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$Si/Si_{1-x}Ge_x$ Strained Layer Superlattices Grown by Photo-Chemical Vapor Deposition at 250° C

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$Si/Si_{1-x}Ge_x$ strained layer superlattices have been sucessfully grown by the mercury-sensitized photo-chemical vapor deposition at a very low temperature of 250°C. Lattice strain and lattice dynamics of the superlattices were examined by Raman scattering and X-ray diffraction measurements and it was found that the in-plane lattice constant of the superlattices was commensurate with the lattice constant of a silicon substrate. From the satellite peaks of the superlattice, the presence of fine superlattice structures was clearly confirmed.

1. Introduction

Interest in semiconductor strained-layer superlattices (SLSs) has arisen because the bandstructure can be tailored according to the specific application[1]. In particular, $Si/Si_{1-x}Ge_x$ heteroepitaxy offers exciting possibilities for infrared photodetectors[2], field-effect transistors (FET)[3] and heterobipolar transistors[4]. Usually, $Si/Si_{1-x}Ge_x$ heterostructures are grown at the substrate temperatures of 350-550°C by MBE.

We have previously reported on a novel silicon epitaxial growth technique using mercury-sensitized photochemical vapor deposition (photo-CVD)[5]. In this technique, epitaxial Si films were grown on Si substrates at growth temperatures of 200-250°C. At this low temperature, auto-doping effects from the substrate and interdiffusion effects at each superlattice interface can be made negligible and an abrupt interface may be potentially realized. In this work, epitaxy of the alloy $Si_{1-x}Ge_x$ and $Si/Si_{1-x}Ge_x$ SLSs by photo-CVD at a very low temperature of 200°C has been studied. The lattice strains and dynamics of the resulting SLSs were examined by Raman scattering and X-ray diffraction measurements.

2. Low temperature epitaxy of SiGe

In this section, we describe the method used for the successful epitaxial growth of silicon-germanium by mercury-sensitized photo-CVD at a very low temperature of 250°C. The detailed experimental procedures were described elsewhere[6]. The RHEED pattern of the grown layers showed elongated streaks which confirmed that single-crystal $Si_{1-x}Ge_x$ film had been deposited. The germanium composition of the grown samples was determined by Raman scattering measurements.

The first-order Stokes Raman spectrum of polycrystalline SiGe consists of three distinct peaks near 300, 400, 500 cm^{-1}, corresponding to local modes of Ge-Ge, Ge-Si, Si-Si atom pairs, respectively[7]. A set of Raman spectra are shown in Fig.1, corresponding to the various GeH_4 flow rates.

From this figure, we estimated the germanium mole fraction, to vary from 0.25 to 0.5 with an increase of the GeH_4 flow rate from 2 sccm to 5 sccm, by comparing the frequency shifts of the Si-Si peak with those of polycrystalline material[8].

Figure 2 shows the variation of the lattice constants and germanium mole fraction as a function of the GeH_4 flow rate. In this figure, the lattice parameter was calculated from the difference between the X-ray diffraction angle of the SiGe alloy and the diffraction angle of the Si substrate from the Cu $K\alpha_1$ line. The germanium mole fraction was determined by comparing the calculated lattice constants with those of the bulk SiGe alloy[8]. The germanium mole fraction was increased monotonously from 0.32 to 0.47 by increasing the GeH_4 flow rate from 2 sccm to 5 sccm. This result is in good agreement with the result obtained from Raman scattering measurements.

