# Nanoimprint Mold Manufacturing with Focused Ion Beam

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## ABSTRACT

Nanoimprint lithography (NIL) is an emerging low cost technique for reproducing sub-45 nm pattern in various applications; however, manufacturing the mold for nanoimprint has been a key challenge in expense and resolution. Focused Ion Beams (FIB) has been known for high resolution but low throughput work in TEM sample preparation, and its extremely well defined 7 nm diameter $Ga^+$ beam make it also a suitable tool for mold manufacturing for nanoimprint, which enable mass reproduction of the FIB work. We find features down to 30 nm can be made with FIB, the actual line width to beam diameter ratio is around 5-6 for an aspect ratio less than 2. A higher than 2 aspect ratio may result in re-deposition of the milled out substrate. Re-deposition can be reduced by a shorter dwell time or gas-assisted etching. There is a trade off between dwell time and feature integrity. Best results can be achieved with high hardness materials; the lack of conductivity for some materials can be remedied with s thin layer of Pt coating on the surface before FIB jobs.

***Keywords***: nanoimprint, focused ion beam, lithography

## 1 INTRODUCTION

According to ITRS roadmap [1], feasible lithography under 45 nm half-pitch has not yet been demonstrated. Present immersion lithography may extend the limit to 45 nm [2], beyond that new solutions need to be found. There are efforts to improve the image quality of traditional lithography [3], and experiments on Extreme Ultraviolet (EUV) [4]. EUV faces three major issues: the available fluence of present UV source is only one-fifth of that needed, the lack of durable high reflectivity mirror, and no suitable material for mask. The estimated cost for EUV mask is roughly ten times higher than what it is now. For sub-45 nm regime, some major foundries are turning their attention to high and low voltage multiple electron beam direct write technique [5], or e-beam projection lithography [6]. The former one requires mass data processing capability; the latter one is slower in speed.

In recent years, publications on Nanoimprint [7-13] have been increasing at an impressive pace, mainly because it is more affordable for academic institution. However, mass production of nanoimprint product is yet to realize mainly due to the much lower throughput than the 193 nm immersion lithography, together with other technical issues and financial concerns. The most important tool in Nanoimprint is the mold, of which resolution, durability, and cost are the three major issues. Present mold for nanoimprint are made by traditional 193 nm I-line lithography for larger than 100 nm mold, and e-beam lithography for resolution down to 10 nm. The materials for mold are Si, quartz, $SiO_2$, and diamond.

Ion beam possesses certain advantage over electron beam: higher energy, and less scattering effect. Focused Ion Bean (FIB) [14-17] represents an alternative new thinking in fast prototype mold manufacturing for nanoimprint. Traditionally, FIB is used in TEM sample preparation for foundries so they can examine in great detail the vertical cross section of the results of processes like diffusion, etching, and deposition. Mask repair is also achieved by ion beam assisted deposition for broken wires and defects. FIB demonstrates excellent capability in beam control (7 nm diameter $Ga^+$ Gaussian beam), stage repetition accuracy, and both etch and deposition capability in a same chamber. Most important of all, FIB is a direct carving process. It does not require development and lift-off of photoresist as in e-beam to complete the pattern transfer, therefore relieve itself of the possible failure in these process [18]. The major issue of FIB today is its low throughput.

The combination of FIB and Nanoimprint may bring new opportunities for these two techniques. The low throughput of FIB can be improved by the repeated process of Nanoimprint, and the high energy ion beam in FIB provide in theory much better resolution than e-beam machine due to its higher energy, and higher throughput because it does not need development of the photoresist.

To apply FIB in Nanoimprint mold brings about complicated and related new issues like: dwell time, critical feature size, pattern area, pattern fill factor, aspect ratio, re-deposition, beam size, etch rate, deposition dose, mold material conductivity, and mold material hardness. We shall discuss the first three issues here with experimental results to illuminate findings on them.

