New Developments in Deep Ultraviolet Laser Metrology for Photolithography

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Abstract. Current and future laser measurement services at 157, 193 and 248 nm will be reviewed. Laser power and energy measurements at 193 nm will be presented; electrical calibration issues will be reviewed. We report an overall calibration uncertainty of laser power and energy meters of less than 2 %. Characterization measurements for ultraviolet materials also will be discussed.

INTRODUCTION

Increasing information-technology requirements have yielded a strong demand for faster logic circuits and higher density memory chips. This demand has led to the introduction of deep ultraviolet (DUV) laser-based lithographic tools for semiconductor manufacturing. These tools, which employ KrF (248 nm) and ArF (193 nm) excimer lasers, have led to an increased demand for accurate laser measurements at the DUV laser wavelengths. As a result, the National Institute of Standards and Technology (NIST), with SEMATECH support, has developed primary standard calorimeters for excimer laser power and energy measurements at both 193 and 248 nm.

UV LASER MEASUREMENTS

There are a number of laser measurements that are important for both tool development and performance. Measurements of a laser's power and energy are used to help stabilize the source's pulse energy and to optimize laser dose at the wafer plane. Optical materials characterization measurements are used in tool design and modeling.

Laser Power and Energy

At this time, NIST is the only national laboratory in the world to offer excimer laser power and energy calibration services. Primary standards and associated measurement systems have been developed to support measurements with KrF and ArF excimer lasers. An 157 nm primary standard and measurement system is under development. The KrF primary standards and measurement system at 248 nm has been discussed in detail elsewhere [1,2]. Therefore, we limit this discussion to the 193 nm primary standards and measurement services.

Primary Standards

The design of the 193 nm primary standard is similar to that of earlier NIST pulsed-laser calorimeters [1-3] . A schematic drawing of the 193 nm primary standard is shown in Figure 1. Optical energy captured within the cavity is converted into thermal energy. Twenty pairs of thermocouples, connected in series, record the temperature difference between the cavity and a surrounding constant-temperature jacket. The calorimeter's thermal response is accurately calibrated by injecting a fixed amount of electrical energy into the cavity through an electrical heater attached to the rear of the cavity (Figure 2). A plot of the electrical calibration factor as a function of injected energy is shown in Figure 3.

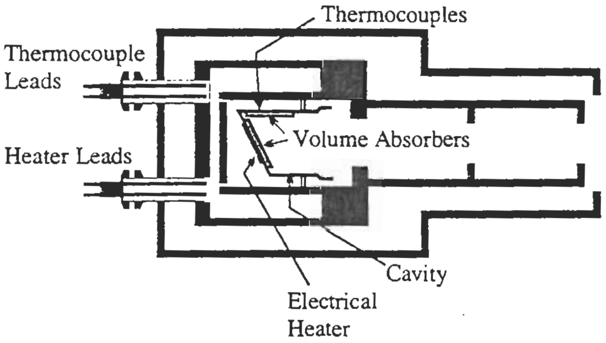

Figure 1. Schematic of 193 nm Calorimeter.

CP550, *Characterization and Metrology for ULSI Technology: 2000 International Conference,*
edited by D. G. Seiler, A. C. Diebold, T. J. Shaffner, R. McDonald, W. M. Bullis, P. J. Smith, and E. M. Secula
2001 American Institute of Physics 1-56396-967-X

The amount of optical energy E injected into the calorimeter is determined by solving the function,

$$E = K\left[V_f - V_i + \varepsilon\int_{t_i}^{t_f}(V - V_\infty)dt\right], \qquad (1)$$

where K is the electrical calibration factor and ε is the calorimeter's cooling constant. The calorimeter's cooling constant is determined by fitting both the rating periods data with a single exponential function. During the rating period, the cavity cooling constant is dominant and the calorimeter thermal response may be characterized by a single exponential coefficient ε.

