第 24 卷第 1 期　　半　导　体　学　报　　Vol. 24, No. 1
2003 年 1 月　　CHINESE JOURNAL OF SEMICONDUCTORS　　Jan., 2003

Optimization Design of Active Structure of Strained MQW DFB Lasers

Zhang Yejin[1], Zhu Lin[1], Gao Zhiguo[1], Chen Minghua[1], Dong Yi[1],
Chen Weiyou[2], Liu Shiyong[2] and Xie Shizhong[1]

(1 *Department of Electronics Engineering, Tsinghua University, Beijing* 100084, *China*)
(2 *Department of Electronics Engineering, Jilin University, Changchun* 130023, *China*)

Abstract: The well number and the cavity length of 1.55μm wavelength $In_{1-x-y}Ga_yAl_xAs$ MQW DFB lasers are optimized using a simple model. A low threshold, maximum operating temperature of 550~ 560K, and high relaxation oscillation frequency of over 30GHz MQW DFB laser is presented.

Key words: $In_{1-x-y}Ga_yAl_xAs$; QW laser; DFB; differential gain; optimization design
PACC: 4255P; 4260; 7340L; 7280
CLC number: TN248.4　　**Document code**: A　　**Article ID**: 0253-4177(2003)01-0006-05

1 Introduction

It is well known that there are two main material systems for fabricating long-wavelength semiconductor lasers. The $In_{1-x}Ga_xAs_{1-y}P_y$ system has been worked on extensively[1,2], and the $In_{1-x-y}Ga_yAl_xAs$ system is starting to produce good results[3] recently. For the $In_{1-x-y}Ga_yAl_xAs$ system, a large band offset of 0.7(= $\Delta E_c/\Delta E_g$) presents better electron confinement, which improves temperature stability.

We know that complex Poisson′s equation, Schrodinger equation, electron and hole continuity equations, along with Helmholtz equation, photon rate equation, and thermal conduction equation have to be solved on every different grid of 1, 2 or 3 dimensions by the method of finite difference and iteration in the conventional simulation of MQW (multi-quantum well) DFB lasers. Using the complex model, the CPU takes a long time and convergent solutions are very difficult to obtain[4], if the initial values are not right. Besides, some parameters used in the calculation can not be obtained exactly, which affects the results of simulation. Using the complex model, we can analyze some special effects, such as longitudinal hole burning effects, but for optimization design introducing a great calculation points, the model is unsuitable. For above reasons we try a simple model for a DFB laser.

In this paper, a simple model is presented to optimize the active structure of $In_{1-x-y}Ga_yAl_xAs$ strained MQW DFB lasers, which begins with the oscillation condition of DFB lasers and some expressions of parameters for MQW, such as gain, confinement factor, density of threshold current, maximum operating temperature and relaxation oscillation frequency, have been derived. Through solving the oscillation condition and application of these expressions, the effect of the well number and the cavity length on threshold current, maximum operating temperature, and relaxation oscillation frequency can be investigated easily in the case of $In_{1-x-y}Ga_yAl_xAs$ system. At the same time, a

---

Received 20 April 2002, revised manuscript received 22 August 2002

complex model which includes substantial calculation as mentioned above is used to this optimization calculation and the result agrees well with the former. Compared the simple model with the complex one, 90% of CPU time can be saved.

We hope that this work is helpful to design high-performance MQW DFB lasers.

2 Model

The oscillation condition of a DFB laser can be written as[5]

$$\frac{(r_{G2}-r_1)(r_{G1}-r_2)}{(1-r_1r_{G1})(1-r_2r_{G2})}\exp(-2i\gamma_s L)=1 \quad (1)$$

where L is cavity length, r_{G1} and r_{G2} represent two complex reflectivity, and can be written as

$$r_{G1}=\frac{\kappa\exp(i\varphi)}{-\gamma_s-\Delta\beta} \quad (2a)$$

$$r_{G2}=\frac{\gamma_s-\Delta\beta}{\kappa\exp(i\varphi)} \quad (2b)$$

where κ is couple coefficient, φ is initial phase of the grating,

$$\Delta\beta=\delta+i\frac{\Gamma g-\Gamma\alpha_{IVBA}-\alpha_0}{2} \quad (3a)$$

