Maskless Etching of Microfabricated Structures with Low-Power Focused Ion Beam

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Abstract - Characteristics of the structures microfabricated by 20-keV Ga⁺ FIB on Si have been investigated with AFM images and photographs from a Nomarski microscope. The images from AFM show redeposition effect inside and near the edges of the holes etched by FIB. The images also show great damages of the as-implanted structures induced by the high current density of FIB. The relationship between the dose of ion beam and the structures fabricated by FIB was studied. The results indicated that the depth of the structures is directly proportional to the dose of the ion beam with sputtering rate of 132 nm/minute, when the beam current is 28 pA. The line width is also directly proportional to the dose, when the implanting time does not reach the critical value. The experimental results revealed the discrepancies between the beam diameter and the width of the microfabricated structures, which is considered to be the results of combined effects from surface charging effects, vibration, and the part of ion beam with weaker intensity.

1. INTRODUCTION

Nanoelectronics, including Micro-Electro-Mechanical Systems (MEMS) and Nano-Electro-Mechanical Systems (NEMS), has become one of research areas that attracts a lot of attentions. At the same time, the technologies to fabricate nanoscale structures have been developed rapidly. One of key technologies is photolithography; however, there are many difficulties to be resolved to make further progress. Focused ion beam (FIB) is one of alternative technologies for photolithography in some applications [1-2]. With a very small ion beam diameter, about 0.1 μm, FIB is suitable for maskless etching, maskless implantation, and maskless ion-assisted deposition, etc.

In order to properly fabricate devices, it is essential to fully understand the fundamental characteristics of FIB system itself, and of the structures fabricated with FIB. Although conventional microscopy method such as scanning electron microscopy (SEM) is good enough to acquire images showing topography of the microfabricated structures, atomic force microscopy (AFM) is known to provide more detailed information for very small structures. With a probe placed very close to the sample, AFM can acquire a detailed image of the sample over a small area by measuring the attractive forces or repulsive forces between the tip and the sample [3]. The forces are then processed by software to show color images on a screen where the color of images represents the friction between a tip and the sample.

In this study, we investigated fundamental characteristics of the structures microfabricated by 20-keV Ga⁺ FIB. AFM was used to examine the surface topography and the depth of the etched specimens, which gave us very detailed information. A Nomarski microscope was also used in our experiments to acquire optical images of microfabricated structures. Three experiments have been done with Si in this study. The first experiment is to examine the surface topography of Si after being bombarded with FIB in dot-mode and area-mode. The second experiment is done to find the relationship between the dose and the depth of holes etched by FIB. The last experiment is to find out the correlation between the implanting time and the width of lines.

The rest of the paper is organized as follows. Section II briefly introduces the fundamentals of stopping mechanisms in solids as well as the redeposition effect associated with ion beam etching. Section III describes the experimental procedures, FIB system, and beam diameter which is an important parameter. Section IV discusses the experimental results and we draw out conclusion in section V.

II. THEORY

A. Stopping Mechanisms

When charged particles are implanted into solids, they collide with atoms of the target and lose energy until stop. There are two kinds of stopping mechanisms for ions implanted into targets, nuclear stopping and electronic stopping. The dominant mechanism is determined by the mass and the energy of the accelerated ions, as well as the mass of the target atoms. Generally, when the energy is relatively low, the stopping is dominated by nuclear stopping, the elastic collisions with nuclei or whole atoms which absorb the impact. On the other hand, when the energy is relatively high, the stopping is dominated by electronic stopping, the inelastic collision with bound electrons of the target atoms so that the atoms of target are excited or ionized. Hence, on the assumption that both mechanisms are independent, the energy loss per distance unit could be expressed as follows:

\[ -\frac{dE}{dx} = N[S_a(E) + S_e(E)] \]  

where \( N \) is the atomic density of the target atoms, \( S_a(E) \) and \( S_e(E) \) are nuclear-stopping and electronic-stopping cross-sections, respectively. In the case of implanting 20-keV Ga⁺ into Si, the major part of energy loss is due to nuclear stopping which contributes to cascade collision and sputtering [4].
B. Redeposition Effect

One characteristic of etching by ion beam is that the etching and the redeposition of nonvolatile etch product species have taken place simultaneously [5]. Hence, the final net sputtering is the result of combined effects between the etching and the redeposition. Other factors that affect the sputtering are the incidence angle of ion beam, the structure of target materials whether it is an amorphous or a crystalline structure, and the orientation of the crystalline structure, etc. Although FIB has much higher beam current density, the similar redeposition effect is expected.

