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Strain Effects of Ge Islands on $Si_{1-x}Ge_x$/Si Quantum Well

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Strain effects of self-assembled Ge islands on SiGe/Si quantum well (QW) have been studied by measurement of the shift of photoluminescence energy. The Ge islands which operate as stressors have anomalous characteristics in their strain effects with increasing Ge coverage. The islands formed at the early stage of the growth of Ge layer give the strengthened strain effects to the QW, with respect to the increase of the Ge coverage. After the early stage, however, the strain effects are decreased abruptly and then maintained to be constant as the coverage increases. The detailed mechanism for these strain effects has not been clarified yet.

1. INTRODUCTION

Recently, researches on low-dimensional structures such as quantum wires and dots have been carried out extensively, because they have a lot of interests to open new fields of device applications as well as physical understandings.[1-2] Strained SiGe/Si heterostructures, on the other hand, are attracting much attention due to their potential to the application to novel devices and high compatibility to the present Si technology.[3] If one realizes the low-dimensional structures in strained SiGe/Si heterostructures, more sophisticated band engineering can be utilized, and then many attempts are now being conducted. One of the attempts is utilizing lateral band gap modulation by the Ge-rich SiGe stressors.[4] Since Ge grows on Si in Stranski-Krastanov mode to form self-assembled islands,[5] the islands can act as good stressors due to their elastic deformation.[6]

In this presentation, we report on strain effects induced by self-assembled Ge islands on an underlying strained SiGe/Si quantum well (QW) when the Ge coverage is increased.

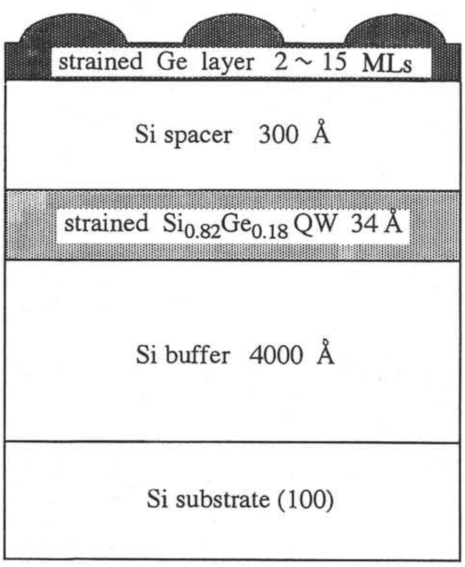

Fig. 1 Schematic illustration of sample structure. The Ge layer was grown in Stranski-Krastanov mode and varied in the range of 2 MLs to 15 MLs.

2. EXPERIMENTAL

Samples studied here, as shown in Fig 1, consist of Ge islands grown in Stranski-Krastanov mode and a single strained $Si_{0.82}Ge_{0.18}$ quantum well (QW) of 34 Å with a Si barrier of 300 Å grown on (100) p-type Si substrates by gas source molecular beam epitaxy (Daido Hoxan VCE-S2020) using disilane and germane as source substances. The growth temperatures of the QW and the Ge layer were 740 °C and 700 °C, respectively. The Ge coverage was varied in the range of 2 monolayers (MLs) to 15 MLs.

Photoluminescence (PL) spectra were obtained in a standard lock-in configuration. An Ar^+ laser for excitation and a liquid-nitrogen-cooled Ge detector (North Coast EO-817L) for detection were used, respectively. The morphology of surface of Ge layer was observed by atomic force microscope (AFM) (Digital Instruments Nanoscope IIIa).

3. RESULTS AND DISCUSSION

Figure 2 shows the PL spectra of samples with the Ge coverage of 3.3 MLs under various excitations. Under high excitation, as shown in the top spectra in Fig. 2, we have observed expected peaks from the QW. However, under the lower excitation, new peaks indicated by arrows in the middle spectra have been observed at lower energies than the peaks of the QW. And then, under very weak excitation, the only new peaks remain, as shown in the bottom spectra in Fig. 2. Here we consider that the new peaks result from modulated quantum structures (MQSs) in the QW induced by Ge islands formed at this coverage. Under very low excitation, the luminescence comes from only the MQSs, since the excited carriers fill only the lower energy states of the MQSs. As the excitation increases, the excited carriers overflow the states of the MQSs and begin to fill the upper energy states of the QW. Therefore, the QW begins to radiate as seen in the middle spectra in Fig. 2. Under the stronger excitation, most of the excited carriers fill in the QW, therefore, the peaks from the MQSs get weak compared with those from the QW. In the top spectra in Fig. 2, the luminescence from the MQSs is hardly seen for this consequence.

