Deep Ultraviolet Laser Metrology for Semiconductor Photolithography

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Recent improvements in calibration procedures have led to reductions in overall uncertainties of laser power and energy calibrations to ±1%. We plan to extend these services to include laser dose measurements and angular response. Deviations from cosine behavior for angular response can introduce measurement errors when dose meters, calibrated with parallel laser beams, are employed in stepper systems. These measurement errors will become important as variable numerical aperture systems become commonplace. Current and future laser measurement services at 193 and 248 nm will be reviewed.

INTRODUCTION

Several years ago, the Optoelectronics Division with Semiconductor Manufacturing Technology (SEMATECH) support, developed primary standard laser calorimeters for 248 nm excimer laser power and energy measurements [1].Our efforts are now focused on addressing the demands for 193 nm measurement capability as quickly as possible. At the same time, we are adding a laser dose, *i.e.*, energy density, capability to our measurement services. Accurate measurements of laser dose are crucial to the development of new mask and resist materials at 248 and 193 nm. Furthermore, transfer standards for dose measurement will be critical to ensure high accuracy to the end user. We will be working with industrial partners to improve transfer standard capabilities.

Since the first draft of the National Technology Roadmap for Semiconductors in 1992, the semiconductor industry has made an organized, concentrated effort to move toward smaller critical dimensions. As a result, there has been a shift toward shorter laser wavelengths in the optical lithography process. Ultraviolet (UV) lasers, specifically KrF (248 nm) and ArF (193 nm) excimer lasers, will be the preferred sources for high resolution optical lithography stepper systems until the future shift to nonoptical lithography for the fabrication of devices with features smaller than 100 nm. Therefore, UV laser metrology is crucial for the development of new optical lithography processes and tools.

LASER CALORIMETRY

Primary Standard Calorimeters

The Optoelectronics Division at NIST has designed and built several laser calorimeters for accurate measurements of laser power and energy [2].Current NIST laser measurement services are listed in Laser calorimetry. Briefly, a laser calorimeter operates as follows [3]: laser radiation is injected into a thermally isolated cavity. Upon absorption, the electromagnetic radiation is converted into thermal energy. The corresponding temperature rise is precisely measured with thermal sensors, such as thermocouples. An electrical heater is used to calibrate the calorimeter's temperature response by injecting equivalent, known electrical energy into the cavity.

Table 1. NIST laser measurement services.

Laser Power and Energy Calibrations			
	Laser	**Wavelength**	**Range**
CW	Argon Ion	488 and 514 nm	1 µW - 1W
	HeNe	633 nm	1 µW - 20 mW
	Diode	830 nm	100 µW - 20 mW
	Nd:YAG	1064 nm	100 µW - 450 W
		1319 nm	100 µW - 10 mW
	HeNe	1523 nm	100 µW - 1 mW
	CO_2	10.6 µm	1 µW - 1 kW
Pulsed	KrF Excimer	248 nm	1 nJ - 200 mJ/pulse 50 µW - 9 W
	ArF Excimer	193 nm	*
	Nd:YAG	1064 nm	1 - 50 mJ/pulse
			10^{-3} - 10 nJ/pulse
		peak power	10 nW - 100 µW

*Available September 1998

The localized temperature rise is related to the volume of absorbing material over which the laser energy is deposited. In order to avoid damage due to the short laser pulses, we use two volume absorbers in the calorimeter's cavity to safely absorb the incident radiation (see Figure 1). The volume absorber materials for both UV primary standards are UV absorbing glasses, chosen for durability for the wavelengths of interest.

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Using this technique, NIST has developed a primary standard ultraviolet-laser calorimeter (QUV) for use at 248 nm, which can provide accurate measurements of UV laser power and energy within ±1%. Additional primary standards for use at 193 nm are now under construction and estimated to be completed in FY 98 (see Figure 1). After extensive testing, an appropriate volume absorber has been selected for the 193 nm standards.

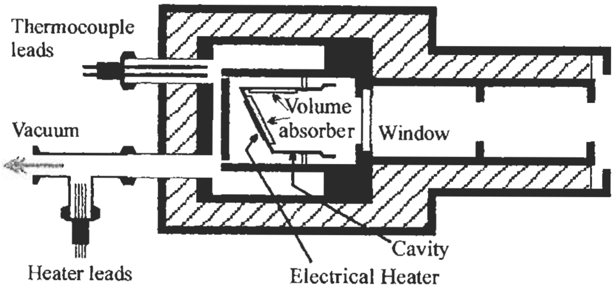

Figure 1. 193 nm laser calorimeter (under construction).

NIST Laser Measurement System

Laser Power and Energy Measurements

A schematic drawing of the NIST UV laser measurement system is shown in Figure 2. The incident laser beam is split with a 2° wedged fused silica beam splitter. The beam splitter ratio, B_Q, is determined from a series of energy measurements using the two primary standards, QUV-1 and QUV-2. The value for this ratio,

$$B = \text{(transmitted energy)/(reflected energy)}, \qquad (1)$$

is approximately 25. Then, the detector under test is substituted for one of the standards and the beam splitter ratio B_{DUT} is measured. The detector calibration factor κ is determined from the ratio of these two beam splitter values,

$$\kappa = B_{DUT} / B_Q \,. \qquad (2)$$

With judicious selection of transmitted and reflected beams, this system can span a four decade range in laser power and energy [4].

