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New developments in excimer laser metrology at 157 nm[†]

M.L. Dowell[a*], R.D. Jones[a], H. Laabs[a], C.L. Cromer[a], and R. Morton[b]
[a]National Institute of Standards and Technology, Boulder, CO 80305; [b]International SEMATECH, Austin, TX 78741

ABSTRACT

We have constructed a prototype calorimeter that will serve as a primary standard for measurements of 157 nm excimer laser power and energy. The construction and performance of the prototype will be discussed. In addition, we have performed a series of thermal characterization measurements on the prototype. From these measurements, we deduce that the uncertainty in the prototype's electrical calibration factor is less than 0.2 %. This number is less than or comparable to the uncertainty of the NIST primary standards for use with 193 and 248 nm excimer lasers. The 157 nm standards are part of a beamsplitter-based measurement system for laser power and energy calibrations. To control and determine the ambient measurement conditions, we have constructed a nitrogen-purged enclosure for this system. We are able to achieve O_2 concentrations of less than 3 parts per million (ppm) inside the enclosure.

Keywords: Ultraviolet laser metrology, ultraviolet laser energy

INTRODUCTION

At this time, 157 nm optical lithography has been proposed as the technical solution in the quest for tools that can print 70 nm feature sizes on semiconductor chips. [1] In general, the selection of stable optical detectors for use with excimer lasers is limited – high photon energies coupled with short laser pulse widths degrade or even damage most conventional optical materials. Therefore, laser metrology becomes more difficult as optical lithography moves towards shorter wavelengths. As a result, the Optoelectronics Division of the National Institute of Standards and Technology (NIST), in collaboration with International SEMATECH and MIT Lincoln Laboratory, is developing a 157 nm excimer laser energy standard and associated measurement facility for the calibration of laser pulse energy, average power, and dose, i.e., energy density, meters. This facility will extend existing NIST excimer laser measurement capabilities to 157 nm; similar NIST measurement facilities are presently in operation at 248 and 193 nm. The current status of the 157 nm facility will be discussed and the performance characteristics of the primary standard will be reviewed.

The NIST 248 and 193 nm laser measurement services employ electrically-calibrated laser calorimeters as primary standards [2-5]. In each of the calorimeters, pieces of ultraviolet-absorbing glass are placed within a thermally isolated cavity. The glass acts as a three-dimensional absorber, converting optical energy into heat within the absorber's volume rather than on its surface (as would be the case for materials such as black paint, for example) thus minimizing damage from the high peak pulse energies. For simplicity we term this "volume absorption" (VA). The corresponding rise in temperature of the cavity relative to a constant temperature reference is precisely measured with thermal sensors, such as thermocouples. An electrical heater is used to calibrate the calorimeter's temperature response to known amounts of injected electrical energy, thus, providing traceability to NIST primary electrical standards. However, due to the dearth of appropriate VA materials at 157 nm, we have changed plans and designed a primary standard that is based on mostly reflective rather than absorbing materials. The absorber surfaces must be polished to maximize the specular component and minimize the diffuse component of the reflected energy. The goal is to spread the energy over a large surface area and minimize damage resulting from long-term exposure at very short wavelengths. As a result, the cavity geometry has been re-designed to capture the light in multiple bounces, rather than the only two specular reflections used in the VA design. [2]

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[*] mdowell@boulder.nist.gov; phone 1 303 497-7455; fax 1 303 497-3387; National Institute of Standards and Technology, M/S 815.01, 325 Broadway, Boulder, CO 80305-3328

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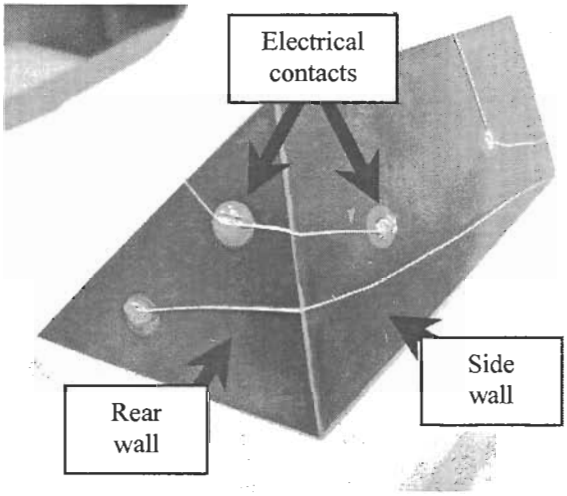

Fig. 1: Rear view of the prototype cavity.