## 2 MOLD MANUFACTURING WITH FIB

### 2.1 Effects of Dwell Time

The FIB machine we use is from SII Nanotechnology Inc. model SMI3050, which can adjust ion beam current density automatically as we change the beam size, pattern size, and the dwell time according to pre-set etching rate of the materials. The default dwell time is 100µs. As the dwell time is turned lower, the ion beam dose is increased proportionally. A shorter dwell time means the ion beam stays in a pixel of a bitmap pattern shorter, and makes the total pattern longer to complete because the beam has to raster scan the pattern so many times to achieve the designated depth. This usually means more FIB time and usage fee cost. A shorter dwell time also means less milled out material on each pixel, thus less re-deposition. It also means less charge accumulation, because the beam is shifted to the next pixel and allows time for the charge to disperse. However, there exists an optimum dwell time for each pattern. A dwell time too short results in distortion of the pattern.

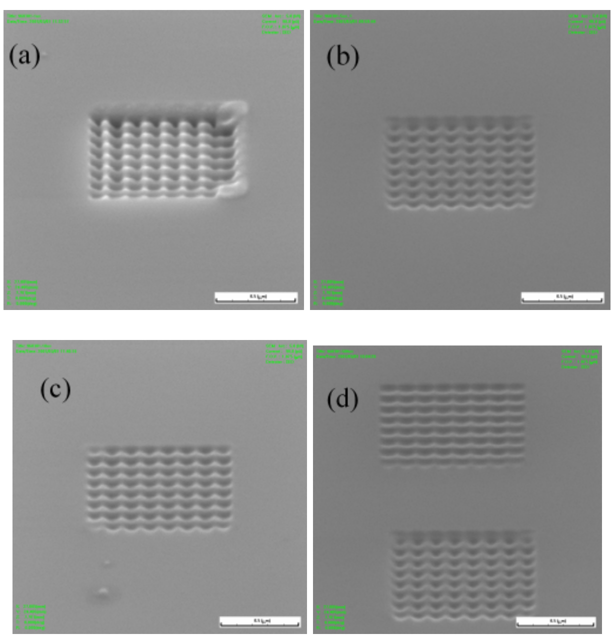


Fig. 1 SEM pictures of the effects of different dwell time, (a): 1 µs dwell time, this pattern takes 12 minutes and 29 seconds to complete. (b) 5µs dwell time, this pattern takes 3 minutes and 54 seconds to complete, (c) 10µs dwell time, this pattern takes 2 minutes and 48 seconds to complete, and (d) 500µs dwell time pattern on top, and 5µs pattern at the bottom. The 500µs dwell time pattern takes 1 minute and 29 seconds to complete.

The patterns in fig. 1 are made with the "View" beam, which is 7 nm in beam diameter, and a Field Of View (FOV) at 24 µm, which means the each pixel equals to 30 nm. Fig. 1 shows the effects of dwell time variations from 1µs to 500µs on a test pattern consists of 8x8 dots, each dot is composed of 2x2 pixels. The pre-set depth for the dots is 120 nm.

We can see from fig. 1 that the pattern carved at 1µs dwell time has much obvious features carved, but the walls between the dots are inclined at an angle. The 5µs pattern has symmetrical walls between dots, but the features are less clear. The 10 and 500µs patters appear to be shallower than the 5µs sample. Since the FIB fee is calculated by the beam time used, the optimum dwell time in this particular case would be 5µs, for higher dwell time may save FIB fee, but the pattern may not be usable. Dwell time lower than 5µs results in distortion of the pattern.

### 2.2 Effects of Critical Feature Size

Fig. 2 (a) to (c) illustrates the effect of critical feature size at a fixed dwell time of 100µs on a highly conductive Si substrate. Their respective critical feature sizes are (a): 5µm, (b): 0.5µm, and (c): 100 nm. We can see the (a) and (b) patterns are reproduced very well, while the (c) pattern shows inclined walls of re-deposition, which is the effect of charge accumulation that deflects the subsequent ion beam.

