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Laser-based technologies for photonic device integration

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As demand is growing for devices capable of performing new and increased numbers of operations within an ever shrinking physical volume the laser has become an increasingly important tool helping to overcome the limitations of conventional microfabrication technologies. In addition to "classical" applications of lasers such as *via* hole drilling, trimming or pulsed laser deposition of thin films, there have been new developments of laser-based technologies for the fabrication of advanced micro- and nano-devices. Of particular interest for photonic applications is the potential of the laser for the fabrication of integrated and monolithically integrated photonic devices and circuits.

1. Introduction

The constantly growing demand of reduced size devices capable of performing new and increased numbers of operations has created strong research in the area of new materials and new materials processing technologies. Historically, the microelectronic industry was the main driving force behind this trend. Recent developments in fiber optics, wireless communications and multimedia applications have been possible due to the emergence of new technologies for manufacturing of advanced optoelectronic and photonic devices. Those developments have often taken advantage of unique features that lasers offer in device manufacturing – a consequence of tremendous progress in both laser technology and our understanding of the fundamental processes involved in laser-matter interaction.

2. Lasers as manufacturing tools

Advancements in UV laser beam technology, mostly represented by the development of excimer lasers that took place between 1970 and 1980, and the development of high-harmonic high-power IR lasers (*e.g.*, Nd:YAG at 355 and 266 nm) observed from the beginning of 1990s, have resulted in a rapid increase in the use of various laser-based technologies for manufacturing. Fabrication of thin films and precision structuring of materials are the most spectacular examples of applications that have been influenced by these developments. The advantages of the use of lasers for these applications include:
a) flexibility, *i.e.*, the ease with which a laser-based process can be switched from one material to another
b) clean vaporization (only the target material is heated)
c) direct deposition of complex materials (three and more elements in the target)
d) possibility of forming exotic heterostructures, such as ferroelectric and high-temperature superconductors
e) patterning of materials by direct ablation
f) possibility of low-damage 3D shaping of materials using a reactive (dry) etching approach

In addition, short-pulse ($\tau < 10\,\mathrm{ps}$) laser processing of materials is a rapidly growing activity due to its potential in precision micromachining. The significant progress observed in this area over the recent 5–6 years has been achieved due to key developments concerning the fs-pulse laser technology. At the moment, this approach however is relatively expensive and it remains to be demonstrated where it could compete with other laser-based technologies for large-scale production of advanced materials and devices, or where unique features of this technology would justify the high costs of its implementation.

Non-contact processing of materials that can be carried out with any laser-based technology is an attractive feature from the process control viewpoint since it makes it possible to carry out *in-situ* monitoring with variety of tools.

3. Applications of lasers for device fabrication

Numerous high- and medium-power lasers have made a significant contribution to the development of advanced manufacturing technologies. Today, some of the most developed applications that involve lasers as tool in the manufacturing process of microelectronic and optoelectronic devices are:

- Precision ablation/micropatterning (*via* hole drilling for printed circuit boards, resistor/capacitor trimming, wire stripping, ink jet nozzle fabrication)
- Marking, scribing (semiconductor and non-semiconductor wafers, solar panels)
- Sub–μm photolithography (248 nm, 193 nm, 157 nm)
- Annealing
  - excimer (a-Si for flat panel displays)
  - non-excimer (quantum well/dot intermixing for integrated photonics)
- Thin film deposition
  - Pulsed laser deposition (high-Tc superconductors)
  - Laser-CVD, laser-CBE (selective area growth)
- Selective doping of semiconductors (GILD)
- Surface processing (planarization, computer hard disks texturing)
- Microwelding (ceramics, glass)
- 3D microstructures (prototyping, Laser-LIGA, MEMS)
- Surface cleaning (sub–μm debris removal)

- Etching (low-damage structuring)

Many of these applications have been discussed at conferences on Laser Applications in Microelectronic and Optoelectronic Manufacturing over the past 5 years.[1–5] Lasers, in addition to offering novel solutions, often become tools of choice because their application leads to cost-effective solutions.

