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Damage testing of partial reflectors for 157 nm laser calorimeters[†]

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Abstract

We determined the damage thresholds and lifetimes of several materials using 157 and 193 nm excimer lasers and a beam profile technique similar to that described in ISO 11254-2. We made these measurements to select an appropriate absorbing material for use in our primary standard laser calorimeter for 157 nm excimer laser energy measurements. The materials we tested were nickel-plated sapphire, chemically-vapor-deposited silicon carbide (CVD SiC), nickel-plated copper, and polished copper. Applied pulse energy densities (or dose) ranged from 80 to 840 mJ/cm^2. We determined the applied dose from a series of laser beam profile measurements. Silicon carbide had the highest damage threshold: 730 mJ/cm^2 per pulse. For this reason, and because of its high thermal and electrical conductivities, we have chosen silicon carbide as the absorber material for the 157 nm calorimeter.

We also conducted long-term exposure studies in cooperation with MIT Lincoln Laboratory at a pulse energy density of 5 mJ/cm^2 to simulate typical calorimeter operating conditions. No aging effects or other surface changes were not observed at these dose levels after 500 million pulses, corresponding to a projected calorimeter lifetime of 50 years.

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Introduction

The demand for higher processor speeds and more dense memory chips has launched a drive towards smaller feature sizes in semiconductor manufacturing. Current lithography tools employ KrF excimer-lasers at a wavelength of 248 nm as the light source; ArF (193 nm) excimer lasers will soon be introduced into semiconductor fabrication lines. The next generation of optical lithography tools will employ F_2 (157 nm) excimer lasers, enabling the shift from 130nm feature sizes to ones smaller than 100 nm [1].

Semiconductor industry demands for increased throughput, through the implementation of larger wafer diameters and higher repetition rate laser sources, have led to more stringent specifications and smaller calibration uncertainties for laser power and energy measurements. NIST currently offers deep ultraviolet (DUV) excimer laser power and energy calibration services at 248 and 193 nm. We are working to extend these services to a wavelength of 157 nm.

The NIST 248 and 193 nm laser measurement services employ electrically-calibrated laser calorimeters as primary standards [2-4]. 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 volume rather than on the surface of the absorber thus minimizing damage from the high peak pulse energies. For simplicity we term this "volume absorption". The corresponding temperature rise 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 volume absorber materials at 157 nm, this design is not appropriate for 157 nm primary standards. The radiation from a 157 nm excimer laser, with high peak pulse energies and short pulse widths, damages most conventional optical materials. Therefore, we have designed a new calorimeter cavity based on reflective, rather than absorbtive, materials. In this new design, an incident laser beam undergoes a minimum of 15 bounces within the cavity before escaping. This corresponds to absorption of 99.9 % of the incident radiation for materials having reflection coefficients of 0.6 or smaller.

We performed damage studies to select an appropriate partially-reflecting material for the cavity. In our studies, candidate materials were exposed to large cumulative doses of low-level UV radiation to determine their lifetimes. We also exposed these materials to single pulses of intense UV radiation to determine their damage thresholds.

Candidate materials

The candidate materials we selected for the lifetime and damage threshold measurements were: nickel-plated sapphire, CVD silicon carbide, nickel-plated copper, and polished copper. We identified these materials on the basis of their thermal and optical properties.

The appropriate material must have the ability to withstand long-term exposure to moderate doses, have a high damage threshold (much greater than 5 mJ/cm^2 per pulse), and a reflection coefficient of ~ 50 %. The reflection coefficient must be large enough to distribute the absorbed energy across multiple surfaces because the absorption length of most materials is small compared to the thickness of the materials themselves. (The majority of the incident radiation is effectively absorbed on the surface, unlike traditional volume absorbers.) The primary damage mechanism for surface absorbers is melting of the material; consequently, a high thermal diffusivity and a high melting point both contribute to a high damage threshold. In addition, a high thermal conductivity is desirable since it will lead to a more uniform redistribution of heat within the cavity on a shorter time scale.

