Evaluation of SIMS depth resolution with Delta Multi-layer Reference Materials

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It has been proposed that well characterized delta multi-layer reference materials can be used for the evaluation of the SIMS depth resolution. We made Ta_2O_5 multi-layers with delta SiO_2 layers and Si multi-layers with delta GaAs layers for delta multi-layer reference materials. For all the SIMS depth profiles studied, the profiles could be fitted with a depth resolution function, which is a convolution of two exponentials with a Gaussian based on three parameters such as the width, the growth and the decay constant.

1. Introduction

Sputter depth profiling by SIMS is widely used for accurate and quantitative characterization of dopant profiles. However, due to the complicated artifacts in SIMS depth profiling such as sputter-induced changes in the dopant depth distribution, surface roughening, matrix effect, and etc., the SIMS depth resolution is difficult to define. Currently, several means are used to evaluate the SIMS depth resolution such as the minimum full width at half-maximum (FWHM), the steepness of the leading/trailing edge of a sharp profile, and the depth over which the intensity changes from 84% to 16% of the peak intensity. Therefore, it is necessary to set up a standard procedure to evaluate the SIMS depth resolution. A SIMS profile of a delta-doped layer can be described with an exponential trailing edge, a Gaussian-like rounded top and an exponential rising part. [1] SIMS depth resolution could be evaluated with three parameters such as the width of the profile, w_{Gauss} and the growth and the decay length, λ_{up} and λ_{down}. With well characterized delta multi-layer reference materials, the evaluation of SIMS depth resolution as a function of the depth can be used to check the instrumental performance such as evenness of etching over an analyzed region, the long-term stability and et al. It can be also used to check any abnormal surface roughening and ion-beam induced segregation. Delta multi-layer reference materials can be used to determine the sputter rate from the spacing between adjacent delta layers without the surface transient effect. Ta_2O_5 multi-layers with delta SiO_2 layers and Si multi-layers with delta GaAs layers were made and used to check requirements and the usefulness of newly proposed delta multi-layer reference materials.

2. Description of delta multi-layer reference materials

First of all, the thickness of the delta layers are thin enough so that the changes of the sputtering rate and the secondary ionization probability of the delta layer component during SIMS depth profiling are negligible. The most ideal delta layer would be a single atomic layer but it is not simple to make a single atomic delta layer and it is even more difficult to confirm it. Appropriate criteria for the thickness of the delta layers would be that it should be much thinner than the ion range of the primary ion beam used in SIMS analysis so that the thickness should not affect the profile shape at all. The chemical state of the sputtered surface layer should not change during SIMS profiling to avoid any matrix effect and any erosion rate change. At present, the proposed multi-layered reference materials are not applicable to shallow delta layers where the chemical and physical state of the near-surface region modified by the incident primary ion beam is not in the steady state. The spacing between adjacent delta layers should be large enough so that the secondary ion intensity can reach the background level between the delta layers. The surface and the delta layers should be sufficiently flat and parallel to each other to avoid any distortion of SIMS profiles. There could be many ways of making delta multi-layer reference materials such as MBE, MOCVD, as have been applied already. We used UHV-ion beam sputter deposition method to grow delta multi-layer reference materials such as Ta_2O_5 multi-layers with delta SiO_2 layers [2] and Si multi-layers with delta GaAs layers. For Ta_2O_5 multi-layers with delta SiO_2 layers, the thickness of Ta_2O_5 layers is 18.6 ± 0.3 nm and that of delta SiO_2 is about 1 nm. The thickness and the interface roughness of the Ta_2O_5 multi-layers with delta SiO_2 layers were evaluated by TEM and X-ray reflectivity analysis.[3] The thickness of Si multi-layers and that of delta GaAs layers was estimated to be 83.8 nm and about 1nm, respectively based on the growth time.

3. Procedure of SIMS depth resolution with delta multi-layerd reference materials

A SIMS profile of a delta-doped layer can be described with an exponential trailing edge, a Gaussian-like rounded top and an exponential rising part. Assuming the SIMS profile of a delta layer to be a convolution of two exponentials with a Gaussian [1] as in the following equation (Depth Resolution Function, DRF hereafter), three parameters are required such as the width of the profile, w_{Gauss} and the growth and the decay length, λ_{up} and λ_{down}.

$$Gauss(z) = \frac{B}{\sqrt{2\pi}\, w_{gauss}} \exp\left(\frac{-z^2}{2 w_{gauss}^2}\right)$$

$$D\exp(z) = A\exp\left(\frac{z - z_0}{\lambda_{up}}\right) \quad for\ z \ge z_0$$

$$A\exp\left(\frac{-(z - z_0)}{\lambda_{down}}\right) \quad for\ z \le z_0$$

To evaluate the rising length, the decay length, and the width, non-linear curve fit software commonly used these days can be used with a user-defined function: y=na*(1/(2*(eu+ed)))*(exp(((x-xc)/eu)+w^2/(2*(eu^2)))*(1+erf(((-(x-xc))/w-(w/eu))*0.7072))+exp((-(x-xc)/ed)+w^2/(2*(ed^2)))*(1+erf(((x-xc)/w-w/ed)*0.7072))), where y is the intensity of secondary ions(counts/s), x is depth(nm), na is the peak intensity of secondary ions (counts/s), eu is the rising length(nm), ed is the decay length(nm), xc is the apparent peak depth(nm), w is the peak width(nm). Background should be subtracted before fitting and the number of data points for a delta layer is recommended to be around 50. Non-logarithmic parts in logarithmic plot of secondary ion intensity vs. depth must be deleted before fitting.

