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Optical Properties of Strain-Balanced $Si_{0.73}Ge_{0.27}$ Planar Microcavities on Si Substrates

K. Kawaguchi[1], K. Konishi[1], S. Koh[1], Y. Shiraki[1], and J. Zhang[2]

[1]Depertment of Applied Physics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5452-5092, Fax: +81-3-5452-5093, E-mail: kawaguti@photonics.rcast.u-tokyo.ac.jp
[2]Centre for Electronic Materials and Devices, Imperial College of Science, Technology and Medicine, Blackett Laboratory, Prince Consort Road, London SW7 2BW, UK

1. Introduction

SiGe heterostructures have been expected for optical device applications on Si substrates. Especially, SiGe/Si distributed Bragg reflectors (DBRs) are strongly desired to realize microcavity devices such as resonant cavity light emitters or photodetectors. SiGe/Si DBRs with high reflectivity, however, are difficult to fabricate due to not only the critical thickness of one SiGe layer but also the limitation of the number of mirror pairs originating from strain accumulation [1]. As a method to overcome the latter limitaion, strain-balanced structures, which are designed to compensate the strain in the one period of double layers using a substrate with the lattice constant between those of the constituent materials, were proposed, and a few attempts for realizing strain-balanced Si/SiGe heterostructures were reported [2], [3].

In this work, strain-balanced SiGe/Si DBRs were fabricated on the relaxed SiGe virtual substrates, and their structural and optical properties were investigated. As an application of SiGe/Si DBRs, strain-balanced SiGe planar microcavity structures were also fabricated, and their optical properties were investigated.

2. Experimental

The samples were grown on Si(001) substrates by gas-source molecular beam epitaxy. The sample structure is shown in Fig. 1. Relaxed $Si_{0.89}Ge_{0.11}$ virtual substrates with the thickness of about 2 μm were grown at 680 °C by means of a standard graded buffer technique followed by an annealing at 800 °C. On the virtual substrate, a bottom DBR mirror with 29 pairs was fabricated by growing quarter-wavelength-thick Si and $Si_{0.73}Ge_{0.27}$ layers alternatively. On the DBR mirror, a one-wavelength-thick $Si_{0.73}Ge_{0.27}$ cavity layer with Si/Ge quantum wells (QWs) of 5 periods was grown, followed by a top DBR mirror with 9 pair. The sample only with a bottom DBR mirror was also fabricated in order to investigate structural and optical properties of strain-balanced DBRs.

Conventional ω-2θ scans were performed using a high resolution x-ray diffractometer (X'pert Philips). Room-temperature Raman spectra were measured in a back scattering geometry with a double monochromator. Surface morphology of the samples was examined by the atomic force microscope (AFM). Reflectivity spectrum measurements were carried out using a quartz-halogen light source and a liquid-nitrogen-cooled Ge photodetector (North Coast EO-817L). PL spectra were recorded using a standard lock-in technique. The excitation wavelength was 532 nm from a second-harmonic generated solid laser pumped by a diode.

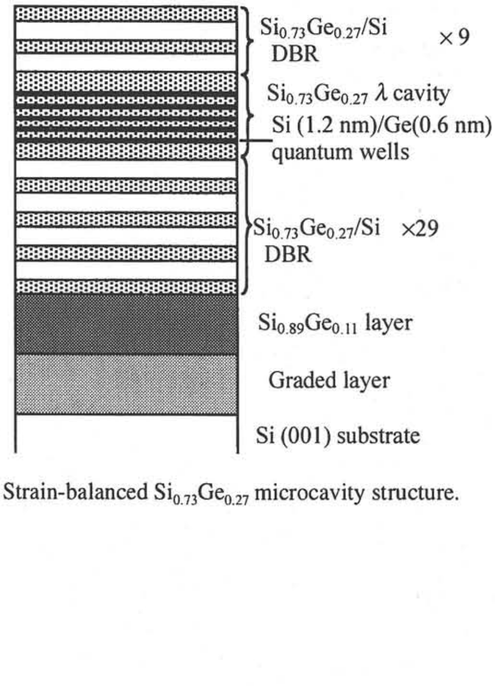

Fig. 1. Strain-balanced $Si_{0.73}Ge_{0.27}$ microcavity structure.

3. Results and discussion

Figure 2 shows an X-ray diffraction spectrum of the strain-balanced $Si_{0.73}Ge_{0.27}$/Si DBR. By comparing the simulation result, it was confirmed that strain balance condition was maintained, that is, both Si layers and $Si_{0.73}Ge_{0.27}$ layers of DBRs were grown pseudomorphically on $Si_{0.89}Ge_{0.11}$ virtual substrate with compressive and tensile

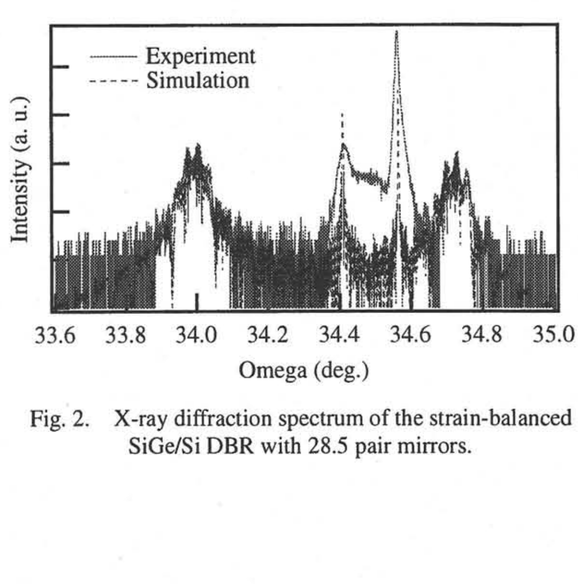

Fig. 2. X-ray diffraction spectrum of the strain-balanced SiGe/Si DBR with 28.5 pair mirrors.

