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Design of Low Threshold GaAs-based Photonic Crystal Surface Emitting Lasers

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Over the past decade, two-dimensional (2D) photonic crystal (PC) has been widely manipulated and researched in many optoelectronic devices such as photonic crystal surface emitting lasers (PCSELs) because of the 2D distributed feedback (DFB) mechanism [1-4]. By adjusting the normalized frequency at the photonic band edges and PC period rigorously, the specific Bragg diffraction will occur to achieve surface emission condition [5-7]. Since 1960s, GaAs-based materials have attracted a great attention and used in the production of red and infrared lasers which were widely applied in optical storage, pumping sources, medical treatments and various applications. Improvement of epitaxial quality and optimization of the device structure in GaAs-based PCSELs has been an important issue. In the previous reports, several groups have demonstrated GaAs-based PCSELs [8, 9], but the impact of the vertical optical confinement factor in the device structure has not been carefully considered yet. Here, we have calculated the optical confinement factor in the device structure by using the transfer matrix method [10] and the threshold gain by using the coupled-wave theory [11] for square-lattice PC patterns. By varying the thickness of the PC layer, inner cladding and optical confinement layers in the PCSEL structures, the optical confinement factor has been optimized and the relation between the threshold gain and the filling factor of the PC is also analyzed by the coupled-wave theory in the optimized PCSEL structures.

The schematics of GaAs-based PCSELs without and with optimization are shown in Fig. 1. The full structure for simulation is composed of a [100] GaAs substrate, a n-type 1.5 μm-thick $Al_{0.6}Ga_{0.4}As$ bottom cladding layer, a three-pair $In_{0.2}Ga_{0.8}As$/GaAs (6 nm/6 nm) multiple quantum wells (MQWs) sandwiched between the n-type and p-type 100 nm-thick $Al_{0.3}Ga_{0.7}As$ optical confinement layers, a 100 nm-thick inner cladding layer and a 1.4 μm-thick outer cladding layer formed by p-type $Al_{0.6}Ga_{0.4}As$, separated by the 100 nm-thick PC layer and an $In_{0.5}Ga_{0.5}P$ etch stop layer (10 nm), and a 100 nm-thick GaAs contact layer shown as Fig. 1(a). The PC layer consisted of SiO_2 and p-type $Al_{0.6}Ga_{0.4}As$, and the filling factor is 0.2 in this design.

To obtain an optimized vertical optical confinement,

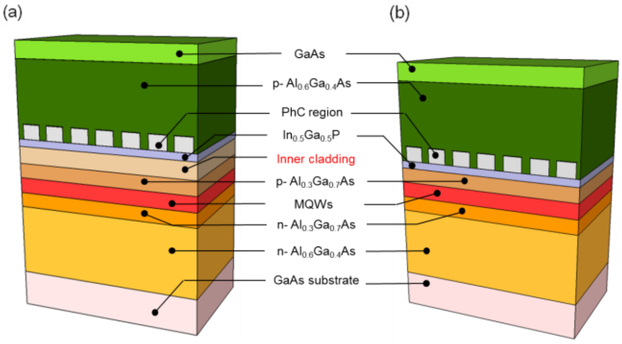

Fig. 1. The schematics of PCSELs (a) without and (b) with optimization. The differences between both structures are the existence of inner cladding layer and the thickness of optical confinement layers.

first is to adjust the thickness of embedded PC layer. Then, the thickness of the inner cladding layer would be determined. Finally, the thickness of optical confinement layer would be optimized.

While the thickness of PC layer is increased from 0 to 200 nm, the confinement factor is improved obviously and saturated at 100 nm. Beyond the critical thickness, the contribution from increasing of PC thickness is relatively negligible. Therefore, the thickness of embedded PC layer is set to be 100 nm. Then, the thickness of optical confinement layers and inner cladding layer are varied simultaneously. The calculated result shows that the best case appears when the inner cladding layer is completely removed. In addition, the threshold gain can be reduced effectively as removing the inner cladding layer. Based on the coupled-wave theory, the lowest threshold gain is calculated with 80 nm-thick optical confinement layers as shown in Fig. 2(a). The threshold gain which utilizes the optimal structure as shown in Fig. 1(b) is calculated to be 155 cm^{-1}. The optical field distribution of the device is shown in Fig. 2(b). Since the optical field is most intense around MQWs, the spacing between MQWs and PC layer should be reduced to enhance the confinement factor. In the optimized PCSEL structures, the optical confinement factor of PC region can be as large as 7.3 %.

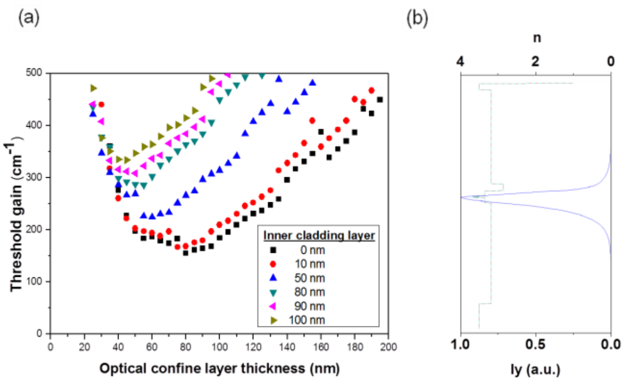

Fig. 2 (a) Threshold gain as functions of the thickness of optical confinement layer for various thicknesses of inner cladding layer. (b) The vertical optical field distribution of the optimal structure.

Among all the different values, the threshold gain is also simulated as a function of the filling factor as shown in Fig 3. We can obtain the optimized filling factor of the device by this calculation method. The filling factor for the lowest threshold gain can be determined to be 0.08.

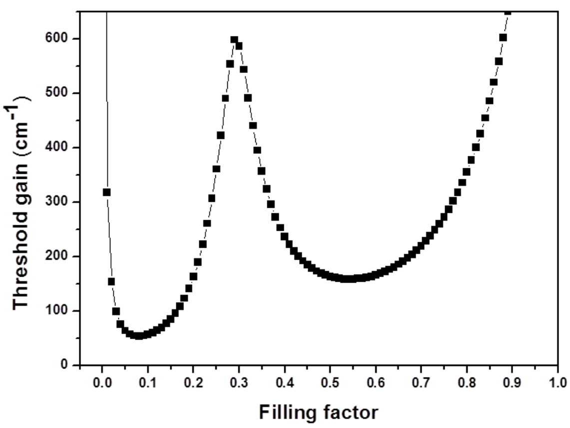

Fig. 3. Threshold gain as a function of the filling factor utilized the optimal structure shown in Fig. 1(b).

In summary, we have established three-step strategy to investigate the influence of various thicknesses on the inner cladding and optical confinement layers by the transfer matrix method, and also simulated the threshold gain of the optimized structure by the coupled-wave theory. In addition, the relation between the threshold gain with filling factor has been considered. This study provides a fast calculation method in designing of PCSEL structures and we believe it is useful for fabrication of the low threshold GaAs-based PCSELs in the near future.

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