PS-5-09
Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp1013-1014

The Si_3N_4 Liner Stressor for Performance Improvement of Tensile-Strained GeSn/SiGeSn Multiple Quantum Well Laser

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Abstract

We theoretically demonstrate a tensile-strained GeSn/SiGeSn multiple quantum well (MQW) laser wrapped in Si_3N_4 liner stressor. The biaxial tensile strain is introduced into the MQW laser by Si_3N_4 liner stressor. The threshold current density J_{th} reduces from 476 to 168 A/cm^2 and a significant enhancement of optical gain can be achieved compared to the relaxed device without Si_3N_4. Further, it is demonstrated that the device performance can be improved with the increase in Sn composition and carrier injection density in the GeSn wells. This proposed structure a practical way to realize high performance laser based on GeSn.

1. Introduction

The rapid development of electronic technology limits its further development and the photonic devices come to being. Low luminous efficiency of Group IV semiconductors, which is caused by the indirect-bandgap, limits their applications in photonic functional devices. By incorporating Sn into Ge, it can achieve the decline in the band gap energies and make it a possible candidate as the gain medium [1, 2]. However, high Sn composition will result in the solid solubility in the device, which is destructive to the overall function of the optoelectronic device. In addition, the thermal stability of GeSn film will also become an obstacle in device fabrication. Therefore, silicon nitride (SiN_x) films are used as an external stressor to induce strain into GeSn. It can reduces the Sn composition needed for realization of direct bandgap, which poses a strategy to make high performance GeSn based devices.

In this work, we propose a strategy to improve the performance of a GeSn/SiGeSn multiple quantum well (MQW) laser by Si_3N_4 liner stressor. The device characteristics are thoroughly analyzed by Sn composition, injected carrier density n_{injected}, and quantum well number n_{well}.

2. Simulation and analysis

Fig. 1 illustrates the schematic diagram of the proposed structure. The $Ge_{1-x}Sn_x/Si_{1-y-z}Ge_ySn_z$ MQW microdisk laser is on $Ge_{1-t}Sn_t$ buffer on Ge/Si virtual substrate, which is wrapped by a Si_3N_4 liner stressor.

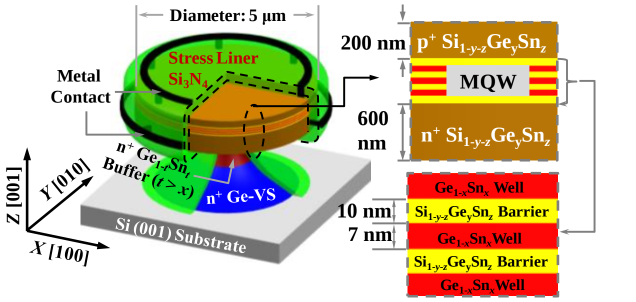

Fig. 1. 3D schematic of the $Ge_{1-x}Sn_x/Si_{1-y-z}Ge_ySn_z$ MQW laser wrapped in a Si_3N_4 liner stressor.

3. Results and Discussion

Strain distribution in GeSn wells

It is observed in Fig. 2 that at the center of the GeSn layer, the values of $\varepsilon_{[100]}$, $\varepsilon_{[010]}$, and $\varepsilon_{[001]}$ are 0.85%, 0.85%, and -0.77%, respectively. The fringe region of the microdisk has the smaller magnitude of strain compared to the central region, which will widen the emission spectrum of the laser.

