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“AMADEUS” Software for Ion Beam Nano Patterning and Characteristics of Nano Fabrication

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ABSTRACT

The shrinking critical dimensions of modern technology place a heavy requirement on optimizing feature shapes at the micro- and nano scale. In addition, the use of ion beams in the nano-scale world is greatly increased by technology development. Especially, Focused Ion Beam (FIB) has a great potential to fabricate the device in nano-scale. Nevertheless, FIB has several limitations, surface swelling in low ion dose regime, precipitation of incident ions, and the re-deposition effect due to the sputtered atoms. In recent years, many approaches and research results show that the re-deposition effect is the most outstanding effect to overcome or reduce in fabrication of micro and nano devices. A 2D string based simulation software AMADEUS-2D (Advanced Modeling and Design Environment for Sputter Processes) for ion milling and FIB direct fabrication has been developed. It is capable of simulating ion beam sputtering and re-deposition. In this paper, the 2D FIB simulation is demonstrated and the characteristics of ion beam induced direct fabrication is analyzed according to various parameters. Several examples, single pixel, multi scan box region, and re-deposited sidewall formation, are given.

Key Words : Ion Milling (이온밀링), Focused Ion beam (집속이온빔, Sputtering (스터퍼링), Re-deposition (재증착), Simulation (전사묘사), Nano Fabrication (나노 패터닝)

1. INTRODUCTION

Ion beam, especially Focused Ion Beam (FIB), processing has drawn increasing interest for high precision manufacturing of various micro and nano structures. Micro-fabrication is one of the main applications of focused ion beams. Micro-fabrication in silicon is especially useful for Micro-Electro-Mechanical systems (MEMS), Micro-Opto-Electro-Mechanical System (MOEMS) and micro sensors/actuators. The key to the FIB direct write or milling technology is its ability to operate a beam with a proper beam size, shape, current, current density, and energy to remove a required amount of material from a pre-defined location in a controllable manner. In this way, high-precision and complex 3D structures can be fabricated.

As ion beam related research, ion beam direct write and ion beam projection systems have been developed. The ion beam projection process is also known as focused ion beam projection lithography, a collimated beam of ions passes through a stencil mask and the reduced image of the mask is projected onto the substrate [1]. More ever, with Projection Focused Ion Multi-beam (PROFIB), by IMS Nanofabrication GmbH. in Vienna, Austria, it is possible to realize 10nm resolution with various ion species(H^+, He^+, Ar^+, Xe^+,…) at low energy ion beam less than 1 nA [1].

In general, when energetic ions hit the surface of the target, a variety of ion-target interactions, including swelling, sputtering, re-deposition, implantation, backscattering and nuclear reactions, can occur. The re-deposition effect is one of the great challenging limitations of FIB technology. Therefore the simulation or prediction of focused ion Beam induced physical and chemical phenomena including topology change is essential to manipulate and fabricate proper micro- / nano shape.

As a related simulation work, Ximen et al. used a simple computer simulation in 3D space without re-deposition, and fabricated various complicated 3D structure, including arbitrary curved paths [2]. The cell based topography simulation program FIBSIM has been developed by a model, which is dynamic Monte Carlo simulation of the collision cascades [3,4]. This code has several features, prediction of the thickness of a doped or damaged layers, and intermixing of different layers.

In this paper, we present 2-dimensional single pixel (rotational symmetric) and multi scan (trench formation) simulations, which have been done with our new simulation code AMADEUS. The comparison of simulation and experimental results show that AMADEUS fairly well predicts the ion beam induced surface topology changes. Furthermore, this paper shows the characteristics of ion beam induced direct fabrication.

2. SIMULATION TECHNIQUE

There are three methods usually used in tracking of evolution of fronts, the string method, cell based methods, and the level set method. A standard approach to modeling moving fronts comes from discrete the "Lagrangian" form of the equations of motion. In this approach, the parameterization is divided into a set of maker particles whose positions at any time are used to reconstruct the front at every time step. This approach is known under a variety of names, maker particle techniques, string method, and nodal segments.

In the string model, sequential points on the evolution front are indexed i (i=0,1,2,…,n). At each point, the normal direction is calculated by two adjacent points, which can be used again to calculate segment length. The point or segment moves along the normal direction of point or line segment at a certain speed (or distance), which is proportion to total flux of point. In this work, the total flux at each position on the surface is calculated based on all the fluxes arriving at and leaving that point, either from the Gaussian incident beam (direct flux) or from other points on the surface (indirect flux). The surface is then moved in the perpendicular direction according to the total flux, normal to the surface, at each point. The incident flux is calculated from sputtering yield.

