Etch Control and SiGe Surface Composition Modulation by Low Temperature Plasma Process for Si/SiGe Dual Channel Fin Application

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ABSTRACT In this study, we discuss Si-SiGe etch characteristics as well as SiGe surface composition modification. It is required to etch Si and SiGe simultaneously for Si/SiGe dual channel Fin-FETs. Therefore, etch control of these two materials is desired. However, not only halogen chemistries but also physical sputtering etch SiGe selective to Si. We found that Si can be etched faster than SiGe by hydrogen plasma. Our analysis presents that hydrogen bonds selectively with Si rather than Ge, which leads to Si selective removal. As for SiGe surface modification, realizing Si-rich surface in SiGe is known to improve SiGe/high-k interface quality in advanced CMOS. It is also presented that the low-temperature hydrogen plasma induces Si-surface segregation (i.e., Si-rich surface) in SiGe, which is confined near the top-surface region. We proposed this may be caused by ion-energy-driven surface reaction. Our study also shows that Ge/Si ratio increases with plasma exposure time, which has correlation with surface roughness. Using the hydrogen plasma and conventional halogen plasma, we successfully demonstrate to etch Si/SiGe dual channel fins with depth and CD value control.

INDEX TERMS Hydrogen plasma, Si segregation, silicon germanium, interface trap density, FinFET.

I. INTRODUCTION

Logic CMOS device scaling still continues in order to further improve the device performance. In the past years, the MOSFET structure was changed from planar structure to Fin-type structure (FinFETs), which improved short-channel effects and led to higher drive current and lower leakage [1]–[3]. However, further miniaturization is getting more difficult as the gate length decreases down to less than 20nm because it requires very narrow fin width, which causes drive current deterioration. One of the promising candidates to further proceed the scaling is to replace conventional silicon (Si) channel by a new material with high carrier mobility, such as silicon germanium (SiGe) [4]–[5]. In sub-10nm process, SiGe is expected to be used for p-FET channel, while Si remains as a channel material for n-FET [5]–[6]. In terms of the anisotropic dry etching of the dual channel structure, Si and SiGe need to be etched simultaneously [7].

However, SiGe etch rate is faster than Si by not only halogen chemistries, but also physical sputtering [7]. Therefore, it is necessary to find an etching chemistry to obtain selective Si etch over SiGe.

As for electrical performance, interface trap density in SiGe/high-k interface deteriorates sub-threshold swing (SS) and carrier mobility. Although SiGe is superior to Si with respect to hole mobility, the interface is known to have large interface trap density. One of the methods to reduce the density is to modulate SiGe surface to be Si-rich [8]. Conventional ways to realize the Si-rich surface are epitaxial growth of Si cap over SiGe fin [9] and GeO_x scavenging by thermal annealing process [10]. These processes, however, require the use of high temperature, which may cause strain relaxation in SiGe channel [11] and Ge diffusion into Si [12]. Therefore, low temperature process to induce Si-rich surface is required in order to maximize the SiGe-base FET characteristics.

In this study, we introduce low temperature hydrogen plasma process. We found that the hydrogen plasma etches Si selective to SiGe. The etch mechanism between Si and SiGe is also discussed by utilizing Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) and X-ray Photoelectron Spectroscopy (XPS). It is shown that the hydrogen plasma, in combination with conventional halogen chemistries, can control Critical-Dimensions (CDs) and depths for the Si/SiGe dual channel pattern. We also found that this hydrogen plasma induces Si-rich surface by Si-surface segregation at the low temperature, which is limited only near the top-surface region. The segregation degree can be changed with different ion energies, which can be explained by ion energy deposition model. We also reveal the correlation between surface roughness and the plasma exposure time.

II. EXPERIMENT

In this study, we used Hitachi microwave electron cyclotron resonance (M-ECR) system. The source frequency and wafer bias frequency are 2.45 GHz and 400 kHz respectively in this system. A chamber has a shower plate through which process gases are introduced. A 300 mm wafer is fixed with electro-static chuck on an electrode, and the temperature of the wafer is controlled by back-side helium cooling system. This system was previously described in detail [13]. In this investigation, an epitaxially-grown $Si_{0.75}Ge_{0.25}$ film with (100) orientation on Si was used. Ar sputtering was used for native oxide removal. Wafer temperature and process pressure were maintained at 20 °C and 0.6 Pa respectively. The gas flow for different gases (Ar, Cl_2, HBr, SF_6, CF_4, and H_2) is set to be 150 ml/min for etch rate evaluation. The value of peak-to-peak voltage for the wafer bias is set to be 220V for this experiment.

