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PREPRINT

Development of High Damage Threshold Optics for Petawatt-Class Short-Pulse Lasers

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DISCLAIMER

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ABSTRACT

We report laser-induced damage threshold measurements on pure and multilayer dielectrics and gold-coated optics at 1053 and 526 nm for pulse durations, τ, ranging from 140 fs to 1 ns. Damage thresholds of gold coatings are limited to 500 mJ/cm^2 in the subpicosecond range for 1053-nm pulses. In dielectrics, qualitative differences in the morphology of damage and a departure from the diffusion-dominated $\tau^{1/2}$ scaling indicate that damage results from plasma formation and ablation for $\tau \leq 10$ ps and from conventional melting and boiling for $\tau > 50$ ps. A theoretical model based on electron production via multiphoton ionization, Joule heating, and collisional (avalanche) ionization is in quantitative agreement with both the pulsewidth and wavelength scaling of experimental results.

Keywords: short-pulse, laser-induced damage, dielectric breakdown, multiphoton ionization

1. INTRODUCTION

The application of chirped-pulse amplification[1] (CPA) to broadband, high energy solid-state lasers has enabled terawatt class systems producing subpicosecond pulses. Further increase in the peak power available from such systems[2] is now limited by damage to optical surfaces due to the intense short pulses. The subpicosecond pulse duration is significantly shorter than the time scale for electron energy transfer to the lattice. As a result, damage caused by subpicosecond pulses is characterized by ablation, with essentially no collateral damage. Many applications, ranging from materials processing to biomedical technologies, could potentially benefit from the more localized energy deposition with these short pulses.

The scaling relationship of the damage threshold as a function of pulsewidth is of interest for all optical components in a high-power laser system: mirrors, polarizers, bulk dielectrics, coatings, and diffraction gratings. At this time, the gratings used for pulse compression typically exhibit the lowest damage threshold of any component. These high-efficiency diffraction gratings have traditionally been based on metallic gratings. High-efficiency multilayer dielectric diffraction gratings[3] offer a promising alternative that should exhibit a damage threshold at least three times that of gold gratings. In this paper we present measurements and theoretical analysis of laser-induced damage to gold-coated, multilayer dielectric, and pure dielectric optical components.

Investigation of the pulsewidth dependence of laser-induced damage to dielectrics has been the subject of numerous studies[4-25]. For pulses longer than a few tens of picoseconds, the generally accepted picture of bulk damage to defect-free dielectrics involves the heating of conduction band electrons by the incident radiation and transfer of this energy to the lattice. Damage occurs via conventional heat deposition resulting in melting and boiling of the dielectric material. Because the controlling rate is that of thermal conduction through the lattice, this model predicts[13] a $\tau^{1/2}$ dependence of the threshold fluence upon pulse duration τ. This is in reasonably good agreement with numerous experiments[16-25] which have observed a τ^{α} scaling with nominally $0.3< \alpha < 0.6$ in a variety of dielectric materials (including samples with defects) from 20 ps to over 100 ns.

Here, we report measurements of damage thresholds for fused silica, calcium fluoride, and multilayer dielectrics for pulses ranging from 140 fs to 1 ns. In each of these large-bandgap materials we observe a change in the damage mechanism and morphology for pulses shorter than 20 ps. Although we observe a strong deviation from the $\tau^{1/2}$ scaling, we find no evidence for an increase in damage threshold with decreasing pulsewidth as reported by Du *et al* [24]. Instead, we observe a decreasing threshold associated with a gradual transition from the long-pulse, thermally-dominated regime to an ablative regime dominated by collisional and multiphoton ionization, and plasma formation. A general theoretical model[25] of laser interaction with dielectrics, based on multiphoton ionization, Joule heating, and collisional (avalanche) ionization, is shown to be in good agreement with the data in this short-pulse regime.

2. DAMAGE THRESHOLD MEASUREMENT

For damage testing, we used laser pulses generated by a 1053-nm Ti:sapphire CPA system[26]. The front-end of this system produced 1-ns stretched pulses of up to 60 mJ at 10 Hz. The pulses were compressed in a four-pass, single-grating compressor of variable length (Figure 1). By varying the dispersive path length of the compressor, we obtained pulses of continuously adjustable duration from 0.3 to 1 ns. Pulse durations were measured with a single-shot autocorrelator (0.3-1.5 ps), streak camera (10-1000 ps), and fast photodiode (100-1000 ps), and calibrated against the linear position of the fold mirrors. The temporal profile of the compressed pulses depends strongly on the spectral and temporal profile of the stretched pulse. Pulse compression with spectral clipping is analogous to diffraction from a hard-edge aperture in the spatial domain, and results in a modulated temporal profile in the "intermediate" range of compression. For these damage measurements, we compressed a near-Gaussian spectral profile to obtain temporally smooth output pulses. This allowed us to easily relate the time evolution of the pulse intensity to the measured fluence.

We also measured damage thresholds with 526-nm light generated by frequency-doubling the 1053-nm compressed pulses in a thin (4-mm) potassium dideuterium phosphate (KD^*P) crystal. The conversion efficiency was kept below 25% to avoid any temporal distortion of the second-harmonic pulse. We measured our shortest 526-nm pulses with a single-shot autocorrelator to be 275 fs. This was in good agreement with the expected $2^{1/2}$ scaling from the 1053-nm pulsewidth (415 fs), so this scaling was used for the other 526-nm pulsewidths. Data was also taken at 825 nm and 140 fs with a Cr:LiSAF CPA system[27] to confirm the decreasing trend in damage fluence with pulsewidth.