The sputtering yield depends on incident angle defined between the discretions of ion incidence and the target surface normal. It is defined as

$$Y = \text{Sputtered atoms / Incident ion} \qquad (1)$$

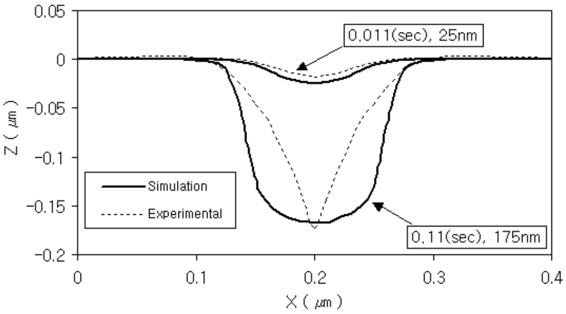

Fig. 1 Comparison of simulated surface contours and experimental results of single-pixel milled hole.

3. 2D FIB SIMULATIONS

3.1 Single Pixel fabrication (Nano dot formation)

Fig. 1 shows the comparison of a simulated surface contour and experimental results of a single pixel milled hole. The experiments were carried out using a Micrion 2500 twin-lens FIB system equipped with a Ga liquid-metal ion source (LMIS). The system was operated at an acceleration voltage of 50 kV with a selectable 50 μm beam-limiting aperture corresponding to a beam current of 45 pA with silicon substrate [5].

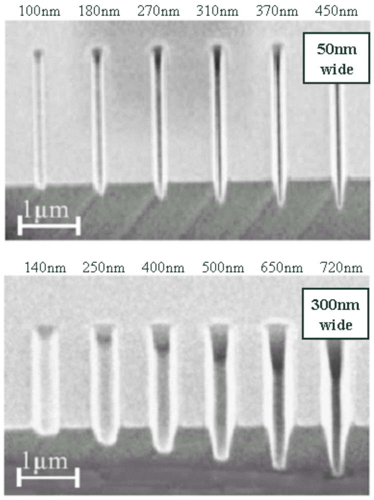

Fig. 2 SEM images of the FIB-prepared cross sectional views of normally 50nm and 300nm wide trenches sputtered in silicon with ion dose from 0.5 to 3 nC/μm^2 in step of 0.5nC/μm^2. The each value above the figure is measured from bottom of each trench.

The experiment was performed at dose of 0.5 pC and of 5pC and corresponding exposure time of 0.011 sec and

0.111 sec, respectively. The beam diameter (FWHM) is 68nm and the current density at center of beam 0.8 A/cm^2. The patterns were subjected to atomic-force microscopy (AFM) in the tapping mode with small tip radii (r ~ 10nm). The upper two surface contours correspond to an ion dose of 0.5pC, while the lower contours correspond to an ion dose of 5pC. In case of the ion dose of 5pC, the surface contours are different. The experimental contour is narrow and sharp, which is likely due to an AFM measurement limitation. The simulation was performed with a sputtering yield which has been obtained from TRIDYN (TRIM.SP Dynamical) [6] and with a cosine emission index of n=1, which is analyzed by the binary collision simulation code IMSIL (Implant Simulator) [7]. The experimentally measured sputtering yield is 2.5 but sputtering yield from TRIDYN is 2.26. The result shows that the simulated data well match with the experimental contours.

3.2 Multi Scan of Box region (Trench formation)

Simulations of multi scan trench formation are performed for 50- and 300nm openings. Fig. 2 shows 50nm and 300nm trenches formed with 50 keV Ga+ ion in silicon substrates, and ion doses from 0.5 to 3 nC/μm^2 in steps of 0.5nC/μm^2. The outmost left trench exhibits a pronounced flat bottom area. When the milling depth exceeds the trench width, the respective sidewalls are larger and material re-deposition occurs to a great extent. Therefore, the bottom area decreases and the milled boxes transform into deep V-shaped trenches [5].

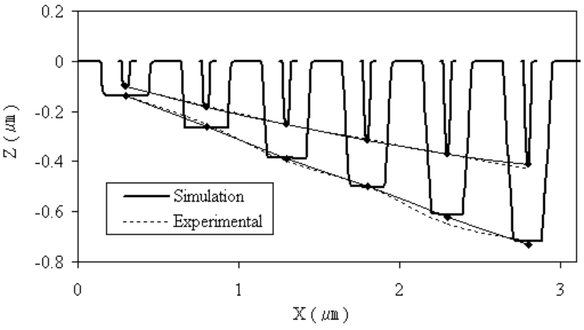

Fig. 3 Simulation contours of 50- and 300nm trenches. Experimental data of the trench depth are taken from Fig. 2.

3.3 ARDE Effect and End Point Detection

One of the important effects in focused ion beam fabrication is a "loading effect" resulting in differences in fabrication rate due to re-deposition. This effect is known as aspect radio dependent etching or ARDE.

Trenches with different widths reach different depths, even if other FIB processing parameters (dwell time, ion dose, ion energy, etc.) are kept the same. Fig 4 shows the ARDE effect by comparing two different openings of 50 and 300nm. One of the important reasons to use the simulation code is pre-calculation of the required dose to reach a desired stop position called end point. In this way, the AMADEUS code can be used for "end point detection".

