論 文 の 内 容 の 要 旨

論文題目　　A study on the focused ion beam sputtering for the development of 3D shave-off SIMS（三次元シェーブオフ二次イオン質量分析法の開発に向けた収束イオンビームスパッタリングの研究)

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Secondary ion mass spectrometry (SIMS) is a powerful surface analysis technique with a vast range of application such as semiconductor industry, materials research, and biological research, etc.

Our group has developed our unique SIMS scanning method called "shave-off" for achieving highly precise SIMS depth profiling with reduction of shape effects. A conventional raster scan method scans over an area rapidly and repeatedly in both vertical and horizontal sweeps. However, the shave-off method is that the primary ion beam always shaves the edge of the sample with the fast horizontal sweep and very slow vertical sweep. Therefore, a section of the sample is shaved off flatly and almost parallel to the axis in the direction of FIB, and the shave-off scan has low sputtering re-deposition and restriction of primary ion implant influence.

The shave-off method has been developed with the data acquisition of SIMS in one-, two-, and three-dimensions. The existing three-dimensional (3D) shave-off SIMS is possible to get images and depth information using by dual focused ion beam (FIB). However, it has taken a long time to analyze due to using two beams alternately, and it is too difficult to catch the vacant area in the sample.

Recently our group has started to develop the new 3D shave-off SIMS. The new 3D shave-off SIMS is using the Y-axis of a mass detector to get the sample depth (Z-axis) information. To obtain the depth information, we introduced the cylindrical lens system which can magnify some μm unit of Z-axis position from the sample to some mm unit on the detector. This concept was simulated by SIMION program, and the results show possibility to have sample depth information to the Y-axis of the detector with element analysis (mass information m/z, X-axis of the detector) at the same time.

The goal of this project is development and instrumentation the 3D shave-off SIMS which can analyze several μm^3 sized solid sample in a short time (1-2 hours) with high spatial resolution (X, Y-axis; a few nm, Z-axis; 10 nm). In order to reach this objective, we divided the process into three steps as follows, 1) Scanning step, 2) Lens system step, and 3) Detection step. Among them, I was in charge of the first part, 1) Scanning step. In this step, I investigated the FIB sputtering under the shave-off condition. Through this investigation, I will determine the relationship between the primary ion beam and sputtered sample, and evaluate the emitted particles that will be a basis of the ion transport trajectory in the lens system.

In this study, I examined the focused ion beam sputtering for the development of 3D shave-off SIMS. Before introducing the lens system which magnifies the z-axis of secondary ions in 3D shave-off SIMS, it is necessary to understand the aspect of the sputtering by the primary ion beam. Hence, I investigated the sputtered atoms with cross-sectional shape relevant to the incidence angle.

Firstly, I needed to understand about sputtering process by the primary ion beam for developing the 3D shave-off SIMS. The sputtering process is affected by a various parameter such as primary ion species, energy, mass and angle of incidence. Among them, the angle of incidence is one of the most important parameters to effect sputtering yield, secondary yield, and depth resolution in SIMS analysis. In the shave-off method, this angle of incidence is very relevant to the cross-sectional shape of the sample after scanning. Unlike the raster method, which repeatedly scans over the scan area, the shave-off method has a distinctive cross-sectional shape, because it always scans only the edge of the sample. Therefore, I observed the cross-sectional shape after shave-off scanning with the samples having different height. The cross-sectional shape was only similar to each other to a certain height (10 μm) despite the same primary beam condition. The resulting parts that show different shapes can be inferred to be affected by other factors, not the beam. The other factors are investigated by simulation of particle bombardment. The most of the scattered gallium particles are directed to the bottom part of the sample, the sputtered target particles which having high energy also affected the bottom part. This novel approach of shave-off which observe the cross-sectional shape will provide the relationship between the primary ion beam and sample surface for the development of 3D shave-off SIMS.

In the shave-off method, which always shaves only the edge of the sample, the angle of cross-sectional shape becomes the incident angle of the primary ion beam. Therefore, I examined the relationship between the incident angle and the sputtering yield through the change of cross-sectional shape as a function of the scan speed. As the same beam conditions, the shave-off scan speed of y-axis changed two-times faster and two-times slower from the standard. The difference in the angles showed the small difference as a function of scan speed, but the sputtering yields have sufficient difference. It appears that the slope of the cross-section increases with decreasing scan speed. Also, the sputtering yield decreases with decreasing scan speed. At the shave-off condition, the reason of decreasing sputtering yield as the increasing angle of incidence is due to the increase in the reflection of ions at the surface.

For the calculation of secondary ion trajectory along the lens system, we have to know the angular and energy distributions of secondary ions. SDTrimSP simulation code was known that has good agreements with experimental data on angular distribution and sputtering yield. However, these reports were done with lower incidence energy and angle than shave-off conditions. For this reason, I simulated angular distribution based on the existing shave-off experiment condition and compared to the experimental data. At the condition of high incidence ion beam energy, the SDTrimSP simulation results show good agreement with the experimental data. However when the condition of high incident angle, the simulation data have smaller emission angles than experimental results, but it shows quite a similar tendency to the experimental results for the angular distribution of sputtered particles. The SDTrimSP simulation is expected to help obtain the basic parameter for calculating of the secondary ion trajectories along the lens system and detector in development of 3D shave-off SIMS.

To compare the position on the detector of secondary ions depending on the sputtering depth position the target, I had decided the nine points on the sample and had investigated the secondary ions sputtered from the point. Each secondary ions sputtered at different depths of the target had different distributions of detection positions on the mass detector. The sputtering position depending on the sample depth had been clearly distinguished on the mass detector by the peak of the secondary ion intensity distribution. The secondary ions of Ge and Si sputtered from the target with a depth of about 2 μm difference had shown at different Z-axis positions of about 0.4 mm and 0.2 mm on the mass detector, and the Z-axis positional resolution was 5.5 μm for Ge and 6.3 μm for Si, respectively. This resolution was able to be improved by adjusting the range of secondary ion initial energy. When decreasing the range of initial energy, the Z-axis positional resolution of secondary ions of Ge and Si were decreased as 2.4 μm and 2.8 μm which are improved by about 45%.

From this study, I have obtained the basic information about the FIB sputtering and verified the possibility of the concept of 3D shave-off SIMS. These investigations such as angle of incidence, control of the cross-sectional shape, and angular distribution becomes an important function to calculate the secondary ion trajectories along the lens system. It can be a good starting point and a base for designing and assembly magnification lens system with the development of 3D shave-off SIMS.