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Strained Si with Smooth and Uniformly Strained Surface Formed by Sputter Epitaxy

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1. Introduction

A global-strain type of strained Si (s-Si), formed on a $Si_{1-x}Ge_x$ strain-relief buffer, has been intensively applied to high-electron mobility transistors such as modulation doped FETs (MODFETs) and CMOS devices. However, when we form the global-strain-type strained Si by gas-source MBE (GS-MBE), we still have a problem in that there causes a cross-hatch undulation morphology on the surface which originates from propagation of dislocations generating in the strain-relief buffer. The surface undulation will cause an uneven strain distribution on the surface and will cause larger dispersion in the performance of devices formed on the strained surface with higher device density.

Recently, we have proposed a new SiGe sputter epitaxy and a strain-relief quadruple-$Si_{1-x}Ge_x$-layer buffer (QL buffer) [1], and with these method and buffer, a smoother strained-Si surface has been obtained than a strained-Si surface formed by GS-MBE [2]. The flattening mechanism with our sputter epitaxy method has been explained with TEM images by multidirectional threading dislocation propagation, whereas one-directional threading dislocation propagation for the GS-MBE case [2].

Therefore, our strained-Si is expected to have more uniform strain distribution and is promising for higher density devices. Raman spectroscopy is one of the useful techniques to evaluate the surface strain distribution; however, its conventional spatial resolution is limited to about 1μm x 1μm due to the diffraction limit.

To obtain higher spatial resolutions, we have applied a near-field and plasmon oscillation coupling method [3-5] and introduced a combination system of AFM and tip enhanced Raman spectroscopy (TERS) for simultaneous measurements of an enhanced Raman spectrum and a surface topography for a strained-Si surface.

In this paper, using the AFM-TERS method, we first report the relationship between the surface roughness and strain distribution, on the nanometer scale, of strained Si on a stepwise $Si_{1-x}Ge_x$-multilayer strain-relief buffer formed by our proposed sputter epitaxy. And the results are compared to those obtained with a GS-MBE method.

2. Experimental

Our proposed quadruple-$Si_{1-x}Ge_x$-layer buffers and 60-nm strained-Si layers on the buffers were grown on 3-4 Ω-cm p-type Si(001), as shown in Fi. 1(b), by our sputter epitaxy at a growth temperature of 500 °C and by GS-MBE using Si_2H_6, GeH_4 as Si and Ge source gasses at a growth temperature of 600 °C. These growth temperatures were set to obtain coherent growth for both the growth methods.

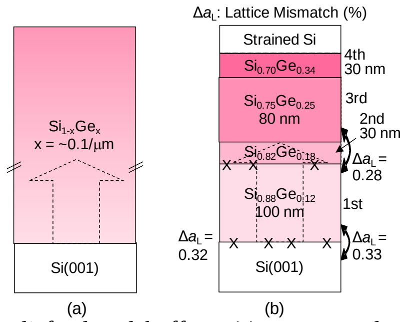


Fig. 1 Strain-relief relaxed buffers: (a) a commonly used thick $Si_{1-x}Ge_x$ graded buffer, (b) our proposed quadruple-$Si_{1-x}Ge_x$ layer buffer and strained Si grown on it. [1]

The AFM-TERS measurements were carried out using an integrated system of *NANONICS MV4000* and *Renishaw InVia Raman* as illustrated in Fig. 2. In the AFM and TERS measurements, Au nano-particle (d=200nm) mounted optical fibered cantilever was used. An Nd:YAG laser, with a wavelength of 532 nm, was used for excitation of surface plasmon oscillation around the Au nano-particle. The laser power was reduced to less than 1 mW.

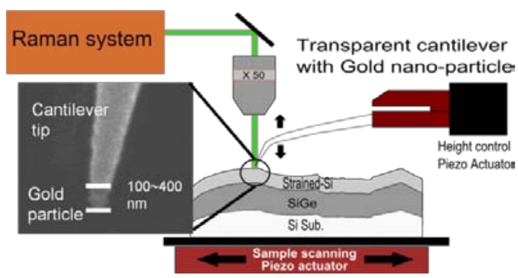
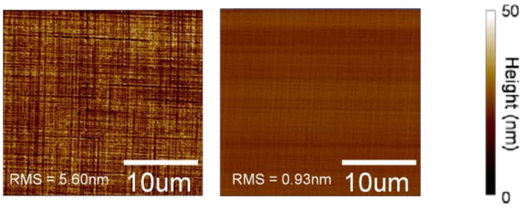


Fig.2 Schematic of AFM-TERS system

3. Results and Discussion

3-1 Surface morphologies of strained-Si layers

In Fig. 3, we show typical AFM images of strained-Si surfaces formed by (a) GS-MBE and (b) our sputter epitaxy. The RMS values of the roughness distributions were 5.6 and 0.93 nm, respectively. We have reported that this difference results from a difference in the crystal growth mechanism (see also Introduction section of this paper) [2].



