Femtosecond Laser Micromachining: Applications in Photonics and Biology

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Introduction

Abstract-A review is given of recent experimental results on laserinduced electric breakdown in transparent optical solid materials. A fundamental breakdown threshold exists characteristic for each material. The threshold is determined by the same physical process as de breakdown, namely, avalanche ionization. The dependence of the threshold on laser pulse duration and frequency is consistent with this process. The implication of this breakdown mechanism for laser bulk and surface damage to optical of this oreaxonown mechanism for user oux and surface namines to optical components is discussed. It also determines physical properties of self-

THE history of laser-induced electric breakdown focused filaments. is almost as old as the history of lasers itself. Early in

1963 Maker et al. [1] reported damage to transparent dielectrics and the production of a spark in air by focusing sulsed ruby laser beam. The importance of these the production of laser-induced dense montolinpart

Laser-Induced Electric Breakdown in Solids NICOLAAS BLOEMBERGEN, FELLOW, IEEE plasmas and for the propagation characteristics of highpower laser beams through solids, liquids, and gases was quickly recognized. The subject of electric breakdown in transparent optical solids, including laser materials, windows, and other optical components, remained, until recently, largely an empirical or engineering science. Although a vast amount of theoretical and experimental effort was expended in the economically and technically important problem of optical damage, quantitative reproducible breakdown thresholds with unambiguous theoretical interpretations have been obtained only during the last two years. The situation was somewhat analogous to the development of our understanding of the problem of de breakdown in electrical insulators. There, too, the field developed largely by engineering trial and error. Basic quantitative understanding was not achieved until reproducible experimental results on well-defined materials were obtained [2]. The difficulties in de is a second to the second seco

Introduction

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Laser-Induced Electric Breakdown in Solids

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T^{int} therein a treatment determined allocates **breakdown** Long-solid Addressed State (out stoket etche all treamed damage versionsparent fielderings with the prediction of a security in an my focusion subsit subsitive them. The importance of these

plusters and for the propagation characteristics of high bitted from by one of such words. Enough and success was querely reconcilied. The subject of electric breakdown of transmission operation and a methodatic based analyticals, action down and other oppical components remained, and seconds, hereby in surplus it or entimetron some Millionable Constraints of theoremical and experimental effort win experiently in the contempoter and rectionate ministrant provident of optical damage automation terreductive breakdown thresholds with unantitude the steps of uncertainty have been obtained unly during the rest two weaks. The scheduling ways and which decided to doe development of our understanding of the problem or de breakdown of the tracit resolutions. The for the tield developed forcely by enconcernational error Wester with an of the standard of the standard with epicolositile experimental peoples on well-defined manstrale were detained (2). the defluctures in ste the infinence of



Introduction



use damage for processing!

Introduction

Outline



Outline

Processing with fs pulses

Role of focusing

Low-energy processing



Du et al., Appl. Phys. Lett. 64, 3071 (1994)

Breakdown threshold and plasma formation

in femtosecond laser-solid interaction

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D. von der Linde and H. Schüler

Combining femtosecond pump-probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of Combining femtosecond pump-probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of laser induced plasma formation has been determined from measurements of the changes of the optical reflectivity associated optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed plasma formation has been determined from measurements of the changes of the optical reflectivity associated. We have observed with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond last with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond laser pulses with bulk optical materials. © 1996 Optical Society of America a remarkable resistance to optical breakdown and material damage in t pulses with bulk optical materials. © 1996 Optical Society of America

J. Opt. Soc. Am. B/Vol. 13, No. 1/January 1996

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The interaction of intense femtosecond laser pulses with 1. INTRODUCTION solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great and any imparty from the point of view of generatwheet wray pulses. To produce such a Id give from the intensity level formation to the time scale

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau et al.⁵ carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic Thus far, the issue of breakdown thresholds in femtosecond laser-solid interaction has barely been touched. man and all carried out laser-induced breakfound silica with pulses ranging in effects. 150 fs. They reported threshold on - of the

D, you doe Limbe and H. Schuler

"... clear evidence that no bulk plasmas ... [and] ... no bulk damage could be produced

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with femtosecond laser pulses."

dama formation has been determined from monostrements of the changes of the Galacies with the desconding placing, it is show on that placing generation secure at the intermediation a primaricable residence to achieve because we and waterial damages in the intermediation with the devolution blacmic. It is shown that plasmic generation secure at the intermition of feature is contribute residence to optical breakdown and waterial domain in the intermition of feature plase with bulk optical materials. I have Optical Society of America optical bacalidaesin in optically transplacent adults with bith temporal and flasmit formation has been determined from manentements of the character with the development character. It is shown that observe interesting and Communities were were really to the process of the second se Combinition formationers in training product to characteristic a wemarkable resistance to optical breakdown and waterial damage in t police with hole optical materials.

The interaction of intense femtosecond laser pulses with 1. INTRODUCTION solids often the possibility of producing a new class of having approximately solid-ators density and von der Linde, et al., J. Opt. Soc. Am. **13**, 216 (1996)

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focus laser beam inside material



Glezer, et al., Opt. Lett. 21, 2023 (1996)







2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm





2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm



2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm



2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm





100 fs 0.5 μJ

200 ps 9 μJ



5 x 5 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm



high intensity at focus...



... causes nonlinear ionization...



and 'microexplosion' causes microscopic damage

Points to keep in mind:

- fs laser processing works
- focusing very important
- no collateral damage

Outline

Processing with fs pulses

Role of focusing

Low-energy processing



Dark-field scattering





block probe beam...





... bring in pump beam...





... damage scatters probe beam












vary numerical aperture in Corning 0211





fit gives threshold intensity: $I_{th} = 2.5 \times 10^{17} \text{ W/m}^2$





vary material...



threshold varies with bandgap



Points to keep in mind:

- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

Outline

- Processing with fs pulses
 - Role of focusing
 - Low-energy processing

threshold decreases with increasing numerical aperture



less than 10 nJ at high numerical aperture!



amplified laser



heat-diffusion time: $\tau_{diff} \approx 1 \ \mu s$

long-cavity Ti:sapphire oscillator



heat-diffusion time: $\tau_{diff} \approx 1 \ \mu s$













waveguide machining



waveguide machining



waveguide mode analysis



near field mode



near field mode



curved waveguides



3D wave splitter



Bragg grating



Bragg grating



monolithic amplifier



epi-fluorescence microscope



mount fluorescently tagged sample



UV illumination...



... causes fluorescence



process with fs laser beam





before





examine in confocal microscope

before




before



before







before



before



before



before



before



before



before



before






































































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For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu

refractive index profiles and near field mode at 633 nm



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bleaching or disruption?



bleaching or disruption?