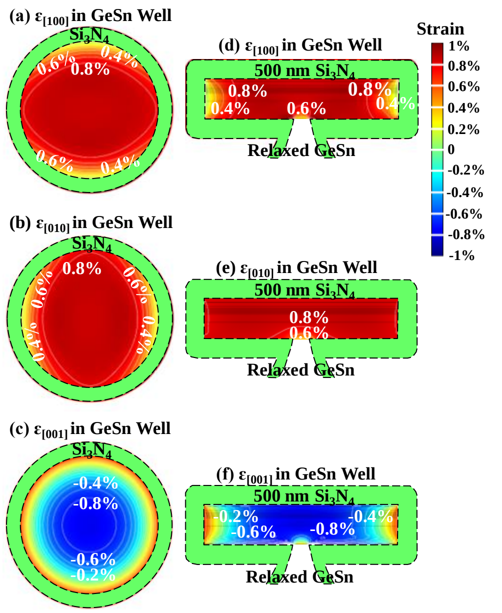

Fig. 2. Contour plots for (a) $\varepsilon_{[100]}$, (b) $\varepsilon_{[010]}$, and (c) $\varepsilon_{[001]}$ in the normal cross section plane and (d) $\varepsilon_{[100]}$, (e) $\varepsilon_{[010]}$, and (f) $\varepsilon_{[001]}$ in the radial cross section plane in GeSn well for the $Ge_{0.90}Sn_{0.10}/Si_{0.161}Ge_{0.695}Sn_{0.144}$ MQW laser wrapped in a 500 nm Si_3N_4 liner stressor.

Energy band structure and carrier distribution in GeSn/Si-GeSn MQW

Fig. 3(a) and (b) show the band diagrams of the relaxed and strained $Ge_{0.90}Sn_{0.10}/Si_{0.161}Ge_{0.695}Sn_{0.144}$ MQW laser device wrapped in a 500 nm Si_3N_4 liner stressor, respectively. It is clear that the electron and hole are both confined in $Ge_{0.90}Sn_{0.10}$ wells, which is in favor of the optical recombination of carriers. It should also be noted that the compared with L valley, Γ conduction valley has a more rapid decline in energy due to the larger deformation potential.

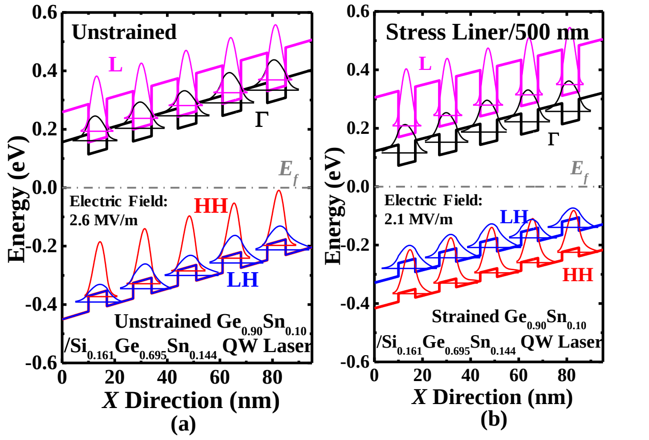

Fig. 3. Energy band diagrams of (a) relaxed and (b) tensile strained $Ge_{0.90}Sn_{0.10}/Si_{0.161}Ge_{0.695}Sn_{0.144}$ MQW laser wrapped in a 500 nm Si_3N_4 liner stressor.

We plot the distribution of electrons in Γ and L conduction valleys in GeSn wells in Fig. 4, which has a great impact on the J_{th} and optical gain of the devices. The increase of electron occupation probability in Γ conduction valley can be conducive to the improvement of optical emission performance in lasers.

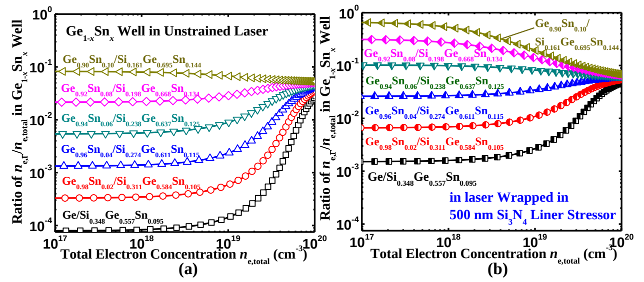

Fig. 4. $n_{e,\Gamma}/n_{e,total}$ in (a) relaxed and (b) tensile strained GeSn/SiGeSn MQW lasers with a 500 nm Si_3N_4 liner stressor.