$$\gamma_s=[(\Delta\beta)^2-\kappa\kappa^*]^{1/2} \quad (3b)$$

where g is the material gain, which is a function of temperature T and the carrier density N[5],

$$g=a_N(T)\ln\frac{N}{N_t(T)} \quad (4)$$

where a_N and N_t represent temperature dependence of characteristics gain and carrier density for transparency respectively, the Harrison´s model and anisotropic parabolic approximation are used to calculate the material gain g of $In_{1-x-y}Ga_yAl_xAs$ compressively strained MQW[5,8].

In Eq. (3), $\alpha_{IVBA}=\gamma n_{th}$ is the loss induced by the intervalence band absorption, γ is the IVBA coefficient, n_{th} is threshold carrier density, δ is offset of wave number, α_0 is the residual loss, r_1 and r_2 represent facet reflectivity, which can be written as

$$r_i=|r_i|\exp(i\varphi_i) \qquad i=1,2 \quad (5)$$

where φ_i is offset of phase caused by facet reflection. Γ is the optical confinement factor of the quantum wells, and is calculated as[5]

$$\Gamma=\frac{nL_z}{nL_z+(n-1)L_b}\Gamma_{conv} \quad (6)$$

where Γ_{conv} is the confinement factor of a five-layer conventional DH structure, n is the well number, L_z is the well thickness, and L_b is the barrier thickness.

From Eqs. (1) and (4), n_{th} can be obtained. n_{th} and the threshold current density have the following relation[6]:

$$J_{th}=qnL_z(An_{th}+Bn_{th}^2+Cn_{th}^3)=kn_{th}^{\xi} \quad (7)$$

where A, B and C represent recombination coefficient. Another aspect, the temperature dependence of the threshold current density, can be described by[6]:

$$J_{th}=J_0\left(1-\frac{T}{T_{max}}\right)^{-\xi} \quad (8)$$

where T_{max} is the maximum operating temperature, which is independent of temperature. A laser with larger T_{max} has higher stability of temperature. The parameter ξ has been found to have a value of 2 more or less.

The value of γn_{th} from IVBA losses in Eq. 3(a) can be described by[7]:

$$(\gamma n_{th})^{-1}=U(N,L)-S(N,L)T \quad (9)$$

where U and S represent fitting parameters.

By solving for n_{th} in Eq. (9) and substituting into Eq. (8), it can be shown that

$$J_{th}=J_{0s}\left(1-\frac{T}{U/S}\right)^{-\xi} \quad (10)$$

According to Eqs. (10) and (8), we have $T_{max}=U/S$.

Relaxation oscillation frequency can be given by

$$f_r=\frac{1}{2\pi}\left[\frac{v_g}{qL_z}\times\frac{\Gamma}{WnL_z}(dg/dN)(I-I_{th})\right]^{1/2} \quad (11)$$

where v_g is the group velocity, W is the active layer width, (dg/dN) is the differential gain, and $(I-I_{th})$ is the driving current pulse height over the threshold.

3 Results of simulation

In this section, we are going to analyze a

-0.78% compressively strained QW structure studied in experiments[3]. The active region consists of $\mathrm{In_{0.65}Ga_{0.34}Al_{0.01}As}$ wells of 5.4nm thick and $\mathrm{In_{0.53}Ga_{0.26}Al_{0.21}As}$ barriers of 5.7nm thick. The MQW stack is sandwiched between an undoped 100nm thick 1.21μm $\mathrm{In_{0.53}Ga_{0.26}Al_{0.21}As}$ SCL matched to InP with the 2000nm InP cladding and 1.5μm stripe. Parameters used can be seen in Table 1 and Refs.[3,5].