This is also supported by the fact that the area occupied by the Ge islands is much less than that without the Ge islands at this coverage, according to the surface

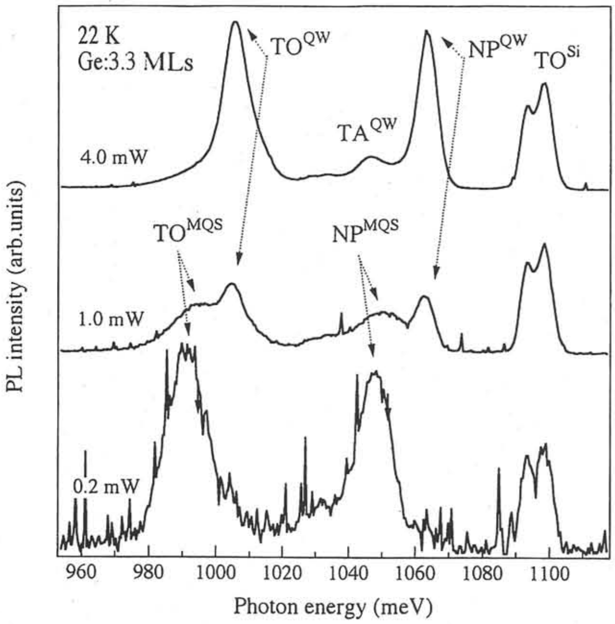

Fig. 2 PL spectra of samples with 3.3 MLs of Ge coverage at various excitations. Superscript of MQS means the modulated quantum structure in the QW induced by the Ge islands.

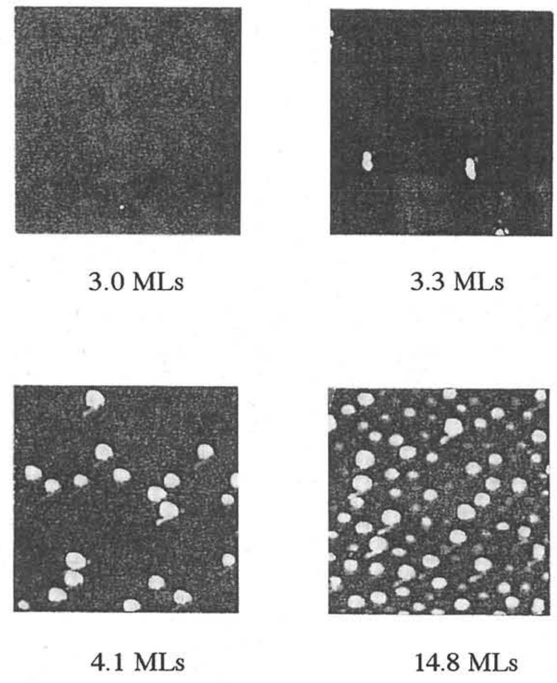

Fig. 3 AFM images of the surface morphology of Ge layers at various Ge coverage. The images are 2 x 2 μm^2 in size.

morphology observation of the Ge layer by AFM image.

Figure 3 shows the surface morphology of Ge layers taken by AFM. The images were taken in size of 2 X 2 μm^2 square of the samples. As seen in this figure, Ge islands are self-assembled initially at the coverage of 3.3 MLs, and the density of the islands is increased as the coverage of Ge increases.

Figure 4 shows the shift of no phonon(NP) energy under low excitation power as a function of the Ge coverage. To the extent of Ge coverage of 3.0 MLs, NP energy almost does not change with the coverage. However, at 3.3 MLs, NP energy redshifts abruptly. This means that the Ge islands playing a role as stressors are formed at this coverage, indicating the changeover of growth mode of Ge on Si to 3-dimensional from 2-dimensional. The onset of formation of the self-assembled Ge islands at 3.3 MLs coverage just agrees with the result of the surface morphology observation by AFM, displayed in Fig. 3. And, as the Ge coverage increases to 3.7 MLs, the quantity of redshift increases. However, at 4.1 MLs the redshift returns to higher energies part suddenly and maintains to be constant with respect to the increase of the Ge coverage.

