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Relaxation Behavior of Sputter Epitaxy $Si_{1-x}Ge_x$ Film on P-Type Si(001) and NDR Observation from Hole-Tunneling RTD at RT

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1. Introduction

$Si/Si_{1-x}Ge_x$ devices are intensively studied and applied as next-generation high-speed devices. The $Si/Si_{1-x}Ge_x$ layers are currently fabricated by MBE (molecular beam epitaxy) and UHV-CVD (ultra high vacuum chemical vapor deposition). Although a sputter deposition method has merits of high resource usability and high safety deposition process, and large area deposition capability, it is hardly used for $Si/Si_{1-x}Ge_x$ deposition due to difficulty in realization of high crystalline quality.

To overcome this difficulty, we have recently developed a UHV-compatible magnetron sputter epitaxy method with a combination of Ar/H_2 mixture working gas. We have found that the strain-relaxation behavior of sputtered $Si_{1-x}Ge_x$ layers depends on the substrate conductivity type. In the previous paper, we have reported on the crystallinity and strain-relaxation controllability of $Si_{1-x}Ge_x$ layers deposited on n-type Si(001) and have demonstrated the performance of an electron-tunneling diode (RTD) [1]. In this paper, we report on the results of a further investigation on the same characteristics of $Si_{1-x}Ge_x$ layers deposited on p-type Si(001). Using the growth mode obtained in this work, we have first succeeded in observing negative differential resistance (NDR) from a $Si/Si_{1-x}Ge_x$ hole-tunneling RTD at room temperature (RT).

2. Experimental

In this work, p-type 0.01-0.02 Ω-cm Si(001) substrates were used for sputtered $Si_{1-x}Ge_x$ layer characterization. $Si_{1-x}Ge_x$ was deposited by simultaneous rf magnetron sputtering of Si and dc magnetron sputtering of Ge in a UHV-compatible chamber system. The working gas is a mixture of Ar and 5 volume % of H_2. The results using Ar as a working gas is also described for comparison.

3. Results and Discussion

Relaxation rate dependency on working gas species

Relaxation rates of 175-nm $Si_{0.77}Ge_{0.23}$ layers grown using Ar or Ar + H_2 as a function of growth substrate temperature, T_S, are plotted in Fig. 1. In the T_S range of 500 to 550 ºC, the layers sputtered using Ar + 5% H_2 exhibits higher lattice coherency than the layers sputtered using Ar, and has almost no relaxation. This result indicates that an epitaxial layer of higher crystallinity is obtained by mixing a small amount of hydrogen into an Ar working gas.

Crystallinity of sputtered $Si_{1-x}Ge_x$ layer

Typical rocking curve spectra obtained from (004) and (111) planes of a 175-nm $Si_{0.77}Ge_{0.23}$ layer grown at T_S = 500 ºC by our sputter epitaxy method and a 80-nm $Si_{0.80}Ge_{0.20}$ layer grown at T_S = 630 ºC by our MBE method [2] are compared in Figs. 2 and 3, respectively. The FWHM (full width at half maximum) values of the (004) rocking curve spectra are the same between the sputtered and MBE layers. In the case of the (111) spectra, the FWHM value for the sputtered layer is less than that for MBE layer by 0.02º. Thus, our sputter epitaxy layer has almost the same crystallinity as our MBE grown film.

Strain-relaxation behavior of sputtered $Si_{1-x}Ge_x$ layer

175-nm $Si_{0.77}Ge_{0.23}$ and 83-nm $Si_{0.80}Ge_{0.20}$ layers grown at T_S = 500 ºC are almost fully strained as shown in Figs. 1 and 4, respectively. However, if the thickness is as thin as ~21 nm, the film is relaxed as shown in Fig. 4. However, we have found that the thin $Si_{0.80}Ge_{0.20}$ layer becomes fully-strained after a 20-min post-anneal at T_S = 500 ºC as shown in Fig. 4. The results suggest that some critical thermal anneal excitation is needed to the initial coherent growth for our sputter epitaxy.

Hole-tunneling double quantum well RTD

A hole-tunneling symmetrical double quantum well RTD consisting of relaxed Si wells and strained $Si_{0.77}Ge_{0.23}$ barriers was formed. The base $Si_{0.77}Ge_{0.23}$ layer was strained during the RTD formation process. As a result, negative differential resistance (NDR) has been first observed from a hole-tunneling $Si/Si_{1-x}Ge_x$ RTD at RT [2,3]. The corresponding peak-to-valley current ratio is ~5.

4. Conclusions

We have introduced high crystalline $Si_{1-x}Ge_x$ epitaxial method using magnetron sputtering with a Ar + H_2 working gas, and have cleared the strain-relaxation behavior. High negative differential resistance has also been first observed from a hole-tunneling $Si/Si_{1-x}Ge_x$ RTD at room temperature.

Acknowledgements

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References

[1] J. Kubota, A. Hashimoto, and Y. Suda, 4th Int. Conf. on Silicon Epitaxy and Heterostructures, 24F-5 (Awaji, 2005).
[2] Y. Suda and H. Koyama, Appl. Phys. Lett. **79**, 2273 (2001).
[3] Y. Suda, ECS Proc. Vol. on Advanced Luminescent Materials and Quantum Confinement II, **PV2002-9** (ECS, NJ, 2002) p. 47.