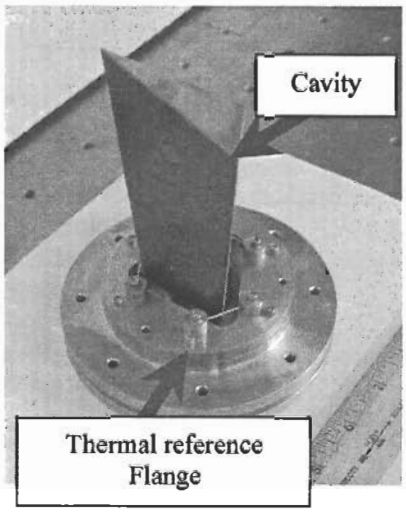

Fig. 2: Cavity mounted on thermal reference flange.

157 NM MEASUREMENT SYSTEM

Primary standards

Each primary standard, or calorimeter, consists of an internal absorbing cavity surrounded by a temperature-stabilized jacket. An electrical heater, imbedded in the cavity, is used for direct electrical calibration of the calorimeter's thermal responsivity. During a laser measurement, optical energy is absorbed by the cavity and converted into thermal energy. The resulting temperature difference between the cavity and surrounding jacket is proportional to the absorbed optical energy. The thermal response of the calorimeter is calibrated by injecting a known quantity of electrical energy into the cavity and recording the associated response of the thermal sensors.[6] The design for these pulsed-laser calorimeters deviates from earlier designs in that the absorbing materials in the cavity have surfaces that are more reflective than those in previous designs. [7]

The calorimeter includes the cavity, thermal sensors, electrical heater, temperature control electronics, and a temperature-stabilized thermal reference. We have designed and built new temperature control electronics that allow us to maintain a constant temperature for the thermal reference at a level of 5 ppm. Fig. 1 depicts the cavity. Fig. 2 is a picture of the cavity mounted on the thermal reference flange. The basic cavity structure consists of four tilted, partially reflecting walls. Any incident radiation up to ± 20° undergoes a minimum of 15 reflections within the cavity before escaping. Materials with reflection coefficients of ≤ 0.54 will absorb more than 99.99 % of the incident optical radiation in 15 reflections. Using this method, the incident radiation absorption is spread over a larger area to avoid damaging the cavity. However, it is important that we determine the damage thresholds of these materials in order to evaluate their suitability for this cavity design and also determine the exposure constraints on the maximum allowable pulse-energy density. Therefore, we performed a series of damage tests on a variety of candidate cavity materials to determine their maximum damage thresholds and associated cavity lifetimes. The materials under consideration were: silicon carbide (SiC), sapphire, nickel, chrome, and copper. We exposed the materials to a cumulative dose of 157 nm radiation that simulated approximately 50 years of use given the current level of demand for calibrations for 193 and 248 nm excimer laser power and energy meters. [8] Based on the damage testing results, we selected SiC as the cavity material. SiC also has good thermal diffusivity (20% greater than that of copper) and the high mechanical stiffness needed for thin cavity walls. In addition SiC can be obtained with electrical conductivity of ~ 1 ohm-cm, which makes it possible to use the wall material as the electrical heater.

