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Contents

LASER-INDUCED SURFACE NANOSTRUCTURES: JOINT SESSION WITH CONFERENCE 9352

LASER NANOSCALE MATERIALS PROCESSING

LASER DIRECT WRITE

LASER MICROMACHINING OF GLASS: JOINT SESSION WITH CONFERENCE 9355

PROCESSES COMPATIBLE FOR LIFT AND ADDITIVE MANUFACTURING I: JOINT SESSION WITH CONFERENCE 9353

PROCESSING OF PHOTOVOLTAICS

DYNAMICS OF LASER ABLATION

ULTRAFAST LASER MICROMACHINING

SYSTEMS FOR HIGH-PRECISION MANUFACTURING

POSTER SESSION

Authors

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4 Laser Direct Write
Stephan Roth, BLZ Bayerisches Laserzentrum GmbH (Germany)

5 Laser Micromachining in Bulk and Thin Film Materials: Joint Session with Conference 9355
Bo Gu, Bos Photonics (United States)

6 Laser Micromachining of Glass: Joint Session with Conference 9355
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7 Processes Compatible for LIFT and Additive Manufacturing I: Joint Session with Conference 9353
Stephan Roth, BLZ Bayerisches Laserzentrum GmbH (Germany)
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8 Processes Compatible for LIFT and Additive Manufacturing II: Joint Session with Conference 9353
Beat Neuenschwander, Berner Fachhochschule Technik und Informatik (Switzerland)
Henry Helvajian, The Aerospace Corporation (United States)

9 20 Years of LAMOM: Anniversary Session
Jan J. Dubowski, Université de Sherbrooke (Canada)
Stephan Roth, BLZ Bayerisches Laserzentrum GmbH (Germany)

10 Processing of Photovoltaics
Yoshiki Nakata, Osaka University (Japan)

11 Dynamics of Laser Ablation
Gediminas Račiukaitis, Center for Physical Sciences and Technology (Lithuania)

12 Thin-film Processing
Andrei V. Rode, The Australian National University (Australia)

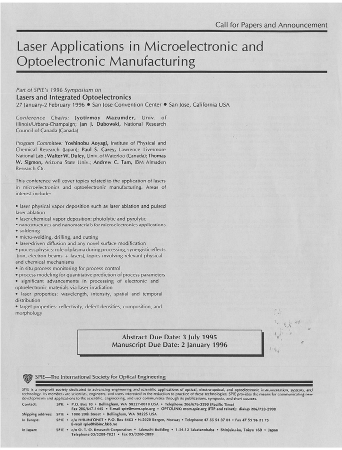
13 Ultrafast Laser Micromachining
Beat Neuenschwander, Berner Fachhochschule Technik und Informatik (Switzerland)

14 Systems for High-precision Manufacturing
Stephan Roth, BLZ Bayerisches Laserzentrum GmbH (Germany)

Introduction

The period from 1984–1994 had seen significantly increased research and development of laser techniques for ablation of solid targets and deposition/epitaxy of thin films. These advancements were, to a large extent, driven by the emerging technology of high-temperature superconducting thin films and the development of highly efficient methods for the fabrication of multicomponent materials enabled by the pulsed laser deposition technique. That period was followed by a significant expansion of laser-based technologies into applications less traditional than those known by the automotive and heavy industries (laser cutting, welding, drilling), such as micro- and non-scale laser machining, and post-processing of solid materials fabricated with conventional techniques.

SPIE Photonics West debuted in San Jose, California, in 1995, and sponsored the first meeting in a series of laser applications for materials processing addressing the growing field of micro- and nano-scale research focused on *Laser-Induced Thin Film Processing* [edited by J. J. Dubowski, Proceedings of SPIE Vol. 2403, (SPIE, Bellingham, WA, 1995)]. The following year, a new meeting on Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) was organized at Photonics West in San Jose [see *Lasers as Tools for Manufacturing of Durable Goods and Microelectronics*, edited by J. J. Dubowski, J. Mazumder, L. R. Migliore, C. Roychoudhuri, R. D. Schaeffer, Proceedings of SPIE Vol. 2703, (SPIE, Bellingham WA, 1996)], which was the beginning of the LAMOM series. Some of the areas of interest listed in the Call for Papers of that meeting included laser vapor deposition and laser ablation. However, LAMOM-I also defined such areas of interest as nanostructures and nanomaterials for micro-electronics, laser-driven surface modification, and process modeling for quantitative description of process parameters. The increasing role of a laser in advancing the field of micromachining and nanotechnology was observed over the next 20 years. The femtosecond laser played an important contribution to these advancements, as highlighted in Dr. Koji Sugioka's presentation in LAMOM-XX's anniversary session.