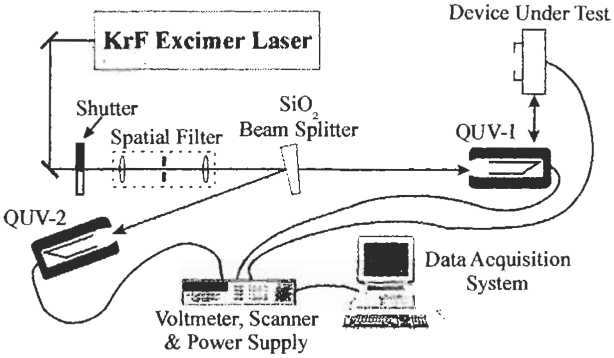

Figure 2. NIST UV measurement system for laser power and energy measurements at 248 nm. QUV-1 and QUV-2 are the primary standard calorimeters. A 2° wedged, fused silica (SiO_2) beam splitter is used as both a monitor and an attenuator for laser power and energy measurements.

Dose and Cosine Response Measurements

As the microelectronics industry moves toward smaller critical dimensions, process tolerances will shrink and accurate measurements of laser energy will play a crucial role in maintaining good quality control. Accurate dose measurements are important because small area photodiode detectors are widely used to monitor the laser energy that is deposited at the wafer plane. Furthermore, absolute dose measurements are important for the development of new mask and resist materials at 248 and 193 nm, since lower dose requirements can translate directly into higher throughput and extend the lifetime of a stepper's optical components as well. The selection and calibration of transfer and working standards for UV dose measurements, and ensuring high accuracy for the end user, will be difficult. In particular, detector damage issues related to long term UV exposure have yet to be fully investigated. We will be working with industrial partners to investigate new transfer and working standards.

One difficulty associated with dose calibrations is cosine, or angular response. Typically, dose meters are calibrated using a parallel laser beam with a uniform energy density. However, with the move toward high numerical aperture (N.A.) stepper systems, significant measurement errors can be introduced because the cosine response of dose meters can vary wildly (see Figure 3). The deviation from a true cosine response can be due to the angular response of a dose meter's constituent parts, the optical diffuser, the UV filter, and the UV photodiode detector (see Figure 4). An example is shown in Figure 3, where the difference in relative angular response between two *i*-line (365 nm) meters that are used in a stepper with off-axis illumination and N.A.=0.5 was approximately 40%.

The development of the calibration facility will evolve in two stages: (1) a 193 nm primary standard calorimeter will be developed and implemented for the calibration of laser energy meters, (2) a measurement system, including beam shaping optics with calibrated apertures, will be established for the direct calibration of dose meters that are used in wafer plane measurements. The techniques and instrumentation developed will also be used to add to the capability for dose meter calibrations to the existing 248 nm calibration facility which currently supports only large area detectors that capture the entire beam. In addition, a cosine response measurement capability will be added in order to ensure an accurate calibration transfer for meters that are used in high N.A. systems.

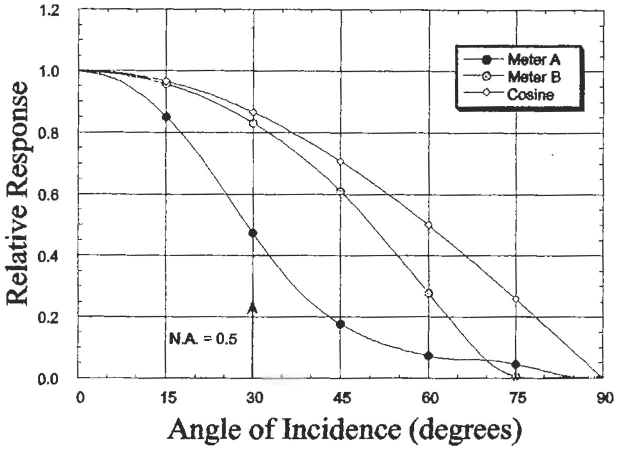

Figure 3. Angular dependence of *i*-line (365 nm) probes [5].The arrow indicates the relative response at a numerical aperture (N.A.) of 0.5. As the plot indicates, a significant measurement error can be introduced due to the imperfect cosine response of a dose meter. This offset would be unaccounted for if the meters were calibrated using a parallel beam, but intended for use in a stepper with off-axis illumination.

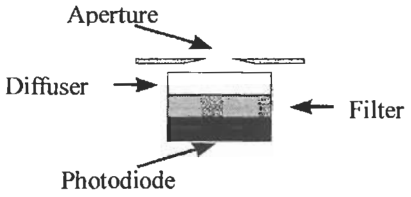

Figure 4. A typical UV detector for dose measurements at the wafer plane.

CONCLUSIONS

With the move towards critical dimensions of 0.2-µm or smaller, the dose exposure tolerances are expected to decrease precipitously. We anticipate that this will translate into a need for accurate, absolute dose measurements at the ±1-2% level [6]. Existing UV transfer standards and calibration methods are unable to meet this need. Therefore, improved transfer standards and techniques will be required to ensure accurate dissemination of the measurements to industry, and to facilitate accuracy improvement activities such as intercomparisons with calibration laboratories and industry round robins. NIST is working toward meeting these requirements by offering laser power and energy measurement services at 248 nm. Laser power and energy measurement services at 193 nm will be available to the general public during the latter part of 1998. Progress has been made towards establishing a calibration facility for dose meters. NIST solicits from end users and equipment manufacturers input that would aid in the identification of new transfer standards and measurement needs.

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Keywords: Laser metrology, dose control, transfer standards, ultraviolet detectors

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