Table 1 Parameters of the simulated DFB laser

Shockley-Read-Hall recombination coefficient	$A=4\times10^{8}\mathrm{s}^{-1}$
Bimolecular recombination coefficient	$B=1\times10^{-10}\mathrm{cm}^{-3}\cdot\mathrm{s}^{-1}$
Auger recombination coefficient	$C=2\times10^{-29}\mathrm{cm}^{-6}\cdot\mathrm{s}^{-1}$
Absorption loss	$\alpha_0=15\mathrm{cm}^{-1}$
Facet reflectivity	$r_1=r_2=0$
Average group velocity	$v_g=8.5\times10^{9}\mathrm{cm/s}$
DH confinement factor	$\Gamma_{\mathrm{conv}}=0.3$
Coupling coefficient	$\kappa=40\mathrm{cm}^{-1}$
Active layer width	$W=3\mu\mathrm{m}$
IVBA coefficient	$\gamma=8\times10^{-17}\mathrm{cm}^{2}$
Driving current pulse height over the threshold	$I-I_{\mathrm{th}}=40\mathrm{mA}$

For the InGaAlAs system, the Harrison´s model and anisotropic parabolic approximation have been used to calculate the material gain g of strained MQW[5]. The characteristics gain and transparency carrier density are presented in Figs. 1 and 2.

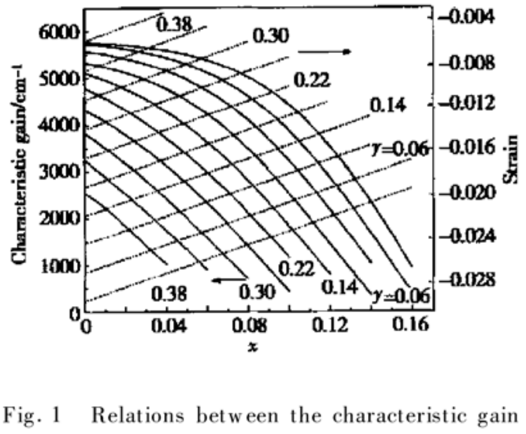

Fig. 1 Relations between the characteristic gain and Al composition

Figure 3 shows that the threshold current varies with the well number and the cavity length. When varying the cavity length or well number, the threshold current has a minimal value for a certain well number or cavity length. We found that large well number and short cavity can result in a low threshold current (7~ 8mA). However, Figure 4 shows that a short cavity leads to a high current density (1600~ 1700A/cm²) and a low maximum operating temperature (450~ 460K), as indicated in Fig. 5. Another aspect, large well number can not lead to low current density, as shown in Fig. 4. Figure 6 shows that f_r has a maximum value with an increase of the well number for a certain cavity length, and the well number of the maximum is about 10. In addition, f_r has decrease with an increase of the cavity length for a certain well number.

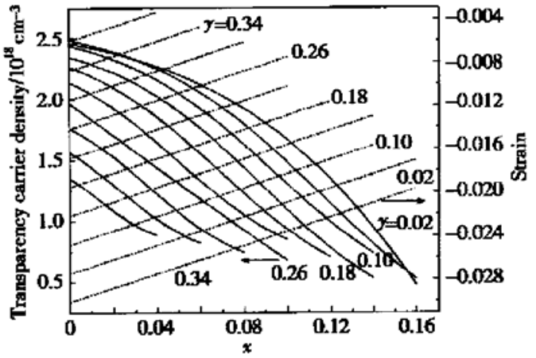

Fig. 2 Relations between the transparency carrier density and Al composition

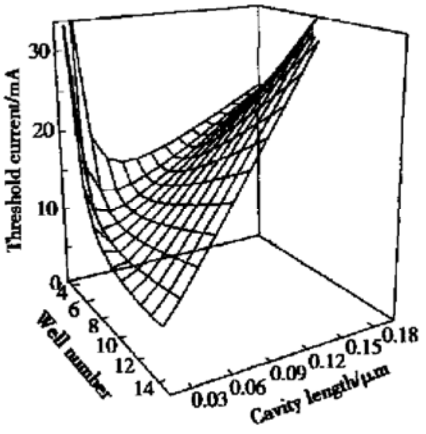

Fig. 3 Threshold current versus well number and the cavity length

According to Figs. 3~ 6, we obtained the optimized well number of 9~ 10, the optimized cavity length of 200~ 300μm, which gives a threshold current of 9~ 10mA, the maximum operating temperature of 550~ 560K, and the relaxation oscillation

