Resonant cavity enhanced photoluminescence of tensile strained Ge/SiGe quantum wells on silicon-on-insulator substrate*

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The tensile strained Ge/SiGe multiple quantum wells (MQWs) grown on a silicon-on-insulator (SOI) substrate were fabricated successfully by ultra-high chemical vapor deposition. Room temperature direct band photoluminescence from Ge quantum wells on SOI substrate is strongly modulated by Fabry-Perot cavity formed between the surface of Ge and the interface of buried SiO_2. The photoluminescence peak intensity at 1.58 μm is enhanced by about 21 times compared with that from the Ge/SiGe quantum wells on Si substrate, and the full width at half maximum (FWHM) is significantly reduced. It is suggested that tensile strained Ge/SiGe multiple quantum wells are one of the promising materials for Si-based microcavity light emitting devices.

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Si-based Ge materials have been extensively applied in the fields of Si-based photo-electronic integration and microelectronic devices due to their advantageous properties. However, it is a great challenge to realize Si-based Ge photonic devices, especially for light emitting applications, due to its nature of indirect band gap. Fortunately, Ge is a pseudo-direct band gap material because of the small energy difference (0.136 V) between its direct gap and indirect gap. With tailoring the band structure artificially by in-plain tensile stress[1-3], low-dimensional quantum confinement effect[4-6] and high concentration n-type doping[7,8], Ge can be used for efficient light emission and optical gain, which can be achieved at its direct band gap energy near 0.8 eV to match the required wavelength of 1550 nm.

Ge/SiGe multiple quantum wells (MQWs) with Ge-rich barriers attract more attention due to the band distributed equally in the conduction band and valence band, so that electron and hole can be effectively limited in the well. Yu-Hsuan Kuo et al[9] and Tsujino et al[10] have observed the direct band transition in Ge/SiGe MQW on relaxed Ge-rich SiGe buffer and demonstrated the electro-absorption modulators based on this effect. Bonfanti et al[11] have observed the low-temperature photoluminescence related to direct band transition in $Ge/Si_{0.15}Ge_{0.85}$ MQWs grown on relaxed Ge buffers. Chen et al[12] reported the room temperature direct band photoluminescence and quantum confinement effect in $Ge/Si_{0.15}Ge_{0.85}$ on Si substrate. However, the photoluminescence from Ge/SiGe MQWs is inefficient due to the indirect band nature. In this paper, we present Ge/SiGe MQWs grown on silicon-on-insulator (SOI) substrate for cavity enhancement of luminescence. The tensile strain is introduced into Ge well layers giving rise to the reduction of the direct-to-indirect band separation. The vertical microcavity is formed between the surface of Ge and the interface of buried SiO_2, so that the light can be well enhanced.

The structure schematic of Ge/SiGe quantum wells on SOI is shown in Fig.1. The sample consists of six periods of 9 nm-thick Ge quantum well sandwiched by 15 nm-thick $Si_{0.13}Ge_{0.87}$ on a Ge virtual substrate on a SOI wafer with a 800 nm top Si on 380 nm of buried oxide (BOX) by a cold-wall ultra-high chemical vapor deposition system with a base pressure of 4×10^{-8} Pa. Firstly, 90 nm thick low-temperature Ge layer was grown at 320 °C and then 350 nm thick high-temperature Ge layer at 600 °C. After that, SiGe/Ge MQWs were grown at 600 °C with a Ge mole fraction of 0.87 in the SiGe barrier layers. The cross-sectional morphology and Ge profile in the sample were measured by scanning transmission electron microscope (STEM). The strain status and crystal quality of $Ge/Si_{1-x}Ge_x$ MQW were evaluated by double crystal X-ray diffraction (XRD) measurement (Bede, D1 system), using a Cu $K_{\alpha1}$ (λ=0.15406 m) X-ray source. In order to check the cavity effect on the photolumines-

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cence of Ge/SiGe MQWs on SOI, the other sample with the same structures was prepared on Si substrate under the same growth conditions for comparison. The photoluminescence of the sample with Ge/$Si_{1-x}Ge_x$ MQWs was measured at room temperature using an Ar^+ laser emitting at 488 nm. The excitation beam was focused onto the sample with a spot of about 10 μm in diameter with a power of 30 mW and the emission was detected with an InGaAs detector array cooled by liquid nitrogen.