III. RESULTS AND DISCUSSIONS – ETCH CHARACTERISTICS FOR SI AND SIGE

SiGe etch rate normalized by Si etch rate is shown in Fig. 1. The etch rate for SiGe is higher than that of Si, using halogen chemistries plasma (Cl_2, HBr, SF_6, and CF_4). Even physical sputtering by Ar plasma shows higher SiGe etch rate than Si etch rate. Several reasons are proposed to explain the selective SiGe etch over Si. It may be attributed to lower bonding energies of Si-Ge (3.12 eV) and Ge-Ge (2.84 eV) than Si-Si (3.25 eV) [14]. Another reason is that this may be caused by selective removal of high strained layer to stabilize the system, because epitaxial grown SiGe on Si is strained due to lattice mismatch [15]. The other reason is that because of narrower bandgap of SiGe, the electronic effect may lead to enhanced chemical reaction of SiGe etch [16]. In order to control SiGe-Si etch, a chemistry to etch Si selective to SiGe is necessary. In this study, it is found that hydrogen plasma etches Si selective to SiGe, as is shown in Fig. 1.

Figure 2 shows ion energy dependence of poly-Si and SiGe etch rate. Plasma potential and wafer potential were measured [17], and the difference was taken to give ion
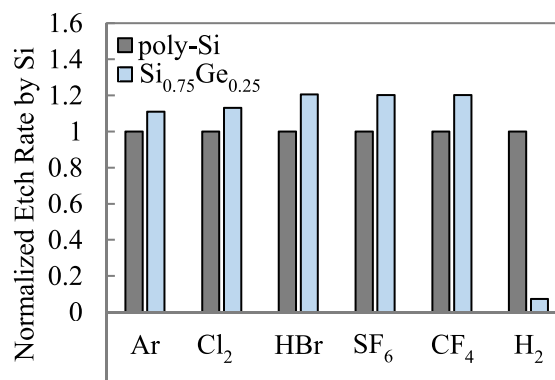

FIGURE 1. SiGe etch rate normalized by Si for different plasmas.
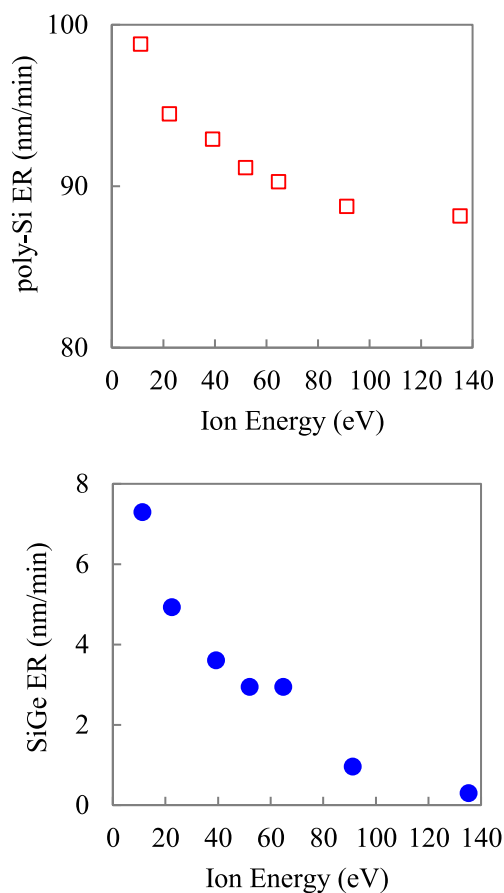

FIGURE 2. Dependence of poly-Si and SiGe etch rate on ion energy of hydrogen plasma.

