Review Article

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Optimized Ordered Nanoprinting Using Focused Ion Beam

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Abstract

Focused ion beam (FIB) is receiving great attention in nanopatterning due to its advantages such as direct milling and deposition. Like conventional lithography methods, dose is still the determining factor of pattern conformity in FIB. However, dose is also determined by many parameters such as ion beam current, pixel size and number of pixels of the bitmap file. In this work, we studied the effect of above parameters on dose per unit area, and thus on the pattern conformity. It was found that a dose approximately of 7.5-8.6 pC/μm^2 or a bitmap file corresponding to 4000-5000 pixels/μm^2 at a beam current of 30 pA is reasonable in order to obtain well-separated nanohole arrays. Although direct pattern designing on FIB working field yields better conformity, it is not practical for large scale patterning. Finally, a relatively larger scale nanoholes arrays with diameter and spacing of 100 nm was achieved by using a dose of 8.6 pC/μm^2. This work offers a few guidelines for nanopatterning on silicon substrate for photonic applications.

Keywords: Focused Ion Beam, Nanoholes, Silicon

Introduction

The nanoholes are commonly used in the characterization of biological molecules, and most recent application is in DNA sequencing [1]. The control and reproducibility of nanometer size holes are difficult, and complicated procedures [2-4]. A reliable control over the holes size and shape is quite tough. In this paper, we have tried to achieve a reliable control over the hole by changing parameters and studying their effect. The current, diameter, number of pixels and scan method are changed individually, and their effect is investigated. After studying their effect and interrelating with best possible parameters, a 100nm diameter size holes are repeatedly fabricated to confirm reproducibility.

Nanofabrication is a fabrication of tiny structures with size less than 100nm in at least one dimension. For machining nanostructures, various techniques like electron beam, FIB, X-ray, deep UV and atomic force microscopy (AFM) are used in conjunction with other lithography and etching method.

FIB technique has gained much importance recently [5,6]. FIB can be used to make directly microstructures without using masks and highly complicated pattern transfer techniques. There is no restriction on geometry and material used and advantage of feature high resolution [7]. However, the major problem in FIB is the throughput that is not high. The speed is low due to direct writing.

To model a complete FIB hole milling process is difficult, due to that once there is an opening made by FIB on the substrate, there will be a beam loss when partial of ion beam reaches the opening. Therefore, it is not easy to say that when this will happen and how big or small the opening will be. The depth and the diameter of the hole, and the material of the substrate all change case by case. The two sputtering and redeposition modeling introduced simulate groove, dent, or non-through-hole FIB process, where no need to consider the beam loss or through-hole material loss.

The controlled FIB process refers that if the FIB milling parameters and the mill-off volume are known of the submicron hole, then we can compute the milling time to control the process. Also, if we know the submicron hole size and the desired nanohole size, then we can compute.

Experimental Results

A. Lens Alignment

Like using all kinds of microscopy tools, the first basic step that should be taken when patterning using FIB is focusing and lens alignment. A poor focusing and lens alignment leads to poor quality pattern while good focusing and lens alignment leads to better quality pattern, as shown in (Figure 1), where holes were not straight and perpendicular to the substrate surface when lens was not well aligned (top arrays) while hole pattern were much more straight and perpendicular to the surface when lens was well aligned.