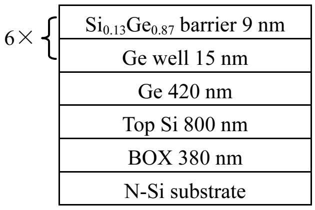

Fig.1 Structure schematic of Ge/SiGe quantum wells on SOI substrate

Fig.2 shows XRD rocking curves of the Ge/SiGe MQW on SOI substrate. Five orders superlattice satellites are observed for the sample, which indicates that the sample has high crystal quality and the sharp interfaces between Ge and SiGe. With the rock distance between Ge epilayer and Si layer, the tensile stain in the Ge epilayer is evaluated to be about 0.17%, which should be due to the large thermal expansion coefficient difference between Ge and Si. The thicknesses of the SiGe layers and Ge layers in the Ge/SiGe MQWs are about 15 nm and 9 nm with Ge mole fraction of 0.87 in the SiGe layer. The tensile strain in the Ge well layers is larger than that in the Ge virtue substrate (about 0.07%) as reported in Ref.[4]. It is suggested that the smaller lattice constant of the SiGe layer increases the strain in the Ge well layer. The tensile strain causes the direct bandgap reduction between the minimum of the Γ valley and the maximum of ligh-hole band, while quantum confinement effect in the 9 nm Ge well will increase the energy separation. Both of them should affect the photoluminescence spectrum.

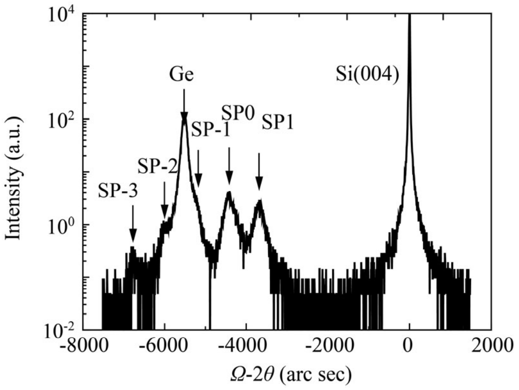

Fig.2 Measured XRD rocking curves of the sample with Ge/SiGe MQWs on SOI substrate

For further compositional analysis of the Ge/SiGe MQWs on SOI substrate, STEM image and Ge profile of the sample are presented in Fig.3. The interface between Ge and SiGe is quite smooth and sharp. The energy dispersive spectrum (EDS) in the inset shows that average Ge mole fraction in the SiGe barriers is about 0.87, which is in good agreement with the XRD analysis.

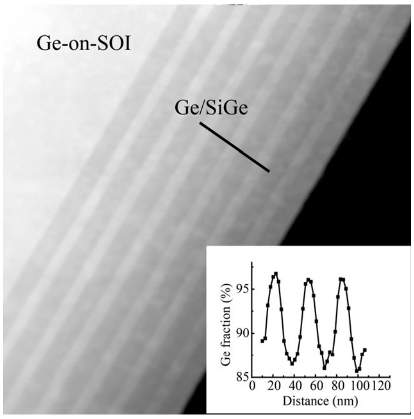

Fig.3 STEM image of the sample with Ge/SiGe MQWs on SOI substrate (The Ge mole fraction with 0.87 in SiGe barrier is indicated.)