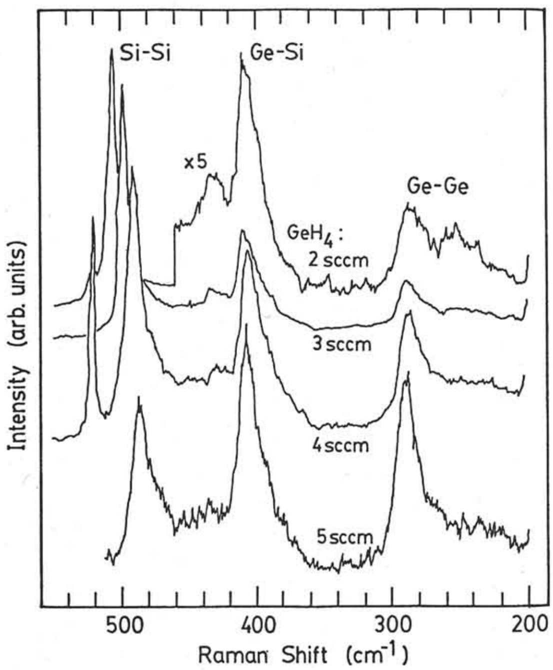

Fig.1 Raman spectra for epitaxial SiGe films

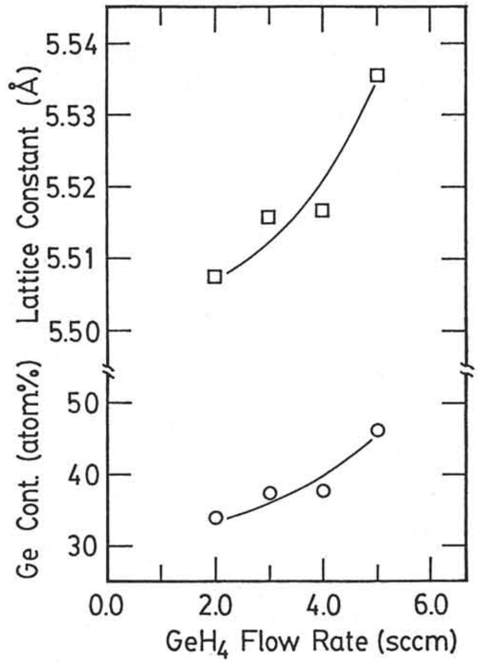

Fig.2 The variation of the lattice constants and germanium mole fraction as a function of the GeH_4 flow rate.

3. Growth of $Si/Si_{1-x}Ge_x$ SLSs by photo-CVD

(a) Sample preparation technique

Figure 3 shows the experimental apparatus for the growth of the SLS structures. $Si/Si_{1-x}Ge_x$ SLSs were grown directly on (001) oriented Si substrates with a Si buffer layer whose thickness was about 300Å. The substrate temperature was 250°C. The SLSs were synthesized by switching the gas flows. The gas flow of SiH_4 and SiH_2F_2 was kept on during the entire growth, while the GeH_4 gas flow was alternated to produce the Si and SiGe layers. The switching of the GeH_4 gas flow was achieved by the

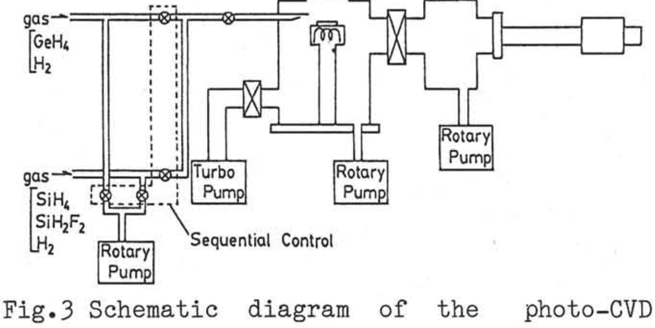

Fig.3 Schematic diagram of the photo-CVD system

on/off operation of pneumatic valves by a sequencer. We introduced 1 min intervals between the deposition of the Si and SiGe layers. During the intervals the mercury lamp was also turned off to produce the abrupt SLS interfaces.

(b) Raman scattering measurements

The lattice distortion in the SLSs was evaluated by Raman scattering measurements. Figure 4 shows the experimental Raman spectra of the superlattices. In this figure, the spectrum from the $Si_{0.62}Ge_{0.38}$ alloy layer, whose Ge mole fraction was determined from the Raman shift of the Si-Si local phonon mode, is also shown. The SLS-4 consists of 40 periods of Si (55 monolayers (MLs)) and $Si_{0.62}Ge_{0.38}$ (31 MLs) and the SLS-6 consists of 80 periods of Si (11 MLs) and $Si_{0.62}Ge_{0.38}$ (7 MLs). From this figure, it is seen that each local phonon mode in the alloy layer of the superlattice shifts towards higher energy compared to the "alloy" layer.

