Extreme Ultraviolet (EUV) Source Metrology for EUV Source Development
Abstract: This report from the LITH150 project describes activities at the National Institute of Standards and Technology (NIST) to calibrate individual components of the Flying Circus (FC2) metrology tool, including seven Zr-based filters, two Mo/Si mirrors, and three extreme ultraviolet (EUV) detectors. The accuracy of NIST’s EUV detector calibrations was also improved by implementing absolute cryogenic radiometer (ACR)-based radiometric standards in the 13 nm wavelength regime. The effects of pulse duration and intensity on the responsivity of EUV detectors were also examined. Two methods were developed for calibrating a fully assembled FC2 instrument: one based on a synchrotron light source and another that incorporates a laser-produced plasma (LPP) source.

Keywords: Extreme Ultraviolet Lithography, Lasers, Plasma, Measuring Instruments, Calibration

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Table of Contents

1 EXECUTIVE SUMMARY ........................................................................................................1
2 INTRODUCTION ..................................................................................................................1
3 RESULTS FROM SPECIFIC PROJECTS .............................................................................1
  3.1 Measurements of FC Components .................................................................................1
  3.2 Comparison of Pulsed and CW Calibrations .................................................................4
  3.3 ACR-based EUV Radiometry .......................................................................................4
  3.4 Calibration of the Assembled FC2 .................................................................................5
4 SUMMARY AND FUTURE PROJECTS ..............................................................................7
APPENDIX A – ANALYSIS OF THE FC2 AT PLEX ...............................................................8

List of Figures

Figure 1 Measured Transmission of Filters for FC2 .............................................................2
Figure 2 Measured Reflectivity of Mirrors for FC2 ...............................................................3
Figure 3 Measured Responsivity of Detectors for FC2 .......................................................3
Figure 4 Saturation Onset with EUV and 532 nm Light .......................................................4
Figure 5 Schematic of ACR Coupling Configuration .........................................................5
Figure 6 Measured Responsivity of Transfers Standards as Measured by ACR and Beamline 9 ................................................................................................................6
Figure 7 Schematic of Coupling Configuration for the Calibration of Intact FC2 ...............6
Figure 8 Schematic of the Setup for the Calibration of the FC2 with a Laser-Produced Plasma ............................................................................................................7
1 EXECUTIVE SUMMARY

In 2003, the National Institute of Standards and Technology (NIST) began calibrating individual components of the Flying Circus (FC2) metrology tool, including seven Zr-based filters, two Mo/Si mirrors, and three extreme ultraviolet (EUV) detectors. NIST has also worked on developing the capability to measure the responsivity of an intact FC2 instrument. To improve the absolute calibration of the NIST EUV working standard detectors used in these efforts, NIST implemented a new radiometric scale in the 13 nm region based on an absolute cryogenic radiometer (ACR), which decreased the absolute uncertainty from 4% to 2% or better. Finally, this project continued to compare the continuous wave (CW) and pulsed responses of Si photodetectors, which will continue into 2004.

2 INTRODUCTION

Extreme ultraviolet lithography (EUVL) is the leading candidate for next generation lithography (NGL) at the 45 nm lithography node. A significant, outstanding problem for commercialization is source power, which is currently a factor of 5 to 10 less than required. To determine source output, accurate metrology is required. Although source intercomparisons using the FC2 are now routinely performed, the absolute output remains somewhat uncertain.

The FC2 consists of a mirror, aperture, filters, and photodiode, all of which are individually calibrated on a CW basis. NIST has customized parts of its EUV metrology program to reduce the uncertainty of measurements made with the FC2. Current work uses NIST’s synchrotron radiation source, the Synchrotron Ultraviolet Research Facility (SURF III). SURF III is a single-magnet storage ring that can operate at electron-beam energies from about 100 MeV to 400 MeV, which can place the peak output wavelength at 13 nm. It serves as the U.S. national standard of irradiance in the ultraviolet. The variable beam energy allows the amount of higher-order and scattered radiation at the end of beamline spectrometers to be characterized. It is also possible to tune the output to suit a particular task.

NIST has also investigated the effects of pulsed illumination on the performance of photodetectors at 532 nm, which serve as a proxy for 13.4 nm because of their similar penetration depth in silicon. This is important because all EUV calibrations are done with CW radiation and all of the sources under consideration for EUVL are pulsed. Limits to the current practice of assuming that the responsivity in a CW calibration of a photodetector applies when that detector is used in a pulsed measurement must be tested to ensure accurate FC2 measurements.