(a) (b)

Fig. 3. Wide-area (30 x 30 μm) AFM topographies obtained from the surfaces of strained-Si on quadruple-$Si_{1-x}Ge_x$-layer buffers formed by (a) GS-MBE and (b) our sputter epitaxy.

3-2. AFM-TERS measurements

We carried out the TERS measurements during AFM scanning for both the sputter-epitaxy and GS-MBE strained-Si surfaces. The TERS spectra are shown in Figs. 4(a) and (b). The AFM images are also inserted in the figures. The TERS spectrum was measured at each point along 1500-nm scanning lines α-α’ and β-β’ indicated in the AFM images. For comparison, we also show conventional Raman spectra with the lowest black curves. In the curves of the figures, tensilely-strained Si (s-Si) peaks are observed at around 515.3 cm^{-1} for the GS-MBE sample and 515.2 cm^{-1} for the sputter epitaxy sample. The s-Si peak positions are connected with solid lines in Fig. 4. Calculated stress values are 1.18 and 1.20 GPa, respectively [6].

In Fig. 5, we show the AFM surface undulation traces and s-Si TERS peak positions measured along the α-α’ and β-β’ lines indicated in the AFM images in Figs. 4(a) and (b). The RMS values for the strained-Si surface roughnesses are 5.5 and 0.9 nm for the GS-MBE and sputter epitaxy samples, respectively. The RMS values of the TERS s-Si peak position variations are 0.71 and 0.36 cm^{-1} for the GS-MBE and sputter epitaxy samples, respectively. The results indicate the strong relationship between the surface flatness and the strain distribution uniformity for strained Si formed on a $Si_{1-x}Ge_x$-multilayer relaxed buffer on the nanometer scale. As a result, a strained-Si layer formed by our sputter epitaxy has a smoother surface and has a more uniform surface strain distribution than the sample formed by GS-MBE.

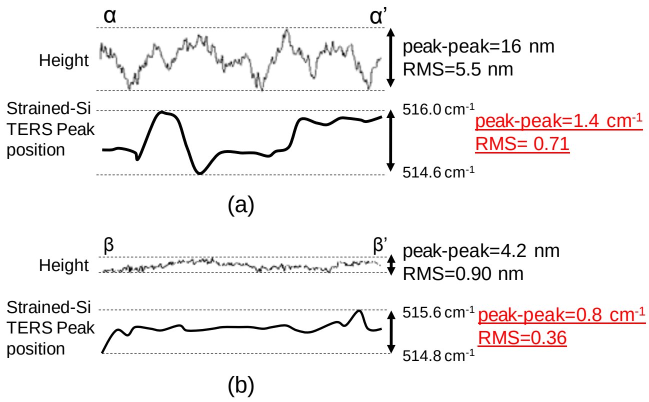
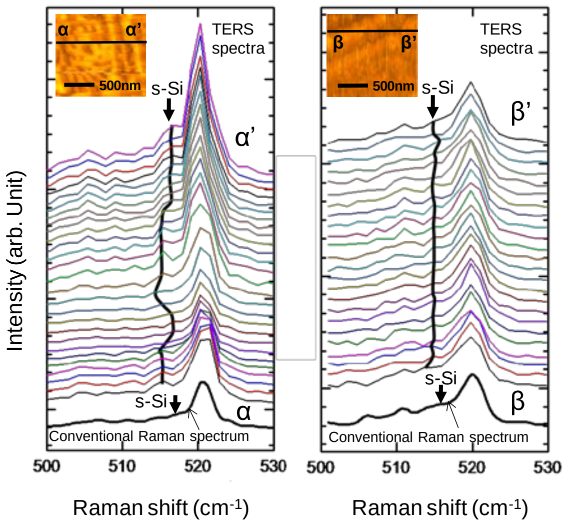


Fig. 5 AFM surface undulation traces and s-Si TERS peak positions measured along the 1500-nm α-α’ and β-β’ lines indicated in the AFM images inserted in Figs. 4(a) and (b) for the samples formed by (a) GS-MBE and (b) our sputter epitaxy.



(a) (b)

Fig. 4 TERS spectra obtained from strained-Si layers on quadruple-$Si_{1-x}Ge_x$-layer buffers formed by (a) GS-MBE, and (b) our sputter epitaxy. The TERS spectra were measured at points along the α-α’ and β-β’ lines (1500 nm) indicated in the inserted AFM images.

4. Conclusions

We have first carried out the simultaneous measurements for the surface strain and undulation distributions for strained-Si layers formed on $Si_{1-x}Ge_x$-multilayer buffers on the nanometer scale using an AFM-TERS combination system. The results show the strong relationship between the surface flatness and strain distribution uniformity. The strained-Si layer on our proposed quadruple-$Si_{1-x}Ge_x$-layer buffer formed by our sputter epitaxy has a smoother surface with more uniform strain distribution than the case with a conventional GS-MBE method and is promising for high-density and high-speed devices with strained Si.

Acknowledgements

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