energy. The maximum value of this quantity is used in Fig. 2. The result shows that both poly-Si and SiGe etch rate decrease with increasing ion energy. Generally, etch rate increases with higher ion energy [18], because incoming ion with high energy enhances etching. However, in the case of hydrogen plasma, the ions penetrate deep inside materials with little collision due to the small atomic radius (i.e., little sputtering effect). Thus, the etch rate trend is different from the conventional trend under hydrogen plasma. This
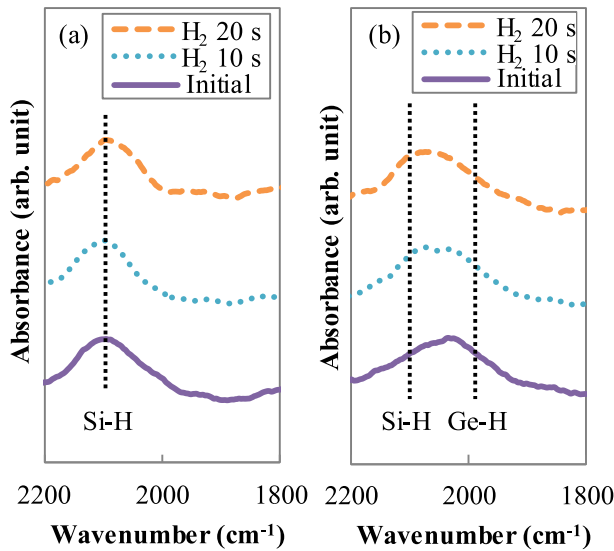
FIGURE 3. Absorbance spectra of (a) Si and (b) SiGe exposed to hydrogen plasma for 10 and 20 s.

	Profile w/ hydrogen plasma	Profile w/o hydrogen plasma
SEM		
CD (Si/SiGe)	31.8/ 32.5nm (Δ-0.7nm)	34.9/32.9 nm (Δ2.0nm)
Depth (Si/SiGe)	258.3/253.9nm (Δ4.4nm)	238.9/253.8nm (Δ-14.9nm)

FIGURE 4. SEM images of Si/SiGe dual channel fin profiles with and without hydrogen plasma.

etch trend (lower etch rate with higher ion energy) can be explained by the ion energy deposition model. It is proposed by Sigmund that each ion penetrates some distance below the surface along its trajectory, where the ion releases its energy following a Gaussian distribution [19]. Ion penetration depth is shallow at low ion energy, while ion penetration is deep at high ion energy. Therefore, ion energy is deposited near surface region when ion energy is low. The energy stored near the top surface can be used for chemical reactions to etch poly-Si and SiGe, which explains the result of higher etch rate with lower ion energy. The poly-Si etch rate decreases only by about 10 %, while SiGe etch rate decreases by about 95 %. This indicates that poly-Si etch rate is dominated by reactions with radicals, while SiGe etch rate is dominated by the enhanced reaction with the deposited ion energy. In both cases, ion energy deposition model is applicable to explain the etch rate trend with ion energy, but it's more obvious for SiGe. In the following analysis, lowest ion energy around 10eV is used.

In order to understand the Si-SiGe etch mechanism, we investigated Si and $Si_{0.5}Ge_{0.5}$ after hydrogen plasma exposure with ATR-FTIR. Fig. 3 shows absorbance spectra of Si and SiGe after the hydrogen plasma exposure for 10 s and 20 s. Stretching mode of Ge-H and Si-H peaks is assigned to 1980 and 2100 cm^{-1} respectively [20]–[21]. For Si surface shown in Fig. 3 (a), Si-H bond does not change after 10 s and 20 s of the hydrogen plasma exposure. On the other hand, for SiGe surface shown in Fig. 3 (b), the broad peak is found between Ge-H and Si-H bonds in the initial sample. The peak moves toward Si-H with increasing hydrogen plasma exposure time, meaning Si-H bond is selectively produced over Ge-H bond. The use of $Si_{0.5}Ge_{0.5}$ for this analysis, instead of $Si_{0.75}Ge_{0.25}$, was selected to emphasize the peak shift toward Si-H, since $Si_{0.75}Ge_{0.25}$ may not
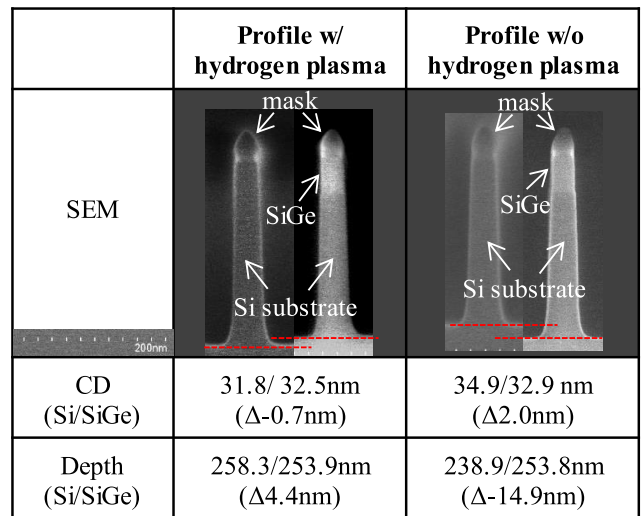
show the peak shift due to originally Si-rich sample. In terms of hydrogen-silicon reaction mechanism [22], SiH_4 is an etched byproduct, while SiH_x (x=1-3) are adsorption forms of hydrogen on Si surface. Therefore, the observed Si-H bonding is adsorbed hydrogen on Si.

