Femtosecond Laser Micromachining: Applications in Technology and Biology

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Laser-Induced Electric Breakdown in Solids

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Abstract—A review is given of recent experimental results on laser-induced 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 dc 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 components is discussed. It also determines physical properties of self-focused filaments.

I. INTRODUCTION

The history of laser-induced electric breakdown 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 a pulsed ruby laser beam. The importance of these early observations for the production of laser-induced dense plasmas and for the propagation characteristics of high-power 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 dc 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 dc breakdown experiments were manifold: the influence of the effects of heating due to a few electron
Laser-Induced Electric Breakdown in Solids

Introduction
Introduction
use damage for processing!
Outline

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

![Graph showing the relationship between $F_{th}$ (J/m$^2$) and pulse duration (ps).]
Processing with fs pulses

\[ F_{th} (\text{J/m}^2) \]

Graph showing \( F_{th} \) (J/m\(^2\)) against pulse duration (ps) with a power law relationship \( \tau^{1/2} \).
Processing with fs pulses

\[ F_{th} (J/m^2) \]

[Graph showing the relationship between pulse duration (ps) and \( F_{th} \) with a \( \tau^{1/2} \) slope from Du et al., Appl. Phys. Lett. 64, 3071 (1994).]
Processing with fs pulses

\[ F_{th} (\text{J/m}^2) \]

\[ \tau^{-\frac{1}{2}} \]

\[ \tau^{-1} \]

\[ \tau^{1/2} \]

Du et al., Appl. Phys. Lett. 64, 3071 (1994)
Processing with fs pulses

Breakdown threshold and plasma formation in femtosecond laser–solid interaction

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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 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 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

1. INTRODUCTION

The interaction of intense femtosecond laser pulses with 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 interest, particularly from the point of view of generating ultra-short x-ray pulses. To produce such a plasma, one would rise from the intensity level over which optical breakdown occurs to the terawatt per cm²-terawatt per cm² 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.6 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 effects.

Thus far, the issue of breakdown thresholds in femtosecond laser–solid interaction has barely been touched. Recently, Du et al.6 carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration as short as 150 fs. They reported on the observation of a new threshold on the scale of the laser pulse duration, which they attribute to the breakdown threshold.
“... clear evidence that no bulk plasmas ... [and] ... no bulk damage could be produced with femtosecond laser pulses.”

Processing with fs pulses

focus laser beam inside material

Processing with fs pulses
Processing with fs pulses

2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm

Processing with fs pulses

2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm

Processing with fs pulses

2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm

Processing with fs pulses

2 x 2 µm array

fused silica, 0.65 NA

0.5 µJ, 100 fs, 800 nm

Processing with fs pulses

- 100 fs, 0.5 µJ
- 200 ps, 9 µJ
Processing with fs pulses

5 x 5 µm array
fused silica, 0.65 NA
0.5 µJ, 100 fs, 800 nm

Processing with fs pulses

microstructure scribed sample
Processing with fs pulses

microstructure scribed sample
fracture along scribe line
Processing with fs pulses

Corning 0211
1.4 NA, 140 nJ
Processing with fs pulses
Processing with fs pulses

high intensity at focus…
Processing with fs pulses

100 fs

... causes nonlinear ionization...
Processing with fs pulses

and ‘microexplosion’ causes microscopic damage
What are the conditions at focus?
What are the conditions at focus?

Processing with fs pulses

Laser deposits energy in ~1 µm³
What temperature?
Processing with fs pulses

What temperature?

\[ \Delta E = C_v \rho V \Delta T \]
Processing with fs pulses

What temperature?

\[ \Delta E = C_V \rho V \Delta T \]

\[ C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \]

\[ \rho = 2.2 \times 10^3 \text{ kg/m}^3 \]
What temperature?

\[ \Delta E = C_V \rho V \Delta T \]

\[ C_V = 0.75 \times 10^3 \, \text{J kg}^{-1} \text{K}^{-1} \]

\[ \rho = 2.2 \times 10^3 \, \text{kg/m}^3 \]

So, 1 \( \mu \text{J} \) in 1 \( \mu \text{m}^3 \) gives

\[ \sim 1,000,000 \, \text{K}! \]
What pressure?
What pressure?

Treat ionized material as an ideal gas:

\[ pV = nRT \]
What pressure?

