Characterization of local strain in $Ge_{1-x}Sn_x$ / Ge fine structures by using microdiffraction

New technology, which enhances the carrier mobility in metal-oxide-semiconductor field-effect transistors, has attracted interest for improving the performance of future-generation ultra-large-scale integrated circuits (ULSIs) [1]. $Ge_{1-x}Sn_x$ as a source/drain stressor is one of the promising candidates for enhancing hole mobility while realizing uniaxial compressive strain in a Ge channel [2]. The precise estimation and control of local strain in a nanoscale region are required in order to design ULSIs and control the mobility. Microdiffraction using synchrotron radiation provides not only high reciprocal space resolution but also high real space resolution with up to sub-μm resolution [3,4]. In this study, we examined the formation of a Ge fine line structure sandwiched with epitaxially grown $Ge_{1-x}Sn_x$ as a source/drain stressor, and demonstrated microdiffraction analysis of the local strain structure in an individual Ge fine line whose width was as small as 25 nm [5].

We prepared Ge fine line structures with widths of 25, 35, and 60 nm by using SiO_2 hard mask layer and a lithography technique. After chemical and thermal cleaning, a 130-nm-thick $Ge_{1-x}Sn_x$ epitaxial layer with a Sn content of 2.9% or 6.5% was epitaxially grown on the recess region by molecular beam epitaxy at a substrate temperature of 150°C or 200°C, respectively. Microdiffraction measurement was performed at beamline **BL13XU** to analyze the local strain structure of Ge and $Ge_{1-x}Sn_x$. Synchrotron radiation light with an energy of 8 keV ($\lambda = 0.154980$ nm) was used, and an incident X-ray microbeam was focused on the sample using a Fresnel zone plate with a narrow slit. The exposed area of the incident microbeam was estimated to be 0.38×0.26 to 0.82×0.26 μm².

Figure 1(a) shows a bird's-eye view scanning electron microscope (SEM) image of a sample. Blue arrows in the figure schematically indicate an incident and diffraction X-ray microbeam. The typical size of the incident microbeam spot is also shown with a yellow ellipse in the figure. The incident microbeam position was moved with a 50 nm step at each reciprocal space mapping. Figure 1(b) shows a cross-sectional transmission electron microscope (TEM) image of a Ge/$Ge_{1-x}Sn_x$ fine line structure. The epitaxial growth of $Ge_{1-x}Sn_x$ layers sandwiching a Ge fine line was observed.

Figure 2(a) shows a typical microdiffraction reciprocal space map for 60-nm-wide Ge fine lines sandwiched with $Ge_{0.935}Sn_{0.065}$ stressors at the microbeam position on a Ge fine line structure. The Bragg reflection corresponding to not only $Ge_{1-x}Sn_x$ 004 but also strained Ge can be clearly observed in the reciprocal space map. Figure 2(b) shows a contour map of the intensity of Ge and $Ge_{1-x}Sn_x$ 004 Bragg reflections obtained by scanning the microbeam position. We can observe the Bragg reflection of strained Ge 004 from each individual Ge fine line.

Figure 3 shows contour maps of Ge and $Ge_{1-x}Sn_x$ 004 Bragg reflections obtained by scanning the microbeam position for Ge fine line samples with various-width. As the line width shrinks, the shift of the peak position related to the strained Ge Bragg reflection is clearly observed, which indicates increasing magnitude of the strain with decreasing width of the Ge fine line. The strain distribution in the fine structure was calculated by the finite element method (FEM), and the line width dependence of the strain observed in the microbeam diffraction experiment was in good agreement with the FEM calculation result. The maximum out-of-plane strain was estimated to be 0.8% for a 25-nm-width Ge fine line by using microdiffraction. Considering the FEM calculation, a uniaxial compressive strain of 1.4% is expected for the in-plane direction in this Ge line.

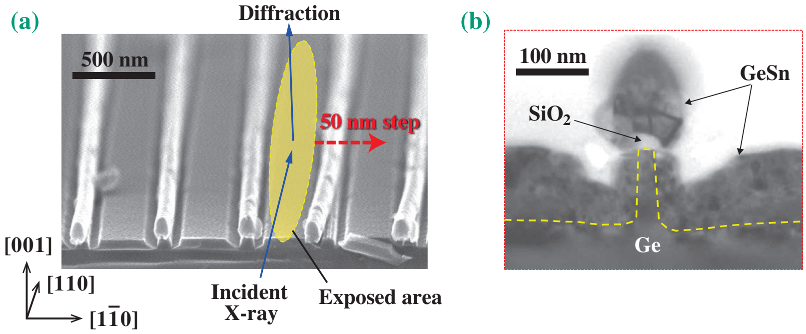

Fig. 1. **(a)** Bird's-eye view SEM image of a sample. A schematic of the incident and diffracted microbeam is superimposed. **(b)** Cross-sectional TEM image of a Ge/$Ge_{1-x}Sn_x$ fine line structure.