III. EXPERIMENTAL

Three experiments have been done. First, Si was bombarded with FIB in dot-mode and area-mode, and the surface topography was observed with AFM. In dot-mode, standing ion beam was implanted into just one point for 1 minute. In area-mode, ion beam was raster scanned into area of 5x5 \( \mu m^2 \) for 2 minute 23 seconds. The distance between the center of adjacent holes and areas was 10 \( \mu m \). The beam current was 28 pA. In the second experiment, FIB was used to etch holes on Si with different dwell time: 1 minute, 2 minutes and 3 minutes. The objective is to find out the relationship between dwell time and the depth of holes. The beam current and the distance between adjacent holes are the same as in the first experiment. The third experiment is to find the correlation between implanting time and the line width on Si. The implanting time was 8 and 82 seconds, while the beam current used in this experiment was 33 pA. We used AFM from Seiko model SPA300 to examine the surface topography and to measure the depth of each holes. A Nomarski microscope was used to acquire the optical images in the last experiment. In all experiments, Czochralski (CZ) grown n-type Si substrates of (100) orientation were used. The size of substrates was 2x2 cm\(^2\). The FIB system is introduced in subsection A, and the definition of beam diameter used in the experiments is described in subsection B.

A. FIB System

The FIB system used in this study is model EFIB-2000S from Eiko Engineering. The ion source was needle-type liquid metal ion source (LMIS) which provides Ga\(^+\) ions. When an ion beam hits a target, atoms of the target are sputtered off, secondary electrons and ions are emitted, and the primary ions are implanted. Hence, FIB could be used as a scanning ion microscope (SIM) to provide high-contrast images during ion bombardment [6]. Prior to using FIB in each experiment, the ion beam was adjusted to get well-conditioned beam and stable beam current.

B. Beam Diameter

There are several methods to find out a beam diameter, such as the knife-edge method, the 1/e\(^2\) optical intensity criterion, and the 1/e electric field strength criterion. In reality, the beam diameter of FIB is affected by several factors, such as beam energy, beam current, etc [7]. In our study, instead of measuring the beam diameter directly, we derived the beam diameter from beam energy and beam current based on the specification from the manufacturer. Assuming that the beam energy is 20 keV, when the beam current is 100 pA the beam diameter is about 0.15 \( \mu m \), and when the beam current is 30 pA the beam diameter is about 0.1 \( \mu m \) [7]. The beam current used in our experiments is around 30 pA. Hence, the beam diameter should be about 0.1 \( \mu m \) by specification. One way to make sure that the beam is focused enough is by viewing the SIM image of a standard sample provided with the FIB system. The standard sample has an Al layer on the top with LATEX particles, which is a type of polymer. Fig. 1 shows the SIM image of LATEX particles, and lines generated by FIB. The diameter of LATEX particles is 1 \( \mu m \) and the width of the line generated by FIB is about 0.2 \( \mu m \). Once we get the image of the LATEX particles clearly, it means that the beam ion beam is well conditioned. However, it is not unusual that the minimum line width of the structure etched by 0.1-\( \mu m \)-diameter FIB would be larger than 0.1 \( \mu m \). The wider minimum line width is caused by the part of ion beam with weaker intensity. It is reported that the minimum line width on Si etched with 0.1-\( \mu m \)-diameter FIB could be 0.5 \( \mu m \) [8]. The discrepancies between the beam diameter and the line width would be further discussed in section IV.

IV. RESULTS AND DISCUSSION

It is known that ion bombardment causes damages to the targets due to elastic collisions with nuclei of target atoms. With beam current density 10\(^2\) times higher than conventional ion beam [8], it is expected that FIB could cause more damages to the targets. The reason that Ga\(^+\) ions were used in our study is due to the large sputtering yield, as well as the stability and the ability to operate at room temperature of the Ga\(^+\) ions LMIS. Fig. 2 is the AFM images showing the surface topography of Si after ion bombardment with FIB in the first experiment. The diameter of two holes in the middle of Fig. 2(a) is 2 \( \mu m \) and the size of implanted areas in Fig. 2(b) is 5x5 \( \mu m^2 \). From the images, it could be seen that the roughness on the edges of holes in Fig. 2(a) and on the implanted areas in Fig. 2(b) is nonuniform. This phenomenon is considered to be the combined effect of cascade scattering and redeposition effect, which were explained in section II.