These variations of the optical phonon energies are fully explained by the presence

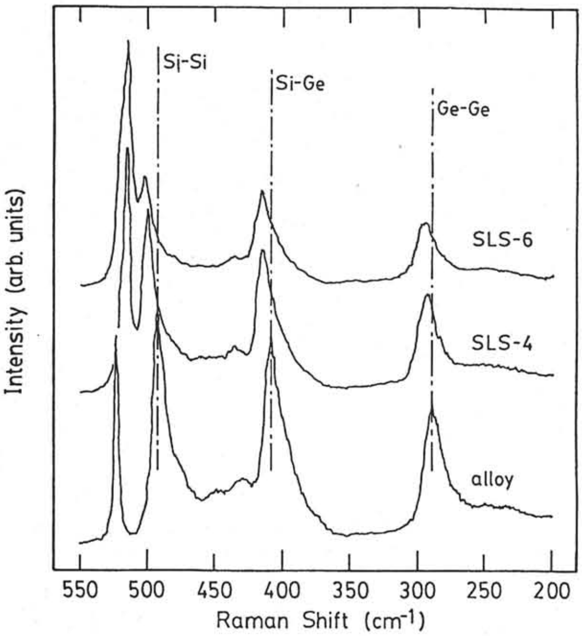

Fig.4 Raman spectra of the superlattices and alloy layer

of misfit strains in the SLSs and this stress effects are strongly depend on the in-plane lattice constant. In this study, we calculated the in-plane lattice constant in the following two cases. In the first case (A), the superlattice was assumed to be commensurate with the silicon substrate and the in-plane lattice constant as being equal to that of the silicon substrate. In this model, only SiGe layers are strained and Si layers are not strained. In the second case (B), the superlattice layers were assumed to be coherently strained with each other and the in-plane lattice constant as being equal to the lattice constant of "free-standing" SLSs. In this case, the lattice constant ($a_{//}$) is given by[9)]

$$a_{//} = a_A(1 + f/(1 + G_A h_A / G_B h_B))$$

where h_i is the individual layer thickness of material i and f is the misfit between the constituent layers.

The calculated results are summarized in Table I. In this table, the frequency shifts of the Si-Si and Ge-Ge local phonon modes were calculated using pure Si and pure Ge bulk parameters, respectively, and the frequency shift of the Si-Ge local phonon mode was calculated using a parameter as used by Cerdeira[10)]. The agreement between the experimental values and the calculation based on the assumption (A) is relatively better than those based on the assumption (B).

Table I Raman shifts of the superlattices
($\Delta\omega_{exp.}$: experiment,
$\Delta\omega_{commen.}$: model (A),
$\Delta\omega_{coher.}$: model (B))

	$\Delta\omega_{exp.}$ (cm^{-1})			$\Delta\omega_{commen.}$ (cm^{-1})			$\Delta\omega_{coher.}$ (cm^{-1})		
	Si-Si	Si-Ge	Ge-Ge	Si-Si	Si-Ge	Ge-Ge	Si-Si	Si-Ge	Ge-Ge
SLS-4	9	7	5	12	7	7	8	5	4
SLS-6	11	8	7	12	7	7	8	5	4

(c) X-ray diffraction measurements

If the SiGe alloy layers were compressively strained by the biaxial stress, then its lattice constant perpendicular to the interface may be larger than that of the bulk material. Therefore, to calculate the satellite peak positions of the SLSs, one has to include this lattice distortion effect in the calculation. For the calculation, we adopted the Segmuller's step model[11].

Figure 5 shows the X-ray diffraction intensity of the SLS-6. In this figure, the solid line indicates the experimental data and the broken line the calculated values. In this calculation, we assumed that the in-plane lattice constant was commensurate with the substrate lattice constant. Both the positions and the intensities of the calculated satellite peaks agreed fairly well with the experimental data. Similar results were also obtained for SLS-4. Thus, it was concluded that, in the $Si/Si_{1-x}Ge_x$ superlattice system, the in-plane lattice constant was commensurate with the substrate lattice constant. This result is consistent with that obtained by Cerdeira[10].

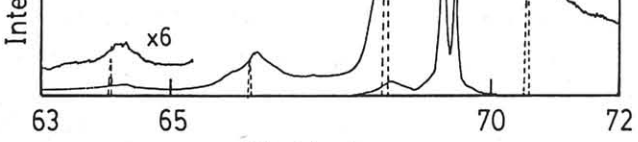

Fig.5 X-ray diffraction pattern of the SLS-6

4.Conclusions

We have successfully grown $Si/Si_{1-x}Ge_x$ SLSs by photo-CVD at a very low temperature of 250°C. From Raman scattering and X-ray diffraction measurements, it was found that the in-plane lattice constant of the superlattices was commensurate with the substrate lattice constant.

Acknowledgments

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