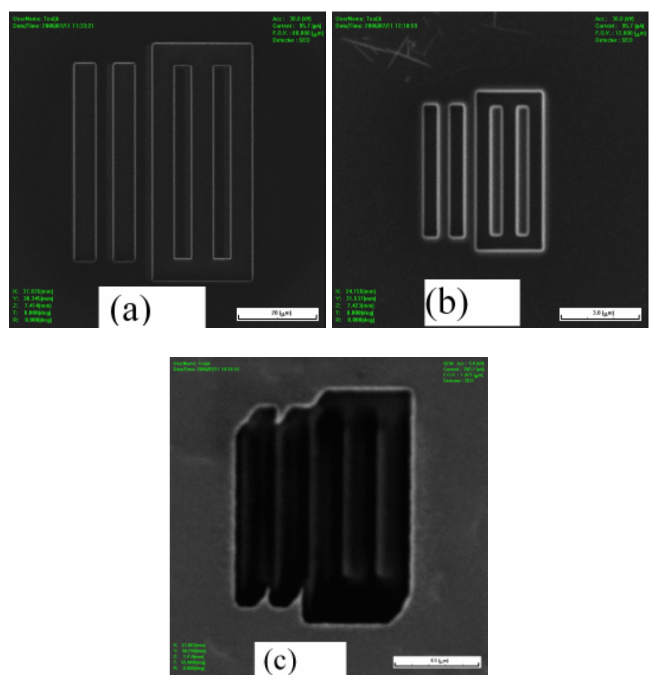

Fig. 2 The effects of critical feature size. (a): top view of concave and convex patter on Si surface. The critical feature is 5μm, and aspect ratio set to less than 1. (b): critical feature is 0.5μm, and (c): critical feature is 100 nm.

## 2.3 Large Area Mold Fabrication

Preparing a mold for nanoimprint with FIB is different from making TEM samples. Uniformity of mold over large area is essential, which means a smooth surface on every trough carved is necessary, therefore bitmap type operation is preferred over manual operation. A pattern must be drawn first then image onto the FOV to decide the actual critical feature size.

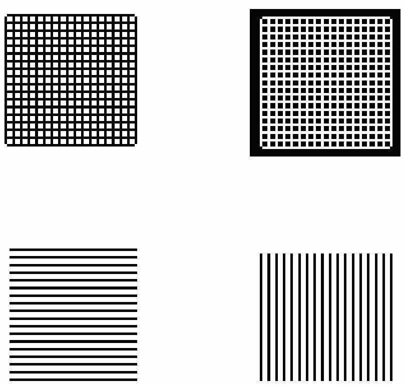

Fig. 3 The bitmap pattern used in producing the mold in the following experiment. Each sub-pattern is composed of 20 lines, each line is composed of 2 pixels, and the spacing between the lines is 2 pixels.

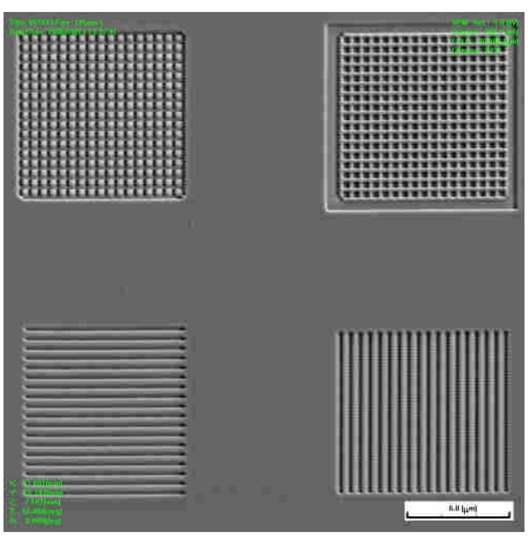

Fig. 4 The FIB result with scale bar 6μm. Each line width is about 50 nm.