The cavity consists of four pieces of SiC assembled into a multiple reflection cavity roughly 12 cm x 5 cm x 5 cm. The SiC material was thinned to 0.38 mm and highly polished on the side inside the cavity. One source of error in the design

of an absorbing cavity design is the diffuse scatter from the first few bounces of the incident radiation inside the cavity, which can escape from the cavity's entrance aperture. Consequently, the best possible polish was required to minimize this error. Numerical simulations of the optical performance of the cavity are shown in Fig. 3. The simulation demonstrates that light within these cavities would experience a minimum of 15 bounces before escaping the cavity, and 99.99 % of the incident light would be absorbed if materials with reflection coefficients of less than 0.6 were used.

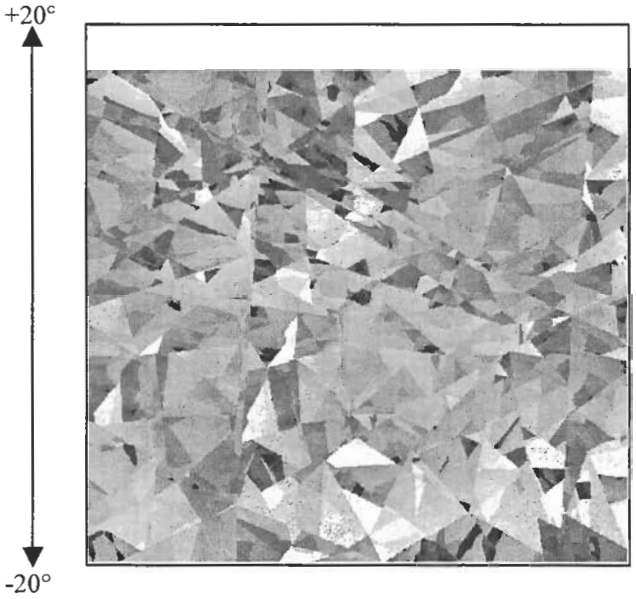

Fig. 3: Numerical simulation results for the relative absorption of light as a function of angle of incidence. The absorption scale increases from white to black, with white (the minimum) corresponding to 99.99% absorption

The sections of SiC were joined together using a thermally conductive, low outgassing epoxy. We performed a series of outgassing measurements using samples of the SiC and epoxy. After one hour of pumping, a residual-gas analysis showed that the level of outgassing contaminants was less than one ppm.

Electrical heat is injected into the cavity via pairs of contact pads. The contact pads located on the cavity's side walls are wired in series and then joined in parallel to those on the rear wall. Using this wiring method, the pattern of electrically deposited energy more closely matches that of absorbed optical energy. The cavity was mounted on the thermal reference with stainless steel pins to provide thermal isolation. A thermopile consisting of 24 thermocouples was used to measure the temperature difference between the cavity and the thermal reference. Not shown in Fig. 2 is a copper enclosure that mounts to the reference flange and provides a constant thermally stable environment around the cavity.

Electrical calibration results

We have completed a series of measurements to characterize the thermal behavior of the prototype calorimeter. The calorimeter's thermocouple voltage is plotted as a function of time in Fig. 4. From the first law of thermodynamics, we can express the energy absorbed by the calorimeter, E, as the sum of the change in the system's internal energy and the heat transferred out of the system:

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

The expression in brackets is referred to as the corrected rise V_{cr}, that can be considered as the effective change in thermocouple voltage proportional to the change in temperature of the calorimeter. The asymptotic voltage at infinite

time after the injection period is defined as V_∞; α is the cooling constant; V_1 is the voltage at t_1, the end of the first injection period; V_2 is the voltage at t_2, the beginning of the second injection period. The change in thermal energy is a function of the change in internal energy less any heat losses from radiation, convection, and conduction. For numerical analysis, the thermocouple voltage data were typically divided into four intervals: first rating period, injection period, settling period, and second rating period. For electrical calibrations, electrical energy was injected into the cavity during the injection period. During the settling period, the thermocouple response was monitored until it could 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 cavity as a whole system. This single exponential behavior in the rating periods is a feature of isoperibol calorimeters [6]. We determined α by performing a least squares fit to the data from the first and second rating periods.