Fig.4 shows the photoluminescence spectra of the Ge/SiGe MQWs on SOI substrate and on Si substrate for comparison. It can be seen that the photoluminescence is strongly modulated by Fabry-Perot cavity formed between the surface of Ge and the interface of buried SiO_2 and the maximum peak intensity is enhanced by about 21 folds at 1.58 μm compared that on Si substrate. The full width at half maximum (FWHM) of the luminescence is significantly reduced. The maximum PL peak of the Ge/SiGe MQWs on Si substrate is about 1.54 μm (0.805 eV), which should be determined by the modification of energy band with the tensile strain and quantum confinement effect. The tensile strain in Ge makes the direct band gap narrow, while quantum confinement effect makes the ground state rise at Γ valley. Both of them have contributions to the PL peak energy shift in contrast, which make the PL peak position is nearly in agreement

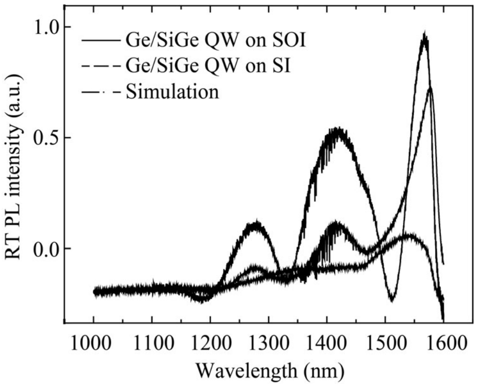

Fig.4 Measured and simulated room temperature photoluminescence of Ge/$Si_{0.13}Ge_{0.87}$ MQWs on SOI and photoluminescence of Ge/SiGe MQWs on Si

with the thick Ge epilayer. However, the PL peak position of the Ge/SiGe MQWs on SOI substrate is mainly determined by the cavity effect. The PL peak intensity is strongly enhanced at the resonant wavelength.

In order to further understand the photoluminescence from SiGe/Ge multiple quantum wells on SOI substrate, the luminescence spectra are simulated by transfer matrix method with considering the direct band radiation from Ge/SiGe quantum wells on Si substrate. The transfer matrix method[13] can be given as follows.

The optical field distribution of the r dielectric layer can be expressed as:

$$E_r(x) = A_r \mathrm{e}^{-\mathrm{i}k_x x} + B_r \mathrm{e}^{\mathrm{i}k_x x}, \tag{1}$$

where the parameter A_r is the forward wave and B_r is the backward wave.

The scattering matrix of the light from the input layer to the reflecting layer can be expressed as:

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} A_N' \\ B_N' \end{bmatrix}, \tag{2}$$

where

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \boldsymbol{D}_0^{-1} \cdot \prod_{r=1}^{N-1} \begin{bmatrix} \cos(\phi_r) & \sin(\phi_r)/\mathrm{i}\eta_r \\ \mathrm{i}\eta_r \sin(\phi_r) & \cos(\phi_r) \end{bmatrix} \cdot \boldsymbol{D}_N, \tag{3}$$

where $\boldsymbol{D}_r$ and $\boldsymbol{D}_r^{-1}$ are the transfer matrix and its inverse matrix, ϕ_r is the phase factor, and η_r is the incidence angle.

The reflectivity of the multilayer films is expected as $R = \left|\frac{M_{21}}{M_{11}}\right|^2$, which can be used to fit the photoluminescence of the material. The simulated result of mode characteristics of the resonant cavity by the transfer matrix method is plotted in Fig.4. Clearly, the resonant wavelength which is controlled by the length of the active region is in agreement with the experimental data.

In conclusion, tensile strained Ge/SiGe MQWs were grown on SOI-based germanium virtual substrates with uniform periodicity and good crystal quality. The photoluminescence spectrum of the Ge/SiGe MQWs on SOI substrate is strongly modified and the maximum peak intensity is enhanced by about 21 times compared with that on Si substrate, and the full width at half maximum is significantly reduced. Those results suggest that the tensile strained Ge/SiGe MQWs on SOI substrate is one of the most promising candidates for Si-based photonic devices.

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