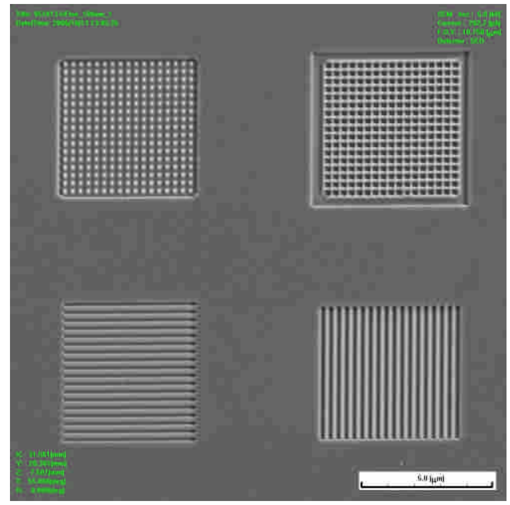

Fig. 5 The FIB result with scale bar 5μm. Each line width is about 30 nm.

The machine we use has 800 pixel maximum resolutions. If a BMP file is equivalent to 24 μm FOV, then each pixel represent 24 μm/800=30 nm. Fig. 3 is an example of bitmap pattern drawn in a commercial software, and fig. 4 and fig. 5 show results of this bitmap pattern carved with FIB onto a highly doped 2 inch 0.005Ω-cm <111> N-type Si wafer. The scale bar of fig. 4 is 6μm, which means each line or dots in fig. 4 is about 50 nm. The scale bar of fig. 5 is 5 μm, which means each line or dot in fig. 5 is about 30 nm. In each etching, the aspect ratio is set to the same value of 1 by changing the etching depth. All were etch with ultra-fine beam of 6 nm beam diameter.

## 3 NANOIMPRINT

Fig. 6 is the nanoimprint result of the 30 nm mold in fig. 5. This is done with EVG-620 hot-embossing nanoimprint machine on a PMMA surface spin-coated on a Si substrate. The temperature is about 160 ℃ at about 1000 N for 3 minutes.

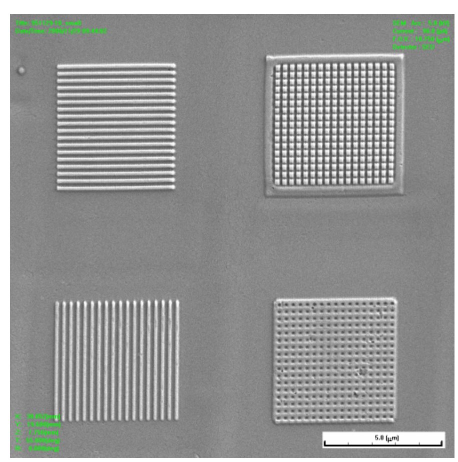

Fig. 6 The nanoimprint result of the 30 nm mold in fig. 5. This is done with EVG-620 hot-embossing nanoimprint machine on a PMMA surface spin-coated on a Si substrate. The temperature is about 160 ℃ at about 1000 N for 3 minutes.

## 4 CONCLUSION

Making nanoimprint mold with FIB is a much simpler process than e-beam lithography, and also much faster. A pattern of 10x10 μm can be done within hours if the process is successful and ready for nanoimprint immediately. The smallest resolution achieved so far is 30 nm, below that re-deposition of milled out substance becomes an issue. The re-deposition can be removed by gas assisted etching if it is available. Due to ion scattering effect, the average line width to beam ratio is around 5-6 for 7 nm diameter beam. FIB can easily produce features around 50 nm. When 30 nm features is desired, a dwell time less than 10 μs is more suitable, or gas-enhanced etching is preferred. FIB results are best when aspect ratio is set to less than 2, from considerations on re-deposition and mold integrity. There have been attempts to achieve high aspect ratio pattern directly in nanoimprint process with high aspect ratio mold, however, experiments show these mold are prone to damage. Anisotropic RIE can produce holes with aspect ratio higher than 70 like those used in DRAM circuit for capacitors. Same consideration goes for low residual layer thickness, which can be resolved in well controlled RIE process. Therefore it is unnecessary to try to obtain high aspect ratio in FIB stage for mold production.

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