The energy of each pulse was monitored with the leakage through a 92% reflectivity mirror. We adjusted the energy delivered to the damage sample with a half-waveplate before compression, using the strong dependence of grating efficiency upon input polarization. The rms energy stability was typically 1.5%, and we report the average value here. We performed damage measurements with laser spot sizes adjustable from 0.3 to 1.0-mm diameter (e^{-2} intensity). Laser pulses were focused onto the damage sample by a 1-m focal length lens, with a variable distance to the sample. The spot size was measured on a CCD camera. With the shortest pulses we used, the intensity (up to 4×10^{12} W/cm^2 on sample) became high enough to cause significant (10% effect) whole-beam self-focusing in the focusing lens and the air path leading to the sample. All beam size measurements were therefore performed with a 4:1 image of the beam taken from a 4% reflection at the position of the damage sample, and at or just below damage threshold. The laser mode at the sample had a 98% or better fit to a Gaussian, so the effective diameter as measured on the camera system was combined with the measured energy to give the pulse energy fluence. Our estimated absolute uncertainty in fluence was 15%, but relative values should be within 5%.

After irradiation, Nomarski microscopy was used to inspect the sample for possible damage. We define damage to be any visible permanent modification to the surface observable with the Nomarski microscope. The smallest damage spots we could observe were approximately 0.5 μm in diameter, a factor of 10^6 smaller in area than the laser spot size and nearly impossible to observe by other methods (e.g., degradation of transmission, scattered light, etc.). To avoid the complications of spatial and temporal distortion caused by self-focusing, group velocity dispersion, and self-phase modulation, we considered only front-surface damage.

Initial damage, at threshold, may have many forms: ablation of a very small amount of material (a few atomic layers); formation of a color center, shallow traps, or lattice defects; or melting of a very small volume. These weak effects are very difficult to detect. In order to "amplify" this damage to an easily observable size, and to minimize statistical uncertainty, we conducted our damage testing with multiple pulses of a given fluence on each site (S:1). This is in contrast to the single-shot measurements of Du *et al*[24], where their diagnostics of pulse transmission and plasma emission require a macroscopic damage site on a single pulse. We typically used six hundred shots at 10 Hz, unless damage was obvious sooner. Many fluence levels (15-30) were examined above and below the damage threshold for a given pulsewidth in order to establish the threshold value.

3. DAMAGE RESULTS

3.1 Gold-coated optics

For use with high-power lasers, the damage threshold of a grating (or mirror) has an importance equal to the diffraction efficiency (reflectivity). We have achieved diffraction efficiencies greater than 95% for 1710 line/mm gold-coated gratings at 1064 nm and efficiencies greater than 94% at 830 nm. This efficiency has been achieved on both small scale (<15 cm) and large scale (30 cm diameter) diffraction gratings.[28] In pulse compression, the damage threshold limits the amount of energy which can be tolerated in the pulse for a given grating area. The low damage threshold of diffraction gratings is also responsible for their limitation to use in low power tunable oscillators. Narrow linewidth, grating cavity systems based on broadband solid-state materials such as Ti:Sapphire, Alexandrite and Cr:LiSAF require gratings exhibiting damage thresholds in excess of 2 J/cm^2 in order to access the high energy storage of these materials.

We have made a systematic study of the relationship between gold-coating thickness and laser damage threshold. We find thickness to be the dominant factor in determining the damage threshold of defect-free metallic gratings. With the exception of gratings ruled directly into the metal, all metal gratings are formed by vapor deposition of a thin metal film onto a dielectric surface. The dielectric may be photoresist, epoxy, or glass. All of these materials exhibit low thermal conductivity relative to the metal film, and so they essentially serve as a thermal barrier.

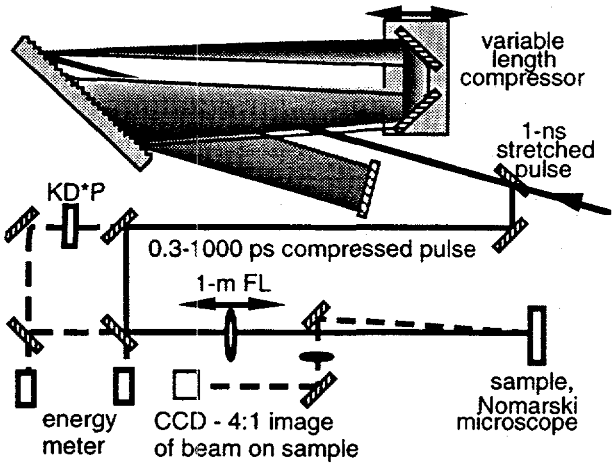

Figure 1. The 1-ns stretched pulses are compressed to 0.3-1000 ps by a variable length compressor. A 1-m focal length lens focuses the pulses on the sample and the spot size is measured with a 4:1 image.

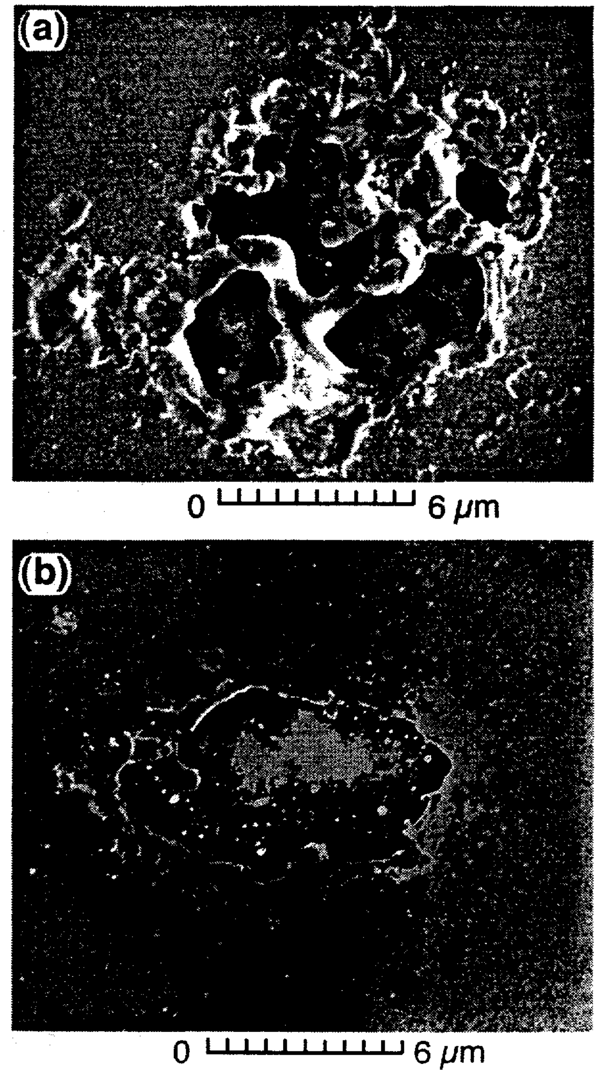

Figure 2. Damage to gold film with 1053-nm pulses: (a) long-pulse, 900 ps, (b) short-pulse, 0.6 ps.

