A primary standard for 157 nm excimer laser measurements†

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Abstract. Two primary standard calorimeters have been developed for accurate measurements of 157 nm (F_2) excimer laser power and energy. The calorimeter specifications and design are discussed. Results from the construction and testing of the calorimeters, control electronics, data acquisition, and N_2 purge system are presented. These calorimeters have demonstrated a two-fold improvement in sensitivity over existing NIST excimer laser calorimeters. The measurement uncertainty from electrical calibrations is a five-fold improvement over the NIST 193 nm primary standard.

INTRODUCTION

Accurate measurement methods and standards for characterizing excimer laser sources and detectors are critical in a number of industrial applications. In addition to optical lithography for semiconductor manufacturing, excimer lasers are used in corneal sculpting procedures for vision correction, for example in photorefractive keratectomy (PRK) and Laser In-situ Keratomileusis (LASIK), as well as in micromachining of small structures such as ink jet printer nozzles. In optical lithography, optical detectors play an important role in both metrology and process control, where they are used as laser dose monitors at the wafer plane and as energy monitors at the laser output to minimize and monitor pulse-to-pulse fluctuations in laser energy. Currently, there is an industry-wide shortage of calibrated optical detectors for applications at 157 nm. As a result, NIST has constructed two primary standard calorimeters for accurate measurements of 157 nm excimer laser power and energy. The measurement uncertainty associated with electrical calibrations of the primary standards thermal response is approximately five times lower than that of the NIST 193 nm primary standard. This is primarily due to the improved temperature control design.

157 NM MEASUREMENT SYSTEM

The NIST 157 nm primary standards are an integral part of a beamsplitter-based measurement system for 157 nm laser power and energy calibrations. The system consists of the two primary standards, a 157 nm excimer laser, and a nitrogen-purged (N_2) enclosure.

157 nm Primary Standard

The performance specifications for the 157 nm measurement system are shown in Table 1 and compared with the existing 193 and 248 nm system specifications.[1-3] At this time, the upper limits on the energy and power ranges are constrained by the maximum pulse energy and power of the laser source. The damage threshold of the cavity materials determines the upper limits on detectable pulse energies and powers of the calorimeters themselves.

TABLE 1. NIST Excimer Laser Calibration Services

Laser	Wavelength (nm)	Energy Range (per pulse)	Power Range (average power)	Expanded Uncertainty (2σ)
KrF Exicimer	248	~1 µJ – 200 mJ	~50 µW – 9 W	< 2.5 %
ArF Excimer	193	~1 µJ – 3 mJ	~50 µW – 3 W	< 2.5 %
Row Name Goes Here	157	~1 µJ – 2 mJ	~50 µW – 2 W	< 2.5 %

The key component of the calorimeter itself is the design of the absorbing cavity. (See Fig. 1.) This cavity represents a departure from previous calorimeter designs in that its materials are somewhat reflective. The basic cavity structure consists of four silicon carbide (SiC) walls that act as both partial absorbers and partial reflectors. In this design, incident radiation undergoes a minimum of 15 reflections within the cavity before escaping. A material with reflection coefficient of 0.55 or smaller was selected, such that 15 reflections correspond to an absorption of 99.99 % or more of the incident optical radiation. By use of this method, the incident radiation absorption is spread over a larger area to avoid damaging the cavity. Therefore, a crucial component of this design centers on material selection and damage testing.

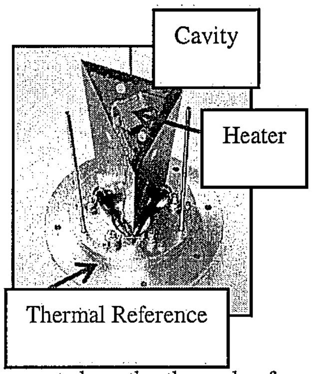

Figure 1. Cavity mounted on the thermal reference flange. A temperature-stabilized reference jacket (not shown) is mounted on the thermal reference flange. This jacket maintains a constant temperature reference. The injected energy is a function of the temperature difference between the cavity and the jacket.