The past studies of hydrogen reaction with SiGe show that hydrogen desorption occurs selectively on Ge sites rather than Si sites in SiGe surface [23]–[24]. Therefore, fewer Ge etched byproducts with hydrogen, GeH_x, are expected to be produced than Si etched byproducts with hydrogen, SiH_x. From this, it is considered that the etch mechanism of SiGe under hydrogen plasma is selective removal of Si over Ge. This also explains the etch rate suppression of SiGe under the hydrogen plasma.

Fig. 4 shows profile comparison of Si/SiGe dual channel fins with and without a hydrogen plasma in conjunction with halogen chemistry plasma. Delta, Δ, shown in the figure denotes a value subtracting CD or depth for Si from CD or depth for SiGe. The CD of the Si fin is larger than that of the SiGe fin, in case of the profile without the hydrogen plasma. The etched depth in the SiGe fin is deeper than that in the Si fin, as is expected from the result in Fig. 1. However, the opposite trend can be obtained by the use of the hydrogen plasma. The profile with the hydrogen plasma shows smaller Si fin CD compared to the SiGe fin as well as larger etched depth for the Si fin. Therefore, the etch rate control between Si and SiGe is achieved in both etch rate and fin profile by utilizing the hydrogen plasma.

IV. RESULTS AND DISCUSSIONS – SI SEGREGATION INDUCED BY LOW-TEMPERATURE HYDROGEN PLASMA

In order to understand the surface condition, XPS analysis was also conducted for 50 nm SiGe film on Si after hydrogen plasma exposure. The results of XPS spectra for Si 2p and Ge 3p are shown in Fig. 5. 10° of take-off angle (TOA) from the surface (i.e., grazing angle near the surface) is used.
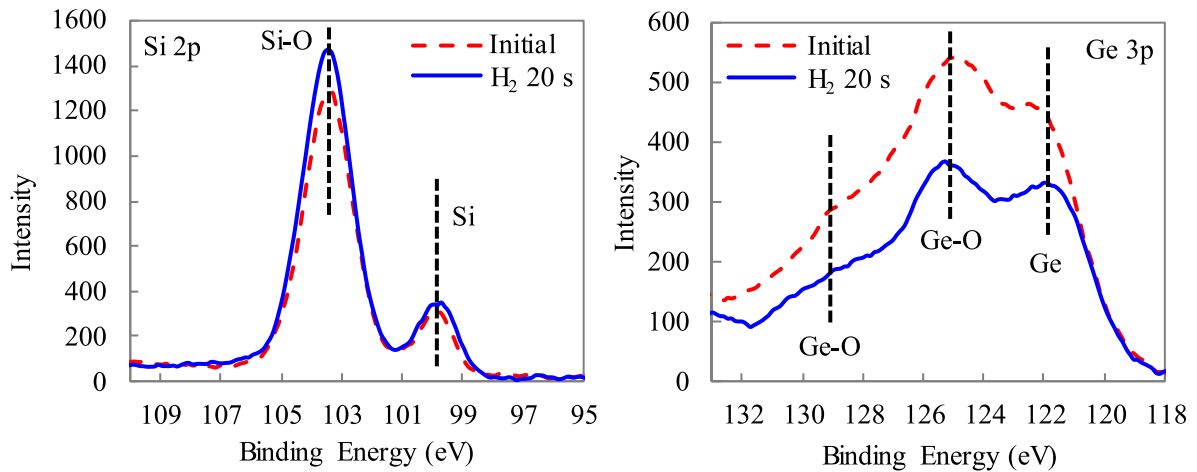
FIGURE 5. XPS Spectra for Si 2p and Ge 3p with 10° of take-off angle from the surface with and without hydrogen plasma exposure.
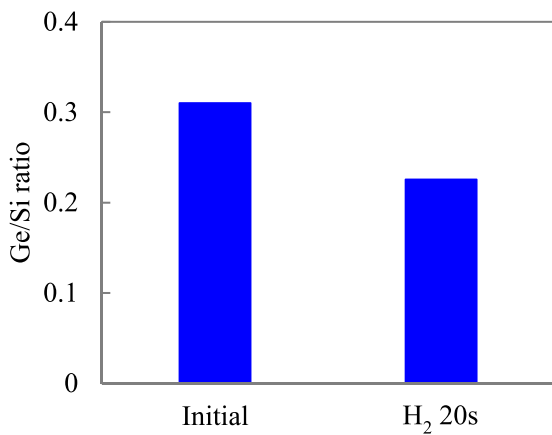

