Imprint of sub-25 nm vias and trenches in polymers

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(Received 17 July 1995; accepted for publication 14 September 1995)

A nanoimprint process that presses a mold into a thin thermoplastic polymer film on a substrate to create vias and trenches with a minimum size of 25 nm and a depth of 100 nm in the polymer has been demonstrated. Furthermore, the imprint process has been used as a lithography process to fabricate sub-25 nm diameter metal dot arrays of a 100 nm period in a lift-off process. It was found that the nanostructures imprinted in the polymers conform completely with the geometry of the mold. At present, the imprinted size is limited by the size of the mold being used; with a suitable mold, the imprint process should mold sub-10 nm structures with a high aspect ratio in polymers. The nanoimprint process offers a low cost method for mass producing sub-25 nm structures and has the potential to become a key nanolithography method for future manufacturing of integrated circuits and integrated optics. © *1995 American Institute of Physics.*

There is a great need to develop low-cost technologies for mass producing sub-50 nm structures since such technology can bring enormous impact to many areas of engineering and science. Not only will the future of semiconductor integrated circuits be affected, but also the commercialization of many innovative devices which are far superior to current devices is hinged on the possibility of such technology. Scanning electron beam lithography has demonstrated 10 nm lithography resolution.[1,2] But, using it for mass production of sub-50 nm structures seems economically impractical due to inherent low throughput in a serial processing tool. X-ray lithography, which can have a high throughput, has demonstrated 50 nm lithography resolution,[3] but the x-ray lithography tools are rather expensive and its ability for mass producing sub-25 nm structures is yet to be seen. Furthermore, lithographies based on scanning probes have produced 10 nm structures in a very thin layer of materials. However, the practicality of such lithographies as a manufacturing tool is hard to judge at this point.

Imprint technology using compression molding of thermoplastic polymers is a low cost mass manufacturing technology and has been around for several decades. Features with sizes greater than 1 μm have been routinely imprinted in plastics. Compact disks which are based on imprinting of polycarbonate are one example. Other examples are imprinted polymethylmethacrylate (PMMA) structures with a feature size on the order of 10 μm (Ref. 4) and molded polyester patterns with feature dimensions of several tens of microns.[5] However, it has never been tested whether sub-25 nm structures with high aspect ratios can be imprinted into polymers. Furthermore, the possibility of replacing the conventional lithographies used in semiconductor integrated circuit manufacturing with imprint technology was never raised.

In this paper, we will demonstrate that imprint technology can produce vias and trenches with 25 nm minimum feature size and 100 nm depth in thin polymers, has the potential to produce 10 nm structures, and can be used as the nanolithography process in integrated circuit fabrication.

As shown in Fig. 1, in the nanoimprint process, a mold is pressed into a thin thermoplastic polymer film on a substrate that is heated above its glass transition temperature. Above that temperature the polymer behaves as a viscous liquid and can flow under a pressure, thereby conforming to the mold. The mold can be made of metals, dielectrics, or semiconductors. In our experiments, silicon dioxide molds were used exclusively. The mold consists of a thick layer of silicon dioxide on a silicon substrate. The mold is patterned with dots and lines with a minimum lateral feature size of 25 nm using electron beam lithography and etched 250 nm into the SiO_2 layer using reactive ion etching (RIE).

The polymer used for the nanoimprint experiment is a 55 nm thick PMMA film spun on a silicon wafer. PMMA was chosen for several reasons. First, PMMA does not adhere well to the SiO_2 mold due to its hydrophilic surface. Good mold release properties are essential for fabricating nanoscale features. Second, the shrinkage of PMMA is less than 0.5% for large changes of temperature and pressure.[6]

During the imprinting, both the mold and PMMA were first heated to a temperature of 200 °C which is higher than the glass transition temperature of PMMA, 105 °C.[4] Then the mold was compressed against the sample and held there until the temperature dropped below the PMMA's glass transition temperature. Various pressures have been tested. It was found that the optimum pressure is about 1900 psi. At that pressure, the pattern on the mold can be fully transferred into the PMMA. At much lower pressures, the pattern cannot be transferred into the PMMA completely. Using higher pressure caused both the substrate and the mold to bow inward, resulting in contact between the PMMA and concave regions of the SiO_2 mold. Also, at significantly higher pressures the nanoscale SiO_2 features on the mold were found to break off.

Figure 2 shows a scanning electron microscope (SEM) image of 25 nm diameter dots with a 120 nm period imprinted into a PMMA film. We have not been able to detect any variation between mold feature size and imprinted feature size due to shrinkage of PMMA. In addition to the nanometer features, the mold also has features as large as tens of microns which have been imprinted nicely into the PMMA as well.

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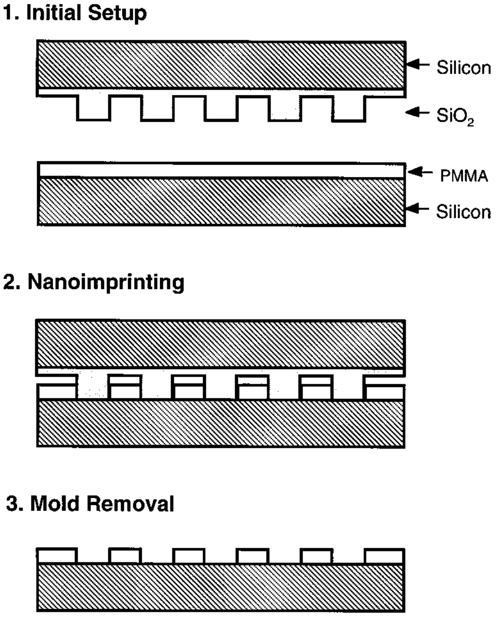

FIG. 1. Schematic of nanoimprint lithography process.