The self-assembled Ge islands grown on Si are in compressive strain and induce elastic deformation to the underlying structures such as Si spacer and SiGe QW. The elastic deformation gives tensile strain under the center part of the islands and compressive strain under the vicinity of the edge part of the islands. The strain of the QW is compressive in our samples and is strengthened or compensated by the strain induced by the self-assembled Ge islands. This is very similar to the case of patterned stressors in III-V semiconductors.[7]

Increasing the Ge coverage to 3.7 MLs is regarded as the increase in the size and height of the Ge islands, and the strain effect is enhanced, giving rise to the increase of the redshift in PL spectra. However the abrupt decrease of the redshift at 4.1 MLs is unexpected. This probably comes from the interaction between islands, that is, the overlapping of strain fields may attenuate the stressor effects , therefore, the decrease of the redshift is caused. The abrupt saturation of the redshift above 4.1 MLs is also unexpected. One possible explanation is that the relaxation of lattice in the Ge islands reaches to the saturation. That is, even if the Ge coverage increases more than 4.1 MLs, the lattice constant of Ge in the islands is not changed anymore and has a saturated relaxed value. However, in order to fully understand the whole behavior of the PL energy change observed here, more detailed studies are necessary.

4. CONCLUSIONS

We observed the strain effects of the self-assembled Ge islands on strained SiGe/Si QW as a function of the Ge coverage. The results unambiguously suggest that the self-assembled Ge islands generate local strain and induce modulated quantum structures, i.e., strain-induced confinement structures are formed in the underlying QW. In the early stage, the energy shift comes from the evolution of the Ge islands and increases with increasing Ge coverage. However, the abrupt change above 4 MLs, that is, the decrease and the saturation of the redshift have been observed unexpectedly, which requires more detailed studies.

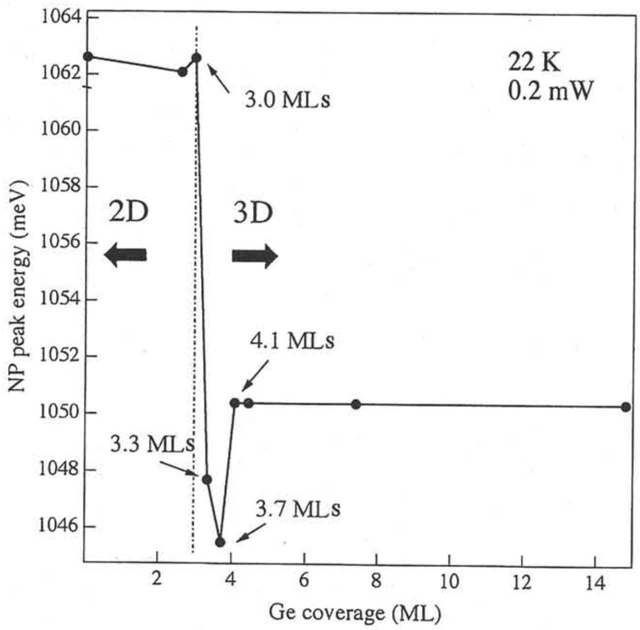

Fig. 4 Shift of the NP peak energy as a function of the Ge coverage. 2D and 3D mean 2- dimensional and 3- dimensional growth, respectively.

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References

1) K. Kash, J. Lumin. **46**, 69(1990)
2) E. Kapon, Proc.of IEEE **80**, 398(1992)
3) R. A. Soref, Proc. of IEEE **81**, 1687(1993)
4) N. Usami, H. Sunamura, T. Mine, S. Fukatsu, and Y. Shiraki, J. Cryst. Growth **150**, 1065(1995)
5) H. Sunamura, N. Usami, S. Fukatsu, and Y.Shiraki, Appl. Phys. Lett. **66**, 3024 (1995)
6) D. J. Eaglesman and M. Cerullo, Phys. Rev. Lett. **65**, 1934(1990)
7) K. Kash, B. P. Van der Gaag, Derek D. Mahoney, A. S. Gozdz, L. T. Florez, and J.P.Harbison, Phys. Rev. Lett. **67**, 1326(1991)