Each calorimeter consists of a SiC cavity, thermal sensors, electrical heater, temperature control electronics, and a temperature-stabilized thermal reference. We have completed a series of measurements to characterize the thermal and optical behavior of these calorimeters. The thermal response of one calorimeter is shown in Fig. 2. The energy injected into the calorimeter is determined from the following expression:[4,5]

$$E = K \cdot V_{cr} = K \cdot \left[\left(V_2 - V_1\right) + \alpha \int_{t_1}^{t_2} \left[V(t) - V_\infty\right] dt \right], \quad (1)$$

where V(t) is the time dependent signal from the calorimeter in volts, and V_∞ is the asymptotic voltage at infinite time after the injection period. The expression in brackets is referred to as the corrected rise, V_{cr}, which is proportional to the change in the internal energy of the calorimeter corrected for heat losses. The data are divided into four periods: first rating, injection, settling, and second rating. Electrical energy is injected into the cavity during the injection period. During the settling period, the thermocouple response is monitored until it can be described by a single exponential, *i.e.*, $V(t) \propto e^{-\alpha t}$, where α, the cooling constant, describes the lowest order thermal behavior of the calorimeter. This indicates the end of the settling period and the beginning of the 2nd rating period. We determined α and V_∞ by performing a least-squares fit to the data from the first and second rating periods. V_1 is the voltage at the beginning of the first injection period; V_2 is the voltage at the end of the settling period.

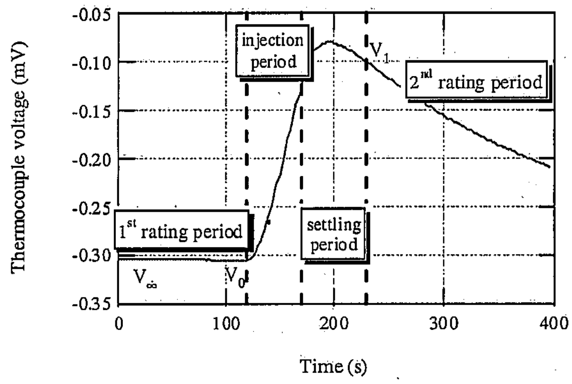

Figure 2. Thermal response of QVUV-1.

A plot of the injected electrical energy as a function of V_{cr} for the two calorimeters, QVUV-1 and QVUV-2, is shown in Fig. 3. The injected energy is defined as the integral of the electrical power *P(t)* as a function of time *t*. The electrical power *P(t)* is the product of the electrical heater voltage $V_h(t)$ and current $I_h(t)$. The slopes of these plots are the electrical calibration factors for the two calorimeters. The QVUV-2 measurements were done in air; the QVUV-1 measurements were performed in a N_2-purged environment, which is how they will used in the calibration system.

The result of a comparison between the NIST 193 nm and 157 nm calorimeters is shown in Fig. 4. The expected theoretical value for Calibration Factor is 1.0000; the average experimental value is 1.0004. The standard deviation of the measurements is 0.37 %; comparable to the performance of the 248 nm calorimeter and three-fold improvement over the performance of the 193 nm calorimeter.

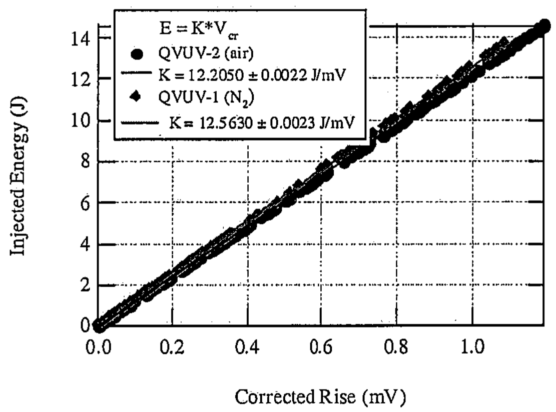

Figure 3. Injected Energy vs. Corrected Rise (V_{cr}) for QVUV-1 and QVUV-2.