4. Example of Evaluation of SIMS depth resolution with delta multi-layered reference materials

A 18nm Ta_2O_5/1nm SiO_2 multi-layer was depth profiled with 10 keV O_2^+, CAMECA 4f and the third peak is shown

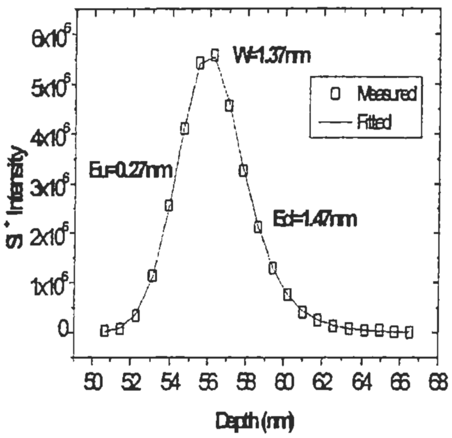

Fig 1. A Si^+ SIMS depth profile of a 1.0nm SiO_2 delta layer below a 56nm Ta_2O_5 layer with the estimated DRF parameters.

in Fig. 1. A SIMS depth profile for 83.8 nm Si/ 1.0nm GaAs multi-layers is shown in Fig 2. 10 kV O_2^+ ions were used and Ga^+ secondary ions were collected. The first peak is shown and analyzed. Fitting with the DRF in Fig 2. seems to be good enough. However, the growth and decay length are much larger than those for Si^+ in Fig. 1, even though the primary ion species and the ion energy is the same. $AsSi^-$ ions were collected with 14.5 kV Cs^+ ions, for which the profile shape was quite different as in Fig 3. The exponential rise is very sharp and the exponential decay is very long.

We tried to fit three different types of SIMS delta layer profiles. Even though the shape of the profiles are quite

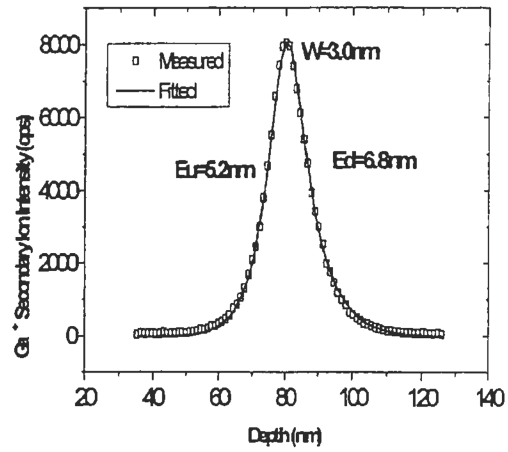

Fig 2. A Ga^+ SIMS depth profile of a 0.7nm GaAs delta layer below a 83.8nm Si layer with the estimated DRF parameters.

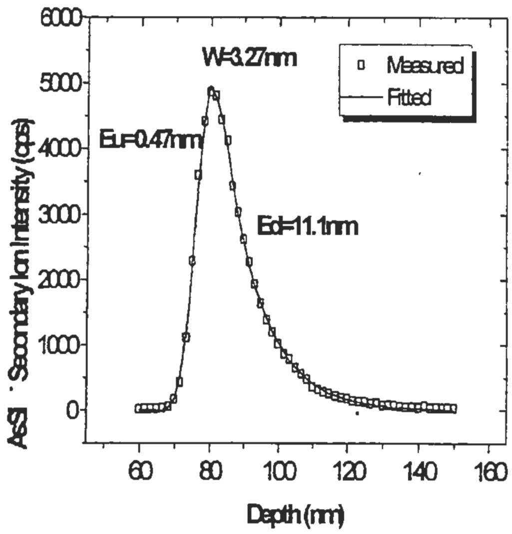

Fig 3. An $AsSi^-$ SIMS depth profile of a 0.7nm GaAs delta layer below a 83.8nm Si layer with the estimated DRF parameters.

different, fittings are reasonably good enough for all the profiles as shown in Fig. 1-3. It suggests that the proposed evaluation procedure of SIMS depth resolution using delta multi-layered reference materials can be applied to most of SIMS depth profiling results. Even though the details are not described here, the growth constant is not significantly affected by the primary ion energy but the width and the decay constant changed consistently with the ion energy. A preliminary comparative analysis of the SIMS depth resolution using delta multi-layered reference materials described in this report is under progress within Korea, Japan, France, Australia and USA. A systematic RRT is being planned as an activity of the study group for development of a procedure for SIMS depth resolution using delta multi-layered reference materials in ISO/TC201/SC6.

Several additional use of the delta multi-layered reference materials can be pointed out here. Evaluation of SIMS depth resolution with delta multi-layered reference materials can be used to check the instrumental performance such as evenness of etching over an analyzed region, the long-term stability and et al. It can be also used to check any abnormal surface roughening and ion-beam induced segregation. Delta multi-layer reference materials can be used to determine the sputter rate from the spacing between adjacent delta layers without the surface transient effect. Since the position and the thickness of the delta layers can be measured accurately, measured SIMS depth profiles can be compared with the original depth profiles to study the deviation of the measured SIMS depth profiles from the original depth profiles.

4. Conclusions

Well-characterized delta multi-layer reference materials can be used for the evaluation of the SIMS depth resolution. It was shown with two types of delta multi-layered reference materials such as Ta_2O_5 multi-layers with delta SiO_2 layers and Si multi-layers with delta GaAs layers.

References

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