The injected electrical energy, which is calculated from the product of the electrical current, heater voltage, and injection period, is plotted as a function of the calculated corrected rise V_{cr} in Fig. 5. Assuming linear behavior, we can fit these data to a straight line to determine an average calibration factor K. The calorimeters behave linearly for injected energies greater than 3 J with an estimated maximum energy of 15 J. However, the calorimeters can be used at lower injected energies so long as the calorimeters are characterized under the same conditions as they are used during optical measurements, *i.e.*, for the same injection time and average power. Therefore, we performed electrical calibration measurements as a function of both injection time and energy to create a lookup table of calibration factors. The average electrical calibration factor is determined from the subset of the electrical calibration data that corresponds to the same injection period and average power as applied during the optical measurement

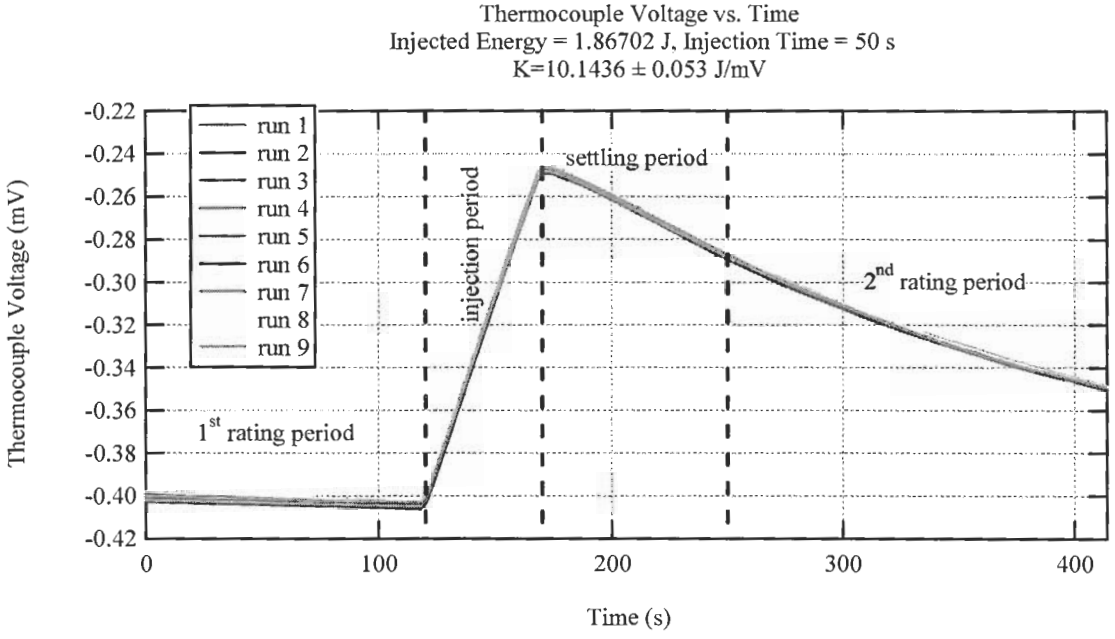

Fig. 4: Thermal response of the prototype calorimeter. Thermocouple data from 9 injection cycles are plotted as a function of time. A corrected rise V_{cr} was calculated for each run. (See equation 1.) The calibration factor K is the injected energy E divided by V_{cr}. For these nine runs, the mean value for K was 10.14136 J/mV with a mean standard deviation of 0.17 %.