Treat ionized material as an ideal gas:

\[ pV = nRT \]

Gives

\[ p = 10 \text{ MBar!} \]
So:

microexplosion

\[ T \approx 1 \text{ MK} \]

\[ p \approx 10 \text{ MBar} \]

\[ \rho = 2.2 \times 10^3 \text{ kg/m}^3 \]
So:

<table>
<thead>
<tr>
<th>microexplosion</th>
<th>sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>$T \approx 1\text{ MK}$</td>
</tr>
<tr>
<td>$p$</td>
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</tr>
<tr>
<td>$\rho$</td>
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Processing with fs pulses

So:

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<td>$\rho$</td>
<td>$2.2 \times 10^3$ kg/m$^3$</td>
</tr>
</tbody>
</table>

creating stellar conditions in lab!
Processing with fs pulses

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
Role of focusing

Dark-field scattering

objective

sample
Role of focusing

block probe beam...
Role of focusing

... bring in pump beam...
Role of focusing

... damage scatters probe beam
Role of focusing

![Graph showing signal (a.u.) over time (µs) for fused silica with 0.1 µJ input.]
Role of focusing

![Graph of signal vs. time for fused silica with 1.0 µJ input](image.png)
Role of focusing

![Graph showing signal (a.u.) vs. time (µs) for fused silica with 1.0 µJ, highlighting plasma effect.](attachment:image.jpg)
Role of focusing
Role of focusing

![Graph showing the thermal transient of fused silica with a peak signal of 1.0 µJ.](image)
Role of focusing

vary numerical aperture in Corning 0211

threshold energy (nJ)

numerical aperture
Role of focusing

Spot size determined by numerical aperture:

\[ E_{th} = I_{th} \tau A = \frac{I_{th} \tau \lambda^2}{\pi (NA)^2} \]

And thus

\[ I_{th} = \frac{E_{th} \pi}{\tau \lambda^2} (NA)^2 \]
Role of focusing

fit gives threshold intensity: \( I_{th} = 2.5 \times 10^{17} \text{ W/m}^2 \)
Role of focusing

![Graph showing the relationship between bandgap (eV) and threshold intensity (10^17 W/m^2).]

- **Bandgap (eV)**
  - 3
  - 5
  - 7
  - 9
  - 11

- **Threshold Intensity (10^17 W/m^2)**
  - 1
  - 3
  - 5

- **Threshold Fluence (kJ/m^2)**
  - 0.2
  - 0.4
  - 0.6

Additional inset graph:

- **Numerical Aperture**
  - 0
  - 0.5
  - 1.0
  - 1.5

- **Threshold Energy (nJ)**
  - 0
  - 100
  - 200

---

**Note:** The graph illustrates the role of focusing on the threshold characteristics, with a focus on how changes in numerical aperture affect threshold energy and fluence.
Role of focusing

vary material...

![Graph showing the relationship between bandgap (eV), threshold intensity ($10^{17}$ W/m$^2$), and threshold fluence (kJ/m$^2$). The graph includes data points for CaF$_2$, fused silica, SF11, and 0211.](image)
Role of focusing

threshold varies with bandgap

![Graph showing the relationship between bandgap and threshold intensity for different materials like CaF$_2$, SF11, and fused silica.](image-url)
Role of focusing

Points to keep in mind:

- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important
Processing with fs pulses

Role of focusing

Low-energy processing
Low-energy processing

threshold decreases with increasing numerical aperture
Low-energy processing

less than 10 nJ at high numerical aperture!
Low-energy processing

amplified laser

heat-diffusion time: $\tau_{\text{diff}} \approx 1 \mu$s
Low-energy processing

long-cavity Ti:sapphire oscillator

heat-diffusion time: $\tau_{\text{diff}} \approx 1 \ \mu s$
Low-energy processing

10 µm
Low-energy processing

$10^2$

50 µm
Low-energy processing

$10^2 \quad 10^3$

50 µm
Low-energy processing
Low-energy processing
Low-energy processing

![Graph showing the relationship between the number of shots and the radius (µm).](image)
Low-energy processing

waveguide machining
Low-energy processing

waveguide machining
Low-energy processing

waveguide mode analysis
Low-energy processing

near field mode
Low-energy processing

near field mode

![Graph showing intensity vs. position with a peak at 15 AU and a scale of 10 µm]
Low-energy processing

refractive index profiles and near field mode at 633 nm

Sagitta, Inc.
Low-energy processing

refractive index profiles and near field mode at 633 nm

Sagitta, Inc.
Low-energy processing

refractive index profiles and near field mode at 633 nm

Sagitta, Inc.
Low-energy processing

waveguide loss measurement

HeNe
Low-energy processing

waveguide loss measurement
Low-energy processing

waveguide loss measurement

[Diagram showing a HeNe laser source connected to an iris followed by a waveguide]
Low-energy processing

waveguide loss measurement

- HeNe
- iris
- waveguide
- D1
- CCD
- D2
Low-energy processing

waveguide loss measurement
Low-energy processing

- at low NA: $1.6 \text{ dB/cm} < \text{loss} < 3.2 \text{ dB/cm}$
Low-energy processing