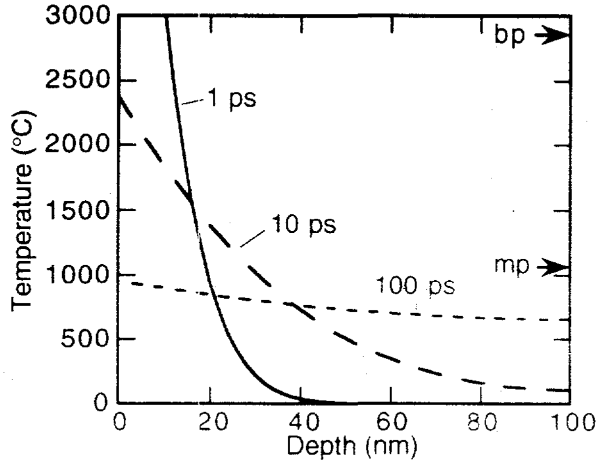

Figure 3. Temperature distribution as a function of depth and pulse duration for an absorbed fluence of 500 mJ/cm^2 delivered to a 100-nm thick gold film. The melting (mp) and boiling (bp) temperatures for gold are indicated

Damage is more readily produced by short pulses than by long ones. Scanning electron microscopy of the damaged regions of the surface of a plain gold film reveals strong clues to the mechanism responsible for damage. The damage spots created by very short pulses exhibit negligible melting or collateral damage (Figure 2a) indicative of extremely rapid ablation and vaporization. In contrast, longer pulses create larger damage regions whose appearance is consistent with melting, flow and subsequent resolidification (Figure 2b). These observations form the basis of a simple model for laser damage to gold-coated optics[28]. Specifically, we assume that damage occurs when the temperature reaches the melting point of the metal for long pulses or the boiling point for short pulses. We model the grating as a one dimensional film subjected to a constant heat flux at the surface (provided by the laser pulse) and permit negligible heat transfer at the interface between the dielectric and the metal. Laser energy is deposited in a skin depth, which for gold at a laser wavelength of 1 μm, is only 3 nm. As a result, we approximate the boundary condition at the surface of the grating as one of a constant heat flux deposited at the surface. The dependence on grating parameters such as groove spacing, depth and shape, can be accounted for by adjusting the absorption coefficient.

Starting with a gold film at a uniform temperature, Figure 3 shows the temperature distribution in a 100-nm thick gold coating immediately following irradiation by 1053-nm laser pulses of various durations at a fluence of 500 mJ/cm^2. For subpicosecond pulses, a depth of less than 10 nm is heated beyond the boiling point, and little heat transfers into the remaining film. This is a result of the finite thermal diffusivity of gold, $\alpha = 143$ nm^2/psec. For such short picosecond pulses the thermal wave cannot penetrate more than approximately 10 nm ($\alpha t/L^2 \approx 1$). Hence, *we would predict that at this fluence, the surface will be damaged, regardless of the thickness of the coating*. For longer pulses the coating thickness has a significant effect on the surface temperature and the resulting damage threshold. The thermal diffusivity is sufficiently high that the metal can efficiently conduct heat away from the surface in a few picoseconds. Thus, for pulses which deposit their energy during a few tens of picoseconds, the surface temperature is depressed by conduction throughout the bulk of the film. For pulses longer than 100 ps, conduction across the film is complete and the temperature becomes constant throughout the film. In this case the bulk temperature, and hence the damage threshold, is determined solely by the thickness of the coating (i.e. the volume of material heated).

Defining the damage threshold as the onset of melting for long pulses and boiling for short pulses, we use this one-dimensional heat-conduction model to predict the dependence of damage threshold on coating thickness and laser pulse width. In Figure 4 we show our calculated and measured damage thresholds for 1053-nm laser pulses incident on a gold film deposited on developed photoresist. For (long) nanosecond pulses, there is an approximately linear dependence on film thickness up to 200 nm, followed by an asymptotic approach to the damage threshold of bulk material. For (short) picosecond pulses, we observe a dependence on film thickness similar to that of nanosecond pulses, but only to a thickness near the penetration depth. Beyond this thickness, the damage threshold is predicted to be independent of film thickness. The difference between the model and the measured data for picosecond pulses for coatings below 100 nm in thickness is due to pinholes and defects in films less than 100 nm. As the coating thickness increased above 100 nm, the coatings became more uniform and increasingly defect free.

The measured damage thresholds of some of our high efficiency gold gratings are also shown in Figure 4. Although the damage threshold of the gratings is always lower than that observed for uniform metal films, we observe the same general dependence on coating thickness up to approximately 200 nm. We expect that gold-coated gratings, when free of surface defects, should have damage thresholds approaching those of gold films. The calculations shown in Figure 4 are applicable to high efficiency gratings where the absorption is determined only by the bulk material properties. In those cases where trapped fields are present[29], the absorption coefficient is dominated by the grating structure, and the damage threshold is significantly lower. We do not account for the possibility of field enhancement and resulting plasma formation. Field enhancement is a weak effect in the high efficiency, near sinusoidal gratings considered here. Furthermore, plasma formation will be dominant only for very short pulses (less than 20 fs) where the effective irradiance is on the order of 10^{13} W/cm^2.