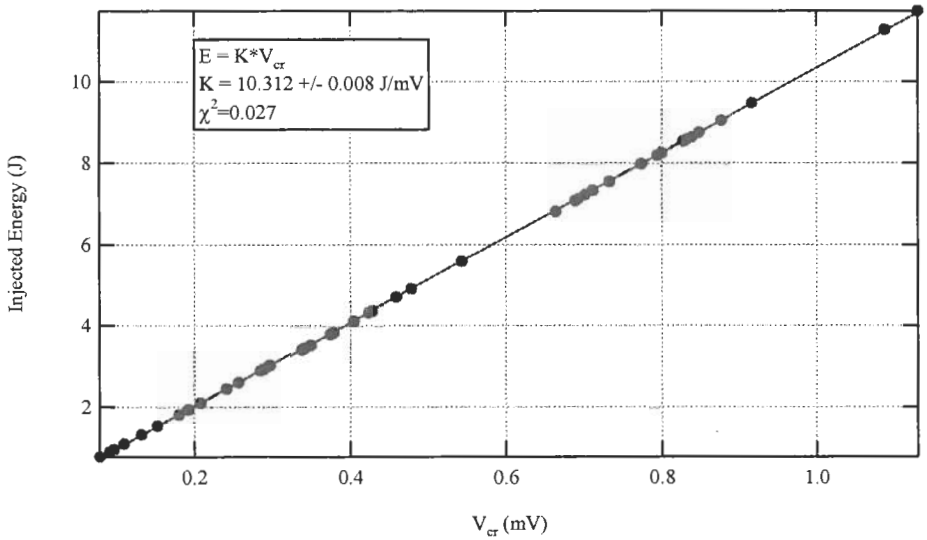

Fig. 5: Injected Energy vs. Corrected Rise (V_{cr}). The injected energy is defined as the product of the electrical power and injection period (see Fig. 4). The electrical power is the product of the electrical heater voltage and current. The corrected rise is proportional to the calorimeter's change in thermal energy corrected for heat losses from radiation, convection, and conduction.

157 nm measurement system

In addition to the prototype calorimeter, we have designed and assembled components for a nitrogen-purged enclosure. This enclosure will house the 157 nm measurement system; calibration measurements cannot be performed under normal laboratory conditions because the absorption length of 157 nm radiation is approximately 1 cm in air. The schematic diagram for the enclosure is shown in Fig. 6. To minimize cross-contamination, the enclosure consists of three nitrogen-purged subsystems isolated by CaF_2 window seals (WS). One subsystem houses the beam-steering optics, consisting of a CaF_2 beamsplitter and beam-shaping optics. The body of this chamber was constructed with copper-gasket conflats on 316 stainless steel tubing with 10.16 cm inner diameter. Metal seals reduce the possibility of contamination from o-ring hydrocarbons that have been shown to viciously degrade the expensive optics. [9] This size allowed us to insert and adjust the 5 cm optics, held in custom stainless steel mounts. The mirrors (M) have dielectric coatings designed to reflect 157 nm light at 45 degree incidence and serve two purposes: steering the beam through the center of the optical train, and filtering the ubiquitous red emission from the F_2 excimer laser beam. Our laser, our calorimeters, and the detectors from a majority of our customers use "Quick Flange"* QF-40 or QF-50 connections, rather than conflat, ISO, or ASA fittings. Therefore, custom adapters were designed and constructed at each WS. The two other subsystems house the instrument under test (IUT) and the calorimeter. Each calorimeter with its mounting base weighs 25 kg. We can substitute the IUT for either reference calorimeter by means of a heavy-duty linear translation stage. We are holding on-going discussions with our calibration customers to determine the specific requirements for the IUT enclosure. We have a long list of customers, including manufacturers of detectors, lasers, and photolithography steppers, who eagerly await the 157 nm calibration service.

* Trade names have been used in order to adequately specify experimental procedures. This use does not constitute either an endorsement or a recommendation by NIST.

