

# Epitaxial Growth and Characterizations of $\text{Ge}_{1-x}\text{Sn}_x$ and $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$ Thin Layers for Nanoelectronic and Optoelectronic Applications

Osamu Nakatsuka, Noriyuki Taoka, Mitsuo Sakashita, Wakana Takeuchi, and Shigeaki Zaima  
Graduate School of Engineering, Nagoya University  
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan  
Tel: +81-51-789-5963, Fax: +81-52-789-2760, E-mail: nakatuka@alice.xtal.nagoya-u.ac.jp

$\text{Ge}_{1-x}\text{Sn}_x$  and  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  alloy thin films are attractive for future Si nanoelectronic and optoelectronic applications such as high carrier mobility MOSFET, photo detector, quantum well laser, photovoltaic cell, and so on. We can engineer the energy band diagram and carrier properties with controlling the lattice constant and strain structures of these thin layers. However, the epitaxial growth of group IV-materials including Sn with its content higher than a few % is not so easy, because Ge-Sn and Si-Sn systems are eutectic, and Sn precipitation easily occurs due to the low equilibrium solid solubility of Sn in Ge and Si. We have developed the low temperature growth technique of  $\text{Ge}_{1-x}\text{Sn}_x$  and the lattice mismatch engineering between  $\text{Ge}_{1-x}\text{Sn}_x$  and various substrates [1-3]. Recently, we achieved the growth of  $\text{Ge}_{1-x}\text{Sn}_x$  epitaxial layers with a Sn content as high as 13% and 27% on Ge and InP substrates, respectively [3].

Engineering the electronic and optical properties of  $\text{Ge}_{1-x}\text{Sn}_x$  is also essentially important for its applications. Figure 1 shows the Hall concentration in undoped  $\text{Ge}_{1-x}\text{Sn}_x$  thin layers grown on Si-on-insulator (SOI) substrates as a function of the Sn content for as-grown,  $\text{N}_2$ -annealed, and  $\text{H}_2$ -annealed samples [4]. We can generally observe p-type conduction even for an undoped Ge epitaxial layer due to unintentional hole generation from vacancy defects in Ge. We found that the Sn incorporation with the content of 0.1% effectively reduces the Hall carrier concentration. We consider that preferential formation of Sn-vacancy pairs is a key to reduce the concentration of electrically active vacancies. In addition, we found that the  $\text{H}_2$ -annealing reduces the Hall carrier concentration of Ge and  $\text{Ge}_{1-x}\text{Sn}_x$  thin layers.

We demonstrate the electrical properties at the interface between  $\text{Ge}_{1-x}\text{Sn}_x$  and a substrate. We prepared a pn junction with a  $\text{p}^+$ -doped  $\text{Ge}_{1-x}\text{Sn}_x$  epitaxial layer on n-Ge(001) substrate. Figure 2 shows the current density-voltage characteristics of the  $\text{p}^+$ - $\text{Ge}_{1-x}\text{Sn}_x$ /n-Ge junction for various measurement temperatures [5]. We found that the Sn incorporation into Ge does not generate any interfacial defects causing excess leakage current. Instead, the Sn incorporation reduces the leakage current at low temperature below 170K in the reverse bias condition compared to a  $\text{p}^+$ -Ge/n-Ge junction sample (*not shown*).

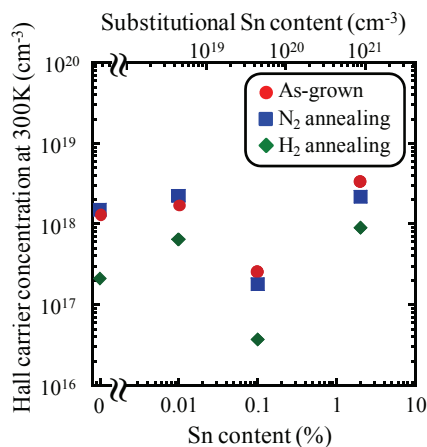
We also examined the epitaxial growth of  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  ternary alloys on a Ge substrate [6]. We can deposit a  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  epitaxial layer whose lattice constant was controlled to match bulk-Ge. Figure 3 shows the x-ray diffraction two dimensional reciprocal space map (XRD-2DRSM) for a  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  layer grown on a Ge(001) substrate. The Si and Sn compositions were determined to be 58% and 15%, respectively, from Raman scattering spectroscopy and Rutherford back scattering methods. We achieved the pseudomorphic growth of  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  ternary layer even with a high Sn content, since the strain of this layer to Ge is suppressed as small as 0.5% with local strain compensation between Si and Sn atoms. The full width at half maximum values of the  $\omega$  rocking curves of pseudomorphic  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  layers are as small as that of a Ge substrate, indicating the superior crystalline structures of  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  layers. Figure 4 shows the Ge-Si-Sn content dependence of the energy band gap calculated assuming Vegard's law. Ge-Si-Sn ternary alloy realizes the energy bandgap engineering with lattice-matching system on Ge [7]. We expected the energy bandgap of  $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$  controlled to be from 0.66 eV of Ge to as high as 1 eV in this study.

