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Depth Resolution Parameters and Sputtering Rates Extracted from Amorphous and Crystalline Silicon Materials for SIMS Shallow Depth Profiling

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Sputtering rates and depth resolution parameters from amorphous and crystalline silicon are compared in order to ascertain the propriety of using the BN delta-doped multilayer (BN delta-doped layers in amorphous silicon matrix fabricated by magnetron sputtering) as a reference material for SIMS shallow depth profiling. The sputtering rate ratio for amorphous silicon fabricated by magnetron sputtering and for crystalline silicon is constant (1.19) and independent of all primary ion energies, and the sputtering rates for depth calibration in crystalline silicon can be obtained from the BN delta-doped multilayer. The trailing edge decay lengths for amorphous silicon fabricated by magnetron sputtering are longer than those for crystalline silicon. The SIMS analysis conditions can be optimized using the BN delta-doped multilayer reference materials. However, SIMS depth profiles cannot be deconvoluted by the depth resolution parameters estimated with the BN delta-doped multilayer reference materials.

INTRODUCTION

Low-energy SIMS has been widely used for measurements of shallow junction depth profiles to develop new ULSI devices. Despite many efforts, ambiguities remain concerning depth calibration and depth resolution for shallow depth profiling. In order to obtain an accurate depth scale, boron nitride (BN) delta-doped multilayer reference materials (BN delta-doped layers in an amorphous silicon matrix fabricated by the magnetron sputtering method) were developed by the Developing International Standards Project of the Japanese Standards Association [1]. A round-robin study using the reference materials showed the variation in sputtering yield before equilibrium [2]. Further, it is expected that the depth resolution parameters obtained from the reference materials will be used to optimize the SIMS analysis conditions and to deconvolute the SIMS depth profiles. However, there is a question as to whether the BN reference materials (amorphous silicon) give the same sputtering rates and depth resolution parameters as those for crystalline silicon. The sputtering rates for the amorphous silicon and crystalline silicon are the same under high-energy primary ion bombardment [3], but there is no data under low energy primary ion. There are depth resolution parameters for amorphous silicon formed by the MBE method [4], but there is no data for amorphous silicon fabricated by magnetron sputtering.

In this study, sputtering rates and depth resolution parameters from amorphous silicon fabricated by magnetron sputtering and crystalline silicon are compared, and the propriety of using the BN delta-doped multilayer as a reference material for SIMS shallow depth profiling is discussed.

EXPERIMENTAL

BN delta-doped layers separated by amorphous silicon spacer layers were fabricated on a silicon-on-insulator (SOI) substrate by magnetron sputtering (Sample A). The sample structure and layer thickness are: a-Si (25 nm)/ δ-BN/ a-Si (10 nm)/

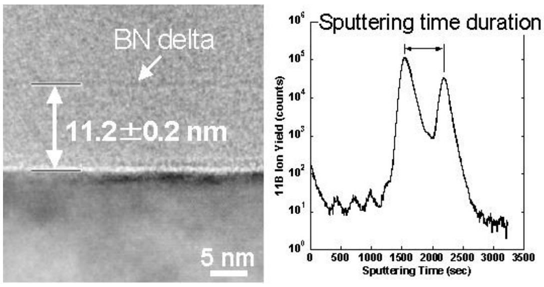

Fig. 1 TEM image of BN delta-doped layers (left) and SIMS boron profile measured with 500 eV primary ions (right) of Sample A.

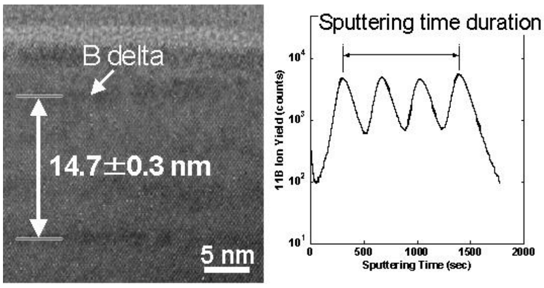

Fig. 2 TEM image of four boron delta-doped layers (left) and SIMS boron profile measured with 500 eV primary ions (right) of Sample B.

