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Imprint Lithography with Sub-10 nm Feature Size and High Throughput

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Nanoimprint lithography, a high-throughput, low-cost, nonconventional lithographic method proposed and demonstrated recently, has been developed and investigated. Nanoimprint lithography has demonstrated 10 nm feature size, 40 nm pitch, vertical and smooth sidewalls, and nearly 90° corners. Further experimental study indicates that the ultimate resolution of nanoimprint lithography could be sub-10 nm, the imprint process is repeatable, and the mold is durable. In addition, uniformity over a 15 mm by 18 mm area was demonstrated and the uniformity area can be much larger if a better designed press is used. Nanoimprint lithography over a non-flat surface has also been achieved. Finally, nanoimprint lithography has been successfully used for fabricating nanoscale photodetectors, silicon quantum-dot, quantum-wire, and ring transistors.

1. INTRODUCTION

One of the major road blocks in developing nanostructures is the lack of a low-cost, high-throughput manufacturing technology. This problem is particularly serious for structures with a size below 0.1 μm. Numerous technologies are under development to solve this problem [1-6]. Recently, we proposed and demonstrated another possible solution to nanostructure manufacturing, namely a new nonconventional lithographic method called nanoimprint lithography [7]. The key advantage of this lithographic technique is the ability to pattern sub-10 nm structures over a large area with a high-throughput and low-cost. Therefore, nanoimprint lithography is a manufacturing technology. In this paper, we will present recent progress in developing this lithographic technique.

2. PRINCIPLE OF IMPRINT LITHOGRAPHY

Nanoimprint lithography has two basic steps as shown in Fig. 1. The first is the imprint step in which a mold with nanostructures on its surface is pressed into a thin resist cast on a substrate, followed by removal of the mold. This step duplicates the nanostructures on the mold in the resist film. In other words, the imprint step creates a thickness contrast pattern in the resist. The second step is the pattern transfer where an anisotropic etching process, such as reactive ion etching (RIE), is used to remove the residual resist in the compressed area. This step transfers the thickness contrast pattern into the entire resist.

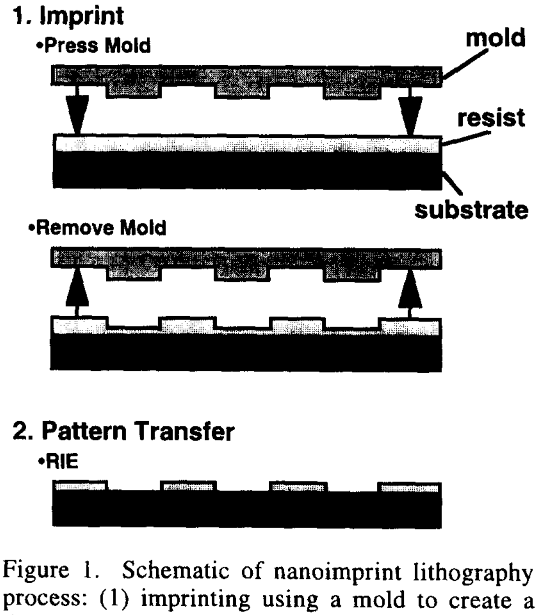

Figure 1. Schematic of nanoimprint lithography process: (1) imprinting using a mold to create a thickness contrast in a resist, and (2) pattern transfer using anisotropic etching to remove residue resist in the compressed areas.

During the imprint step, the resist is heated to a temperature above its glass transition temperature. At that temperature, the resist, which is a thermoplastic, becomes a viscous liquid and can flow, and therefore can be readily deformed into the shape of the mold. The resist's viscosity decreases as the temperature increases.

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Unlike conventional lithography methods, imprint lithography itself does not use any energetic beams. Therefore, nanoimprint lithography's resolution is not limited by the effects of wave diffraction, scattering and interference in a resist, and backscattering from a substrate. Furthermore, imprint lithography is fundamentally different from stamping using a monolayer of self-assembled molecules [8]. Imprint lithography is more of a physical process than a chemical process. It is conceivable that in the future, the mold used in imprint lithography can be made using a high-resolution but low-throughput lithography, and then imprint lithography can be used for low-cost mass production of nanostructures.