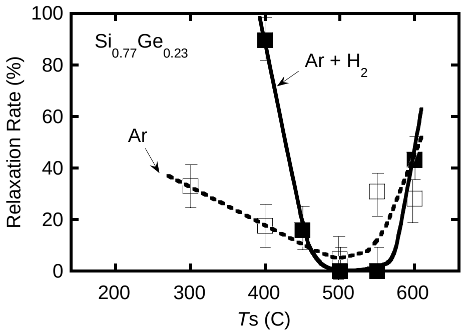

Fig. 1. Comparison of relaxation rates of 175-nm $Si_{0.77}Ge_{0.23}$ films obtained using Ar or Ar + H_2 as a working gas.

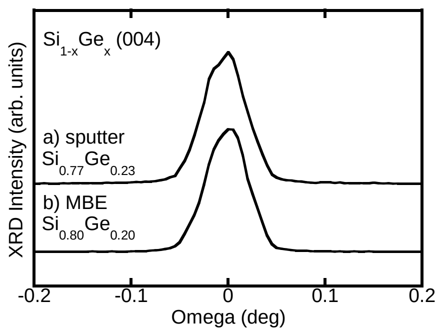

Fig. 2. Rocking curves (ω scan cueves) obtained from (004) planes of a) a sputtered film and b) a MBE grown film.

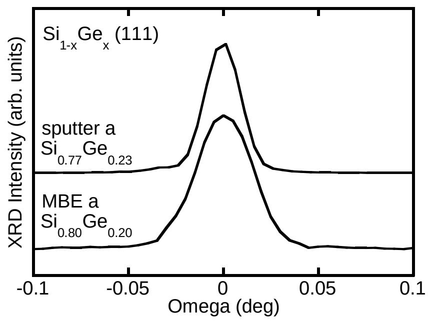

Fig. 3. Rocking curves (ω scan curves) obtained from (111) planes of a) a sputtered film and b) a MBE grown film.

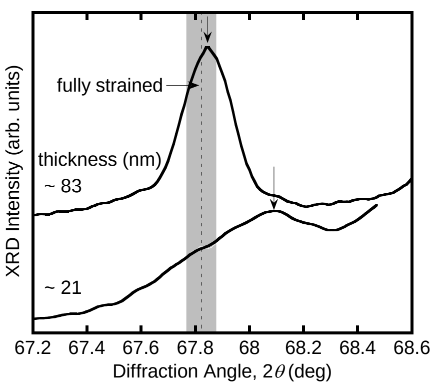

Fig. 4. XRD intensity spectra obtained by θ–2θ scan from $Si_{0.80}Ge_{0.20}$ films with thicknesses of 21 or 83 nm grown at T_S = 500 ºC. The 83-nm film was almost fully strained.

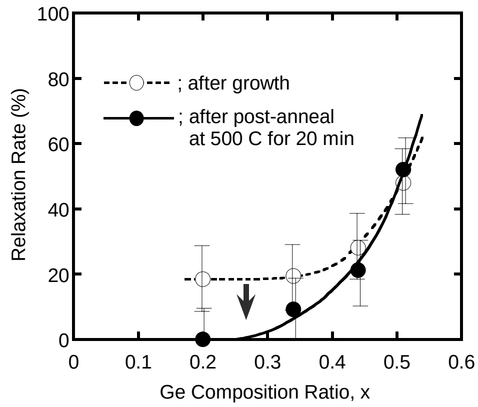

Fig. 5. Effects of post-annealing of 21-nm thin $Si_{1-x}Ge_x$ films, grown at T_S = 500 ºC, on their relaxation rates. The post-annealing was carried out at T_S = 500 ºC for 20 min. After the post-anneal, the $Si_{0.8}Ge_{0.2}$ film became almost fully strained.

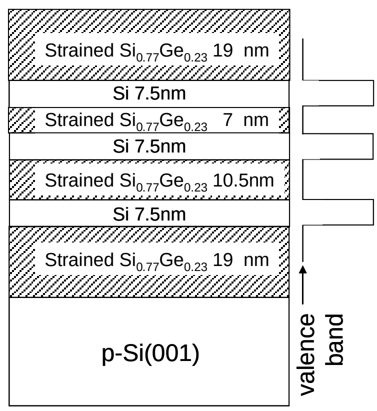

Fig. 6. Schematic of hole-tunneling symmetric double quantum well resonant tunneling diode (DQWRTD) formed on p-Si(001).

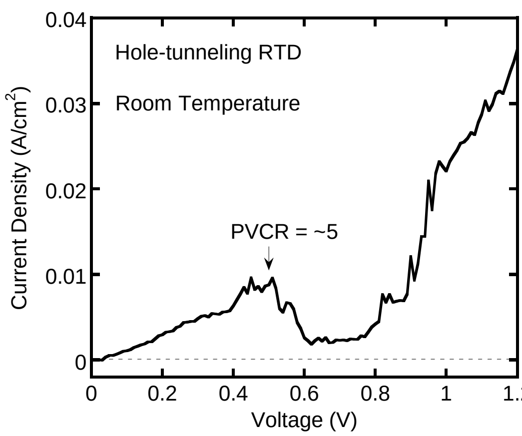

Fig. 7. *I-V* characteristics obtained with the RTD corresponding to Fig. 6. Negative differential resistance has been first observed from a hole-tunneling $Si/Si_{1-x}Ge_x$ RTD at room temperature. The peak-to-valley current ratio (PVCR) is ~5.