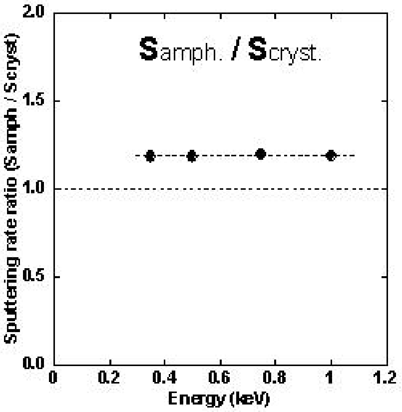

Fig. 3 The ratios of sputtering rates (Samph. / Scryst.) for amorphous silicon fabricated by magnetron sputtering and crystalline silicon against primary ion energy.

δ-BN/ SOI substrate (the thickness of the surface silicon layer of the SOI wafer is 28 nm). The fabrication method, deposition system, and delta layer thickness of BN delta-doped layers are the same as in the references [1, 2]. SOI substrates were used to make samples for backside analysis [5]. The surfaces of some SOI substrates were amorphized by germanium ion implantation.

Four boron delta-doped layers were formed on a silicon substrate by MBE growth (Sample B). The 5-nm spacer layers were crystalline silicon.

SIMS experiments were performed using a Physical Electronics ADEPT1010 quadrupole SIMS instrument. Oxygen ions were used for the primary ion beam with oxygen flooding, and secondary ions of B^+ and Si^+ were detected. The impact energy values of the primary ions ranged from 350 eV to 1 keV. The incident angle was set at 45 degrees. The pressure of O_2 flooding was approximately 8×10^{-7} Torr. The SIMS conditions including ion current density for Sample A and Sample B were the same at each primary ion energy in order to compare sputtering rates and depth resolution parameters.

RESULTS AND DISCUSSION

Comparison of sputtering rates between amorphous and crystalline silicon

The sputtering rates for amorphous silicon fabricated by magnetron sputtering were calculated from sputtering time durations of SIMS boron profiles (primary ion energy of 350 eV to 1 keV) and the distance between two BN delta-doped layers of Sample A (Fig. 1). The distance was measured with a cross-sectional TEM image using the d_{111} distance of crystalline silicon for calibration. The sputtering rates of crystalline silicon were calculated using the first and fourth boron delta-doped layers of Sample B (Fig. 2). Boron and nitrogen concentrations of the BN delta-doped layers are less than 1 at% even at the peaks, and they do not influence the sputtering rates of the amorphous and crystalline silicon.

Figure 3 shows the ratios of sputtering rates for amorphous and crystalline silicon against primary ion energy. The ratios are constant for all primary ion energies tested, and the ratio (1.19) is significantly larger than 1, which means the sputtering rates for amorphous silicon are larger than those for crystalline silicon.

Comparison of depth resolution parameters between amorphous and crystalline silicon

Depth resolution parameters for amorphous and

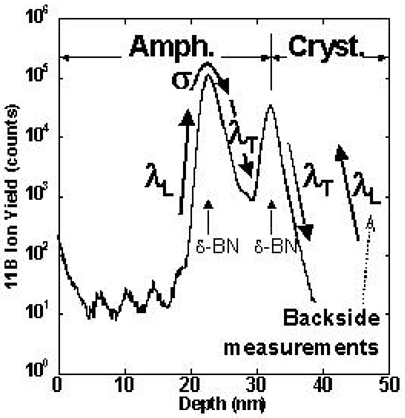

Fig. 4 SIMS boron profile of Sample A measured with 500 eV primary ion. Arrows indicate the positions where depth resolution parameters were extracted.

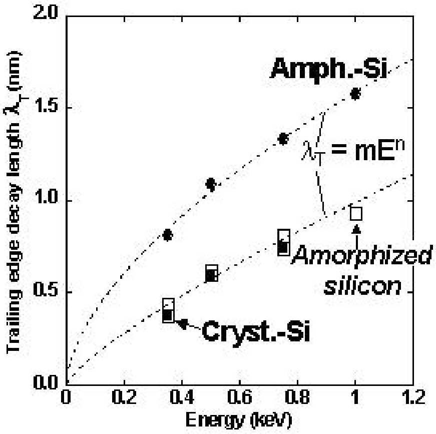

Fig. 5 Trailing edge decay lengths λT for amorphous silicon fabricated by magnetron sputtering (solid circles) and crystalline silicon (solid squares) against primary ion energy. The dashed lines are fitted with form mE^n for each element. Open squares indicate λT for silicon amorphized by germanium ion implantation.