Threshold current and gain coefficient in the laser

Fig. 5 shows the relationship between the ΔE_f and the $n_{injected}$ in relaxed and tensile strained GeSn/SiGeSn MQW lasers with different Sn compositions. As the Sn composition increases, the onset of population inversion n_{onset_pi} decreases. Under the tensile strain, the n_{onset_pi} further decreases due to the decline in the sub-bandgap $E_{sub\text{-}G}$ of GeSn wells. The tensile strained $Ge_{0.90}Sn_{0.10}/Si_{0.161}Ge_{0.695}Sn_{0.144}$ MQW laser demonstrates a n_{onset_pi} of 0.5×10^{18} cm^{-3}, which is much lower than that of the relaxed device, 3.8×10^{18} cm^{-3}.

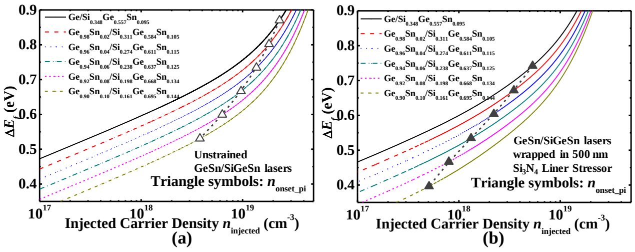

Fig. 5. ΔE_f versus $n_{injected}$ for (a) relaxed and (b) strained GeSn/SiGeSn MQW lasers with 20 wells wrapped in a 500 nm Si_3N_4 liner stressor with different Sn compositions.

As shown in Fig. 6(a) and (b), the J_{th} and optical gain α in GeSn/SiGeSn lasers are modeled as a function of Sn composition in GeSn wells and injected current density, respectively. Here, L_z is the thickness of the potential well. By introducing the tensile strain, it can be clearly seen that the J_{th} decreases from 476 to 168 A/cm^2 at a Sn content of 0.1. For comparison, the values of $\Gamma_{MQW,TE}\ g_{\Gamma\text{-HH}}$ and $\Gamma_{MQW,TM}\ g_{\Gamma\text{-LH}}$ are calculated as a function of injected current density J for the relaxed and tensile strained $Ge_{0.90}Sn_{0.10}/Si_{0.161}Ge_{0.695}Sn_{0.144}$ MQW lasers, as shown in Fig. 6(b). The calculation results indicate that J decreases significantly to achieve a same α for the strained $Ge_{0.90}Sn_{0.10}$ device.

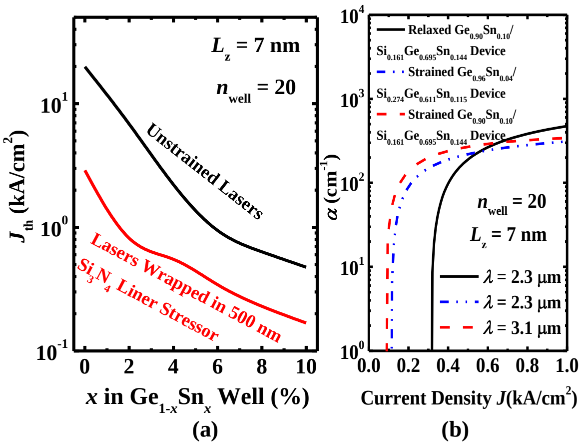

Fig. 6. (a) Modeled J_{th} as a function of the Sn composition in GeSn wells for relaxed and tensile strained GeSn/SiGeSn MQW lasers wrapped in a 500 nm Si_3N_4 liner stressor. L_z is 7 nm and n_{well} is 20. (b) Modeled optical gain α as a function of injected current density J for the relaxed and tensile strained MQW laser.

3. Conclusions

In summary, a tensile strained GeSn/SiGeSn MQW laser is designed and analyzed. The simulation results indicate that with the assistance of a Si_3N_4 liner stressor, both J_{th} and α can be improved. Moreover, by increasing the Sn composition and carrier injection density in the GeSn wells, the device performance can be further improved. This proposed strategy can contribute to the development of GeSn based mid-infrared laser.

References

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