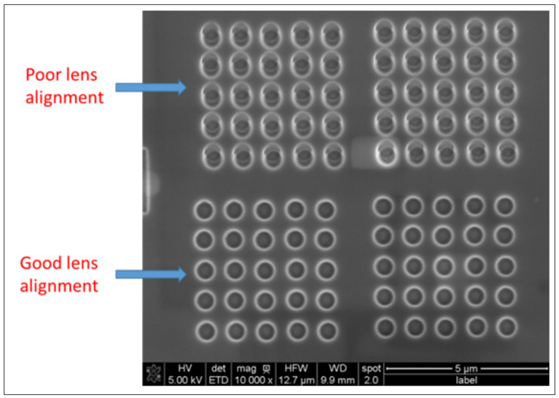

Figure 1: Lens alignment effect on pattering conformity

B. Effect of Current on Patterning Conformity

While uniformity can be easily obtained using FIB, conformity, defined as the deviation between the designed and experimentally obtained values of hole diameter, hole depth and, and side wall angle, are determined by many aspects. We investigated the effect of current on the conformity of nanohole patterning. (Figure 2), shows the SEM images of two sets of nanohole arrays obtained by using two different current 30 pA and 49 pA, respectively. In both patterns, the pixel value of the bitmap file used was 744^2, designed depth of holes was 100 nm and designed diameter and spacing of holes were both 200 nm. It can be clearly observed from the images that when applied current was 30 pA hole diameter was closer to designed value while milling of hole walls were more significant when applied current was 49 pA. However, we did not change or optimize a number of pixels for each current. When the current increases (decreases), the spot size or radius of the Gaussian beam also increases (decreases) (Figure 3a and b). Accordingly, a number of pixels within the spot size should also be adjusted to make sure that total dose used in both cases are the same, which was not done in this part (Dose and pixel are discussed in the following sections). Therefore, the results obtained from the (Figure 2) could be somewhat misleading and should be carefully used. In our later work, the current used was fixed at 30 pA unless mentioned.

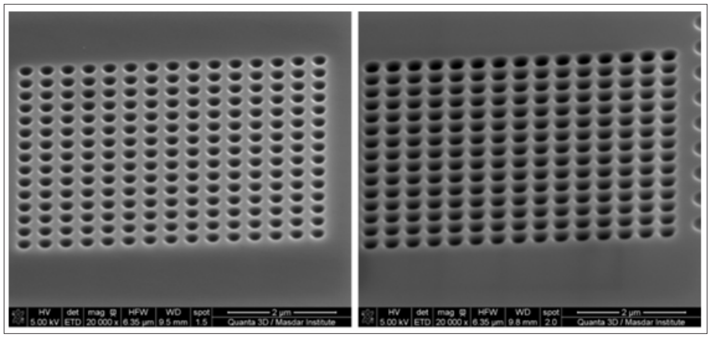

Figure 2: Current effect on the conformity of nanohole arrays. Applied current was (a) 30 pA and (b) 49 pA. Designed hole depth was 100 nm; and designed diameter and spacing of holes were both 200 nm. The bitmap file sued has a number of pixels of 744^2. The SEM images were taken at a tilt angle of 52˚

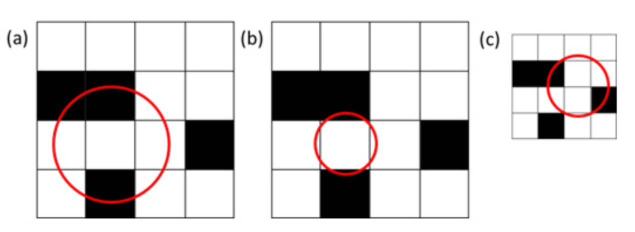

Figure 3: Schematic of the spot size of the ion beam (red circle) and individual pixel size (black and white squares) of a bitmap file used for patterning. Theoretically, white pixels are milled away while black pixels remain untouched. However, the mismatch between the spot and pixel size leads to overbilling. a. Spot size is larger than the pixel size, leading to over-milling. b. Decreased spot size (due to decreased current) and fixed pixel size (same bitmap file), leading to less over-milling. c. Unchanged spot size while pixel size is decreased by simply zooming in the bitmap file, which again leads to over-milling

C. Effect of Pixel Size (In a Bitmap File) on Pattern Conformity

Bitmap files are often used as a "mask" in FIB patterning. Unlike the case of other lithography techniques which uses a physical mask, each pixel of the bitmap file acts as mask generally and theoretically, white pixels represent the physical area that needs to be milled way while black pixels represent the area that remains the constant. However, the spot size or Gaussian diameter of the ion beam, which is determined by the ionic current discussed in the above section, requires the size of pixels in the bitmap file to match the spot size. If the spot size is larger than the pixel size (Figure 3a), over-milling takes palace. In the worst case, if there are many pixels within the spot size, repeated milling occurs, and the result will be catastrophic. The current and thus the spot size is fixed. Therefore, bitmap file is determining parameter together with milling time. If the same bitmap file is repeatedly used for different patterns with, e.g. different hole diameter, the conformity of patterns obtained after milling may be more or less affected depending on the Dose used on a unit surface area, which is discussed in the following section.