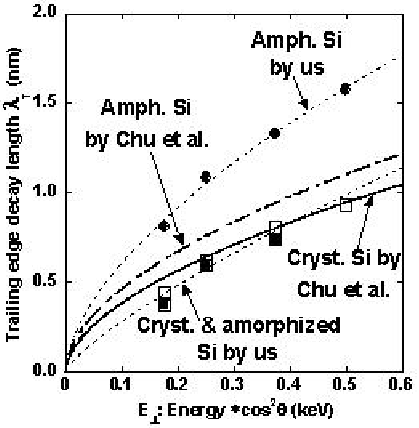

Fig. 6 Comparison of the trailing edge decay lengths λT estimated by Chu and Dowsett (dash-dot line: amorphous silicon formed by MBE, solid line: crystalline silicon)[4] and by this work. λT is plotted against the normal component of the primary ion energy ($E_\perp$: energy.cos$^2\theta$) to compare these results.

crystalline silicon were extracted by fitting the SIMS boron profiles (primary ion energy of 350 eV to 1 keV) of delta-doped layers of Sample A with Equation (1) [6, 7]. The equation is a convolution of the two exponentials for the exponential leading and trailing edges, with a Gaussian distribution, and it has three depth resolution parameters: the leading edge decay length λ_L, the trailing edge decay length λ_T, and the Gaussian broadening σ.

$$I(z)=\frac{C}{\lambda_L+\lambda_T}\left\{\begin{array}{l}(1+erf\xi_1)\exp\left[\dfrac{z-z_0}{\lambda_L}+0.5\left(\dfrac{\sigma}{\lambda_L}\right)^2\right]+\\(1+erf\xi_2)\exp\left[-\dfrac{z-z_0}{\lambda_T}+0.5\left(\dfrac{\sigma}{\lambda_T}\right)^2\right]\end{array}\right\} \tag{1}$$

$$\text{where } \xi_1=\frac{1}{\sqrt{2}}\left(-\frac{z-z_0}{\sigma}-\frac{\sigma}{\lambda_L}\right) \tag{2}$$

$$\xi_2=\frac{1}{\sqrt{2}}\left(\frac{z-z_0}{\sigma}-\frac{\sigma}{\lambda_T}\right) \tag{3}$$

Three depth resolution parameters for amorphous silicon were extracted from boron profiles of the BN delta-doped layer between amorphous silicon spacer layers of Sample A (Fig. 4). The trailing edge decay length λ_T and the leading edge decay length λ_L for crystalline silicon were extracted from the surface-side and backside boron profiles of the BN delta-doped layer at the amorphous-crystalline interface of Sample A (Fig. 4). Sample B was not used for estimating depth resolution parameters because the surface of the sample has many dimples with a depth of a few nm. In this study, the results of the trailing edge decay lengths λ_T are mainly discussed.

Figure 5 shows the trailing edge decay lengths λ_T for amorphous silicon fabricated by magnetron sputtering and for crystalline silicon against primary ion energy. The sputtering rate differences between amorphous silicon and crystalline silicon were taken into account. We don’t believe that the measured decay lengths are a result of diffusion of the BN delta-doped layers during their growth. Supporting evidence comes from backside boron profiles that have leading edge decay length λ_L with values below 0.2 nm for the BN layer at the amorphous-amorphous and amorphous-crystalline interfaces of Sample A. The λ_T values, especially for amorphous silicon, strongly depend on the primary ion energy. Surprisingly, the λ_T values for amorphous silicon are 1.6 - 2.0 times longer than those for crystalline silicon. The trailing edge decay lengths λ_T for silicon amorphized by Ge ion implantation were also measured (see the open squares in Figure 5). The values are identical to those for crystalline silicon. These results indicate the trailing edge decay lengths λ_T do not solely depend on the crystallinity of silicon.