In addition to testing our own gratings, we have tested, at 1053 nm, the laser damage threshold of samples of several commercially available gold coated diffraction gratings. For *nanosecond* pulses, the damage thresholds have varied widely from as low as 50 mJ/cm^2 to over 400 mJ/cm^2 for holographic gratings, and up to 800 mJ/cm^2 for gold coated ruled gratings. Our tests showed little correlation between diffraction efficiency and damage threshold. The commercial metallic gratings varied dramatically in composition, ranging from holographic masters in which the metal film is deposited directly on the developed photoresist to replica gratings where the metal is deposited on an epoxy. Surface preparation, groove shape and coating thickness all varied greatly between samples from different suppliers.

3.2 Fused silica

Since gold-coated optics cannot withstand fluences much greater than 500 mJ/cm^2 in the short-pulse (subpicosecond) regime, we turned to multilayer dielectrics to create the high damage threshold gratings[3] necessary for pulse compression of high-energy (kJ) laser pulses. We began with the desire to understand the physical damage mechanism in dielectrics, and chose fused silica as our first sample due to its availability in high-purity samples and its extensive physical characterization in the literature.

The results presented here were obtained with 1-cm thick "super-polished" fused silica samples (Corning 7940) exhibiting less than 1-nm rms surface roughness. We measured the same damage thresholds with a 200-μm thick fused-silica etalon, which was tested to examine any possible differences between thick and thin samples. Some samples were cleaned initially with acetone or methanol, and all were cleaned when damage debris accumulated on the surface. No difference in threshold was found between samples or areas on a given sample that were or were not cleaned. Defects visible through the microscope were avoided. With short (0.4 ps) pulses, damage always occurred at the location corresponding to the peak of the Gaussian intensity profile, indicating that defect sites did not contribute to our measured thresholds. Ramping the fluence with short pulses, which would ionize and ablate any low-

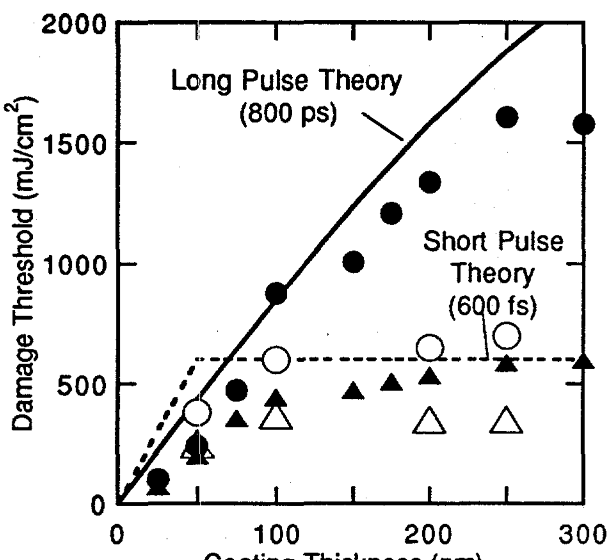

Figure 4. Predicted and measured 1053-nm damage thresholds for gold films. Filled symbols show measured values for gold deposited on photoresist, open symbols show measured values for gold gratings. Circles are long-pulse (800 ps), triangles are short-pulse (600 fs). Lines show theoretical predictions.

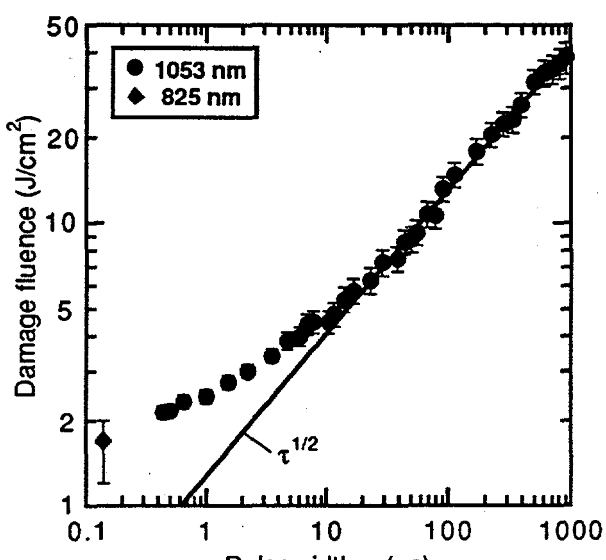

Figure 5. Pulsewidth dependence of threshold damage fluence for fused silica

lying states or surface contamination with lower threshold, gave the same threshold as our measurements with constant fluence. We thus believe that our measurements correspond to a uniform, defect-free surface and can be compared to calculations based on the intrinsic properties of fused silica.

Our measured threshold damage fluence for fused silica at 1053 nm as a function of laser pulse length (FWHM) is shown in Figure 5. In the long-pulse regime (τ>20 ps), the data fit well to a $\tau^{1/2}$ dependence (actual fit: $\tau^{0.504}$), characteristic of transfer of electron kinetic energy to the lattice and diffusion during the laser pulse. The damage occurs over the entire area irradiated as shown in the electron micrograph of Figure 6(a) (All damage micrographs shown are the result of multiple pulses). The damage is thermal in nature and characterized by melting and boiling of the surface. This is more easily seen in Figure 7(a), which shows the edge of the long-pulse damage spot. For pulses shorter than 20 ps, the damage fluence no longer follows the $\tau^{1/2}$ dependence and exhibits a morphology dramatically different from that observed with long pulses. Short-pulse damage is confined to a small region at the peak of the Gaussian irradiance distribution (Figure 6(b)). Damage occurs only over an area with sufficient intensity to