D. Consequence of Using The Same Bitmap File for Patterns with Different Dimensions

It may be a common practice (mistake) to use the same bitmap file for similar patterns but with different dimensions. (Figure 4) shows the SEM images of nanohole arrays (no holes obtained in the first one) with designed diameter and spacing of 50 nm, 100 nm, 200 nm, and 400 nm, respectively, obtained by using the same bitmap file with 744*744 pixels. The number of holes in all patterns was 15*15, and designed hole depth *h* was 50 nm. That means total dose used for each pattern was the same while the surface area of each pattern was increasing in sequence: 1.5*1.5 µm^2, 3*3 µm^2, 6*6 µm^2, and 12*12 µm^2, respectively. During patterning, it was observed that the time needed for each pattern turned out to be the same, around 36 s for each and 4*36 for all, which also indicates dose is determined only by a number of pixels and time when current remains constant. As can be seen, in the first image (D = 50 nm) all the surface area within the pattern was milled away while nanopillars instead of nanoholes were obtained in the second pattern (D = 100 nm). The hole boundaries in third (D = 200 nm) and fourth (D = 400 nm) patterns were clearly visible, with the fourth having much better conformity than the rest. This should not is misunderstood, in any case, that the larger the hole size, the better the conformity.

Instead, it should be explained by the dose or pixels per unit area. Dose per unit area is given by:

$$\text{Dose} = \frac{It}{A} \quad (1)$$

Moreover, pixels per unit area is given by:

$$Px = \frac{744^2}{A} \quad (2)$$

Where I is the milling current, and t is the time needed for milling a pattern with surface area of A, 744^2 is the number of total pixels of the bitmap file. (Figure 5) gives the dose and pixels per unit area of each pattern in (Figure 4). As shown, decreasing dose or pixels per unit area led to the increasing conformity in (Figure 4). Also, according values given on the curves, in order to get a better conformity of hole arrays with a depth of 50 nm, the does and pixels per unit area should be less than 7.5 pC/µm² and 3844 pixles/µm².

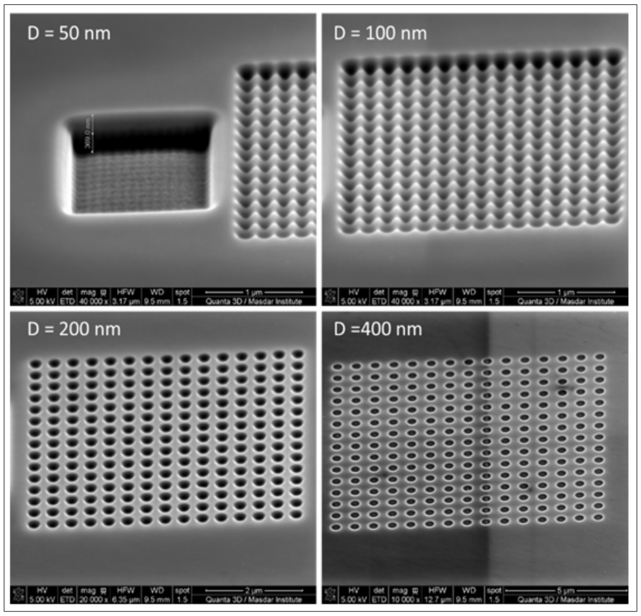

Figure 4: The consequence of using same bitmap file (744*744 pixels) for patterns with different dimensions. The hole diameter of four patterns is 50, 100, 200, and 400 nm, respectively. The conformity is increased with increasing pattern dimension, due to the decreased dose per unit area as given in (Figure 3). Designed hole depth was all 50 nm while actual hole diameter differs significantly

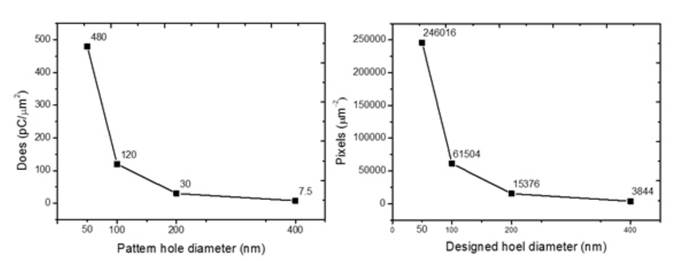

Figure 5: Dose (a) and pixels (b) per unit area of four patterns with different hole diameter in (Figure 3). Since the same bitmap file and thus, the same amount of total dose was used, dose or pixels per unit area decreased with increasing surface area, leading to better conformity as shown in (Figure 3)

E. Using Different Bitmap Files for a Pattern Design

We also used different files with a different number of pixels to further investigate the effect of pixels and dose per unit area on the pattern conformity. Unlike the above cases, where pattern size was wrongly controlled by zooming in and out the same bitmap file, that led to failure in conformity of smaller hole demotions. We kept constant the pattern dimension and used two different bitmap files respectively with 1488^2 and 372^2 pixels obtained by increasing and reducing the number of pixels of the original bitmap file using the resize function of the painting tool. (Figure 6) shows the SEM images of two sets of nanohole arrays obtained using the two files mentioned. Defined depth of holes and diameter were 50 nm and 200 nm, respectively. As can be seen, holes were well separated when the bitmap file with fewer pixels was used (bottom pattern) while over-milling of hole walls was evident in the top pattern that had 4^2 times the pixels and does of the bottom pattern. This conformity of bottom pattern is similar to the pattern 4 in Fig 5 where pixels and does per unit area was less.