FIGURE 6. Ge/Si ratio of SiGe by XPS before and after hydrogen plasma exposure.

FIGURE 7. Schematics of epitaxially-grown SiGe film on Si etched by hydrogen plasma.

FIGURE 8. H_2 time dependence of SiGe film remaining thickness and Ge/Si ratio.

Fig. 5 shows that Si-O and Si peak increase, while Ge-O and Ge peak decrease, after hydrogen plasma exposure for 20 s. This indicates that Si-rich surface is induced by the hydrogen plasma. In order to confirm that, the stoichiometry change in SiGe surface was investigated in Fig. 6. The Si 2p and Ge 3p were utilized to obtain Ge/Si ratio [16], because photoelectrons have similar kinetic energy and escape depth of 2.5 nm [25]. The Ge/Si ratio decreases after the hydrogen plasma exposure for 20 s. Thus, Si-rich surface is found after the plasma exposure. Based on the etch mechanism of SiGe with hydrogen plasma described above, Si is selectively removed out of SiGe surface. However, the surface becomes Si-rich. This seems contrary to the etch mechanism described in previous section, but can be explained by hydrogen-plasma-induced Si segregation.

In order to verify the Si segregation, we conducted the following experiment. Epitaxially-grown SiGe film on Si substrate was etched by hydrogen plasma down into the Si, as is shown in Fig. 7. Fig. 8 shows the SiGe film remaining w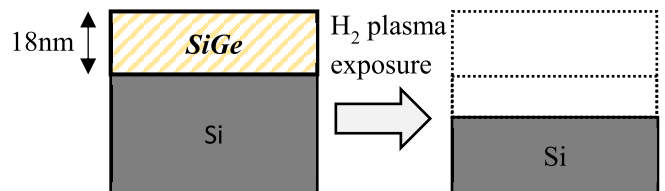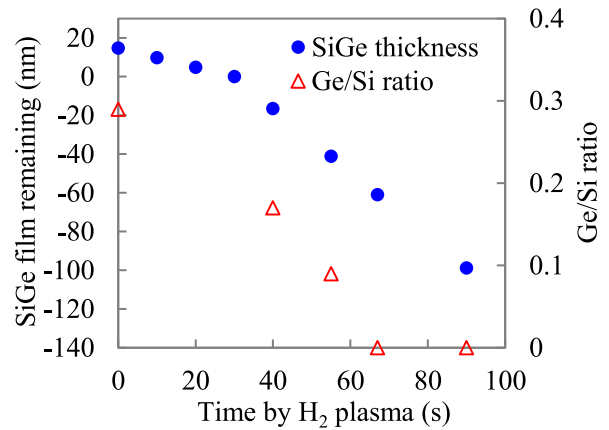ith different hydrogen plasma exposure times. The Ge/Si ratio is also shown in Fig. 8. The negative value in the SiGe film remaining corresponds to the depth etched into the Si substrate. After 55 s of hydrogen plasma exposure, SiGe film is completely etched, and 40 nm of the Si under the SiGe film is also etched. However, the Ge/Si ratio is still shown to be positive value, indicating Ge diffuses into the Si substrate. In Si segregation, Si is replenished to the SiGe surface, while Ge is pushed down into bulk region. Therefore, the Ge remaining after complete removal of SiGe film indicates that Si segregation is induced by the hydrogen plasma. The Si segregation is induced because Si-H bond formation
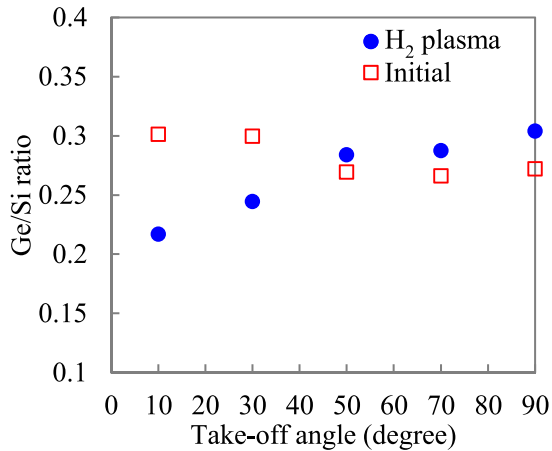
FIGURE 9. Ge/Si ratio in SiGe with different take-off angles by XPS.