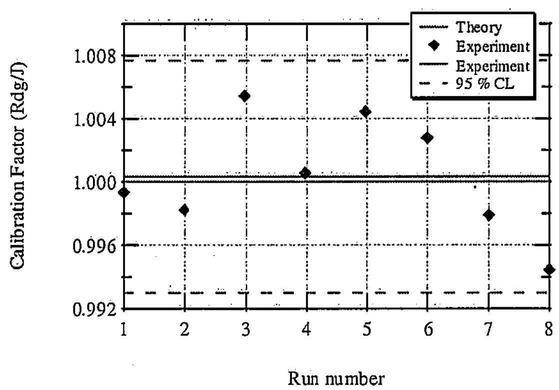

Figure 4. Comparison of 193 nm NIST primary standard and QVUV-1 calorimeter at a laser wavelength of 193 nm. Expected theoretical value of for the Calibration Factor is 1.0000 (blue line); the average experimental value (red line) is 1.0004. the red dashed lines indicate the 95 % confidence level for the Type A uncertainty, based on the statistical analysis of the experimental observations.

157 nm Measurement Enclosure

Calibration measurements cannot be performed in air because the absorption length of 157 nm radiation in air is approximately 1 cm. Therefore, we constructed an N_2-purged enclosure to house the optical delivery system. The schematic diagram for the enclosure is shown in Fig. 5. With this system, we have achieved O_2 concentrations of less than 0.5 parts per million within the N_2-purged enclosure.

CONCLUSION

The low energy threshold of the 157 nm primary standards is 2.5 times lower than originally designed and represents a significant improvement over the 193 nm primary standard design. The measurement uncertainty associated with electrical calibrations of the primary standards thermal response is approximately five times lower than that of the NIST 193 nm primary standard. This is primarily due to the improved temperature control design. We are in the process of testing the 157 nm measurement system by performing calibrations on a series of NIST transfer standards and commercial detectors to characterize the system. This characterization process involves confirming the measurement uncertainties and verifying the repeatability of the calibration procedures.

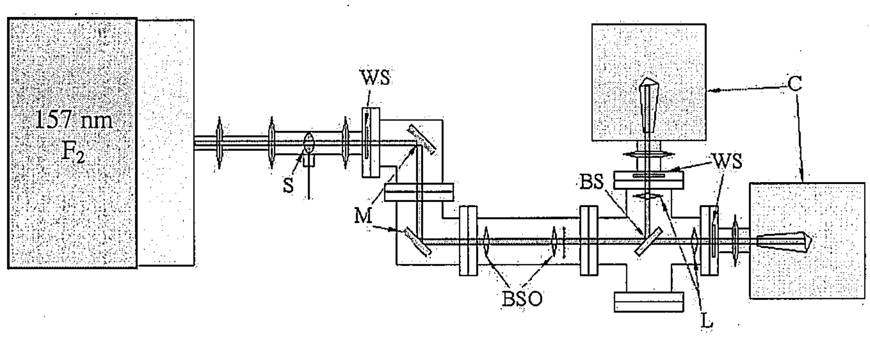

Figure 5. Schematic diagram of 157 nm measurement system. CaF_2 window seals (WS) separate the optics from the laser and the calorimeters (C). A shutter (S) defines the optical injection period. Beam-steering optics (BSO) and a beamsplitter (BS) deliver a homogenized beam to the calorimeters C. Two UV mirrors (M) are used to separate the UV light from the collinear red light of the F_2 laser. During a calibration, the detector under test is substituted for either of the two calorimeters.

ACKNOWLEDGMENTS

We thank SEMATECH for their ongoing support of this program

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