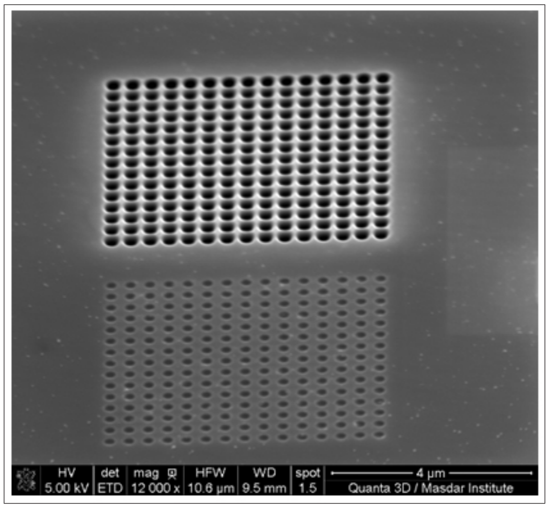

Figure 6: Top pattern was obtained by using a bitmap file with 1488^2 pixels (50% expansion of the bitmap file with 744^2 used in Figure 2) while the bottom pattern was obtained by using a file with 372^2 pixels (50% shrinkage of the same file)

F. Dose control by changing hole depth or time

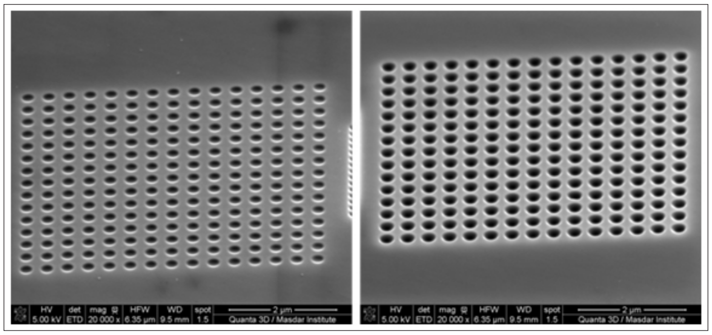

Figure 7: Does control by changing the designed hole depth. Nanohole arrays with designed hole depth of 50 nm (a) 100 nm (b). Designed hole diameter and spacing were 200 nm

In the previous section, we discussed how the bitmap file used affected the dose and thus resulting conformity of patterns. In this section how dose can be controlled by simply changing the designed depth of holes are discussed. (Figure 7) shows the SEM images of two sets of nanohole arrays with designed hole depth of 50 nm and 100 nm, respectively, while other parameters were the same. As the designed hole diameter increased, conformity decreased with a pattern having hole diameter significantly larger than designed value (right pattern). It is because when designed hole depth increased, the time needed for patterning also increased accordingly, meaning more exposure to the ion beam, which resulted in decreased conformity.

G. Bitmap file vs. Direct Pattern Designing

In all the cases discussed in above sections, bitmap files were used for patterning. The advantage of this method is the design can be prepared using the tools such as painting, power point or excel before running the FIB milling. However, this method also has a significant problem that the beam scans the surface in raster mode (Figure 8, left). Since the ion beam cannot be completely turned off while moving from one hole to another and the mismatch between the spot size and pixel size may occur, it is hard to avoid milling of the areas that should not mill. Repeated scanning further worsen the problem.

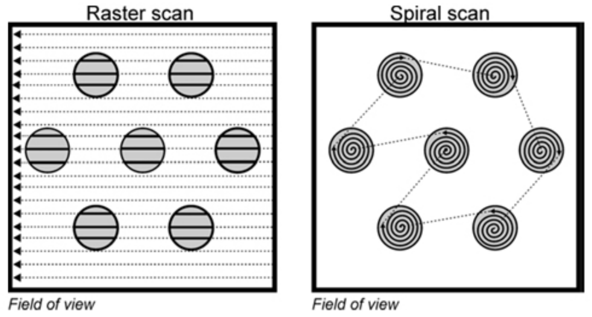

Figure 8: Scan methods: raster scan (left) and spiral scan (right)

Compared with using a bitmap file, designing of the pattern directly on the FIB working field uses spiral scanning (Figure 8, right), can avoid the repeated scanning of the areas that should not be milled, and as a result, most importantly, can increase the pattern conformity. As shown in (Figure 9), conformity of the nanohole arrays obtained by direct pattern designing (right image) was better than that obtained by using bitmap file (right image). Both cases had the same hole diameter (200 nm) and spacing (200 nm), and milling time (83 s). However, direct pattern designing (or spiral scan) also has a disadvantage that direct designing of large-scale patterns are not practical. Of course, this disadvantage may be overcome by developing codes for direct pattern generation on the FIB working field, or by using NanoBuilder designing tool by FEI Company.

