the Exposure Chamber as shown in Figure 6; the EUV optical axis points into the image, while the ellipsometer beam path is from right to left. The system operates at two wavelengths, 405 nm and 604 nm. It has a 70 degree angle of incidence. The imaging resolution is 0.1 mm in the plane of the sample surface. Full ellipsometry maps over the field of view of 15mm can be measured once per minute; raw camera data can be retrieved at a much greater rate. The ellipsometer is calibrated using 2 standard calibration samples, one wafer with a SiN coating, and one with its native oxide. For the calibration, two polarizers can be inserted into the illumination and detection arm. These polarizers are positioned inside the vacuum such that the effects of the vacuum windows are included in the calibration. The calibration procedure yields all parameters of the ellipsometer, calibration polarizers and calibration samples and thus does not rely on any a priori data[8].

Alignment marks on sample holder, and scintillator, will allow overlay of the EUV spot and the various analyses to 0.1 mm, an order of magnitude better than both EUV spot size and XPS spot size. For photomasks, the ellipsometer will be able to detect the edges of the mask and interpolate with the same accuracy.

7. CONCLUSION

The EBL2 detailed design has been completed. Compared to the existing Beam Line system, large improvements in EUV power, intensity, metrology, reliability, and flexibility have been achieved.

All major components have been ordered, and system integration is underway in the second half of 2016. First light is expected at the end of the year. EBL2 will become accessible for users in the first quarter of 2017.

TNO would like thank its technology partners Ushio, Inc. and ASYS Automatic Systems GmbH & Co. KG for the open and constructive collaboration in designing EBL2.

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