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Strained SiGe-on-Si beam for tunable near-infrared light emission

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1. Introduction

A tunable light source is one of the most important devices in Si photonics in order to control the emission wavelength under a temperature fluctuation/distribution in a chip as well as to realize the wavelength-division multiplexing (WDM) communications.

In this work, we propose a method to control the wavelength of near-infrared light emission from a germanium-rich SiGe epitaxial layer grown on an SOI wafer. A cantilever/beam structure of SiGe is prepared, and a mechanical stress is externally applied to the beam structure. This stress induces a tensile lattice strain in SiGe, which leads to the bandgap narrowing. Photoluminescence spectra experimentally show a bandgap narrowing under a mechanical stress, indicating a tunability of emission wavelength by applying a mechanical stress.

2. SiGe composition and stress for C+L band emission

As shown later, a uniaxial tensile stress is used to reduce the bandgap energy of SiGe. In order to control the emission wavelength, or the direct bandgap energy, in the C+L band (0.77~0.81eV), SiGe should have the bandgap energy of 0.81 eV or above without an external mechanical stress. Si content should be more than 1%, according to Ref. 1, and 4% was experimentally used as the Si content in this study.

The bandgap energy of $Si_{0.04}Ge_{0.96}$ was calculated as a function of uniaxial [100] strain using the deformation potential method[2]. Elastic constants in Ref. 3 and deformation potential values in Ref. 4 were used in the calculation. Since the Si content is as small as 4%, the values for SiGe were replaced to those for pure Ge, except for the bandgap energy without the strain. The calculated bandgap energies under the [100] uniaxial stress are shown in Fig. 1. The direct bandgap energy is found to be tunable over the C+L band by controlling the tensile strain in the range from 1.5 to 2%.

3. Structures and Simulations

In order to induce such a large tensile strain in SiGe layer, beam structures of SiGe on Si were examined, as shown in Fig. 2. When the tip of beam is pushed down applying an external force, the top SiGe surface is stretched, leading to a generation of large tensile strain. A strain distribution in Fig. 2 for a SiGe beam (5μm × 25μm) with a depression of 3 μm shows a generation of tensile strain at the other edge of beam connected to the wide slab. Under this condition, which was used in the experiments, the maximum tensile strain is found to be 1.2%. Further strain as large as 2% should be generated by increasing the depression.

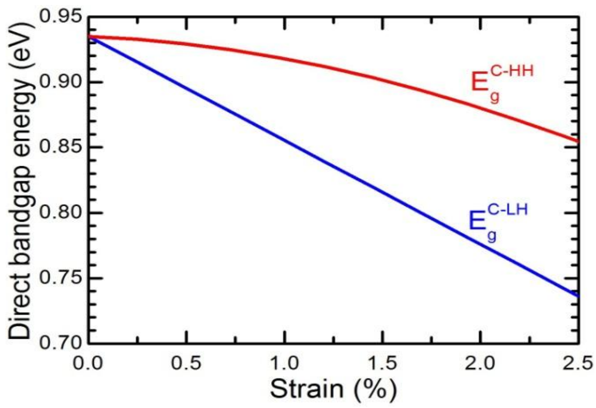

Fig. 1. Direct bandgap energies of $Si_{0.04}Ge_{0.96}$ under [100] uniaxial tensile stress.

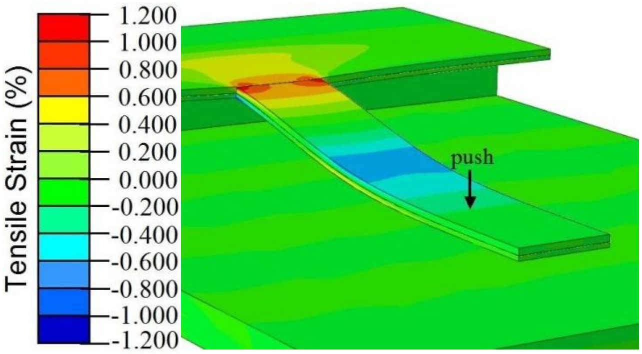

Fig. 2. Strain distribution on SiGe-on-Si beam by finite element analysis.

4. Experimental results

i. Fabrication

We fabricated a 5μm × 25μm SiGe beam. A 350-nm-thick SiGe layer with a 50-nm-thick Si cap was epitaxially grown by a two-step UHV-CVD[5] on silicon-on-insulator (SOI) wafer with a 250-nm-thick top Si and a 3-μm-thick buried-oxide (BOX) layers. The beam patterns were defined by an electron-beam lithography. After the patterning, SiGe and Si were selectively etched with the resist masks by a reactive ion etching using Cl_2 and O_2 gases. Finally, the BOX layers were removed both in the dry-etched area and below the beam by a wet-etching with a diluted HF solution.

