Characterization of Local Strain Structures in Heteroepitaxial $Ge_{1-x}Sn_x$/Ge Microstructures by using Microdiffraction Method

S. Ike[1], Y. Moriyama[2], M. Kurosawa[1,3], N. Taoka[1], O. Nakatsuka[1], Y. Imai[4], S. Kimura[4], T. Tezuka[2], and S. Zaima[1]
[1]Graduate School of Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[2]Green Nanoeletronics Center, AIST, West 7A, Onogawa 16-1, Tsukuba 305-8509, Japan
[3]Research Fellow of JSPS
[4]Japan Synchrotron Radiation Research Institute/SPring-8 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan

Strained Ge is one of attractive candidates for channel material of high-speed and low-power metal-oxide-semiconductor field effect transistors (MOSFETs). The effective hole mobility of Ge(001) channel with a uniaxial compressive strain of 1% is expected to transcend that of conventional strained-Si(001) channel [1]. We are focusing on $Ge_{1-x}Sn_x$ as a source/drain (S/D) stressor for a uniaxial compressive strained Ge in the same manner as strained Si channel p-MOSFET with $Si_{1-y}Ge_y$ S/D [2]. Eutectic alloy $Ge_{1-x}Sn_x$ has a larger lattice constant than that of Ge, and we can control its lattice constant with the Sn content. In order to induce a uniaxial compressive strain of 1%, a substitutional Sn content of at least 5% is required for $Ge_{1-x}Sn_x$ stressor [3]. However, Sn precipitation from the $Ge_{1-x}Sn_x$ layer easily occurs due to the very low equilibrium solid solubility of Sn as low as 1% into Ge. Thus, $Ge_{1-x}Sn_x$ layers must be grown locally at S/D regions without dislocations and Sn precipitations. Previously, we reported the growth of a fully strained Ga-doped $Ge_{0.922}Sn_{0.078}$ blanket layer on Ge(001) without any dislocations and stacking faults was achieved by using molecular beam epitaxy (MBE) method [4]. On the other hand, the local growth of $Ge_{1-x}Sn_x$ at S/D regions and the local strain structure in $Ge_{1-x}Sn_x$/Ge microstructures have not been clarified in detail yet. In this study, we examined the formation of $Ge_{1-x}Sn_x$/Ge microstructures and investigated the microscopic local strain structure in Ge and $Ge_{1-x}Sn_x$ by using synchrotron x-ray microdiffraction [5, 6].

A SiO_2 thin layer on a Ge(001) substrate was patterned into line/space (= 1/1 μm) structure parallel to the [110] direction of Ge. Subsequently, 370 nm-depth Ge S/D structures were formed with anisotropic wet etching. After chemical and in-situ thermal cleaning of the substrate, a 490 nm-thick $Ge_{1-x}Sn_x$ (x=5.3%) layer was grown on the patterned Ge substrate at 150˚C by using MBE system. Post deposition annealing (PDA) was performed at 500˚C for 30min in N_2 ambient. Scanning electron microscope (SEM) and transmission electron microscope (TEM) were used to observe the sample structures and characterize the crystallinity structures of $Ge_{1-x}Sn_x$ layers, respectively. The x-ray microdiffraction two dimensional reciprocal space mapping (XRMD-2DRSM) was performed at BL13XU in SPring-8 to analyze the local strain structure in the Ge and locally grown $Ge_{1-x}Sn_x$. A synchrotron radiation light with an energy of 8 keV was used, and the light was focused on the samples with a beam area size of 0.48×0.28 μm^2.

From the SEM and TEM observation of the prepared $Ge_{1-x}Sn_x$/Ge structure, $Ge_{1-x}Sn_x$ deposited on SiO_2 is found to be polycrystalline structure, while $Ge_{1-x}Sn_x$ on Ge recess regions is epitaxially grown, that indicates the locally epitaxial growth of $Ge_{1-x}Sn_x$ at S/D regions.
From the result of XRMD-2DRSM around the $Ge_{1-x}Sn_x$ 004 reciprocal lattice point, the diffraction pattern from the $Ge_{1-x}Sn_x$ S/D regions fluctuates depending on the irradiated position and inclines to the ω-direction, while that from the blanket $Ge_{1-x}Sn_x$ layer appears just aligns to the Ge 004 peak. It is considered that tilting of the $Ge_{1-x}Sn_x$ occurs due to the local crystal deformation, in other words, the elastic strain relaxation of $Ge_{1-x}Sn_x$ in the microscopic S/D region. The fluctuation of the tilt angle of $Ge_{1-x}Sn_x$ 004 diffraction peak was estimated to be between −0.13˚ and 0.12˚ for the as-grown sample. Moreover, through analyses of the Ge $2\theta/\omega$ diffraction with various irradiated positions for the samples before and after PDA, we can see not only the signal of the diffraction related to bulk-Ge but also the additional diffraction related to the strained Ge for the both samples. Especially for the sample after PDA, from the elastic theory for anisotropically strained structure [7], we estimated the maximum value of the in-plane uniaxial compressive strain to be 0.19% near the $Ge_{1-x}Sn_x$/Ge edge. This value agrees roughly with an average strain value expected by a finite element method (FEM) simulation [8, 9] considering the penetration depth of x-ray in Ge. These results suggest that x-ray microdiffraction measurement can reveal the strain structure buried in $Ge_{1-x}Sn_x$/Ge microstructures with sub-micron scale resolution without destructive method for samples.

In summary, we examined the formation of locally strained $Ge_{1-x}Sn_x$/Ge microstructures with low temperature MBE method. We have investigated the microscopic local strain structure in Ge and $Ge_{1-x}Sn_x$ by using synchrotron x-ray microdiffraction. We achieved the local heteroepitaxial growth of $Ge_{0.947}Sn_{0.053}$ on the recess regions. Local stain relaxation in $Ge_{1-x}Sn_x$ S/D regions occurs. We revealed that the maximum in-plane uniaxial compressive strain of 0.19% is locally induced in Ge. In our presentation, we will also report the comparison of crystallinity and strain structure between various S/D sizes of $Ge_{1-x}Sn_x$/Ge structures.

This research is funded by the JSPS through the FIRST Program initiated by the CSTP. The synchrotron radiation experiments were performed at SPring-8 with the approval of JASRI as Green/Life Innovation proposal (No. 2012B1783/BL13XU) and general proposal (No. 2013A1682/BL13XU).

References

[1] T. Krishnamohan et al., IEDM Proc., 899 (2008).
[2] C. Auth et al., VLSI Sym. Tech. Dig., 128 (2008).
[3] B. Vincent et al., Microelectronic. Eng., **88**, 342 (2010).
[4] Y. Shimura et al., Thin Solid Films **520**, 3206 (2012).
[5] S. Takeda et al., Jpn. J. Appl. Phys. **45**, L1054 (2006).
[6] Y. Imai et al., AIP Conf. Proc. **1221**, 30 (2010).
[7] K. Arimoto et al., J. Appl. Phys. **104**, 063512 (2008).
[8] Y.-C. Yeo et al., Appl. Phys. Lett. **86**, 023103 (2005).
[9] T. Benabbas et al., J. Appl. Phys. **86**, 1945 (1999).