## Acknowledgements

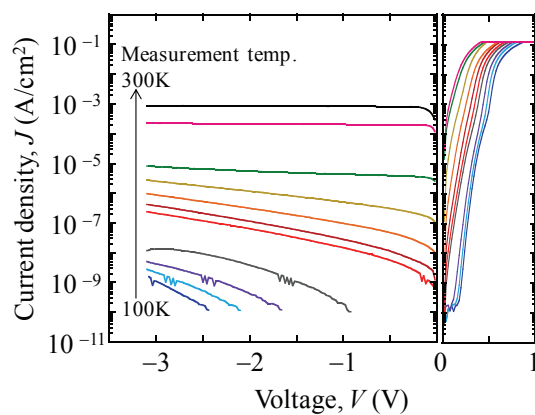
This work was partly supported by a Grant-in-Aid for Specially Promoted Research (No. 22000011) from the MEXT and the ALCA Program from JST in Japan.

## References

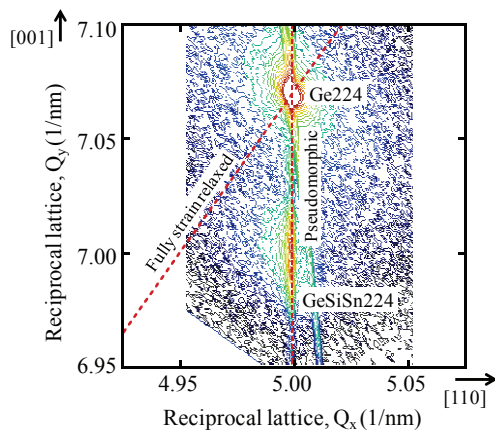
- [1] S. Takeuchi *et al.*, *Semicond. Sci. Tech.* **22**, S231 (2007).
- [2] Y. Shimura *et al.*, *Thin Solid Films* **518**, S2 (2010).
- [3] M Nakamura *et al.*, *Thin Solid Films* **520**, 3201 (2012).
- [4] O. Nakatsuka *et al.*, *Solid-State Electron.* *submitted*.
- [5] S. Asaba *et al.*, in *Abstr. of IUMRS-IECM*, Yokohama, Japan, Sept., 2012, *accepted*.
- [6] T. Yamaha *et al.*, *Electrochem. Soc. Trans.*, *accepted*.
- [7] V. R. D'Costa *et al.*, *Phys. Rev. Lett.* **102**, 107403 (2009).



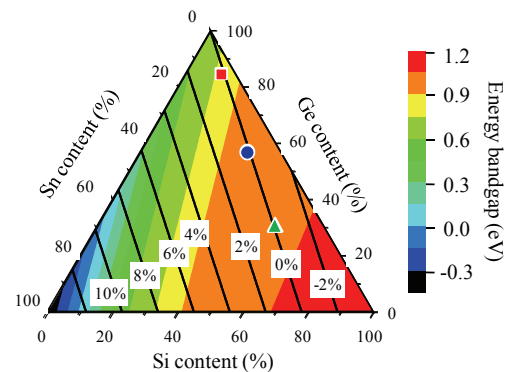
**Fig. 1** The Sn content dependence of the Hall concentration in undoped  $\text{Ge}_{1-x}\text{Sn}_x$  thin layers grown on SOI substrates for as-grown,  $\text{N}_2$ -annealed, and  $\text{H}_2$ -annealed samples [4].



**Fig. 2** The current density-voltage characteristics of the  $\text{p}^+\text{-Ge}_{1-x}\text{Sn}_x/\text{n-Ge}$  junction for various measurement temperatures.



**Fig. 3** XRD-2DRSM around the Ge224 Bragg reflection for a  $\text{Ge}_{1-x}\text{Si}_x\text{Sn}_y$  epitaxial layer grown on a Ge(001) substrate.



**Fig. 4** The Ge-Si-Sn content dependence of the calculated energy bandgap. The solid lines with percentages correspond to the lattice mismatch for bulk-Ge. Some symbols indicate the content conditions of samples prepared in our study.