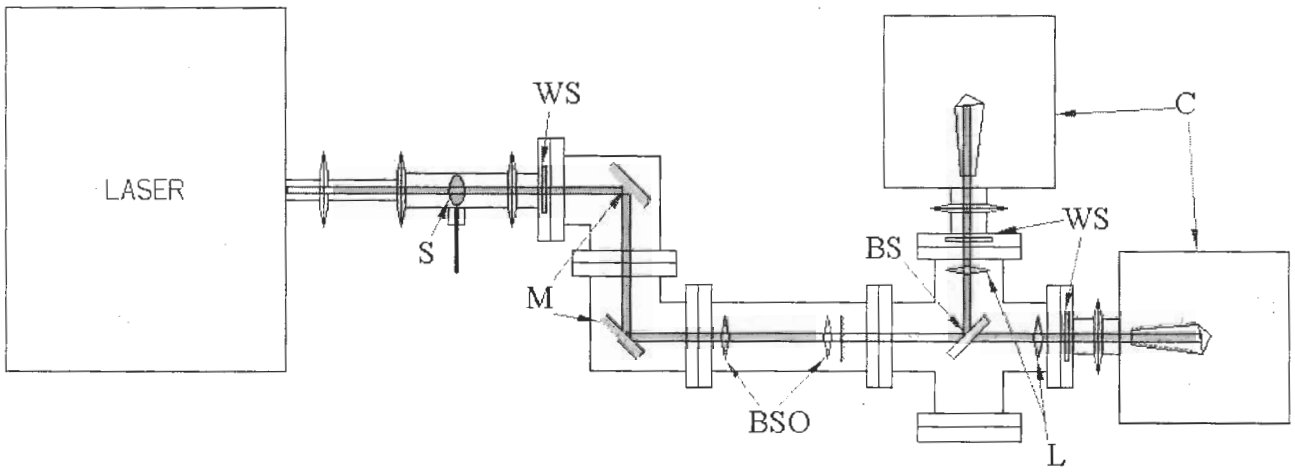

Fig. 6: Schematic diagram of the calibration system. The window seals (WS) are CaF_2 substrates: S is a shutter, M are dielectric mirrors, BSO are beam shaping optics consisting of a cylindrical lens beam expanding telescope, BS is a beamsplitter, L are spherical lenses, and C are the calorimeters. The IUT is calibrated by substituting it for the upper calorimeter.

The incident laser beam is split by the CaF_2 beamsplitter into two beams. The beamsplitter ratio, B_Q, was determined from a series of energy measurements using the two primary standards. This ratio is defined as,

$$B_Q = \text{(transmitted energy)/(reflected energy)}. \tag{2}$$

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

$$\kappa = B_{DUT}/B_Q \,. \tag{3}$$

With judicious selection of transmitted and reflected beams, this system will span a range of three decades in laser power and energy. [10]

At some point in the future, we intend to extend the 157 nm measurement service to include dose measurements. Laser dose is a critical parameter in the photolithographic manufacturing process. Measurements of laser dose are used as part of a feedback mechanism for laser stabilization. In addition, measurements of laser dose at the wafer plane of a photolithography stepper system are used to determine the optimum dose that will achieve the highest resolution of small feature sizes on semiconductor wafers. 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 an exposure tool's numerous and costly optical components. The selection and calibration of transfer and working standards for excimer laser dose measurements, as well as ensuring high accuracy for the end user, will be a challenge requiring careful shaping and monitoring of the beam profile. Recently, we established a 193 nm dose measurement system. It is our intention to apply the technical knowledge that we gained during that project to establishing a 157 nm dose measurement system. In the process of developing the193 nm dose measurement system, methods for characterizing the propagation of excimer laser beams were developed. In particular, beam uniformity is critical to accurate measurements of laser dose. Beam uniformities of 1.5 % or better were measured using a beam homogenizer and pyroelectric camera system. This work will be discussed in a future publication.

CONCLUSIONS

A new prototype calorimeter for measurement of 157 nm excimer laser power and energy has been constructed and tested. The new calorimeter uses a novel, multiple-reflection absorbing cavity constructed from SiC. Results show that

the new calorimeter's sensitivity and thermal performance are comparable to that of the existing NIST calorimeters in use at excimer laser wavelengths of 193 and 248 nm. A new measurement system for performing calibrations at 157 nm has been constructed and outgassing tests have been performed. The low level of O_2 contamination in the measurement system meets the requirements for 157 nm stepper systems.

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