3. MOLDS, RESISTS, AND PROCESS CONDITIONS

In our experiments, silicon dioxide and silicon were used as the mold materials. Certainly other materials such as metals and ceramics could also be used. The mold was patterned with dots and lines with a minimum lateral feature size of 10 nm using electron beam lithography and RIE. Polymethyl methacrylate (PMMA) was our primary resist, although we have had success with AZ and Shipley novlak resin based resists as well. The PMMA showed excellent properties for imprint lithography. PMMA has a small thermal expansion coefficient of $\sim 5\text{x}10^{-5}$ per °C and a small pressure shrinkage coefficient of $\sim 3.8\ \text{x}10^{-7}$ per PSI [9]. Mold release agents were used to reduce the resist adhesion to the mold. The pressure and temperature for the imprint process depend on the resist used. For PMMA, which has a glass-transition temperature of about 105 °C, the imprint temperature used in our experiments is typically between 140 and 180 °C, and the pressure is from 600 to 1900 PSI. For that temperature and pressure range, the PMMA thermal shrinkage is less than 0.8 percent and the pressure shrinkage is less than 0.07 percent (a smaller volume at a higher pressure), therefore the shape of the PMMA should conform with that of the mold. To reduce air bubbles, the imprint process should be done in a vacuum. The gas used in the RIE pattern transfer, which also depends on the resist used, was oxygen for PMMA.

Typically, the intrusion of the mold is from 40 nm to 200 nm and the aspect ratio for the smallest mold features is 4:1. The thickness of the resist is from 50 to 250 nm. The resist was kept thicker than the mold intrusion to prevent the mold from contacting the substrate. This is essential to prolong the lifetime of the mold.

4. RESULTS AND DISCUSSION

4.1. Imprint

Various nanostructures have been imprinted into PMMA including 10 nm diameter holes with a 40 nm period and 15 nm wide trenches with a 60 nm period. Figure 2 shows a scanning electron micrograph of imprinted PMMA strips before RIE. The strips, which are 70 nm wide and 200 nm deep, have very smooth (a roughness less than 3 nm) and vertical sidewalls, and nearly 90° corners. The spacing between the strips was intentionally made large to allow for examination of the sidewalls. The terminal face of the PMMA strips is not from cleaving, but directly from imprinting.

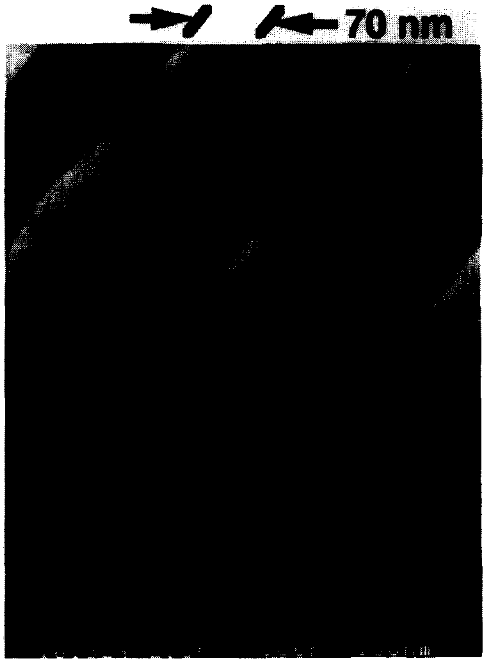

Figure 2. SEM micrograph of a perspective view of strips formed into a PMMA film by imprint. The strips are 70 nm wide and 200 nm tall, have a high aspect ratio, a surface roughness less than 3 nm, and nearly perfect 90° corners.

4.2. Effect of RIE on Lateral Dimension of Imprinted PMMA Patterns

To examine the effects of the oxygen RIE pattern transfer step on removing the residue resist in the compressed areas and on changing the lateral dimension of the PMMA features, the PMMA resist structures created by imprint lithography were used as the template for a lift-off of metals. The RIE process was done with a power of 400 W and a pressure of 90 mtorr using oxygen gas. In the lift-off process, 3 nm Ti and 10 nm Au were first deposited onto the entire sample, and then the metal on the PMMA surface was removed when the PMMA was dissolved in acetone. We compared the SEM image of the imprinted PMMA template before the oxygen RIE transfer step to that of the metal patterns after the lift-off. Figure 3 shows 10 nm diameter dots with a 40 nm period and figure 4 shows 15 nm linewidth and 60 nm pitch metal gratings lifted off from a PMMA template fabricated using imprint lithography. Comparing these metal features with the imprinted PMMA templates before RIE, there is no noticeable difference between the lift-off metal structures and the PMMA patterns. This indicates that during the oxygen RIE process, the compressed PMMA areas were completely removed while the lateral size of the PMMA features experienced little change.

4.3. Estimation of Ultimate Lithography Resolution

The minimum feature size of imprint lithography shown in the previous section is limited by the minimum feature size on the mold. Further experiments have shown that a few nanometer variation on the mold can be successfully transferred into the PMMA side walls [10]. This means that if the polymer has sufficient mechanical strength, imprint lithography should be able to produce sub-10 nm feature size in the polymer. Details of 10 nm feature sizes imprinted into PMMA will be presented elsewhere [11].