Call for Papers and Announcement

Laser Applications in Microelectronic and Optoelectronic Manufacturing

Part of SPIE's 1996 Symposium on
Lasers and Integrated Optoelectronics
27 January-2 February 1996 • San Jose Convention Center • San Jose, California USA

Conference Chairs: **Jyotirmoy Mazumder,** Univ. of Illinois/Urbana-Champaign; **Jan J. Dubowski,** National Research Council of Canada (Canada)

Program Committee: **Yoshinobu Aoyagi,** Institute of Physical and Chemical Research (Japan); **Paul S. Carey,** Lawrence Livermore National Lab.; **Walter W. Duley,** Univ. of Waterloo (Canada); **Thomas W. Sigmon,** Arizona State Univ.; **Andrew C. Tam,** IBM Almaden Research Ctr.

This conference will cover topics related to the application of lasers in microelectronics and optoelectronic manufacturing. Areas of interest include:

- laser physical vapor deposition such as laser ablation and pulsed laser ablation
- laser-chemical vapor deposition: photolytic and pyrolytic
- nanostructures and nanomaterials for microelectronics applications
- soldering
- micro-welding, drilling, and cutting
- laser-driven diffusion and any novel surface modification
- process physics: role of plasma during processing, synergistic effects (ion, electron beams + lasers), topics involving relevant physical and chemical mechanisms
- in situ process monitoring for process control
- process modeling for quantitative prediction of process parameters
- significant advancements in processing of electronic and optoelectronic materials via laser irradiation
- laser properties: wavelength, intensity, spatial and temporal distribution
- target properties: reflectivity, defect densities, composition, and morphology

Abstract Due Date: 3 July 1995
Manuscript Due Date: 2 January 1996

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Figure 1: first call for papers for LAMOM conference in 1996

Numerous challenges and opportunities lay ahead for the laser-driven microelectronic and optoelectronic platforms before they could offer attractive solutions, not only in the conventional areas of applications — such as telecommunications or the consumer market — but also in areas such as life sciences, environmental monitoring, or energy. These solutions will become increasingly available as we advance our understanding of the laser-matter interaction, develop advanced methods of controlling the output of a laser, and as we explore thermodynamics of systems far from equilibrium. This theme resonated in another LAMOM-XX anniversary presentation given by Dr. Henry Helvajian.

We are still at the beginning stages of discovering the laser as a tool to fabricate new materials and to provide engineering solutions at nanoscale. For example, 3D printing could be understood not only as a mechanical approach to fabricate micro- or nano-scale objects, but also as a technology of nano-scale manipulation that would provide interlinks required to make fully functional bio-imprinted 3D microstructures.

We wish to thank all the co-chairs, session chairs, program committee members, and colleagues who have helped organize the LAMOM series and who also went a step further, creating "spin-off" conferences which address the exciting field of lasers as tools for exploration and fabrication of otherwise unattainable material architectures. Our special thanks go to the SPIE management for harboring LAMOM and providing a stimulating atmosphere at Photonics West.

Jan J. Dubowski
SPIE Fellow
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On behalf of:

Stephen Roth
Yoshiki Nakata
Beat Neuenschwander
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Laser Applications in Microelectronic and
Optoelectronic Manufacturing (LAMOM) XX
Conference Chairs

Advances in ultrafast laser processing in the last two decades and the future

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The unique characteristics of ultrafast lasers, such as picosecond and femtosecond lasers, have opened up new avenues in materials processing that employ ultrashort pulse widths and extremely high peak intensities. The short pulse width suppresses the formation of a heat-affected zone (HAZ), which is vital for ultrahigh precision fabrication, whereas the high peak intensity allows nonlinear interactions such as multiphoton absorption and tunneling ionization to be induced in transparent materials, which provides versatility in terms of the materials that can be processed. More interestingly, irradiation with tightly focused femtosecond laser pulses inside transparent materials makes three-dimensional (3D) micro- and nanofabrication available due to efficient confinement of the nonlinear interactions within the focal volume.