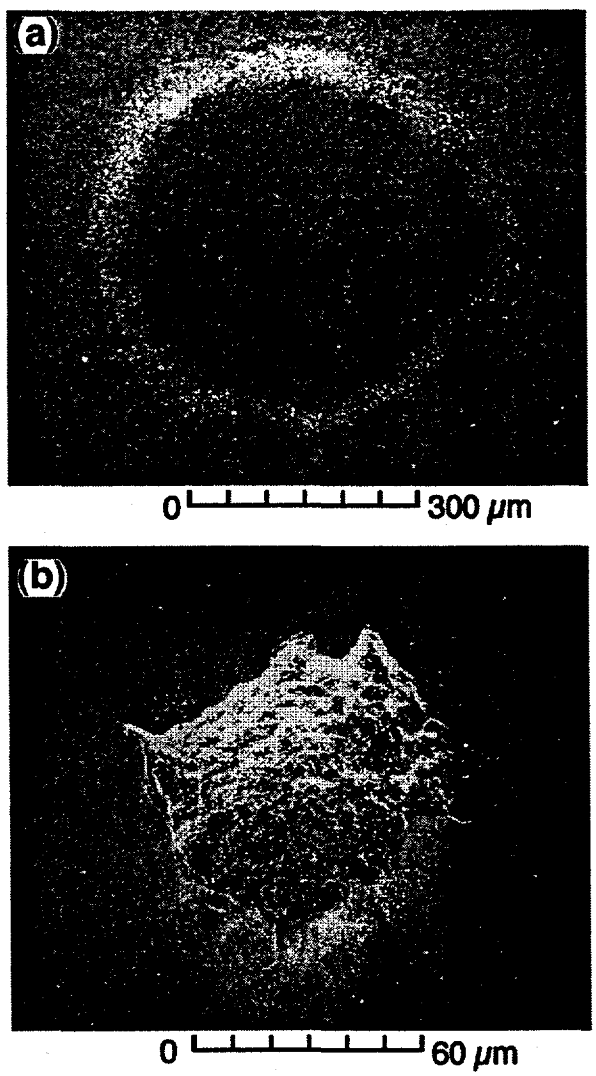

Figure 6. Laser damage spots on fused silica created by: (a) long-pulse, 900-ps, 300 μm diameter, (b) short-pulse, 0.4-ps, 500-μm diameter.

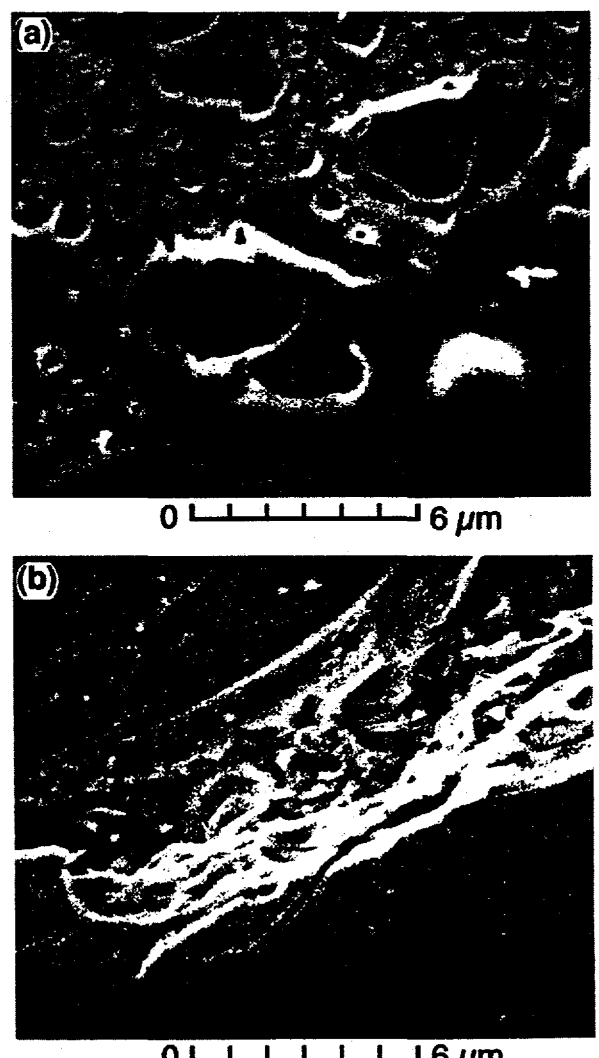

Figure 7 .Edges of laser damage spots of Fig. 6: (a) long pulse, 900 ps, (b) short-pulse, 0.4 ps.

produce ionization. With insufficient time for lattice coupling, there is no collateral damage. As a result, the damaged area can be many orders of magnitude smaller with short (τ<10 ps) pulses than with long pulses. For the case of fused silica shown in Figure 6, the damaged area produced by the 0.5-mm diameter, 500-fs pulse was two orders of magnitude smaller than that produced by the 0.3-mm diameter, 900-ps pulse. Short-pulse damage appears as a shallow fractured and pitted crater characteristic of a thin layer of material removed by ablation (Figure 7(b)). We found damage in the short-pulse limit to be deterministic, with only a couple percent fluence range between damage and no damage. Fused silica irradiated with 10000 shots at 2% below our determined threshold showed no evidence of damage with 0.4-ps pulses. For long pulses we found a roughly 10% range in fluence where damage would or would not occur.

Optical breakdown in transparent materials can be understood in terms of an electron avalanche[5,6,12,14,15] in which conduction-band electrons, oscillating in response to the laser field, transfer energy by scattering from phonons. If an electron can achieve an energy equal to the bandgap, subsequent impact ionization promotes another valence electron into the conduction band. The resulting avalanche, similar to that in gases[30], leads to an irreversible change in the bulk structure. We have developed[25] a general theoretical model of laser interaction with dielectrics in which very short intense pulses produce initial conduction band electrons by multiphoton ionization. Because the pulses are so short, collisional heating of the electrons occurs before there is significant transfer of energy from the electrons to the lattice. This heating and energy diffusion, combined with impact ionization, result in an electron avalanche which can be described by a kinetic equation for the electron distribution function.