4.4. Mold Durability, Process Repeatability and Uniformity

Imprint lithography process repeatability and mold durability are two key issues in making imprint lithography a manufacturing technology. We have used the same mold to imprint PMMA over 30 times and examined the mold and the PMMA profile every time. We did not observe any noticeable changes in either the PMMA profile or the mold. Although over 30 times imprinting is hardly considered a repeatability and durability test, we should expect the process to have a good repeatability and the mold to be durable. This is because mold release agents gave a good release, the PMMA held above its glass-transition temperature is very soft, and the mold intrusion does not touch the substrate. We have found that the imprint process is uniform over an area of 15 mm by 18 mm. In addition, imprint lithography has been shown to work over nonflat surfaces [10].

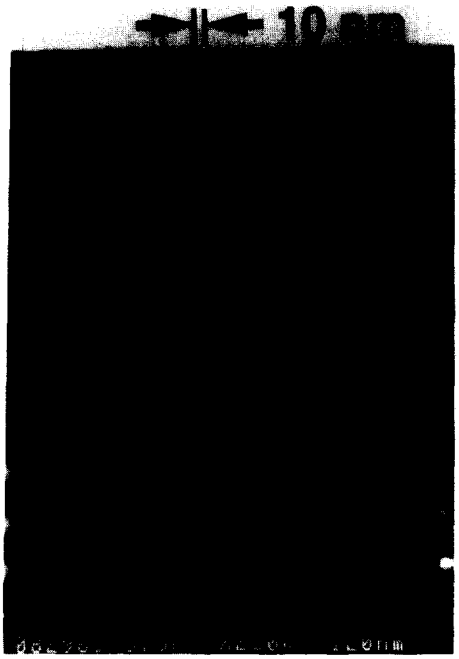

Figure 3. SEM micrograph of 10 nm diameter and 40 nm period metal dots fabricated by imprint lithography and a lift-off process.

4.5 Fabrication of Nanodevices Using Imprint Lithography

In parallel with developing imprint lithography, we have used imprint lithography to fabricate nanodevices. One example is the MSM photodetectors fabricated using imprint lithography and optical lithography. In addition, we fabricated quantum-wire, quantum-dot, and ring transistors in silicon using imprint lithography and RIE of silicon. Quantum effects and single electron effects were observed in these devices which will be reported elsewhere [12].

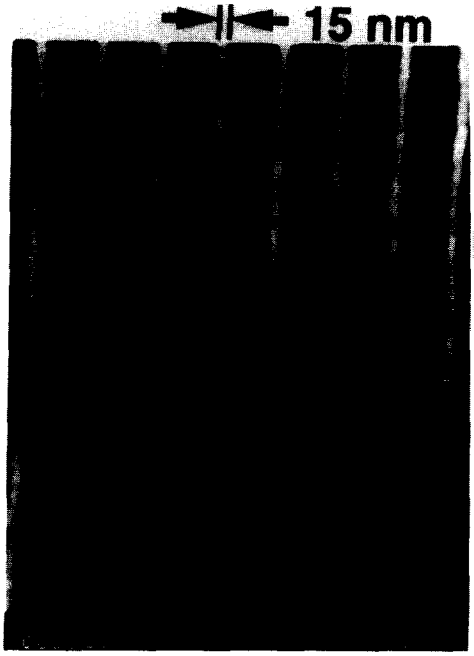

Figure 4. SEM micrograph of 15 nm wide and 60 nm period metal lines fabricated by imprint lithography and a lift-off process.

5. FUTURE IMPROVEMENT AND CHALLENGES

No doubt, imprint lithography is still at its infancy and further investigations are needed to make it a manufacturing technology. Currently, we have not fully characterized and fully understood imprint lithography. The press we used is rather primitive. The surface sticking problem, which has been greatly reduced in our current work, still needs more improvement. Molding conditions are not optimized yet. The effect of thermal expansion on lithography resolution has not been studied. Molds with smaller feature size are needed to explore the ultimate resolution. We also need to prove that the area for a single imprint can be much larger than one square inch. Finally, multilevel alignment is one of the biggest challenges.

6. CONCLUSION

We have demonstrated that imprint lithography can achieve 10 nm feature size and 40 nm pitch, vertical and smooth sidewalls, nearly 90 degree corners, and uniformity over an area of 15 mm by 18 mm in a single imprint. Our study indicates that imprint lithography can potentially have sub-10 nm resolution over a large area much greater than one square inch, and can have good repeatability and durability. Therefore, imprint lithography has a high-throughput and a low-cost. With further development, imprint lithography can become the technology for manufacturing nanostructures, and can have strong impact to many areas such as integrated circuits, biology, and chemistry. No doubt, the current study of imprint lithography is preliminary. Yet, the future of the imprint lithography seems very promising.

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