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Photoluminescence of SiGe Quantum Wells Grown on SIMOX by Gas Source MBE

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A study of the photoluminescence properties of Si/SiGe/Si quantum wells grown on SIMOX substrate by gas source MBE is presented. Intense photoluminescence and carrier confinement in the quantum well are demonstrated. It is found that buried SiO_2 isolates the top SOI from the back Si of SIMOX, and alters the photoluminescence properties of SIMOX compared to those of bulk Si. The SOI layer is found to be free of any strain. A SiO_2/Si/SiO_2 optical cavity is proposed by depositing SiO_2 on SIMOX. A substantial enhancement of the photoluminescence intensity of SiGe quantum well is found, which is attributed to the optical confinement of incident beam in the cavity.

1. INTRODUCTION

The SOI (silicon on insulator) technology using SIMOX (separation by implantation of oxygen) substrate has become very important for VLSI applications because of its many advantages such as improved device isolation, radiation hardness, short-channel effect, and circuit speed.[1,2] Recently, SIMOX has also been used to fabricate SiGe-based MOSFET,[3,4] and photodetector.[5] For Si-based optical device applications, SIMOX substrate is attractive because optical devices on SOI can be isolated from the underlying back Si by the buried oxide. Furthermore, a large difference in refractive indices of Si (3.44) and SiO_2 (1.46) can be exploited to build wave-guide structures on SIMOX. Although the growth of Si/SiGe/Si quantum wells on SIMOX has been demonstrated by solid source MBE,[3,4,5] no photoluminescence (PL) property of these quantum wells on SIMOX has been reported. In this letter, we present for the first time a systematic study of PL properties of Si/$Si_{0.82}Ge_{0.18}$/Si quantum wells, which were grown by gas source MBE on commercially available SIMOX wafers. A SiO_2/Si/SiO_2 optical cavity formed on SIMOX has been employed to enhance the PL intensity of the SiGe quantum well.

2. EXPERIMENT

The state-of-the-art SIMOX wafers were used in experiment. Bulk Si wafers were used as controls. These 3-in. SIMOX wafers have 1521 Å SOI and 4151 Å buried oxide. An undoped Si/$Si_{0.82}Ge_{0.18}$/Si quantum well was grown by gas source MBE[6] (Daido Hoxan VCE S2020) at 740°C. In all SIMOX samples studied in this work, a 1000 Å Si buffer is first grown on SOI before the growth of SiGe layer. A multi-line Ar laser was employed for PL excitation, and PL spectra were recorded using standard lock-in technique.

3. RESULTS AND DISCUSSION

Fig. 1 compares PL spectra of a Si/$Si_{0.82}Ge_{0.18}$/Si quantum well (34 Å) grown on SIMOX and bulk Si. Intense PL spectra are obtained from the quantum well on SIMOX. The large peak at 1.098 eV represents the transverse-optical (TO) phonon-assisted transition from Si material of SIMOX (i. e. Si epi, SOI, and back Si substrate). Two peaks at 1.063 and 1.005 eV correspond, respectively, to no-phonon (NP) and its TO replica from the SiGe quantum well. They are separated by 58 meV, the optical phonon energy of Si. The positions of these PL peaks from the quantum well match exactly with those from the quantum well on bulk Si. These PL peak positions are consistent with the quantum confinement results reported by others using bulk Si.[6] Intense photoluminescence and quantum confinement results demonstrate that high quality Si/SiGe/Si quantum wells can be grown on commercially available SIMOX substrate. The PL intensity of SiGe quantum well on SIMOX is found to be significantly higher than that of SiGe quantum well on bulk Si (Figs. 1 and 2). The electron hole droplets (EHD in Fig. 1) are readily formed in case of SIMOX substrate, implying an increased density of the photo-excited carriers.

The SOI layer is found to be free of any strain during SIMOX formation. If there were any strain in SOI, it would have different bandgap than Si substrate. No additional PL peak from SOI is found, suggesting that SOI has the same bandgap as bulk Si. Also, any strain in SOI will affect the strain in SiGe epilayer, which will change the PL peak positions of the NP and TO transitions from the quantum well. But the NP and TO transition peaks from the quantum well on SIMOX and bulk Si coincide exactly. These results confirm that no strain is present in the SOI layer.