FIGURE 10. Ion energy dependence of Ge/Si ratio in SiGe after hydrogen plasma exposure by XPS.

FIGURE 11. Plasma exposure time dependence of Ge/Si ratio.

at the surface is energetically favorable to Ge-H bond [26]. This leads to Si-rich surface after the hydrogen plasma exposure. However, it is known that Si segregation is observed at high temperature above 250 °C by atomic hydrogen [26]. In this study, we found that hydrogen plasma also causes Si segregation at the temperature as low as 20 °C. It is obvious that the plasma energy is a driving force of this segregation. This low-temperature hydrogen plasma process gives an advantage to avoid thermally activated behavior such as atomic diffusion at high temperature. These analyses were done with SiGe (100). However, it is worth discussing the case of SiGe (110) surface, because SiGe (110) is exposed as a sidewall of SiGe fin and acts as a dominant channel surface of SiGe FinFET. Since the mechanism of Si segregation phenomenon is attributed to the different bonding energy between Si-H and Ge-H, it is expected that Si segregation can be still observed at (110) surface orientation.

To understand the segregation thickness, Ge/Si ratio in SiGe after hydrogen plasma exposure for 20 s was investigated as a function of take-off angles by XPS, shown in Fig. 9. The initial sample has slightly higher Ge/Si ratio for TOA of 10° and 30° (top surface region). This slightly higher Ge/Si ratio near the surface might be related to Ge segregation during the SiGe epitaxial growth [27]. The Ge/Si ratio decreases after the plasma exposure for TOA of 10° and 30°. This indicates that the thickness of Si segregation is confined near top-surface region. Based on the escape depth of the photoelectron described above, the thickness of the Si-rich layer is estimated to be about 1.3 nm. On the other hand, the Ge/Si ratio in the data for 50° or higher, increases after the plasma exposure. This may prove that Si underneath the top-surface diffuses upwards, to the surface, and the Ge originally on the surface is pushed below. Therefore, it is also presented that Si segregation occurs only near the SiGe surface layers by this hydrogen plasma.

Fig. 10 shows ion energy dependence of Ge/Si ratio by XPS with TOA of 10° after hydrogen plasma exposure for
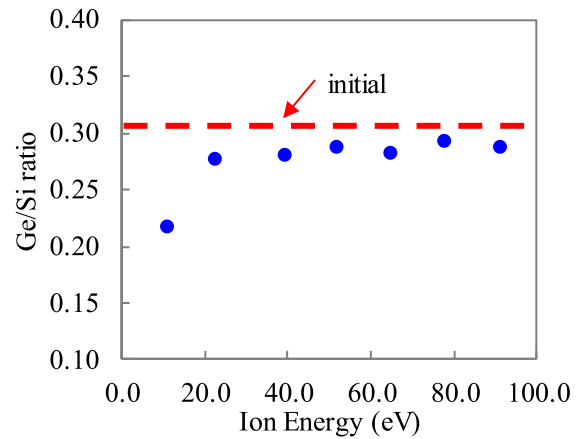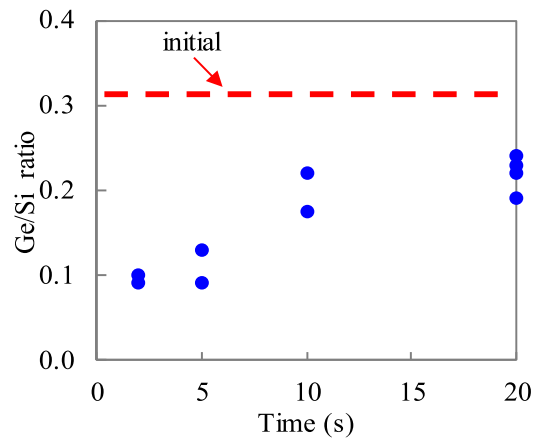
20 s. The dashed line shows the Ge/Si ratio of an initial sample. Only the lowest ion energy around 10 eV decreases Ge/Si ratio, while all other data shows little change of the Ge/Si ratio from initial. This means that Si segregation is induced when ion energy is very low. This may be also explained by the ion energy deposition model described in Fig. 2, meaning that ion energy deposited near the surface is utilized for not only etch rate enhancement but also Si segregation.