A microscopic image of the fabricated beam is shown in Fig. 3. All the beams were found to bend upwards. This up-bending is due to the release of the tensile strain in SiGe generated during the cooling from the growth temperature by the large difference of thermal expansion coefficient between germanium-rich SiGe and Si[1, 4].

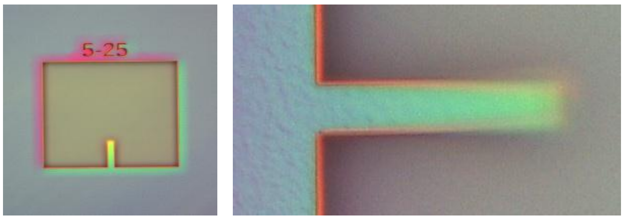

Fig. 3. Microscopic images (top views) for a fabricated 5μm × 25μm SiGe-on-Si beam.

ii. Photoluminescence measurement

In order to evaluate the bandgap change for SiGe under a tensile strain induced by the bending of beam structure, micro-photoluminescence measurements were carried out while pushing the beam with a sharp probe tip. A 457-nm semiconductor laser with the intensity of 2.3 mW and the diameter of ~1 μm were used as the excitation source. Cooled InGaAs diodes were used as the detector. Fig. 4 shows typical PL spectra taken at the edge of beam, which is indicated as a white circle at the top left of Fig. 4. Using different locations to push, the depression of beam was changed. In the case without the external stress (pushing), the peak position is the same before and after the pushing, as shown by the black and green lines, indicating the bending of beam elastically occurs. Although it was expected that luminescence peaks shifted to the lower energy direction as pushing the beam, peak position in pushing 1 (red line) showed a higher energy shift compared to that without pushing. Beam structure was easy to accumulate the heat from the laser, which generated bandgap shrinkage, and this opposite shift was caused by the release of the heat with a contact between beam surface and probe tip or beam surface and bottom Si layer below beam. Obviously, there was an effect of bandgap shrinkage with the tensile strain induced by the bending of beam, however, bandgap extension due to the heat release was larger than such a bandgap narrowing, leading to the reverse peak shift. In the case of pushing 2 (blue line), where applying furthermore tensile stress, spectrum was found to show a lower energy shift of 25meV. This was contributed to by the tensile strain, and this peak energy of 0.884eV corresponded to 0.6% tensile strain as shown in Fig.1, which was a little bit smaller than the calculated amount of strain of 0.6-1.2% as in Fig.2. This reduction may be due to the compressive strain along the short length beam direction induced under bending the beam in such a way.

This result indicated the possibilities to control the bandgap energy with the tensile strain using the beam-shaped structure.

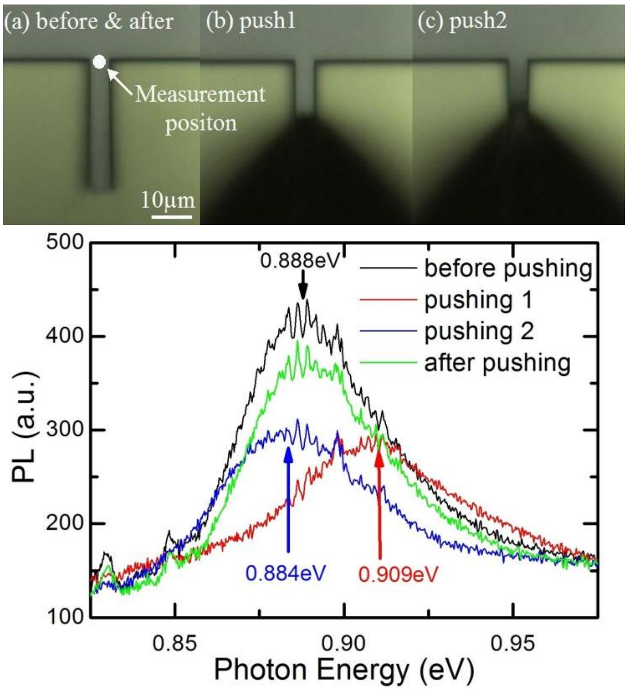

Fig. 4. PL spectra of SiGe at different pushing intensity.

5. Conclusion

We proposed a method to control the wavelength of near-infrared light emission from germanium-rich SiGe epitaxial layer grown on an SOI wafer. A beam structure of SiGe was fabricated, and an external mechanical stress was applied to the beam structure. Since this stress induced a tensile lattice strain in SiGe, which generated to the bandgap shrinkage, photoluminescence spectra experimentally showed a bandgap narrowing under a mechnanical stress, indicating a tunability of emission wavelength by applying a mechanical stress.

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