The temperature dependence of PL spectra from SiGe quantum wells on SIMOX and bulk Si are shown in Fig. 3. PL spectra originating from the quantum wells of SIMOX and Si show similar temperature dependence, which signifies that high crystal quality can be achieved for SiGe epilayers on SIMOX. In contrast, PL from the substrates (i. e. Si material in SIMOX; bulk Si substrate) at 1.098 eV exhibit completely different temperature behavior. For bulk Si, PL from the substrate rapidly decreases and vanishes at 52 K, whereas for SIMOX, PL from the substrate persists up to 86 K. This discrepancy is attributed to the presence of buried SiO_2 in SIMOX, which isolates SiGe quantum well from the back Si underneath the buried oxide. In case of the bulk Si, photo-generated carriers in Si can travel freely to fall into the SiGe quantum well, which is the lowest energy state in the entire heterostructure. This thermal process is exacerbated with increasing temperature as carriers become thermally more energetic. Therefore, PL energy peak from the bulk Si substrate rapidly weakens with temperature. This process can not occur in SIMOX as buried SiO_2 presents a large energy barrier to photo-excited carriers that are created in the back Si substrate beneath the buried oxide. The substrate spectra (coming from Si material) for SIMOX show different activation energy (48 meV) compared to that for bulk Si (26 meV). This difference in activation energy is not understood, but it could arise due to the structural differences between the two systems.

The difference in the optical indices of Si and SiO_2 can be employed to form optical cavities, which can be used to improve the performance of optical devices on SIMOX. In this work, we propose to form a $SiO_2/Si/SiO_2$ cavity by sputter depositing a SiO_2 layer on top of the epilayer grown on SIMOX. Optical waves traveling from the SOI or epilayer towards the top and buried SiO_2 are reflected at the Si/SiO_2 boundaries. Furthermore, optically generated carries also suffer reflections at the top and buried SiO_2 boundaries, which results in enhanced carriers concentration in the quantum well. Fig. 4 demonstrates that a significant improvement of PL intensities from the SiGe quantum well can be achieved with this optical cavity. The concept of optical cavity is further verified by changing the angle of incidence of the excitation light. PL spectra for two incident angles (α and β, where $\alpha < \beta$) are given in Fig. 4. It is evident in this figure that PL intensities from the quantum well are enhanced with increasing incident angle. For the smaller angle α, the formation of electron-hole-droplet (EHD) is quite pronounced, implying a significant increase in the concentration of optically generated carriers.

4. SUMMARY

In summary, intense PL spectra and quantum confinement in MBE-grown $Si/Si_{0.82}Ge_{0.18}/Si$ quantum wells on SIMOX have been obtained. It is shown that the buried SiO_2 optically isolates SOI from the back Si in case of SIMOX, and alters the PL properties of SIMOX compared to those of bulk Si. No strain is found in SOI layer. A $SiO_2/Si/SiO_2$ optical cavity formed on SIMOX has been shown to enhance the PL intensities of SiGe quantum wells. This study opens up new opportunities for the fabrication of Si-based optoelectronics on SIMOX.

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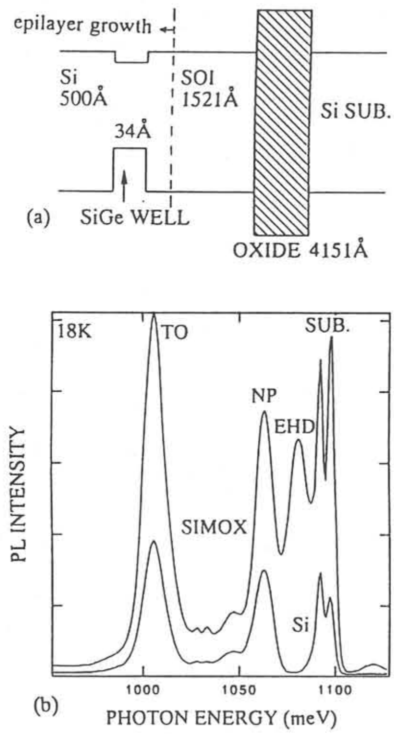

Fig. 1 : (a) Schematic band diagram of the SiGe quantum well on SIMOX, and (b) PL from this structure at 18K.