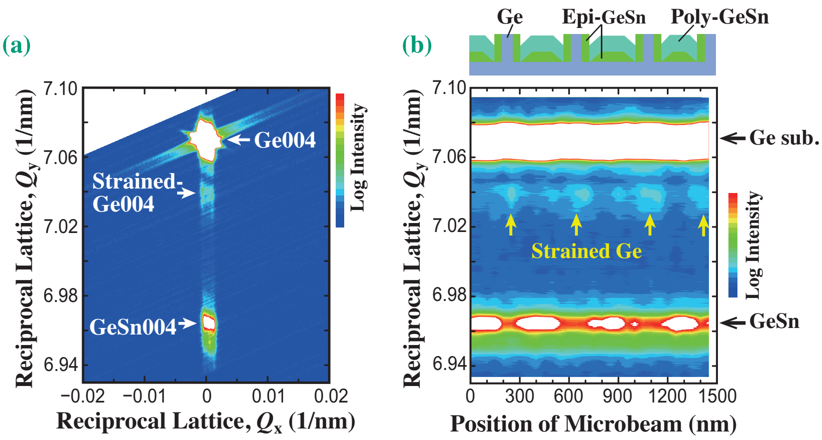

Fig. 2. **(a)** Typical microdiffraction reciprocal space map at the microbeam position on a Ge fine line structure. **(b)** Contour map of the intensity of Ge and $Ge_{1-x}Sn_x$ 004 Bragg reflections obtained by scanning the microbeam position for 60-nm-wide Ge fine lines sandwiched with $Ge_{0.935}Sn_{0.065}$ stressors. The diffraction signals from Ge substrate, strained Ge, and $Ge_{1-x}Sn_x$ layer are indicated with arrows.

In summary, we examined the formation of $Ge_{1-x}Sn_x$/Ge fine structures and investigated in detail the local strain with submicron resolution by microdiffraction measurement and the FEM. We successfully formed a locally strained Ge fin structure sandwiched with epitaxially grown $Ge_{1-x}Sn_x$. The microdiffraction revealed an anisotropic local strain in an individual Ge fine line structure with a width as small as 25 nm. Microdiffraction enables direct observation of the local strain structure with high spatial and strain resolution in submicron-scale semiconductor devices in future nanoelectronic applications.

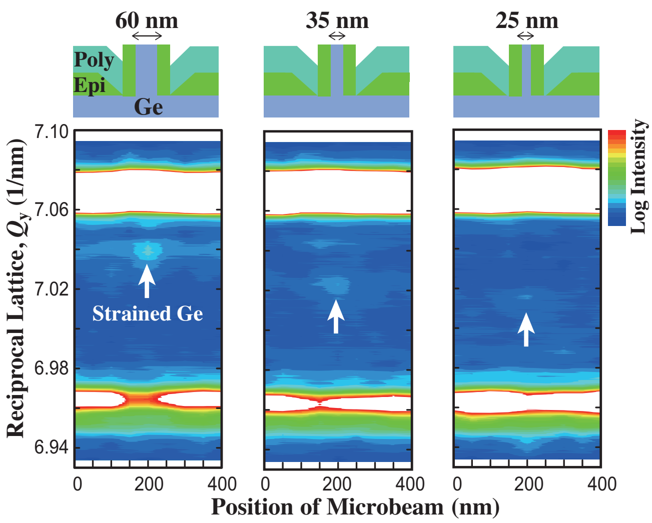

Fig. 3. Contour maps of Ge and $Ge_{1-x}Sn_x$ 004 Bragg reflections as a function of the microbeam position for Ge fine lines with various-widths. The diffraction signals from strained Ge are indicated with white arrows.

Osamu Nakatsuka[a,*], Shinichi Ike[a,b] and Shigeaki Zaima[a,c]

[a] Graduate School of Engineering, Nagoya University
[b] Japan Society for the Promotion of Science (JSPS), Research Fellowship
[c] Institute of Materials and Systems for Sustainability (IMaSS), Nagoya University

*E-mail: nakatuka@alice.xtal.nagoya-u.ac.jp

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