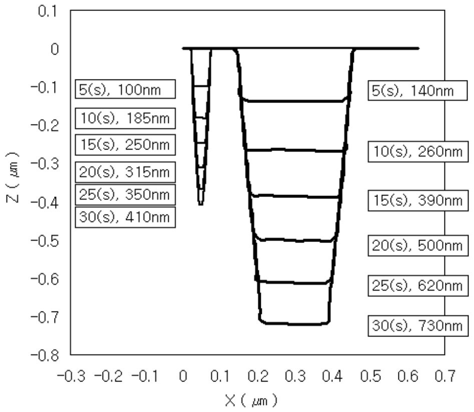

Fig. 4 Simulation results and ARDE effect (each solid line presents the contour of substrate).

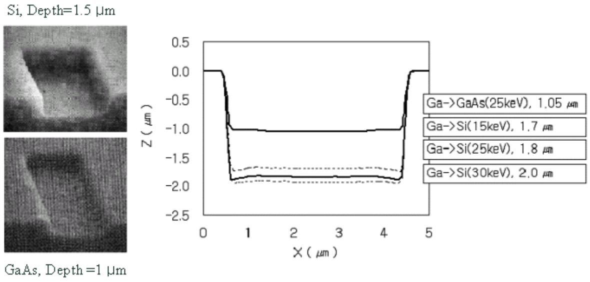

Fig. 5 SEM images and simulation results (two solid line illustrate simulation results of Si and GaAs at 25keV incident energy, and two doted line are the additional comparison at 15keV and 30keV incident energies in case of silicon, from Ref. [8])

3.4 Multi Scan of Box Region in Si and GaAs

Trench formations on Si and GaAs substrates have been experimentally carried out with a gallium ion beam with 360pA beam current and 25 keV energy in serpentine scan [8]. The sputter yields obtained from the experiment are 1.9, 5.3 for silicon and GaAs, respectively. For the simulation the sputter yields from TRIDYN, 2.08 for Si and 5.17 for GaAs, are used. Fig. 5 shows simulation results and the cross sectional SEM images. The experimental depths, 1.5μm for Si, 1μm for GaAs, agree well with the simulation results, which are 1.8μm for Si and 1.05μm for GaAs, respectively. As can be seen, with focused ion beam fabrication, it is really possible to form flat bottoms with almost vertical walls.

3.5 Re-deposited Sidewall Formation

Re-deposition of sputtered atoms has been demonstrated for device translation and connections between the conductive layers isolated by an oxide, while no re-deposition is desired for the other applications [6].

To check the re-deposition effect during trench formation, experiments were performed with a 50keV gallium ion beam and silicon substrate. The maximum current density was 0.8 A/cm^2, the beam diameter (FWHM) was 68nm, and the pixel spacing was 10nm. The important point in formation of re-deposited sidewalls is that they are fabricated not by multi pass mills but by single pass mills. If it is fabricated by multi pass, the normal trench shape with flat bottom is formed.

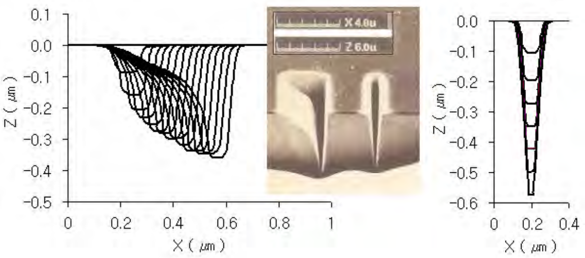

Fig. 6 Simulation results of re-deposited sidewall and deep trench formation with multi pass

To check and compare correctly re-deposition at the sidewall with experiment, it is necessary to simulate in 3D space, because re-deposited sidewall formation is not a 2D trench based effect. But the effect may qualitatively be checked by 2D simulation. The re-deposition flux due to the sputtered atoms is deposited on the opposite sidewall and bottom is shows in Fig 6. The beam moves from left to right so that the sputtered atoms are re-deposited mainly on the left sidewall. This re-deposition effect causes the unexpected surface shape. In addition, single scan with multi pass simulation result is in right side of Fig. 6. The narrowed V-shape groove is formed by single scan with multi pass is shown in the right side of Fig. 6. The aspect ratio of the V-shape groove is about 3.

4. CONCLUSION

The most significant challenging problem in FIB milling is the re-deposition effect due to sputtered atoms. The ion beam induced fabrication mechanism is quite different to normal machining process. Therefore, to fabricate micro- and nano scale devises, it is essential to predict or avoid the re-deposition effect precisely. AMADEUS, a simulation code for Focused Ion Beam (FIB) induced direct fabrication, has been developed, which treats the sputtering and re-deposition by string method. Several examples have been presented and compared, single pixel milling, trench formation, and re-deposited sidewall formation with one pass. The results fairly well predict the surface topology changes. Furthermore, the aspect ratio dependence etching (ARDE) effect, sidewall slope of trench, and End Point Detection have been effectively verified with the newly developed code AMADEUS.

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