![Fig. 1. The SIM image of LATEX particles and lines generated by FIB.](#)
Fig. 3 is the AFM images showing top view and cross section of the holes on Si in the second experiment. The line above holes in the middle of Fig. 3(a) is a reference line to display the cross section of the holes. Here, the holes under the line could be separated into three groups: two on the left, three in the middle, and two on the right. The dwell time for each group is 1 minute, 2 minutes and 3 minutes, respectively. The rough areas near the holes in Fig. 3(a) are the same damages at the implanted areas as in Fig. 2. Two vertical lines in the middle of Fig. 3(b) are also reference lines used to measure the depth of the holes. The cross section in Fig. 3(b) shows some interesting characteristics. First, the feature profile of the holes is not anisotropic, but conical. This is due to the energy distribution profile of ion beam, which has the highest current density at the center, combining with the redeposition effect taking place near the bottom of the holes [9]. Second, the two holes with the shortest dwell time have a two-peak feature profile. This could be explained with the AFM image in Fig. 2(b). When the dwell time is not long enough, the sputtering process is continuing at the surface and the area could be nonuniform. Third, there are two hones at the edges of the holes with the height of left hones directly proportional to the dwell time. These hones are also considered to be the result of redeposition effect. The same effect also caused faceting near the edges of two holes with the longest dwell time. Fourth, the diameter of the holes on the surface of Si substrate is about 2 μm, which is the same for all holes.

Fig. 4 shows the relationship between dose and the depth of holes. The depths of holes were measured by AFM. Dose is used instead of dwell time, because the beam current is hard to precisely control and make it continuously stable. Fig. 4 indicates that the depth of the holes is directly proportional to the dose. This is because when the number of ions bombarded the target increases, the number of target atoms sputtered out also increases. In this case, when the beam current is 28 pA, the sputtering rate of 20-keV Ga⁺ FIB ion etching with normal incident angle beam is 132 nm/minute.
In the third experiment, we used FIB to draw lines in vertical and horizontal directions on Si with different implanting time, as shown in Fig. 5. The objective is to find out the correlation between implanting time and line width. When the implanting time is 8 seconds, the line width is 1.3 \( \mu \)m. The line width increased to 2.7 \( \mu \)m, when the implanting time is 82 seconds. The dots in vertical direction are caused by the line-drawing mechanism of the FIB system, which uses a raster scan. Fig. 5(a) shows that the scan mode used in this experiment has large space between lines. With longer implanting time, each dot increases the size and connects to each other; however, the trace of raster scan still remains.

The results from all three experiments show one common issue. The size of pattern on Si is much larger than the beam diameter in specification, 0.1 \( \mu \)m. Although we expected that the size of pattern could be up to 0.5 \( \mu \)m, the results from experiments went beyond that. Hence, we need other explanations in addition to contribution from the part of ion beam with weaker intensity. Here, there are few experimental results that gave us some insight. First, the holes in Fig. 3(a) and the dots in Fig. 5(a) are not complete circles, which could be the neutralization of surface charging effect. Secondly, in Fig. 5(a), there are two possible reasons for this. One is small vibration of the equipment, and the other is the part of ion beam with weaker intensity. In fact, it might be the combined effects of both. Due to small feature size fabricated in our experiment, even small amount of vibration might affect the line width. Third, the diameters are the same for all holes in Fig. 3. This might look contradictory to the previous fact; however, there is an explanation for this. With a few seconds of short implanting time, only the central part of beam could etch the target, so the line width is narrow. When the implanting time also increases, the part of beam with weaker intensity shows accumulated effects on the target, so the line width increases. On the other hand, when the implanting time is long enough to reach the critical value, for example, more than 1 minute for etching a hole, the diameter of the hole does not increase any further. This is because the weaker part of ion beam has already played the role.

Three experiments have been done to investigate the fundamental characteristics of the FIB system and the structures on Si microfabricated with 20-keV Ga\textsuperscript{+} FIB. The first experiment is to examine the surface topography of Si after being bombarded with FIB in dot-mode and area-mode. The results show nonuniformity on the implanted area and at the edges of the holes due to the combined effect of cascade scattering and redeposition effect. The second experiment is to find the relationship between dose and the depth of holes etched by FIB, which indicates that the depth is directly proportional to the dose. The results also show the conical shape of the holes, except when the dwell time is not long enough which the bottom of the holes would not be smooth. In addition, there were evidences of redeposition effect causing holes and faceting near the edges of the holes. The last experiment is to find out the correlation between implanting time and the width of lines, which shows that the line width is also directly proportional to the dose. However, further analysis suggests that the line width is directly proportional to the dose only when the implanting time is shorter than the critical value. In other words, the hole diameter and the line width should remain the same beyond the critical value. In addition, our analysis suggests that the discrepancies between the beam diameter and the size of fabricated structure are possibly due to surface charging effect, vibration, and the part of ion beam with weaker intensity. Further studies shall be done on other kinds of materials to confirm the analysis and obtain deeper insight in FIB system and the structures fabricated with FIB.

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REFERENCES


Fig. 5. Lines drawn on Si with FIB. (a) Implanting time is 8 seconds. (b) Implanting time 82 seconds.