- at low NA: $1.6 \text{ dB/cm} < \text{loss} < 3.2 \text{ dB/cm}$
- losses mostly due to scattering
Low-energy processing

Numerical aperture of waveguide

<table>
<thead>
<tr>
<th>Input NA</th>
<th>Loss Coefficient (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>0.05</td>
<td>1.8</td>
</tr>
<tr>
<td>0.10</td>
<td>2.1</td>
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<tr>
<td>0.15</td>
<td>2.4</td>
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<tr>
<td>0.20</td>
<td>2.7</td>
</tr>
<tr>
<td>0.25</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Graph showing the relationship between input NA and loss coefficient (dB/cm).
Low-energy processing

numerical aperture of waveguide

![Graph showing the relationship between input NA and loss coefficient (dB/cm)]
Low-energy processing

numerical aperture of waveguide

\[ NA = \sqrt{n_1^2 - n_2^2} = 0.065 \]
Low-energy processing

numerical aperture of waveguide

\[ NA = \sqrt{n_1^2 - n_2^2} = 0.065 \]

\[ n_2 = 1.52 \]
Low-energy processing

numerical aperture of waveguide

\[ NA = \sqrt{n_1^2 - n_2^2} = 0.065 \]

\[ n_2 = 1.52 \]

\[ \Delta n = 1.4 \times 10^{-3} \]
Low-energy processing

curved waveguides
Low-energy processing

curved waveguides

![Graph showing transmission loss vs bending radius.](image-url)
Low-energy processing

3D wave splitter

He:Ne
Low-energy processing

Bragg grating

$n\lambda$
Low-energy processing

Bragg grating
Low-energy processing

monolithic amplifier

laser active glass
Low-energy processing

epi-fluorescence microscope

UV lamp

objective

CCD camera
Low-energy processing

mount fluorescently tagged sample

UV lamp

objective

camera

cCD
Low-energy processing

UV illumination…

UV lamp → objective → sample → CCD camera
Low-energy processing

... causes fluorescence
Low-energy processing

process with fs laser beam

UV lamp

fs laser

objective

sample

fluorescence

CCD camera
Low-energy processing

- UV lamp
- Sample
- Objective
- Fluorescence
- CCD camera
Low-energy processing

examine in confocal microscope
Low-energy processing

before

after
Low-energy processing

before

after
Low-energy processing

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Low-energy processing

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Low-energy processing
Low-energy processing

before  after
Low-energy processing
Low-energy processing

10 µm
Low-energy processing
Low-energy processing
Low-energy processing

channel

5 µm
Low-energy processing

cavity

channel

5 µm
Low-energy processing
2 nJ/pulse
1 s exposure
Summary

The diagram shows a graph with the x-axis labeled 'rep rate (MHz)' and the y-axis labeled 'E (nJ)'. The graph contains two shaded regions, with one representing 100 nJ and the other representing 1000 nJ, both at 1 MHz.
Summary

The graph shows the relationship between the rep rate (MHz) and the energy (E, nJ) for single-shot disruption effects and cumulative effects. The x-axis represents the rep rate in MHz, while the y-axis represents the energy in nJ. The graph indicates that as the rep rate increases, the energy required for both single-shot and cumulative effects also increases.
Summary

The graph shows the relationship between rep rate (MHz) and energy (nJ) for single-shot disruption and cumulative effects.

- Single-shot disruption is represented by a bar at an energy level of 1000 nJ.
- Cumulative effects have a broader range of energy levels, starting at 100 nJ.

Cell manipulation is indicated on the lower part of the graph.
Summary

The diagram illustrates the relationship between energy (E) in nanojoules (nJ) and repetition rate (MHz) for cell manipulation and device fabrication. The y-axis represents energy levels ranging from 10 to 1000 nJ. The x-axis represents repetition rates ranging from 1 MHz. The diagram is divided into two sections: SINGLE-SHOT DISRUPTION and CUMULATIVE EFFECTS. The bar on the left indicates the energy levels for cell manipulation, while the bar on the right indicates the energy levels for device fabrication at different repetition rates.
Summary

- SINGLE-SHOT DISRUPTION
- CUMULATIVE EFFECTS

- Data storage
- Cell manipulation
- Device fabrication

- E (nJ)
- Rep rate (MHz)
Summary

- **SINGLE-SHOT DISRUPTION**
  - *E* (nJ): Low values
  - Basic science

- **CUMULATIVE EFFECTS**
  - Rep rate (MHz): High values
  - Data storage

- **Cell manipulation**
  - *E* (nJ): Medium values

- **Device fabrication**
  - Rep rate (MHz): Low values

- **He:Ne**
Conclusions

- stellar conditions
- precision micromachining
- exciting new applications
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For a copy of this talk and additional information, see:

http://mazur-wwww.harvard.edu