There is a design tradeoff that involves the reflectivity of the absorbing material. A higher reflection coefficient leads to a higher damage threshold. However, the number of reflections necessary to trap 99.9 % of the incident radiation within the cavity, for a fixed cavity geometry, increases with increasing reflectance. If the surface area of the cavity s increased by building a larger cavity to trap the radiation, then this results in a larger thermal capacitance for the cavity with a longer thermal time constant.The calorimeter output will then be noisier and measurements will be more time consuming. Furthermore, there is a minimum thickness of cavity sidewall for a given thermal diffusivity and a requirement that the thermal relaxation times of the cavity components be much shorter than the thermal time constant for the overall cavity response. With these constraints in mind, we have settled on a design in which incident radiation within a full acceptance angle of 30° and an open aperture of 25 mm diameter will undergo at least 15 reflections before exiting the cavity. These constraints place an upper limit of 63 % on the surface reflectance of the absorbing material, and can be accomplished with a cavity length of ~ 12 cm. The reflectance of nickel is approximately 25% at 157 nm; however, nickel has relatively poor thermal conductivity and a moderate melting point. Copper has a reflectance of ~ 20 %, and a higher thermal conductivity and lower melting point. Interestingly enough, the calculated fluences for melting copper and nickel are nearly the same at 0.5 J/cm^2 per pulse. CVD SiC has both a high melting point and a high thermal conductivity with a calculated melting fluence of > 1 J/cm^2. The reflectance of CVD SiC at 157 nm is ~ 50 %; CVD SiC can now be obtained in very large thin sheets (12 cm^2 area with 0.35 mm thickness).

Damage study

Our experimental set-up for the damage test is shown in Fig. 1. The whole system is placed in a nitrogen-purged environment where the oxygen concentration is maintained at 0.2 % or less. An excimer laser beam at a wavelength of 193 nm is split into two beams. A monitor detector, placed in one beam, records the pulse energy with an overall uncertainty of ±1.25 %. The other beam is focused by a spherical plano-convex lens with a radius of curvature of 257.5 mm. This lens is made of VUV grade MgF_2 and is uncoated. The damage tests were performed at pulse repetition rates of 5 Hz and 100 Hz. The laser pulses had a full-width-at-half-maximum (FWHM) duration of approximately 10 ns.

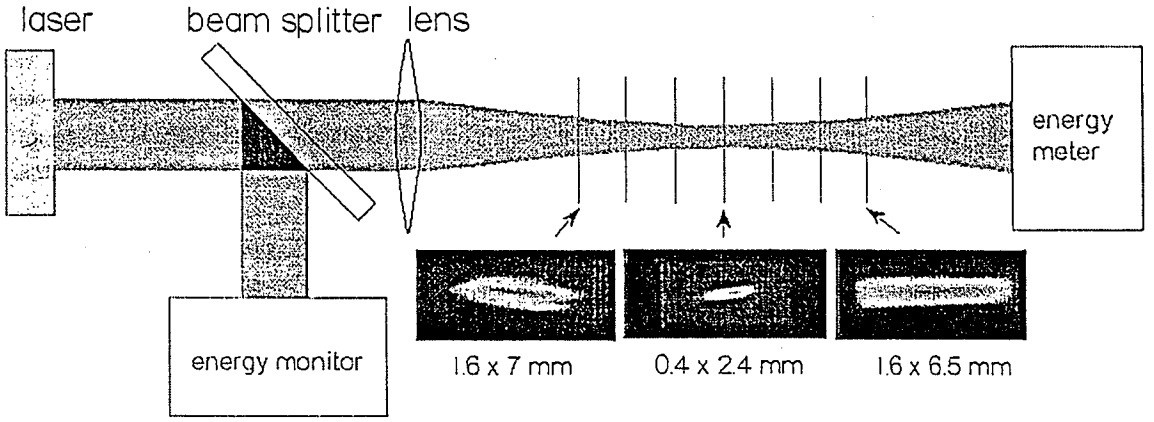

Figure 1. The damage threshold arrangement. A calibrated energy meter was placed at the end of the propagation path after the lens to calibrate the energy monitor. The beam profiles were recorded and characterized at 22 planes along the propagation axis using a CCD camera and quantum converter. Then, the camera was removed and samples were positioned in those same planes and the energy deposited onto the samples was recorded. Three energy density distributions at inner- and outer-most positions, together with their dimensions, are shown. The dimensions are based on the calculation of the second moments according to ISO 11146 [4].