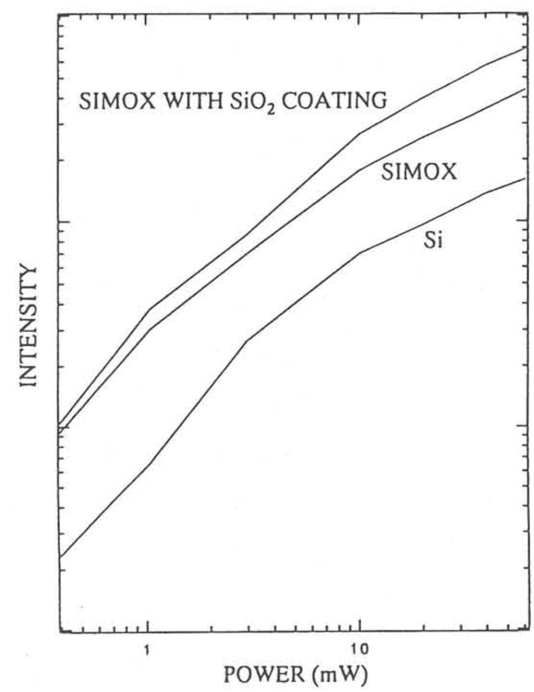

Fig. 2 : Intensity of SiGe quantum wells grown on Si, SIMOX and SIMOX (with a top SiO_2 coating after the growth).

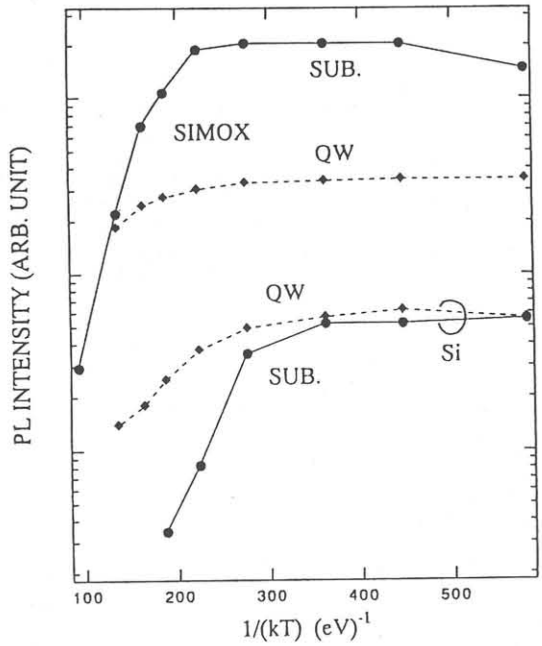

Fig. 3 : Temperature dependence of PL intensities as a function of excitation power for SiGe quantum wells grown on Si and SIMOX.

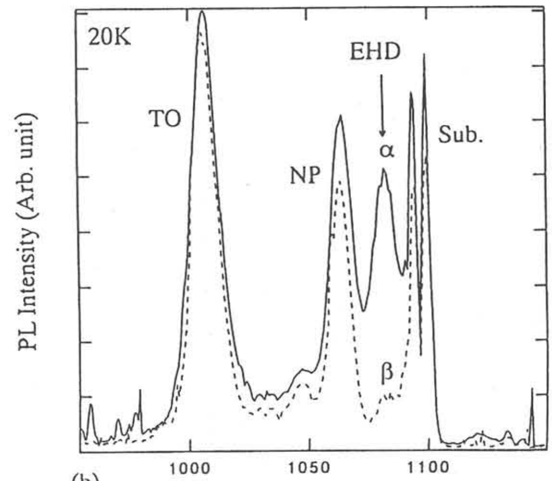

Fig. 4 : Demonstration of cavity effect in a $SiO_2/Si/SiGe/Si/SiO_2$ structure. PL intensity has been shown to depend on the incidence angle of the excitation beam.