LASER 3D-STRUCTURED MATERIALS

Saulius Juodkazis and Hiroaki Misawa

Research Institute for Electronic Science, Hokkaido University, Sapporo 001-0021, Japan

Introduction

Femtosecond (fs) laser pulses allow to perform large-scale three-dimensional (3D) micro-/nano-structuring of materials with typical feature sizes of 0.1-1 μm. These characteristics make fs-laser microfabrication a highly suitable technique for the fabrication of 3D photonic crystals (PhCs) and their templates. Here, we discuss physical principles underlying the 3D laser structuring techniques: holographic [1] and direct laser writing [2]. We also describe application of these techniques for the fabrication of 3D PhCs, and demonstrate some recent results achieved in this field as well as discuss mechanisms of light-matter interaction taking place during 3D material processing.

Results and Discussion

The PhCs are expected to play an important role in photonics and optoelectronics due to their capabilities to control the emission and propagation of light via the photonic band gap (PBG) effects. These capabilities can be best exploited in the 3D PhC. However, the direct large scale 3D microfabrication of PhCs from semiconductor materials is expensive and does not yet provide required resolution; hence, more efficient fabrication strategies are highly required. Some of these strategies are based on microfabrication of PhC templates using more feasible techniques and materials. The templates can be subsequently infiltrated by other materials having higher refractive index, e.g., silicon [3]. Also, the photo-polymerized templates can be coated by metals using electroless deposition [4], which forms an uniform layer of 50 - 200 nm nm of metal (Ni, Ag, Au, etc.) over the frame of the structure. Such metal coated photonic structures perform as edge filters with a controllable spectral position of the edge, typically, in IR spectral region.

The structures are “seen” by light as metallic since only the skin-depth of tens-of-nanometers is necessary to determine their optical response, while the spectral position of the edge filter is determined by the geometry of the polymeric template [4]. These structures can be used for spintronic (coated by Ni, Fe, Co) and plasmonic (Ag, Au, Cu) applications. We demonstrate that mechanical properties, e.g., the bulk modulus, of the photo-polymerized structures can be flexibly tuned to the required range by controlling the volume fraction and cross-linking of the polymers [5].

Creation of high pressure and temperature conditions inside the bulk materials by tightly focused laser pulses can be used to reach dynamic shock-compression pressures reaching and exceeding 1 TPa [6] (much higher than those attainable in a static diamond anvil cell). The example of a transmission electron microscopy (TEM) image of the void recorded inside crystalline sapphire is shown in Fig. 1. The application potential of the shock-processed materials is discussed as well as a possibility to create new high density phases of nano-crystallites using this

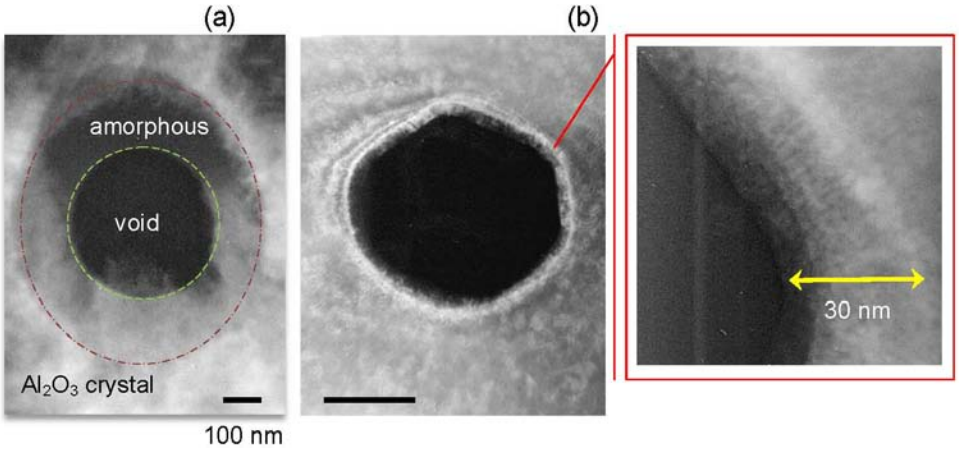

Fig. 1 TEM top-views of the void recorded inside sapphire by a single laser pulse (a) and by two pulses (b). Pulse energy at the focus was 220 nJ (a) and 180 nJ (b), respectively; the pulse duration 150 fs at 800 nm central wave-length. Pulse propagation was along c–axis (perpendicular to the plane of view). Inset in (b) is a close up of the rim.

"photonic" anvil cell, where the 3D enclosure of the micro-explosion creates unique ultra-fast thermal quenching conditions favorable for a recovery of new materials when ultra-short laser pulses are implemented.

The micro-explosion induced by a single laser pulse creates the void and amorphous phase around it [6]. Here, we demonstrate that double exposure at the same focusing conditions creates a rim which is poly-crystalline (see, inset of Fig. 1b). The entire amorphous region is absent due to grinding step of sample preparation for TEM observation. This was typical for several regions recorded at different pulse energies in two tested samples. The amorphous part was only recovered intact in the case of single pulse exposure. It had a distinct few-atomic-layers-wide edge of transition between the amorphous and crystalline parts. Formation of the nano-crystallites inside the amorphous region without void formation we have reported earlier in the case of multi-pulse exposure inside sapphire. Here, the re-growth of the rim in the case of double pulse exposure shows a possibility of solid-state epitaxial regrowth. Interestingly, when the void is present after the first laser pulse, the epitaxial regrowth takes place from the densified amorphous phase.

These unusual crystal formation conditions deserve further studies. Possibly, new crystalline phases and unusual composite materials could be formed from the thermally activated regrowth of the shock-amorphised and densified phase of material in the bulk without any contact with surrounding atmosphere.

Support via a Grant-in-Aid from the Ministry of Education, Science, Sports, and Culture of Japan No. 19360322 is highly acknowledged.

References

1. T. Kondo, S. Juodkazis, V. Mizeikis, S. Matsuo, and H. Misawa, Fabrication of three-dimensional periodic microstructures in photoresist SU-8 by phase-controlled holographic lithography, *New J. Phys.* **8** (2006) 250 - 256.
2. K. K. Seet, V. Mizeikis, S. Matsuo, S. Juodkazis, and H. Misawa, Three-dimensional spiral - architecture photonic crystals obtained by direct laser writing, *Adv. Mat.* **17** (2005) 541 - 545.
3. K. K. Seet, V. Mizeikis, K. Kannari, S. Juodkazis, H. Misawa, N. Tetreault, and S. John, Templating and replication of spiral photonic crystals for silicon photonics, *J. Selec. Topics Quant Electr. (IEEE)* **14** (2008) 1064 - 1073.
4. V. Mizeikis, S. Juodkazis, R. Tarozaite, J. Juodkazyte, K. Juodkazis, and H. Misawa, Fabrication and properties of metalo-dielectric photonic crystal structures for infrared spectral region, *Opt. Express* **15** (2007) 8454 - 8464.
5. S. Juodkazis, V. Mizeikis, K. K. Seet, H. Misawa, and U. G. K. Wegst, Mechanical properties and tuning of three-dimensional polymeric photonic crystals, *Appl. Phys. Lett.* **91** (2007) 241904-1/3.
6. S. Juodkazis, K. Nishimura, S. Tanaka, H. Misawa, E. E. Gamaly, B. Luther-Davies, L. Hallo, P. Nicolai, and V. Tikhonchuk, Laser-induced microexplosion confined in the bulk of a sapphire crystal: evidence of multimegabar pressures, *Phys. Rev. Lett.* **96** (2006) 166101-1/4.