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Laser microfabrication of photonic crystal structures on silicon wafers

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ABSTRACT

A new, versatile approach, applicable to virtually all substrate compositions on laser precision microfabrication of silicon wafers to achieve long-range ordering of colloidal crystals is proposed and demonstrated. In the absence of any surface pattern, the colloid spheres assemble in a randomly packed fashion. However, the presence of a surface pattern induces an ordered packing of the spheres on the lands with hexagonal packing. The colloidal crystal order can be controlled by choosing suitable spatial period of the laser micro-machined template.

Keywords: laser microfabrication, photonic crystals

1. INTRODUCTION

Photonic crystals have caught great attention for their applications in novel optoelectronic devices with reduced size, high level of integration and faster processing.¹⁻³ Closely packed monodisperse microspheres, i.e., colloidal crystals, provide a promising approach to fabricate photonic crystals at low cost and meet large scale requirements of mass production. Several techniques have been reported to control the growth of the colloidal crystals in the literature, which include patterned substrates (grooves and pyramid shaped pits)⁴ and electrically driven deposition⁵. However, the techniques reported so far are applicable to specific substrates and microspheres only. Advanced photonic circuits will need complex architectures, sufficient number of spheres to ensure the presence of a photonic band gap effect in all directions, as well as electrically addressable materials. The development of a universal method to realize photonic crystals is crucial for their practical applications such as switches, mirrors, filters, polarizers, waveguides, lasers or superprisms.⁶

In this article, we demonstrate that the deposition of colloidal crystals on textured Si substrates, fabricated using laser precision microfabrication method, is promising to induce a long-range order in the crystal spheres.

2. EXPERIMENTAL DETAILS

Figure 1 schematically illustrates the work station used in this study for the laser micro-machining of silicon wafers. A UV laser beam from a frequency-tripled diode-pumped solid-state Nd:YAG laser (355 nm, pulse width ~40 ns) was used. The laser beam was focused onto the sample surface using a microscope objective mounted on a Z-translation stage. The samples were fixed on a holder, which was mounted on a computer-controlled X-Y translation stage. The resolution of the translation stages was 1 μm . A Si wafer of 380 μm in thickness was used as the target material to be machined. The morphology of the specimens was observed mainly with optical microscopy and WYKO interferometric microscope (NT-2000).

The colloidal spheres used in this study were silica microspheres with an average diameter of 3.14 μm in water with solid concentration of 10 wt%.

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Fig. 1. Schematic illustration of a laser micro-machining system

3. RESULTS AND DISCUSSION

3.1. Silicon template fabrication using laser micro-machining

For template fabrication, periodic arrays of microchannels⁵ and pits⁷ are very important for photonic crystal structures. Many microfabrication techniques reported in the literature are applicable to either specific target materials or simple patterns. However, laser microfabrication technique is applicable to virtually all material compositions and capable of fabricating complex features through CAD/CAM programming. In our experiments, the laser beam was focused onto the sample surface in ambient with a minimum spot diameter of about 8 μm . The sample was moved at a scanning rate of 2.5 mm/s in the fabrication process. Figure 2 shows the laser-machined microchannels on Si at different laser intensities with a repetition rate of 1 kHz under the best focusing condition. For the three microchannels starting from the top in Fig. 2, the corresponding laser intensities were 1.6×10^5 , 3.2×10^5 , and $4.8 \times 10^5 \text{ W/cm}^2$, respectively. By careful selection of laser machining parameters, different sizes (widths and depths) of the microchannels and the spacing between them can be fabricated on the Si surface.

Fig. 2. Microchannels on Si fabricated by laser micro-machining at different laser intensities under the best focusing condition. For microchannels starting from the top, the corresponding laser intensities were 1.6×10^5 , 3.2×10^5 , and $4.8 \times 10^5 \text{ W/cm}^2$, respectively.

3.2. Colloidal crystal growth on laser micro-machined Si wafer

For colloidal crystal deposition, a uniform microchannel array was fabricated on Si wafer. An example of a template after laser micro-machining is shown in Fig. 3. Although debris could be produced during the laser micro-machining process, it was removed using diluted etchant HF solution before the growth of colloidal crystal. The wafer was further cleaned in deionized water using ultrasonic bath, then hydrophilized in a H_2O_2 (35%): NH_3 (25%): H_2O (1:1:5) bath for 3 hours, and rinsed in deionized water. The sedimentation was carried out by self-assembly of a diluted suspension of monodisperse silica spheres (1 wt%), following the procedures reported in Ref. 8. All the operations were carried out at room temperature.