The time dependence of Ge/Si ratio with hydrogen plasma exposure is shown in Fig. 11. The dashed line represents the Ge/Si ratio of an initial sample. As the plasma exposure time increases, the Ge/Si ratio increases. The ratio for 10 s and 20 s almost saturated. Si segregation is caused even at 2s of the hydrogen plasma exposure. In Fig. 12, the SiGe surface condition with different plasma exposure times was also investigated by tilt view of Scanning Electron Microscopy (SEM). The plasma exposure times were changed from 2 s, 10 s, and 20 s. The surface condition with the exposure time of 2 s is very similar to initial in Fig. 12. However, as the exposure time increases to 10 s and 20 s, the surface gets rougher. This
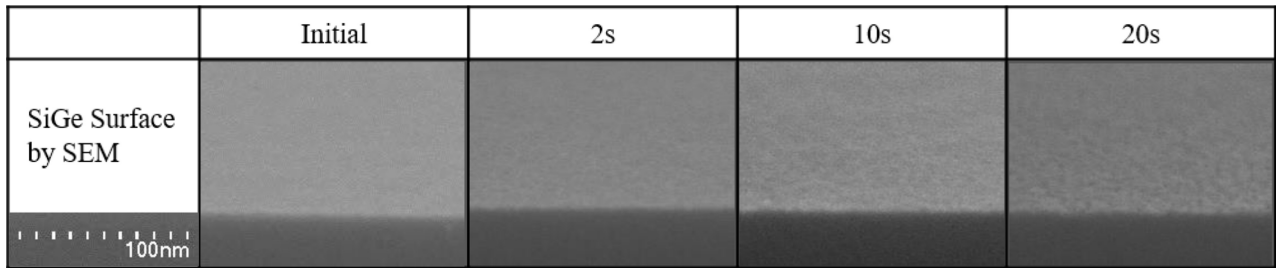
FIGURE 12. Tilted images from SEM of SiGe surface with different exposure times to hydrogen plasma.

may indicate that the rough surface exposes Ge underneath Si-rich top surface induced by Si segregation, which leads to the increase of the Ge/Si ratio. In order to maximize the electrical performance, Si-rich top surface is required to achieve low interface trap density at SiGe/high-k interface. We hereby successfully developed a low-temperature hydrogen plasma to induce Si-rich surface by Si segregation. However, ion-radical separation test may be necessary as a future study, in order to fully understand the mechanism of Si segregation and surface roughness.

V. CONCLUSION

In this study, Si-SiGe etch control was investigated for the application of Si/SiGe dual channel fin patterning. It is presented that not only halogen chemistries but also physical sputtering etches SiGe selective to Si, while hydrogen plasma etches Si selective to SiGe. This is because the Si-H bond formation is energetically favorable to Ge-H bond formation, that is, surface Ge would prevent the etch byproduct formation. We also proposed an ion energy deposition model to explain etch rate decrease with increasing ion energy. By utilizing the developed etch chemistries, the difference of CDs and etched depths for Si and SiGe fins were controlled from positive to negative values. During this investigation, it is also shown that this low-temperature hydrogen plasma induces Si segregation on SiGe surface. This is also due to the energetically favorable hydrogen-bonded Si surface. Even though the Si-rich layer is formed, etching is still prevented since keeping the Si-rich layer is energetically stable compared to SiGe surface. The Si-rich layer is found to be limited near the top surface. We also presented that low ion energy with short time plasma exposure is necessary to maximize Si-rich surface, which is useful to minimize interface trap density at Si/high-k interface in terms of electrical performance.

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