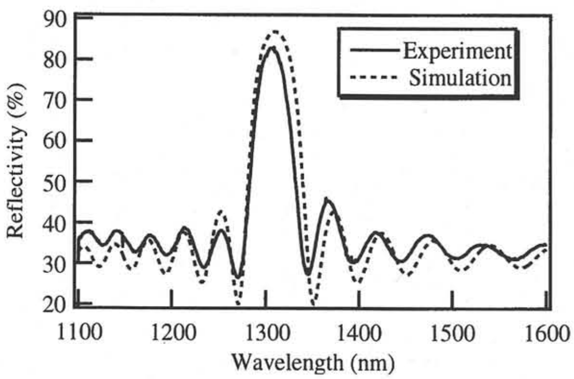

Fig. 3. Reflectivity spectrum of the strain-balanced SiGe/Si DBR with 28.5 pair mirrors.

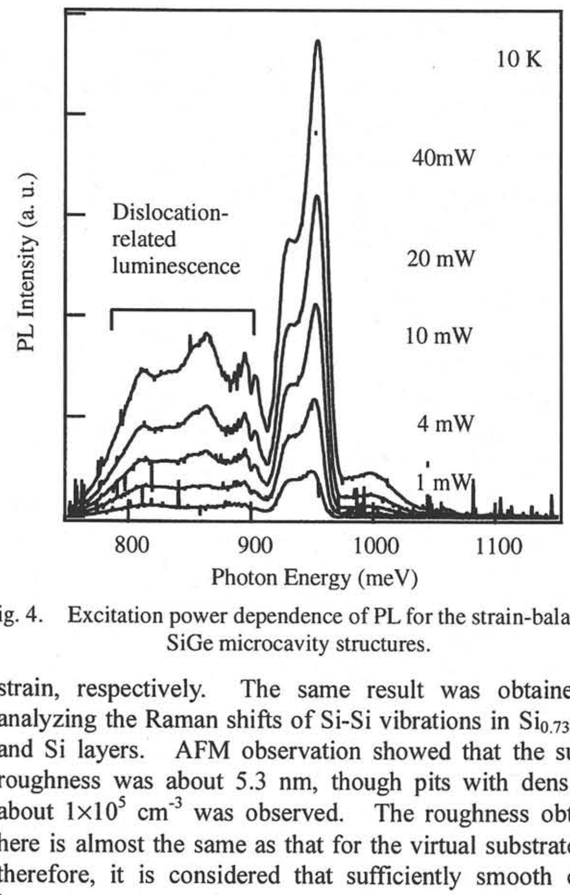

Fig. 4. Excitation power dependence of PL for the strain-balanced SiGe microcavity structures.

strain, respectively. The same result was obtained by analyzing the Raman shifts of Si-Si vibrations in $Si_{0.73}Ge_{0.27}$ and Si layers. AFM observation showed that the surface roughness was about 5.3 nm, though pits with density of about 1×10^{5} cm^{-3} was observed. The roughness obtained here is almost the same as that for the virtual substrate, and therefore, it is considered that sufficiently smooth cavity layers are grown on the DBR structure.

A reflectivity spectrum of the strain-balanced DBR mirror is shown in Fig. 2. A record reflectivity of 83% was achieved at 1.31 μm. A large improvement of the reflectivity was realized compared with conventional SiGe/Si DBRs on Si substrates [1], and the reflectivity obtained here was almost the same as the calculated value. It should be noted here that the loss of reflectivity due to the deterioration of the crystalline quality coming from strain accumulation is hardly seen. Figure 4 shows PL spectra for the SiGe planar microcavity structures with 9 pair top mirror and 29 pair bottom mirror. The luminescence observed about 940 meV is assigned as the radiative recombination in the Si/Ge QWs. The broad peaks below 900 meV are assigned as the dislocation-related luminescence (D-line). To our best knowledge, this is the first report of the luminescence from SiGe microcavity structures with SiGe/Si DBRs. With increasing excitation power, the energy corresponding to the cavity resonance wavelength that is about 15 meV higher than the transition energy of QWs became significant, which is considered to be a modulation due to the planar microcavity effect. It is predicted that the directivity of radiation and extraction coefficient are drastically improved compared with conventional Si/SiGe quantum wells, which will be demonstrated at the conference.

4. Conclusion

We successfully fabricated strain-balanced SiGe/Si DBRs on the relaxed SiGe virtual substrates, and their structural and optical properties were investigated. As an application of SiGe/Si DBRs, we also fabricated strain-balanced SiGe planar microcavity structures and observed the luminescence that was modulated. These results imply the possibility of realizing microcavity optical devices on Si substrates by using SiGe heterostructures.

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