Figure 8 illustrates the calculated evolution of electron density for a 100-fs, 12-TW/cm^2 pulse. The pulse intensity and the electron density produced by photoionization alone are included for reference. Because photoionization is extremely intensity dependent, the electron production takes place principally at

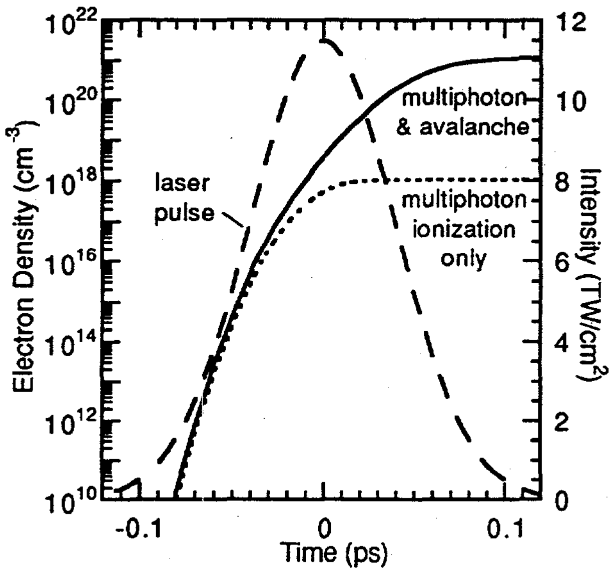

Figure 8. Total (upper solid) and multiphoton produced (lower solid) electron densities are plotted along with the Gaussian pulse shape. Seed electrons are produced by multiphoton ionization at the pulse peak after which an avalanche produces a critical density.

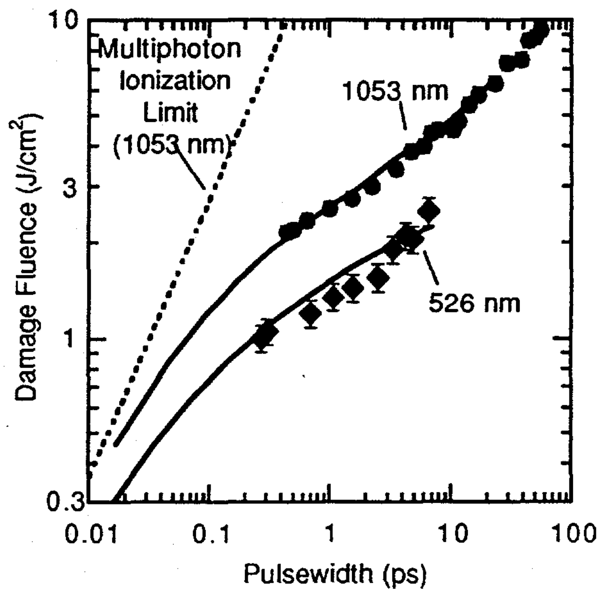

Figure 9. Measured and calculated (solid lines) damage fluence for fused silica at 1053 and 526 nm. Dashed line indicates calculated damage limit due to multiphoton ionization alone.

the peak of the pulse. After these "seed" electrons are produced, a small electron avalanche achieves a critical density plasma. It is important to note that the dense plasma is not produced until late in the pulse. Only this last part of the pulse experiences strong absorption or reflection. We expect thresholds to be more sensitive to the pulseshape for longer pulses, where the avalanche is relatively more significant.

In our modeling, we take the damage threshold to be indicated by the occurrence of a sufficiently high electron density. A reasonable lower limit would be on the order of 10^{19} cm^{-3}, roughly the density at which the energy density of conduction electrons equals the binding energy of the lattice. A more realistic choice is the critical electron density, n_{cr}, at which the plasma becomes reflective (10^{21} cm^{-3} for 1053 nm), since it is just below this density that the laser is strongly absorbed. Our calculations indicate the theoretical threshold is only logarithmically dependent on this choice.

In Figure 9, we compare our measured and calculated damage thresholds at 526 nm and 1053 nm. The solid curves are the results of our theoretical modeling of laser-induced damage in the short-pulse limit, and are in very good agreement with both the *pulsewidth* and *wavelength* scaling of the measured data. As shown, with decreasing pulsewidth the damage threshold will asymptote to the limit where multiphoton ionization alone creates sufficient electron density to cause damage. At 1053 nm this asymptotic limit scales as $\tau^{7/8}$, and in general scales as $\tau^{(m-1)/m} n_{cr}^{1/m}$ when m-photon ionization is the dominant process.

3.3 Fluorides

The damage threshold of calcium fluoride exhibits a similar pulsewidth dependence to that of fused silica (Figure 10). In the long-pulse limit, the threshold fluence also scales as $\tau^{1/2}$, and then changes to the short-pulse limit near 20 ps. For long pulses the damage morphology is again consistent with melting. Figure 11(a) shows the melting and recrystalization of the calcium fluoride surface layers, which occurred with no evidence of an avalanche breakdown. This is consistent with the measurements of Jones *et al* [15] on wide-gap alkali halides. Short-pulse damage clearly initiates on scratches left from the polishing process (Figure 11(b)), although as observed by Milam[31] with 125 ps pulses, the damage threshold did not appear to be greatly influenced by the polishing sleeks. The short-pulse (0.4 ps) damage thresholds of BaF_2, CaF_2, MgF_2, and LiF (included in Figure 14) scale with bandgap energy, as expected from multiphoton initiated avalanche ionization.