3 RESULTS FROM SPECIFIC PROJECTS

3.1 Measurements of FC Components

The transmission of seven filters for use in the FC2 were measured in the NIST/Defense Advanced Research Project Agency (DARPA) EUV reflectometer. The primary material used in the filters was Zr. The filters were of various thicknesses; some incorporated a supportive mesh. The filters were constructed in one of two diameters: 6 mm or 10 mm. The spot size at the filter plane during the measurement was 0.3 mm × 3 mm (full-width half-maximum [FWHM]), which was small enough to avoid any occulting of the input beam. The results from these measurements are shown in Figure 1. These measurements have an uncertainty of ~2% (1 σ). The reflectivity of
two multilayer mirrors was measured in the same facility. The results are shown in Figure 2. Note that sample FS0196 was used in the FC2 for measurements at a source supplier; the reduced reflectivity is assumed to be due to exposure to the environmental conditions in the source.

In addition, the responsivity of three Si photodetectors was measured on the EUV detector calibration beamline at NIST. The results are shown in Figure 3. These detectors, which were measured before implementing ACR-based radiometry scales, have an uncertainty of 4% (1σ). The PLEX detector differs from the FOM detectors because it incorporates a directly deposited filter comprised of a Ti-Zr-C stack. This reduces the effective responsivity and shields the detector from visible light contamination. The integrity of the directly deposited filter was evaluated by scanning the diode’s surface with a focused laser beam. The results showed only a few insignificant spots of light leakage in the central filtered area. The sum total of the light leakage was in a minimal area of the detector and translated into an inconsequential amount of signal offset. The uncoated area is effectively 1E-04%.

![FOM Filter Transmission Measurements](image)

**Figure 1** Measured Transmission of Filters for FC2
Figure 2  Measured Reflectivity of Mirrors for FC2

Figure 3  Measured Responsivity of Detectors for FC2
3.2 Comparison of Pulsed and CW Calibrations

Experiments were conducted to compare the responsivity of Si photodetectors under various illumination conditions. Some illumination experiments were done using a 532 nm laser as a proxy for 13.4 nm. This wavelength was chosen for three reasons: 1) the penetration depth of 532 nm in silicon is roughly equivalent to that of 13.4 nm, meaning that the spatial distribution of photogenerated electron-hole pairs in the Si photodiode is similar to what is produced by 13.4 nm radiation; 2) variable energy, short pulses at 532 nm are easy to produce with a laser; and 3) optics to manipulate the 532 nm radiation are simple and readily available. Initial results from these studies have already been published.

To check the validity of the assumption that photodiode performance at 532 nm could serve as a proxy for performance at 13 nm, the behavior of a low saturation-threshold SXUV100 diode was studied under high intensity CW illumination. The results, depicted in Figure 4, show similar saturation performance at both wavelengths. Future plans are to extend these studies to higher intensities.

![Graph showing comparison of responsivity](image)

**Figure 4** Saturation Onset with EUV and 532 nm Light

3.3 ACR-based EUV Radiometry

A pair of photodiodes were calibrated against the absolute cryogenic radiometer (ACR) using the NIST/DARPA reflectometry beamline at the SURF III. An ACR is an electrical substitution detector with an absorbing cavity that is cooled with liquid helium (He) to ~4°K. The cooled cavity is heated to a slightly higher temperature by a heater that has a temperature feedback circuit to keep the temperature constant. To measure the power of incident radiation, it is directed into the temperature-controlled cavity of the ACR, where the radiation is absorbed. The feedback circuit reacts to the heat from the absorbed radiation and reduces the power from the heater to maintain the cavity temperature. The difference between the power needed to maintain the temperature with and without the absorbed radiation is an absolute measurement of the optical power of that radiation.

The ACR calibration incorporated two transfer optics to relay a collimated beam of light out of the reflectometer sample chamber into a vacuum cross, which housed the detector under test (DUT). The ACR was connected to the vacuum cross further downstream. This configuration is shown in Figure 5. The transfer optics produced a ~4 mm × 4 mm beam, which decisively underfilled the 8 mm diameter cavity of the ACR as well as the 10 mm × 10 mm aperture of the DUT.
The sample photodiodes are both Si n-on-p junction photodiodes. One is the same type as the NIST transfer standard photodiodes, with a thin nitrided oxide layer. The second is a Si photodiode with a thin oxide layer and a bandpass-limiting stack of thin metal films: 6 nm Ti, 200 nm Zr, and 50 nm C at the vacuum interface. This type of coated photodiode is widely used in the EUVL community for optical power measurements near 13.4 nm. The results of the calibration against the ACR have been compared to a calibration against the ionization chamber currently the realization of NIST’s detector-based radiometry scale. The difference between the two calibrations is smaller than the combined standard uncertainty of the two measurements. While the uncertainty of the ACR-based calibrations is still being evaluated, the relative combined standard uncertainty of the ACR-based photodiode calibration should be 2% or less (1 \( \sigma \)). The results of these measurements are shown in Figure 6.

