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Ge(110),(100)面の水素アニールによる原子レベル平坦化

Atomically Flat Planarization of Ge (110) and (100) Surface by H_2 Annealing

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【Background】 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 [1] and reliability improvement of gate dielectrics [2]. Therefore, the control of germanium (Ge) surface should also be critically important for Ge MOSFET technology. We have already reported the atomically flat surface formation on Ge (111) surface by H_2 annealing [3]. In this work, we report the H_2 annealing on the planarization of (100) surface and (110) one. The former one is the most conventional orientation in the industry in Si, and the later one is a key orientation in terms of the lowest conductive effective mass in p-MOSFET.

【Experimental】 Ge (110) and (100) substrates were cleaned by methanol, diluted-HCl and diluted-HF sequentially. After the chemical cleaning, the H_2 annealing was performed at 450-850^{o}C for 15min. The detail of H_2 annealing was described elsewhere [3]. The surface structure and roughness were measured by atomic force microscopy (AFM).

【Results and Discussion】 The roughness root mean square (RMS) at 1 x 1 μm^2 of chemically cleaned Ge (110) and (100) were estimated to be 0.2 and 0.3 nm, respectively. The roughness RMS of (110) surface was slightly better than that of (100) surface. Atomically flat surface with the step and terrace structure is observed on Ge(110) in H_2 annealing above 500^{o}C as shown in **Fig. 1(a)**, which is similar to the (111) surface [3]. The almost step consists of the single step (= 0.20 nm). Whereas, to obtain the step and terrace structure on Ge (100) surface, the annealing temperature above 700^{o}C is needed. Typical AFM image of (100) surface with step and terrace structure is shown in **Fig. 1(b)**. Alternate straight and rough step structure is same as the single S_a and S_b steps observed on Si (100) surface annealed in H_2 or in Ar [4]. The step on (100) surface is also composed by the single step (= 0.14 nm).

The difference of the lowest annealing temperature to form atomically flat surface between (110) and (100) is next discussed. Considering the low surface energy of H-terminated and reconstructed Ge (100) which are comparable to those of (110) and (111) [5], it might be due to the surface orientation dependence of planarization kinetics or the difference of initial roughness before H_2 annealing. We verified the latter one with intentionally roughened (110) and (111) surfaces by H_2O_2. Although the roughness RMS values were ~1 nm on (110) and ~0.6 nm on (111) before the H_2 annealing, the step and terrace structure were clearly observed after the H_2 annealing at 650^{o}C for 15 min irrespective of the initial RMS in the range of this work. This result suggests that the planarization on (100) is quite slow compared with those on (111) and (110) and it is speculated that the Ge etching in H_2 atmosphere above 700^{o}C [3] much accelerates the surface planarization on (100).

【Conclusion】 Atomically flat Ge (110) and (100) surfaces are realized by H_2 annealing for 15 min above 500 and 700^{o}C, respectively.

【Reference】[1] J. Koga et al., IEDM 1994. [2] R. Kuroda et al., JJAP **48**, 04C048 (2009) [3] T. Nishimura, et al., APEX **5**, 121302 (2012). [4] L. Zhong et al., PRB **54**, R2304 (1996). [5] A. A. Stekolnikov et al., PRB **65**, 115318 (2002).

(a) Ge (110) 600^{o}C 1x1um^2　(b) Ge (100) 850^{o}C 1x1um^2

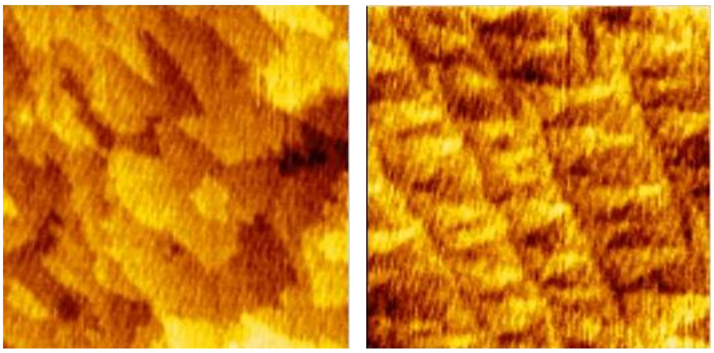

Fig. 1 (a) AFM image of Ge (110) surface at 1 x 1 μm^2 in H_2 annealing at 600^{o}C. A step and terrace structure is clearly observed. (b) AFM image of Ge (100) surface at 1 x 1 μm^2 in H_2 annealing at 850^{o}C. Characteristic alternate straight and rough steps are observed.