3.4 Multilayer dielectrics

We have tested several different multilayer dielectric mirrors and polarizers, with each multilayer stack consisting of approximately 20 individual layers of thickness 0.1-0.3 μm. Figure 12 shows the pulsewidth dependence of the 1053-nm damage threshold fluence for a 45° high-reflector and a 57° polarizer used in reflection. The long-pulse scaling of each is slightly less than $\tau^{1/2}$, and again there is a transition to the short-pulse regime near 20 ps. The long-pulse damage morphology of the mirror is again characterized by melting and flow (Figure 13(a)), whereas short pulses cause ablation of the individual dielectric layers (Figure 13(b)). As has been thoroughly characterized by Kozlowski, *et al*[32], the initiation of damage with long (ns) pulses is dominated by nodules and defects. We find the same behavior with short (0.4 ps) pulses, where the presence of defects reduces the damage threshold by up to 50%, depending on the size and type of defect. We tried laser-conditioning[33] the mirror to improve the short-

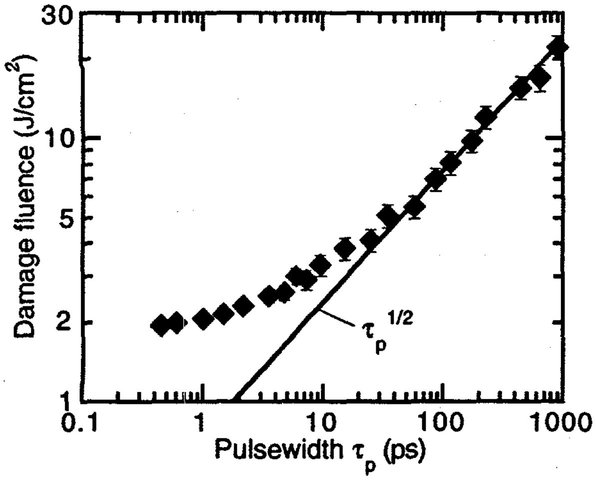

Figure 10. Pulsewidth dependence of threshold damage fluence for calcium fluoride.

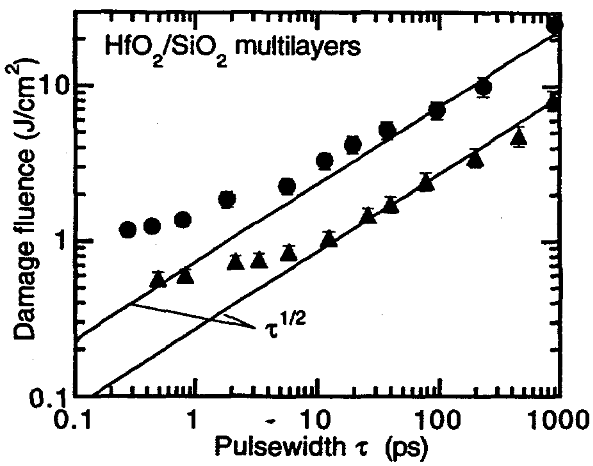

Figure 12. Pulsewidth dependence of threshold damage fluence for two different HfO_2/SiO_2 multilayer dielectric samples on relatively clean areas: (●) 57°S polarizer, (▲) 45°S mirror.

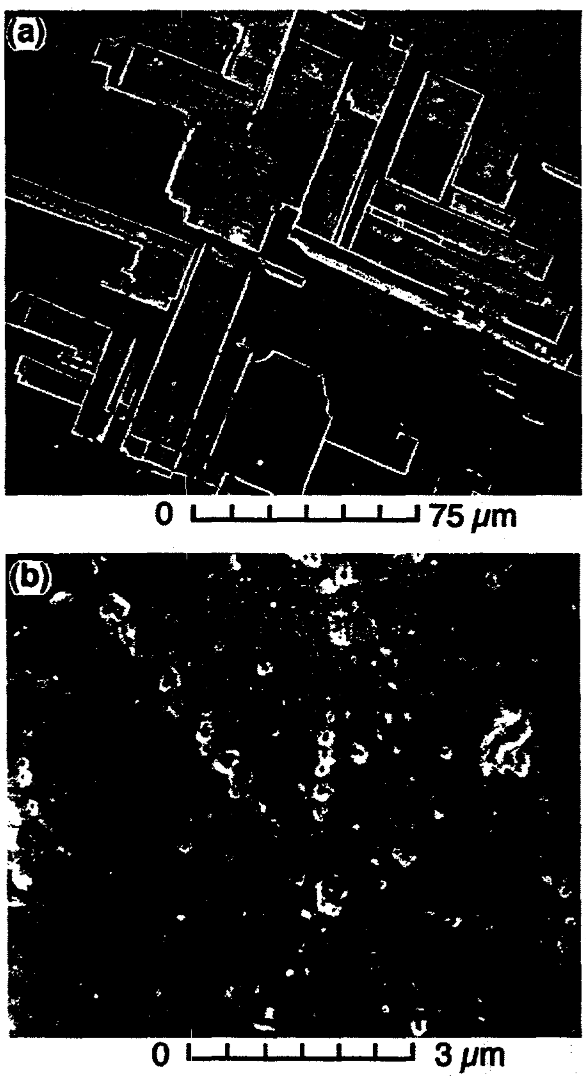

Figure 11. Laser damage morphology of calcium fluoride for (a) 900 ps, and (b) 0.4 ps pulses.