3.4 Calibration of the Assembled FC2

Two schemes for the calibration of an assembled FC2 at NIST have been developed. The first uses the NIST/DARPA EUV reflectometer beamline with the transfer optics described in Section 3.3. A schematic of the configuration is shown in Figure 7. The output from the transfer optics is directed into a similar vacuum cross housing a transfer standard, which measures the incoming radiation. The FC2 is connected further downstream. It is tilted to allow the incoming beam to fall directly in the center of the mirror of a single channel of the instrument. This mirror relays the EUV to the detector plane where the output is recorded. Measurements are done by recording the measured signal of the transfer standard during a wavelength scan from 12 to 14.5 nm and repeating this same scan with the light incident on the FC2. The FC2 signal is normalized by the working standard and then multiplied by the measured responsivity of the working standard to generate an absolute responsivity for the FC2. To date, initial overall responsivity measurements on the intact FC2 agreed to within 1% with those predicted, based on the calibrations of each of the individual components. These results will be finalized in a NIST report in early 2004.
Photodiode Responsivity Traceable to Ionization Chamber and to ACR Calibrations

![Graph showing measured responsivity of transfer standards](image)

**Figure 6** Measured Responsivity of Transfers Standards as Measured by ACR and Beamline 9

**Figure 7** Schematic of Coupling Configuration for the Calibration of Intact FC2
The second method uses a Xe-based laser-produced plasma (LPP) (see Figure 8). Two EUV mirrors image the plasma in two separate channels. One channel, which observes the LPP at all times, houses a normalizing detector. The second channel images the LPP onto the mirror of the FC2, which relays the light onto the detector plane of the instrument. To determine the amount of radiation impinging on the FC2, a calibrated detector is placed into the beam path of the FC2 channel. This technique when used for similar LPP measurements resulted in good linearity (1% standard uncertainty). This facility will come on line some time in 2004.

Figure 8  Schematic of the Setup for the Calibration of the FC2 with a Laser-Produced Plasma

4  SUMMARY AND FUTURE PROJECTS

NIST has measured the performance of several individual FC2 components including mirrors, filters, and detectors. These results have been used for FC2 calibrations at multiple locations. The accuracy of the NIST EUV detector calibrations was also improved by implementing ACR-based radiometric standards in the 13 nm wavelength regime. This work is complemented by the examination of the effects of pulse duration and intensity on the responsivity of EUV detectors. This work will continue into next year using a higher power CW laser and EUV source to characterize detectors. Finally, two methods were developed for calibrating a fully assembled FC2 instrument. The first method, based on a synchrotron light source, has recently been implemented and will be fully reported on in early 2004. The second, which incorporates an LPP source, will be implemented some time in 2004. Additional future work includes measuring other FC2 components and conducting a feasibility study of the use of Al₂O₃ photo-emissive detectors under pulsed conditions.
APPENDIX A – ANALYSIS OF THE FC2 AT PLEX

A NIST representative was present at an FC2-based source calibration at PLEX, a source developer located in Boston, MA. The optical configuration was analyzed using a raytrace code to determine if any geometrical obscurations were present that could have affected the measurement. Based on this analysis, it was determined there was an obscuration factor of 14% by the aperture placed at the mirror of the FC2 based on the dimensions given by FOM and PLEX; this differs slightly from the 10% used by FOM.

The bias circuit used in the FC2 for these experiments was also evaluated. The circuit was evaluated experimentally and theoretically. These results show that the ratio of the photodiode’s and bias circuit capacitor’s capacitances must be very small to ensure that the oscilloscope records all of the photodiode’s output signal. The typical capacitance of an AXUV-100 like those used in the FC2 is about 20 nF and is reduced to ~6 nF when biased with 9 V as FOM does. When this detector is used in the FOM bias circuit, it is in series with a 100 nF capacitor that isolates the DC voltage from the oscilloscope. This ratio of 6 nF:100 nF reduces the current recorded by the oscilloscope measuring the signal by a factor of 6/106 = 5.7%. This can vary due to variations in capacitance in detectors and capacitors, thus a ratio this large should be avoided. By increasing the bias circuit’s capacitance to the µf range and possibly increasing the bias voltage on the detector, this effect will be reduced.
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