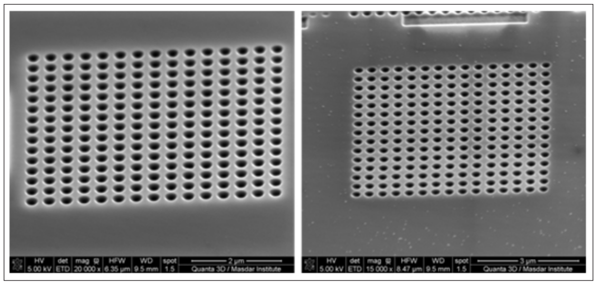

Figure 9: Nanohole arrays obtained by suing bitmap file (right), and direct pattern designing on FIB are working field. Accordingly, these two patterns used raster and spiral scan, respectively. Both patterns have the same hole diameter (200 nm), spacing (200 nm), and, milling time (83 s)

H. Large-Scale Patterning of Nanohole Arrays of 100nm

It can be concluded from above sections that the conformity of a pattern obtained using a bitmap file may not depend on the designed dimension of this pattern. However, it is mainly on the dose per unit area that can be controlled by changing many factors including ion beam current, a number of pixels per unit area, milling time or depth, e.t.c. Therefore, once the designed dimension of a to-be-milled pattern is determined, and an optimum current e.g. 30 pA is chosen, conformity of the resulting pattern can thus be optimized by changing the number of pixels of the bitmap file used. (Figure 10) shows the SEM images of a milled pattern with designed hole diameter, spacing and, depth of 100 nm, and with a surface area of 164 μm^2 (not the hole is shown in the image) obtained by using a bitmap file with 1047*789 pixels. Total milling time was only 47s. Thus, calculated dose and pixels per unit area are 8.6 $pC/\mu m^2$ and 5056 $pixels/\mu m^2$, respectively, both closer to the values of pattern 4 with better conformity in (Figure 4). This results gain confirms the fact that not the dimension of the pattern, nor other parameters, but the dose per unit area is the mainly determining parameter of pattern conformity.

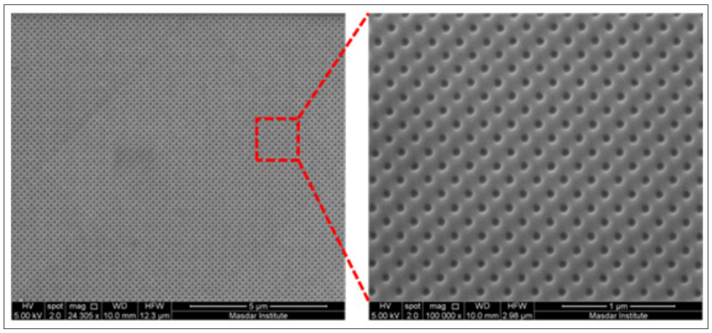

Figure 10: SEM images of the nanoholes array with excellent conformity. Designed hole diameter, spacing and depth was all 100 nm. Thus, calculated dose and pixels per unit area are 8.6 $pC/\mu m^2$ and 5056 $pixels/\mu m^2$, respectively

Conclusion

In this work, we studied the effect of ion beam current, number of pixels of the bitmap file, and milling time (time is proportional to designed milling depth), on the dose per unit area, and thus on the pattern conformity on silicon substrate. It was found that a dose approximately of 7.5-8.6 $pC/\mu m^2$ or a bitmap file corresponding to 4000-5000 $pixels/\mu m^2$ at 30 pA beam current was appropriate in order to obtain well-separated nanohole arrays of different sizes. If spacing smaller than designed values area needed, it can be achieved by resonantly increasing milling time/depth, or the number of pixels of the bitmap file. Finally, a relatively larger scale nanohole arrays with diameter and spacing of 100 nm was achieved by using a dose of 8.6 $pC/\mu m^2$. This work offers a few guidelines for nanopatterning of silicon substrate for photonic applications [8-15].

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