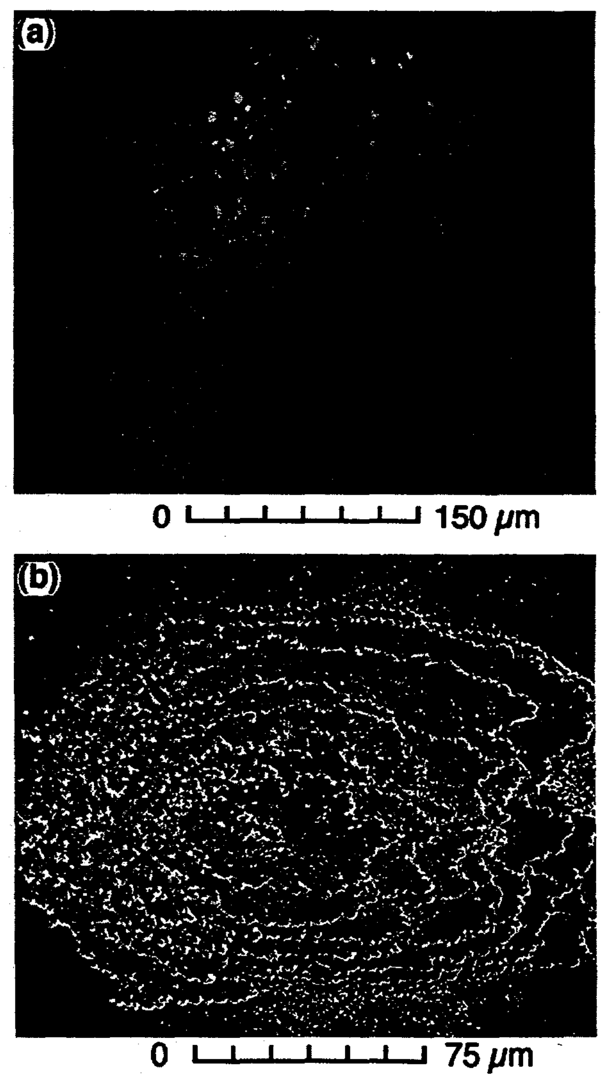

Figure 13. Laser damage morphology of a multilayer dielectric mirror for (a) 900 ps, and (b) 0.4 ps pulses.

pulse damage threshold. Unfortunately, neither long nor short-pulse conditioning resulted in a higher short-pulse damage threshold.

The short-pulse (0.4 ps) damage thresholds of many of the multilayer dielectrics we tested are included in Figure 14. These samples consisted of a variety of mirrors and polarizers with either HfO_2/SiO_2 or Ta_2O_5/SiO_2 multilayers deposited by e-beam evaporation or ion-beam sputtering. The cross-hatched area indicates thresholds achieved on "clean" areas, as opposed to areas with obvious defects. As with long pulses, we find the key to achieving increased short-pulse damage thresholds is the reduction in size and number density of the defects. The highest damage threshold we have found on any multilayer dielectric sample with 0.4-ps pulses at 1053 nm is 1.4 J/cm^2. We expect that, with proper design and production, diffraction gratings based on these multilayer structures will exhibit damage thresholds comparable those of the multilayer itself.

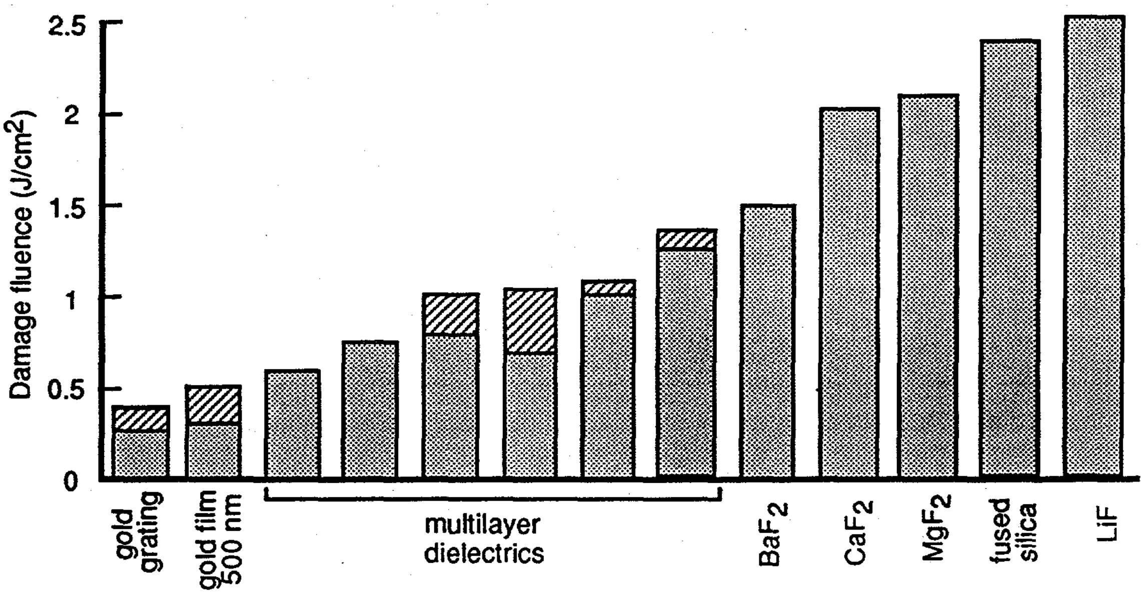

Figure 14. Short-pulse (0.4 ps), front-surface threshold damage fluences for gold film, gold grating, multilayer dielectrics (polarizers and mirrors), and pure dielectrics.

4. DISCUSSION

We have investigated the pulsewidth dependence of laser-induced damage in pure and multilayer dielectrics and gold-coated optics over the range 0.1-1000 ps. The damage threshold of gold films increases with greater thickness for long (ns) pulses, where there is sufficient time for thermal diffusion. However, with subpicosecond pulses the damage threshold is limited to approximately 500 mJ/cm^2, and is independent of thickness.

In dielectrics, we observe a strong deviation from the long-pulse $\tau^{1/2}$ scaling of laser damage fluence for pulses shorter than 20 ps, below which electrons have insufficient time to couple to the lattice during the laser pulse. The damage threshold continues to decrease with decreasing pulsewidth, but at a rate slower than $\tau^{1/2}$ in the range 0.1 to 20 ps. This departure is accompanied by a qualitative change in the damage morphology indicative of rapid plasma formation and surface ablation. The damage site is limited to only a small region where the laser intensity is sufficient to produce a plasma with essentially no collateral damage. A theoretical model, in which initial electrons provided by multiphoton ionization are further heated resulting in collisional (avalanche) ionization, predicts short-pulse damage thresholds in excellent agreement with both the pulsewidth and wavelength scaling of our measurements. For extremely short pulses (τ<30 fs), multiphoton ionization alone will provide the critical density of electrons.

5. ACKNOWLEDGMENTS

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