Figure 3 shows the cross section of a 60 nm wide trench 100 nm deep imprinted into a PMMA film. The initial PMMA film was 55 nm thick, but molding displaced PMMA resulting in a thicker PMMA film outside of the vias and trenches. Moreover, PMMA lines with 50 nm width, 175 nm spacing and 150 nm height have been imprinted, but fell over due to poor adhesion to the silicon substrate. Nonetheless, SEM examination shows that the sidewalls of imprinted PMMA lines conform with the mold and are therefore very straight. From our observations, it is clear that the feature size imprinted is limited by our mold size. From the texture of the imprinted PMMA, it appears that 10 nm features can be imprinted.

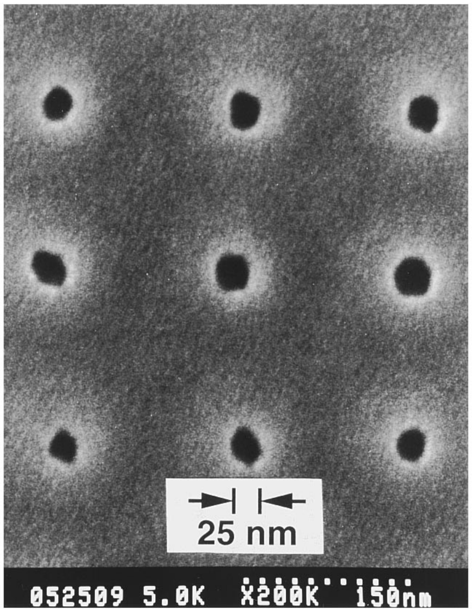

FIG. 2. SEM micrograph of dot pattern imprinted into PMMA. The dots have a 25 nm diameter and 120 nm period.

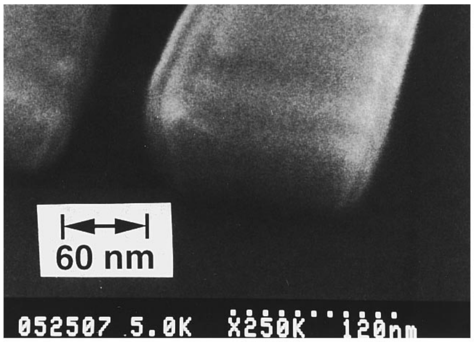

FIG. 3. SEM micrograph of a 60 nm wide trench imprinted into PMMA. The PMMA lines are 100 nm tall.

The PMMA film patterned with nanoimprint technology was used to replace the nanolithography in the fabrication of nanoscale metal features through a lift-off technique. After nanoimprint of PMMA, O_2 RIE was used to remove 10 nm of the PMMA to make sure the bottoms of the imprinted via and trench regions were free of any PMMA residue. Next, 5 nm of titanium and 15 nm of gold were evaporated onto the wafers. The wafers were then soaked in acetone to lift off metals which were on the remaining PMMA. Figure 4 shows an SEM micrograph of 25 nm diameter Ti/Au dots with a 120 nm period which were fabricated using nanoimprint lithography. Dot arrays with 100 nm period have also been fabricated, but have a 5 nm variation in dot size due to variations of the mold.

The use of nanoimprint as a lithography process is very significant. First, as discussed previously, there is no other low-cost and high throughput lithography technology with the resolution of the nanoimprint lithography. Second, nanoimprint lithography will not have the backscattering and

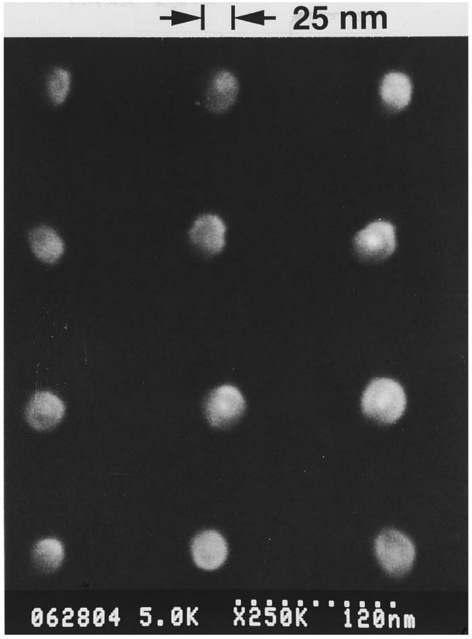

FIG. 4. SEM micrograph of Ti/Au dot pattern on a silicon substrate fabricated using nanoimprint lithography and a lift-off process. The dots have a 25 nm diameter and 120 nm period.

interference problems encountered in other lithographies which degrade the resolution. Therefore, nanoimprint lithography is suitable for nanolithography on high atomic number material substrates. We believe that with a proper selection of the polymer and mold materials and an optimization of the pressing conditions, the sticking and defect problems associated with the traditional contact printing can be avoided, making the nanoimprint lithography a viable manufacturing technology.

In summary, we have demonstrated a nanoimprinting technology that can imprint sub-25 nm vias and trenches in a PMMA film using nanoimprint lithography with a SiO_2 mold. Nanoimprint has replaced lithography to lift off arrays of 25 nm diameter Ti/Au dots. The nanoimprint process should be able to produce 10 nm features with high aspect ratios and provide a unique low cost technology in mass producing sub-25 nm structures. Finally, nanoimprint lithography has the potential to be used as a key nanolithography process in future integrated circuits and integrated optics.

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