Calibration Method

A diagram of the NIST laser measurement system is shown in Figure 4. A pair of 193 nm primary standard calorimeters is used in conjunction with a specially designed calibration measurement system consisting of a nitrogen-purged enclosure; a 2° wedged, fused silica beamsplitter; and beam-shaping optics. The incident laser beam is split by the beamsplitter. The beamsplitter ratio, B_Q, is determined from a series of energy measurements using the two primary standards, QDUV-1 and QDUV-2. The value for this ratio,

$$B_Q = (\text{transmitted energy})/(\text{reflected energy}), \qquad (2)$$

is approximately 19 (Figure 5). Then, the detector under test is substituted for one of the standards and the beamsplitter ratio B_{DUT} is measured. The detector calibration factor κ is determined from the ratio of these two beamsplitter values,

$$\kappa = B_{DUT}/B_Q \,. \qquad (3)$$

With judicious selection of transmitted and reflected beams, this system can span a range of four decades in laser power and energy [4]. Calibration results are shown in Figure 6.

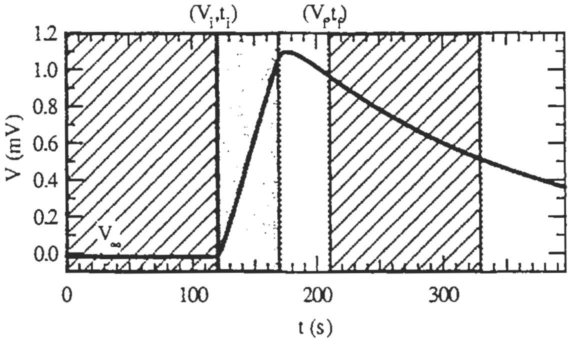

Figure 2. Series Thermocouple Voltage Response versus time. In this example, 11.66 J of optical energy was injected into the calorimeter over a 49.96 s interval (gray shaded region). The hatched regions represent the rating periods before and after energy was injected into the calorimeter. The calorimeter responses to injections of optical and electrical energy are equivalent.

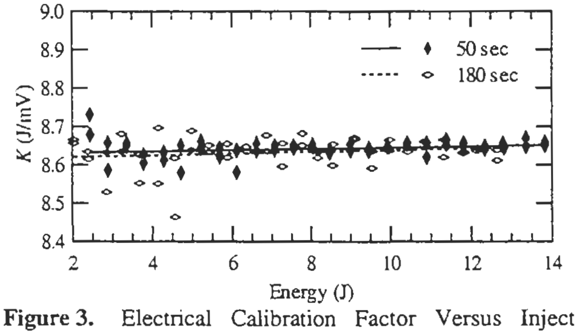

Figure 3. Electrical Calibration Factor Versus Injected Energy for Two Injection Times. The electrical calibration factor K was determined by injecting a fixed amount of electrical energy into the calorimeter during a given interval and solving for K in Equation (1) (Figure 2). The calibration factor is relatively insensitive to injection time.

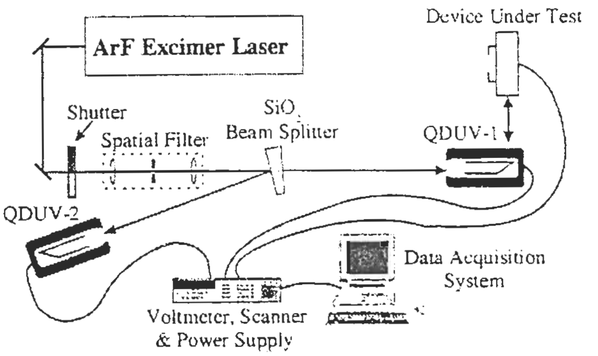

Figure 4. NIST UV measurement system for 193 nm laser power and energy measurements. QDUV-1 and QDUV-2 are the primary standard calorimeters. A 2° wedged, fused silica (SiO_2) beamsplitter is used for monitoring the power and providing attenuation. The entire system is placed within a nitrogen-purged enclosure. This 193 nm system is similar to the 248 nm measurement system, although the 248 nm measurements are performed in air rather than nitrogen.