First, we measured the beamsplitter ratio with two NIST-traceable calibrated pyroelectric energy meters. Having done this, we could determine the absolute pulse energy impinging on the samples using the reading from the monitor detector (see Fig. 1).

Second, we recorded intensity profiles of the laser beam along its propagation axis with a quantum-converter and a CCD-camera [5]. (See Fig. 1.) The beam was attenuated by a pair of 45° dielectric mirrors positioned at normal incidence between the laser and beamsplitter. The quantum converter consisted of a UV-grade fused silica substrate of a thickness of 1 mm coated with a phosphor powder (type: P43: Gd_2O_2S:Tb; thickness: 4 μm; grain size: 1 μm). The UV light excited the phosphor powder, which thenfluoresced in the green wavelength region with an intensity proportional to the incident UV energy density. The plane of the phosphor layer was imaged onto the sensing chip of the CCD-camera. The CCD-camera had 1317 x 1035 pixels, a pixel separation of 6.8 microns and was cooled to –40 °C to reduce noise.

Since the spatial beam profiles fluctuated from pulse to pulse, we captured between 8 and 20 intensity profiles and their average was calculated. The uncertainty in the beam area led to an overall uncertainty of ± 20 % for the calculated dose. Fig. 1 shows some averaged intensity profiles at different positions along the propagation axis. We recorded intensity profiles at 22 positions along the propagation axis of the beam within a total range of 280 mm, corresponding to five Rayleigh lengths [6]. In this manner, we were

able to vary the energy density by a factor of approximately 12 by varying the beam size while maintaining constant pulse energy.

The third step was to expose the samples. The samples were positioned along the propagation axis at a location closest to the lens, that is, in a region where the pulse energy density was low. (See Fig. 1.) We exposed the samples to varying laser pulse energies from 10 to 80 mJ for between 5 and 20 pulses while monitoring the laser pulse energy. Afterwards, we visually inspected the samples for damage. If no visible damage was present, the pulse energy density was increased and the sample was exposed again. The pulse energy density was increased by either increasing the laser pulse energy or by decreasing the laser beam size, that is, by placing the sample closer to the focal point of the lens.

We then examined the samples for damage with an optical microscope and measured the diameter of the damaged area by comparing its size with a calibrated graticule. We obtained a value for the damage threshold for the two main axes from the recorded intensity profiles, the monitored energy, and the dimensions of the damaged spots. The final damage threshold is the arithmetic average of these values.

Long term exposure study

Long-term exposure studies on the candidate materials were completed in collaboration with MIT Lincoln Laboratory. These studies were carried out with a F_2 excimer laser system at a wavelength of 157 nm. The samples were placed in a nitrogen-purged enclosure where the oxygen concentration was maintained at a level below 2 parts per million. The samples were exposed to 500 million pulses at an energy density of 5 mJ/cm^2 per pulse; 500 million pulses correspond to a projected lifetime for the calorimeters of 50 years. The energy density of 5 mJ/cm^2 corresponds to the maximum energy density at which the calorimeters will be used.

Results

The results of the damage threshold measurements are summarized in Table 1. The most damage resistant material was polished SiC. The damage area was slightly discolored (from black to light brown and white with some bubbles). The damage threshold was 730 mJ/cm^2 at 5 Hz. The damage threshold at 100 Hz was greater than 170 mJ/cm^2; energy densities greater than 170 mJ/cm^2 could not be obtained with the laser operating at 100 Hz. No samples showed visible surface or volume change after the long term-exposure test. The most appropriate material for the cavity, based on the results of both the damage threshold and lifetime measurements, was CVD SiC. We are now testing a prototype cavity constructed of CVD SiC.

Material	Damage threshold at repetition rate (mJ/cm^2 per pulse)	
	5 Hz	100 Hz
Nickel coating on sapphire substrate (sapphire side towards the laser)	430	150
Nickel coating on sapphire substrate (nickel side towards the laser)	490	150
Silicon carbide	730	> 170
Nickel coating on copper substrate	430	150
Polished copper	430	150

Table 1: Damage thresholds of various candidate materials at 5 Hz and 100 Hz laser repetition rates. The single pulse-energy densities ranged from 80 to 840 mJ/cm^2. CVD SiC is the most damage resistant material with the highest damage thresholds at repetition rates of 5 and 100 Hz.

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