Fig. 3. Laser microfabricated Si template for colloidal crystal deposition: (a) morphology, and (b) height profile.

3.2.1. One-dimensional colloidal crystal growth

By judicious selection of the parameters for laser micro-machining, it is possible to fabricate microchannels to match the sphere sizes, thus a periodic one-dimensional colloidal crystal can be formed. Figure 4 shows a one-dimensional periodic colloidal crystal embedded in a microchannel.

Fig. 4. One-dimensional colloidal crystal inside the microchannel on a Si wafer.

Fig. 5. Two-dimensional colloidal crystal inside the microchannel on a Si wafer.

3.2.2. Two-dimensional colloidal crystal growth

Similar to the one-dimensional colloidal crystal fabrication inside the microchannel, it is also possible to fabricate two-dimensional colloidal crystals inside the microchannels if the widths of the microchannels commensurate with the

hexagonal packing and the depths of the microchannels are deep enough to accommodate the spheres. Figure 5 shows a two-dimensional periodic colloidal crystal embedded in a microchannel. In this case, two arrays of spheres were embedded inside one microchannel.

Besides the possibility of colloidal crystal growth inside the microchannels, it is also possible to realize colloidal crystal growth on the lands of Si wafers. In the absence of any surface pattern, the colloid spheres assembled themselves in a random fashion, as shown in Fig. 6(a). Here, the domains with the numbers of spheres from 1 to 17 randomly spread over the Si surface and order starts to emerge for domains with larger sphere numbers. A two-dimensional sphere array in Fig. 6(b) clearly indicates its high order of periodicity and the tendency for further growth. The spheres are hexagonal-packed. Due to the spontaneous growth of sphere domains which is evident in Fig. 6(a), the orientations of individual domains are different, which makes the formation of uniform hexagonal-packed colloidal crystal over a large area very difficult.

Fig. 6. Two-dimensional self-assembled colloidal crystals on silicon wafers at initial stages: (a) isolated domains with small number of spheres, and (b) growth of colloidal crystal with hexagonal packing.

Fig. 7. Two-dimensional colloidal crystals with hexagonal packing on structured Si wafers of different land widths: (a) 10 μm , and (b) 25 μm .

However, the presence of a surface pattern induced an ordered packing of the spheres on the lands with ideal hexagonal ordered packing. Figure 7 shows hexagonal ordered packing of the first monolayer on templates with different land widths of 10 and 25 μm .

3.2.3. Three-dimensional colloidal crystal growth

The effectiveness of a template in the fabrication of a three-dimensional colloidal structure is also obvious from Fig. 8. In the absence of any surface pattern, the colloid spheres assembled themselves in a randomly packed fashion, as shown in Fig. 8(a). However, the presence of a surface pattern induced an ordered packing of the spheres on the lands (Fig. 8(b)) with hexagonal ordered packing which can be found in the inserted figure. It was found that the hexagonal packing could be achieved only when the land width corresponds to the width of an integer number of rows of spheres. Since the laser fabricated microchannels serve as the confinement to help the self-assembly of the microspheres in which the attractive forces between the spheres maintain themselves in contact on the surface. When this condition is not met, the packing of the spheres could not be periodic, resulting in gaps in the coverage.

Fig. 8. Three-dimensional self-assembled colloidal crystals on silicon wafers: (a) without template, and (b) with template.

4. SUMMARY

A new, versatile method for controlling the growth of large-scale colloidal crystals, applicable virtually to all substrates using laser precision machining technique is demonstrated. The arrangements of the colloidal crystals can be controlled by fabricating suitable spatial periodic structure on a template. Ordered one-, two-, three-dimensional colloidal crystals have been successfully fabricated. High precision laser micro-machining technique is capable of designing and fabricating complicated features through CAD/CAM programming. The techniques to fabricate these complex and delicate features also have potential applications in microfluidic systems, biomedical devices and nonlinear optical devices, in addition to their applications in photonic bandgap structures.

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