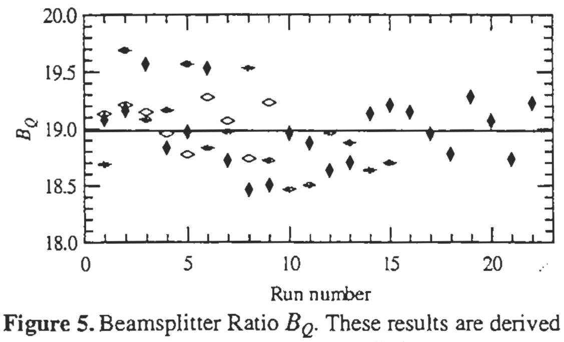

Figure 5. Beamsplitter Ratio B_Q. These results are derived from data that were taken under three distinct operating conditions. The mean value of these data sets is 18.984, with a standard deviation of 1.62%. Beamsplitter measurements are performed before and after each set of calibration measurements to ensure consistent calibration results.

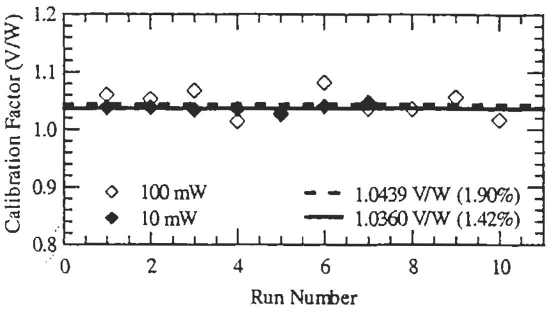

Figure 6. Calibration Results. The detector under test, a 25 mm diameter pyroelectric detector, was calibrated at two incident laser powers, 10 and 100 mW. For each power setting, a series of calibration runs were performed. The calibration factor κ (solid and dashed lines) was determined by computing the mean value of the individual runs. The overall uncertainty of the calibration, including Type A and Type B contributions, is less than 2 % [1].

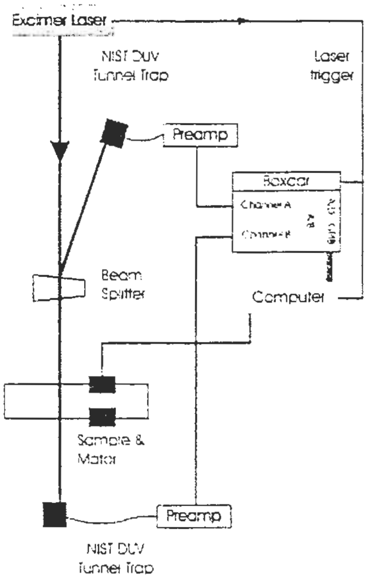

Figure 7. Excimer Laser Transmittance Measurement System. Transmittance measurement services are available as a special test.

Optical Materials Characterization

Optical material characterization measurements, such as transmittance and birefringence, are important for tool development and performance as well. In 1999, at the request of SEMATECH, we established an 193 nm laser transmittance measurement service to resolve discrepancies between laser- and lamp-based transmittance measurements. (Figure 7.) At short wavelengths, a surface cleaning process occurs when samples are exposed to intense laser light. Therefore, it is important, particularly in an exposure tool which may contain as many as 30 optical elements, to measure the transmittance of the individual elements in the same manner in which they will be used.

Birefringence can be an inherent property of the material, or it can be introduced during the manufacturing process or by applying mechanical stress, such as clamping a mask. In particular, spatial variations across phase-shifting masks can lead to spatial variations across exposed wafers. Current measurements of stress-optical coefficients and birefringence are made in the visible at helium-neon laser wavelengths. We have initiated a two-pronged effort to provide UV birefringence measurements and to develop a two-dimensional imaging polarimeter. This effort will allow us to pinpoint spatial nonuniformities in photomasks and to provide absolute retardance measurements at the appropriate UV wavelengths.

CONCLUSIONS

NIST excimer laser measurement services in support of DUV optical lithography have recently been extended to include ArF excimer laser power and energy measurements at 193 nm as well as optical materials characterization measurements. Efforts are underway to extend these services to include F_2 excimer lasers at 157 nm as well.

ACKNOWLEDGEMENTS

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