Materials processing using ultrafast lasers was first reported in 1987 by Srinivasan et al. [1] and Küper and Stuke [2]. They demonstrated the clean ablation of polymethyl methacrylate almost without the formation of HAZ. In 1989, Küper and Stuke also showed that the extremely high peak intensities of ultrafast lasers can induce strong absorption by transparent materials due to multiphoton absorption, enabling high quality machining of the transparent materials [3, 4]. These experiments had a significant impact and the research in this field was rapidly expanded in the 1990s. In addition, development of the chirped-pulse amplification technique in Ti:sapphire regenerative amplifiers [5], which emit energetic femtosecond pulses without inducing damage or undesirable nonlinear effects in the amplification medium, further accelerated fundamental research on ultrafast laser processing. In 1996, Davis et al. [6] and Glezer et al. [7] pioneered the internal modification of transparent materials based on the multiphoton absorption and demonstrated respectively optical waveguide writing and formation of nanovoid arrays inside glass. Currently, internal microfabrication is widely applied to the fabrication of photonic devices and biochips. It was also reported in 2001 that multiphoton absorption improves spatial resolution to exceed the diffraction limit, due to the nonlinearity combined with the threshold effect [8]. One of the major application fields of this feature is two-photon polymerization for the fabrication of 3D micro and nanostructures. In the 2000s, it was determined that ultrafast laser irradiation at intensities near the ablation threshold forms nanoripple structures on various materials with periodicities much shorter than the wavelength [9]. Regular arrays of conical microstructures were also produced on Si by irradiation with an ultrafast laser beam in a halogen atmosphere (e.g., SF_6 or Cl_2) [10]. A robust, stable, and very compact fiber chirped pulse amplifier was also developed in the 2000s [11], which facilitated the application of this research. More recently, a rare-earth-doped laser medium was adopted to realize a compact and high-power ultrafast laser system by diode pumping, although the pulses were much broader than pulses generated by Ti:sapphire systems [12, 13]. In the 2010s, ultrafast laser processing is thus becoming to be used for practical and industrial applications.

Continuous improvement in understanding the physical mechanisms and advances in the development of fabrication techniques as well as laser systems will help accelerate the widespread use of ultrafast laser processing over a broad range of applications, including electronics, optoelectronics, integrated optics and photonics, microfluidics and optofluidics, mechanics, vechicles, tissue engineering, and medical equipment and treatment, etc. The more detailed review of this field is available in ref. [14].

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Locally adjusting material properties via phase change: Demonstrations over the 20 years of LAMOM and a plausible course to advancing the technology further

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Since its invention, lasers have been applied to materials processing with the foremost reason given for its utility is the ability to locally alter materials by inducing a phase change, including the minute changes that upset long or short range order. Consequently, lasers have found practical use in welding, cutting, annealing, shock peening, material compaction, amorphization and crystallization. Over the years many laser control schemes have been developed to reduce the heat affected zone (i.e. HAZ) and the advancement of the femtosecond laser has proven that HAZ can be significantly reduced if the applied energy is abrupt. But it was the development of the all-solid state laser and the supporting optical modulation techniques that permitted the metering of the photon flux with higher finesse than was possible just two decades ago. In the past twenty years, LAMOM has been the appropriate forum for presenting all these discoveries, demonstrations and the new capabilities thus gained. We now chance a glimpse twenty years hence and to the possible challenges that will have to be faced by the laser material processing community. A quick exploration of the forthcoming challenges shows that it is primarily elicited by the material developers and the established success of demonstrating precision processing with lasers. Three primary developments should be noted.

1) There is an increasing trend to develop materials using multiple elements (e.g. high entropy alloys). While these systems have shown to have unique properties for applications, the phase diagram and the spinodal decomposition points are rather complex. 2) There is an increasing trend to develop materials with graded properties. Consequently, this entails either a gradual change in the elemental material distribution or a phase change that is graded accordingly. It is the case that some of these systems are “supersaturated” solid solutions and precipitation of compounds may become an issue if traditional laser processing approaches are applied. 3) Laser processing will have to deliver a desired microstructure more often because so many physical properties depend on this parameter. The microstructure form is not only dependent on the amount of laser energy applied but also on the kinetic processes that are induced within a material by the laser. The laser processing of these new materials will require either maintaining or producing a particular phase. For lasers to be useful in the examples noted, more care will have to be accorded to “guiding” the evolution of the laser activated material (i.e. far from equilibrium) as it approaches a phase transition point. From thermodynamics we know that the phase transition event can be represented by a bifurcation in the reaction coordinate where the material state changes onto one of the many available paths.

The question we address in this seminar is the following. Is there any way to “guide” the material through this phase transition event so that a preselected path is selected? Experimental results show that near a bifurcation point (i.e. threshold point); many of the thermodynamic parameters vary widely. Instabilities set in and the system (laser + material) progresses toward chaos. Intuition would argue that there can be no type of control applied under these conditions, but the very nature of the laser and how it functions serves as an exemplar that control can in fact be applied in chaos. A laser, below pump threshold, has available to it a number of frequencies within the gain medium that it could lase. But by applying a low power seed laser it is possible to “guide” the laser through the threshold event so only a preselected mode (i.e. frequency) lases. A second example might be the use of a seed crystal to grow large crystals from a hot melt (e.g. Czochralski process). In the laser example, a small amount of energy is used to control energy. In the crystal growth example, seed-matter is used to control matter. For the future of laser material processing, we ask if a small amount of energy can be used to control matter transformation events. By analogy we present STED microscopy (stimulated emission depletion microscopy) in which photons are used to suppress molecular fluorescence (2014 Nobel Prize in Chemistry, E. Betzig, S. W. Hell, and W. E. Moerner).