Comparing Chu and Dowsett's result [4] and ours, the trailing edge decay lengths λ_T were re-plotted against the normal component of the primary ion energy in Figure 6. Our λ_T for crystalline silicon agrees well with theirs. However, our λ_T for amorphous silicon fabricated by magnetron sputtering is longer than theirs for amorphous silicon formed by MBE. The amorphous silicon films made by magnetron sputtering are unusual because it has a stronger influence on boron decay lengths than do amorphous silicon films by MBE or by Ge implantation.

Can the bn delta-doped multilayer be used as reference material?

Here we discuss whether the BN delta-doped multilayer developed by the Developing International Standards Project of the Japanese Standards Association [1] can be used as a reference material for sputtering rate estimation to calibrate the depth scale, and for depth resolution parameter estimation to optimize SIMS analysis conditions and to deconvolute SIMS depth profiles.

The sputtering rates for amorphous silicon fabricated by magnetron sputtering are larger than those for crystalline silicon, but the ratio of sputtering rates is independent of the primary ion energy. Therefore, sputtering rates for crystalline silicon can be obtained from the BN delta-doped multilayer reference materials using the constant sputtering rate ratio, and the depth scale for a shallow depth profile in crystalline silicon should be calibrated accurately. It is necessary to investigate sputtering rate ratios under other measurement conditions (for example, 0 degree bombardment).

The trailing edge decay lengths λ_T for amorphous silicon fabricated by magnetron sputtering are longer than those for crystalline silicon. The λ_T values for amorphous silicon are more sensitive to changes in the primary ion energy. The BN delta-doped multilayer reference materials do not give the λ_T for crystalline silicon, but the sensitivity to the primary ion energy, i.e., the ease with which ion mixing occurs may be effective for optimizing SIMS analysis conditions.

The ratios of trailing edge decay lengths λ_T for amorphous silicon fabricated by magnetron sputtering and crystalline silicon are not constant against the primary ion energy (see Fig. 5). Therefore, it is difficult to use the BN delta-doped multilayer reference materials to estimate depth resolution parameters for deconvolution of boron depth profiles in crystalline silicon.

The cause of the enhanced sputtering rate and trailing edge decay length for amorphous silicon fabricated by magnetron sputtering

Surface binding energy, bulk binding energy, displacement energy, and atomic density influence the sputtering rate and depth resolution parameters [8]. The density of deposited amorphous films is usually lower than that of crystalline material. The X-ray reflectivity of the amorphous silicon film fabricated by magnetron sputtering was measured, and the calculated density was 2.3 ± 0.5 g/cm^3. This value is not significantly different from the density of crystalline silicon (2.3283 g/cm^3). Therefore, the origin of the enhancement is not the density of the amorphous silicon.

For silicon amorphized by Ge ion implantation, in which Si-Si bonds were cut off, the trailing edge decay lengths λ_T are the same as those for crystalline silicon, and it is thought that the differences in binding energy and displacement energy between amorphous and crystalline silicon do not influence λ_T. In conclusion, the cause of the enhanced sputtering rate and trailing edge decay length for the amorphous silicon fabricated by magnetron sputtering has not been found. Further work is needed to solve this question and to improve the BN delta-doped multilayer.

CONCLUSION

The sputtering rates and depth resolution parameters from amorphous and crystalline silicon are compared in order to judge the propriety of using the BN delta-doped multilayer (amorphous silicon matrix fabricated by magnetron sputtering) as a reference material for SIMS shallow depth profiling. The sputtering rates for depth calibration in crystalline silicon can be obtained from the BN delta-doped multilayer using the constant sputtering rate ratio between amorphous and crystalline silicon. The trailing edge decay lengths for amorphous silicon are longer than those for crystalline silicon. The SIMS analysis conditions can be optimized using the BN delta-doped multilayer reference materials. However, the depth resolution parameters for deconvolution of the depth profiles cannot be estimated with the BN delta-doped multilayer reference materials. Improvement in the BN reference materials is needed.

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