Atomically Flat Germanium (111) Surface by Hydrogen Annealing

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In silicon (Si) MOSFET technology, the surface planarization is quite important in terms of morphology control for non-planar FETs, mobility enhancement at high carrier density and reliability improvement of gate dielectrics. Sacrificial oxidation[1], wet chemical treatment[2], argon (Ar) or hydrogen (H_2) gas annealing[3,4] has already been reported. Although, in germanium (Ge) MOSFET technology, the surface planarization should also be critically important, an ultra high vacuum process has been only reported to form the atomically flat surface. In this work, we report the impact of H_2 annealing on the planarization of Ge (111) surfaces which is a key orientation in terms of the lowest conductive effective mass in n-MOSFET.

First, the impact of H_2 annealing on the structure and morphology of as-cleaned surface is discussed. We used (111)-oriented Ge wafers. Ge substrates were cleaned with methanol, 7% HCl and 2% HF at room temperature. The roughness of as-received and as-cleaned surface was analyzed by an atomic force microscope (AFM). The roughness root mean square (RMS) in a 1 x 1 μm^2 area was estimated to be roughly 0.2~0.3 nm. Following the chemical cleaning, the pure H_2 (99.999 vol.%) annealing at 350~750^{o}C for 15 min was performed. The surface structure on Ge (111) was drastically changed in the H_2 annealing above 500^{o}C. As shown in the AFM images of **Fig. 1**, the step and terrace structure is clearly observed on the (111) surface. The step structure formed by H_2 annealing is composed of a single step on (111) which is equal to 0.33 nm. **Figure 2** shows the height distribution on a single terrace on H_2 annealed surface is significantly narrower than that on chemically cleaned surface. The RMS roughness at 100 x 100 nm^2 on a single terrace is estimated to be the 0.05 nm which is almost comparable to the detection limit of the present AFM system. Therefore, it is expected that the surface on a single terrace is really atomically flat.

Second, the terrace width controllability is discussed.

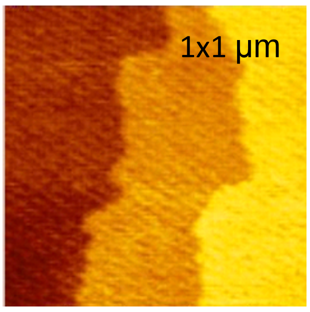

Fig. 1 AFM image in 1x1 µm region on Ge (111) surface in H_2 annealing at 650^{o}C. Each step is detected with a single step with 0.33 nm height difference on Ge (111).

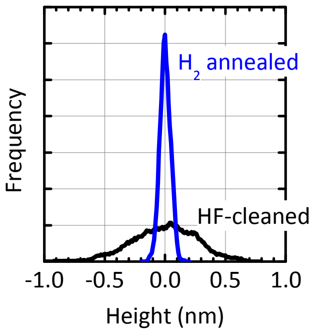

Fig. 2 Comparison of the height distribution histograms on Ge (111) in 100 x 100 nm region between in H_2 annealing and conventional chemical cleaning.

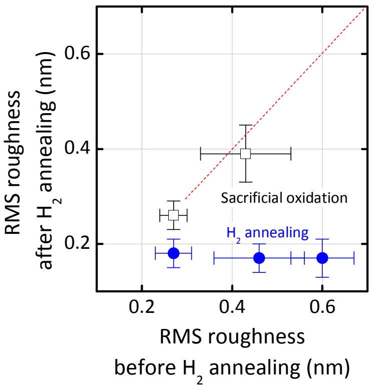

Fig. 3 The relation between the surface roughness RMS in 1 x 1 µm region before and after H_2 annealing at 650^{o}C. The results in the sacrificial oxidation by high pressure oxidation at 550^{o}C followed by 400^{o}C O_2 annealing are also shown for comparison (Ref. 6).

We also investigated the effect of off-angle on the step and terrace structure. Ge (111) substrates with various off-angles were annealed in H_2 at 650^{o}C. A good correlation was also detected between the surface tilt-angle calculated from the step density of AFM image and the off-angle of substrates determined by the precise X-ray diffraction measurement. This fact indicates that the terrace width on (111) surface is controllable predominantly by the off-angle of initial surface, and that no step bunching which is observed on Si (111) surface has been observed [5].

Third, the effect of H_2 annealing on the surface planarization of process-induced surface roughness is shown. After the chemical cleaning, the surface roughness of Ge substrate was intentionally increased by immersing into 30% H_2O_2, followed by removing the grown chemical oxide by 2% HF. By the roughening treatment, the RMS surface roughness in the 1 x 1 µm region was increased up to 0.6 nm from ~0.3 nm. **Figure 3** shows the surface roughness of Ge substrates before and after the H_2 annealing at the typical temperature of 650^{o}C. The Ge(111) surface exhibited the single step and terrace structure, irrespective of the large RMS values before the H_2 annealing. Therefore, the roughness RMS values are effectively reduced down to below 0.2 nm, in contrast to the case of sacrificial oxidation[6].

Finally, atomically flat surface mechanism is discussed. Etching and migration should be associated with the planarization. We experimentally estimated the etching process of Ge by H_2 annealing of Al_2O_3 line/space patterns formed on the Ge substrate after the H_2 annealing. The Ge was little consumed at 700^{o}C in 15 min in H_2 at least. Therefore, it is conjectured that the atomically planarization by H_2 annealing is dominantly achieved by the migration enhancement of Ge atoms in H_2 at relatively low temperature of around 500^{o}C.

The impact of H_2 annealing on the planarization of Ge surface was studied. The atomically flat surface on Ge (111) can be achieved only by H_2 annealing. Thus, the H_2 annealing is quite beneficial for the scaled Ge CMOS technology.

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Reference

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