Advanced large scale colloidal lithography for sub-100 nm direct and indirect structuring: application to silicon and metals

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ABSTRACT

By combining Reactive Ion Etching (RIE), metal evaporation technique and polystyrene (PS) nanosphere lithography, we demonstrate fabrication of sub 100 nm 2D structures on silicon substrates. In this work, we concentrated on the self-organization of PS beads (diameters ~ 100 nm) dispersed on silicon substrate. Afterwards, the effect of dry etching by RIE-O₂ on a monolayer and bilayers of PS beads was also studied. Our goal was to decrease the size of the beads from 100 to 40 nm and to change its form from simple to a complex structure. In the final step, by using evaporation technique we deposited metal on monolayer structure. After lift-off we obtained a metal film with holes and nanotriangles. Finally, as prepared monolayers of PS beads and patterned metal film containing holes and nanotriangles were used as etching masks to realize different sub-100 nm silicon structures such as nanospheres, nanocones, nanoholes, nanotriangles, nanodots.

Keywords: nanosphere lithography, nanosphere, nanocones, nanoholes, nanotriangles, nanostarts.

1 INTRODUCTION

Development of large scale methods of fabrication is one of the most active fields in nanotechnology. There are numerous methods of synthesising nanomaterials, one of them is the traditionally used photolithography technique [1-2]. However, this method is becoming extremely complex, therefore other nanolithography methods are becoming strong competitors due to their cost effectiveness and they are easy to use. In particular, nano-sphere Lithography (NSL) is a great technique to fabricate structures at a large scale [3-10] as compared to other lithographic methods. This process is a bottom approach for fabricating well-ordered structures down to the nanoscale regime. In this study, by combining Reactive Ion Etching (RIE) and polystyrene (PS) nanosphere lithography we demonstrate using a simple, inexpensive and rapid procedure to realize sub 100 nm 2D structure in or on silicon substrates.

2 RESULTS AND DISCUSSION

In this work, we optimized the self-organization of PS beads of diameters of 100 nm on silicon substrates, as for larger diameter beads, we observed that the deposited particles are very sensitive to different physico-chemical parameters [11-12]. Colloidal concentration and the nature of the solvent were the two important parameters which affect the self-organization of the beads. The optimization of these parameters allowed us to produce large-scale colloidal 2D templates. Initially we used only water as a solvent, however, it did not cover the entire surface due to hydrophobicity. Hence, we decided to use a solution of 50% water and 50% ethanol. The use of this solvent mixture resulted in well dispersed and ordered structures. Afterwards, the effect of dry etching on a monolayer of PS beads was studied. Silicon substrates with PS beads on them were directly and indirectly etched. Different sub-100 nm structures have been obtained. A schematic of the overall process is shown in Fig. 1.
Figure 1: Schematic of the process for fabricating sub-100 nm structures using direct and indirect structuring colloidal lithography methods.

On the first step we directly etched the structure by using PS beads as a mask [13-14]. In this case, we obtained half nanosphere of silicon having a diameter of roughly 80 nm. A reduction of the diameter of the PS beads from 100 nm to 94 nm was observed for an etching time of 19 s. SF\textsubscript{6}/O\textsubscript{2} at power of 90W was chosen to etch the silicon wafer anisotropically. This gas mixture provides good selectivity between silicon and the polystyrene mask. The depth of the silicon master template can be controlled in this step by controlling the SF\textsubscript{6}/O\textsubscript{2} etching time. After etching, the polystyrene spheres were removed from the silicon substrate by RIE-O\textsubscript{2} during a time period of 2 min. Finally, we obtained silicon nanostructures produced by direct etching by using PS beads as a mask as shown in Fig. 2.

We also tried to decrease the diameter of PS beads (100nm) before etching. Our goal was to obtain sub-50nm silicon structures. The size of the beads was further lowered by using oxygen plasma treatment for 10s. This resulted in smaller size nanospheres (diameter 75nm). The diameter of the polystyrene beads can be controlled by adjusting the oxygen plasma etching time. By using plasma O\textsubscript{2} we varied the diameter of the beads from 100 nm to 75 nm (Fig. 3 (b)). A reduction of the silicon structures size down to 42 nm (using PS beads of diameter 75nm) has also been observed as shown in Fig. 3(c) and (d). Etching time used was 19 s for O\textsubscript{2} and SF\textsubscript{6}. The PS spheres were removed from the substrate by O\textsubscript{2} plasma during 2 min.

Figure 2: Direct nanostructuring (a) SEM image of a monolayer PS beads ( b) master 30°tilted SEM views.
Next, we also tried indirect etching. The structures were obtained using hexagonally ordered dot arrays of metal formed from by metal evaporation technique using a single colloidal mask. A 15 nm thick Cr film was directionally evaporated onto the silicon substrate followed by lift-off which was done by removing the beads by O\textsubscript{2} plasma during a time period of 1 hour. This produces nanodot arrays of metal on the silicon substrate having a diameter of 20 nm as shown on Fig. 4(b). We used this Cr nanodots mask as an etching mask to realize nanocones of silicon having a height of 60 nm and a diameter (base) of 20 nm as shown in Fig. 4(c).

The size of the PS beads was reduced by O\textsubscript{2}-RIE. A reduction of the diameter of the PS beads from 100 nm to 54 nm was observed for an etching time of 30s using an O\textsubscript{2} plasma (Fig.5(b)). This served as a lift-off template for the fabrication of a 15 nm thick Cr hole mask on top of the silicon substrate (Fig.5(c)). The PS beads were then removed by O\textsubscript{2} plasma (6 sccm, 90W) during 30 min. This mask of Cr containing was used on silicon substrate to realize holes in silicon having a height of 100 nm and a diameter of 100 nm. The diameter of the silicon holes was increased from 76 to 100nm as shown in Fig.5(d). Etching time was 19 s using O\textsubscript{2} and SF\textsubscript{6} plasma.
3 CONCLUSION

In summary, we demonstrated a simple, inexpensive and rapid procedure to produce sub-100 nm silicon and metallic structures. The technique relies on large-scale organization of colloidal 2D monocrystals. Polystyrene beads (PS) on silicon surface were used as etching masks to realize different sub-100 nm silicon structures such as nanospheres, nanocones, nanoholes, nanotriangles and finally nanodots. Such structures can be used as a mold for nanomastering. Further perspectives include assisted self-assembly as recently demonstrated for mesoscopic beads [15]. This kind of study can also be extended to a variety of substrates of different materials paving the way to large-scale patterning related applications such as enhanced (bio)sensing or light harvesting to only name a few.

REFERENCES