4. Laser technologies for new materials and devices

Pulsed laser deposition (PLD) is one of the most successful laser technologies that have contributed significantly to the development of new materials and devices. It is a leading approach in fabricating thin films of oxides and, especially, high-temperature superconductors. Numerous proceedings from symposia, conferences and books on this topic were published between 1990 and 1999 and they give a wide-ranging overview of the progress and status in this field.[6–11] It is interesting to note that PLD offers extremely high deposition rates, as well as the ability to control deposition rates at a monolayer level, or less, per pulse. Thus, in addition to manufacturing capabilities, PLD is an important tool in the investigation of growth mechanisms of thin films and formation of material systems that are not attainable with conventional methods of film deposition, *e.g.*[12]

Laser-assisted dry etching (LDE) is an example of laser-based technology that has drawn steadily growing attention. One of the most attractive features of LDE is that it is a direct patterning process, which means that structuring of materials can be achieved without the use of photoresist. In addition, the laser pulse energy (fluence) required for etching in a reactive atmosphere of gasses such as Cl_2 or HBr is much smaller than that normally required during direct laser ablation.[13] Consequently, LDE leads to reduced-damage or damage-free patterning of materials, which is one of the most desirable features in processing of optical components and semiconductor micro- and nano-devices. Complicated patterns are typically achieved by projecting conventional masks made of metallic thin films (*e.g.*, Cr on glass) or a stack of dielectric films. More advanced applications, where utilization of the beam is an important issue, can be realized with phase-shift or diffractive masks designed specifically for a particular application. If fast processing is not critical, the patterning or 3D shaping (laser carving) can be carried with a tightly focused laser beam. The LDE process has the potential of offering cost-effective solutions in the manufacturing of some microelectronic and optoelectronic devices, especially if the microfabrication process does not require lateral resolution better than $\sim 1\,\mu$m. Examples of successful implementation of the LDE technology for device fabrication include patterning of InAlAs/InGaAs high-electron-mobility transistors[14] and GaAs/AlGaAs multiple quantum well circular ring lasers.[15]

Laser-induced quantum well intermixing (Laser-QWI) is a relatively new technology investigated for the fabrication of monolithically integrated photonic devices (MIPD). Individual photonic devices such as semiconductor lasers, waveguides, optical switches and amplifiers require different material architecture, which is realized either with dedicated growth runs or with different bulk materials. An MIPD structure can be fabricated if regions of material with different band-gaps are formed within same wafer. Typically, this can be achieved by implementing growth-related techniques such as molecular beam epitaxy (MBE), chemical beam epitaxy (CBE) or metal-organic vapor phase epitaxy (MOVPE). Two the most popular approaches involve growth/etch/regrowth and growth on patterned substrates. However, it is important to realize that the advanced epitaxial growth is highly complex and any new step such as re-growing on a partially etched wafer adds even more complexity to that process. The controlled intermixing between the barrier and quantum well material – a process referred to as quantum well intermixing (QWI) is a post-growth process that makes possible the fabrication of material with regions of different band-gap materials. The possibility of using lasers to achieve QWI has been investigated in recent years.[16,17] The method of laser-induced QWI (laser-QWI) has the potential for rapid fabrication of novel microstructures (prototyping) due to the flexibility in matching laser parameters required for efficient processing of a particular microstructure. It has been demonstrated that laser-QWI can be successfully used for selective area band-gap tuning (in excess of 140 meV) in $Si/Si_{1-x}Ge_x$ QW microstructures.[18] Application of this technology to III-V material systems, such as InGaAs/InGaAsP QWs, offers the possibility of fabricating QWI material with continuously changing band-gap along one direction. This feature may find application in the fabrication of broad-spectrum light emitting diodes. A multicolor array of telecommunication lasers, operating between 1.4 and 1.5 μm, is an example of probably the most advanced MIPD device fabricated thus far by laser-QWI.[19]

5. Conclusion

Laser-based technologies play a constantly increasing role in the manufacturing process of advanced microelectronic and optoelectronic devices. The key features that drive these trends are: a) the precision in micro-scale machining of variety of materials, b) the uniqueness of the process which allows new solutions, c) compatibility with the many characterization techniques due to the non-contact character of processing with lasers. Micro-hole drilling and trimming of resistors and capacitors demonstrate the most successful applications of laser technologies in microelectronics. Advanced optoelectronic and photonic devices require both a manufacturing precision applied to the variety of materials and processing that could help realizing a device integration concept. Especially demanding in this respect is the concept of a monolithic integration of photonic devices. This challenging area has been addressed with limited success by conventional microfabrication techniques and, consequently, it has become one of the most attractive experimental topics in the investigation of new laser-based technologies for manufacturing of advanced devices. The results indicate that this approach has the potential for the writing of photonic materials - where “writing” signifies the geometrical microshaping as well as 3D modification of the material properties. A multicolor array of telecommunication lasers, operating between 1.4 and 1. 5 μm, is an example of probably the most advanced monolithically integrated photonic device fabricated thus far with a laser-based technology.

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