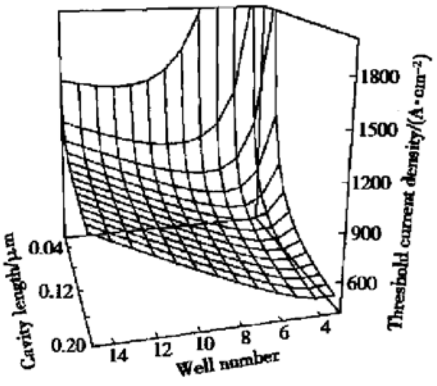

Fig. 4 Threshold current density versus well number and cavity length

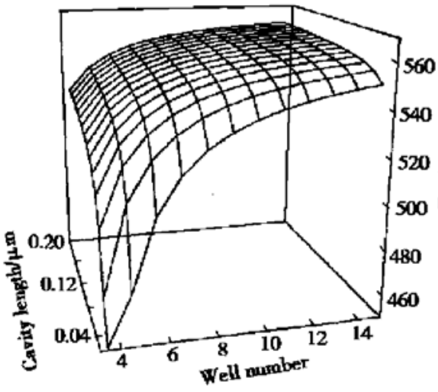

Fig. 5 Maximum operating temperature versus well number and cavity length

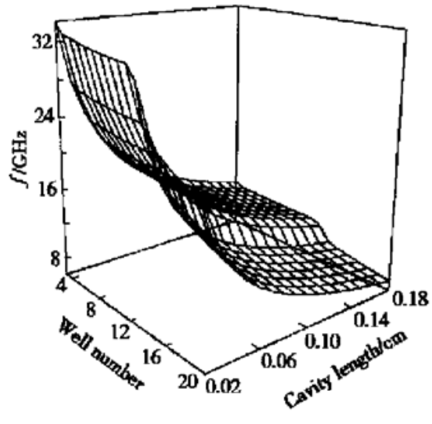

Fig. 6 Relaxation oscillation frequency versus well number and cavity length

frequency of over 30GHz.

As comparison, some results obtained from the simple model, the normal complex model and available are presented in Table 2. We found that the results of simple model are almost the same as the results of complex one, and 90% of CPU time can be saved.

Table 2 Comparison of results

n,	Simple	Complex	Exp.
L/μm	I_{th}/mA, T_{max}/K, f_r/GHz	I_{th}/mA, T_{max}/K, f_r/GHz	I_{th}/mA
3, 200	35, 500, 34. 3	37, 487, 32	–
4, 500	16, 520, 21. 3	17. 6, 513, 20. 7	–
5, 890	12. 6, 525, 19. 2	12. 8, 519, 13. 1	12. 0[3]
9, 800	17. 4, 550, 16. 4	16. 9, 547, 15. 9	–
10, 500	13. 2, 556, 22. 3	12. 9, 549, 21. 7	13. 5[5]

4 Conclusion

To optimize the well number and the cavity length of $In_{1-x-y}Ga_yAl_xAs$ strained MQW DFB lasers, a simple model is presented. Theoretically, a low threshold current, high maximum operating temperature, and high relaxation oscillation frequency $In_{1-x-y}Ga_yAl_xAs$ strained MQW DFB laser are investigated. We find that the simple model is advisable for optimization design of MQW DFB lasers.

References

[1] Osinski J S, Zou Y, Grodzinski P, et al. Low-threshold-current-density 1.5μm lasers using compressively strained InGaAsP quantum wells. IEEE Photonics Technol Lett, 1992, 4: 10

[2] Thijs P J A, Tiemijer L F, Binsma J J M, et al. Progress in long-wavelength strained-layer InGaAs(P) quantum-well semiconductor lasers and amplifiers. IEEE J Quantum Electron, 1994, 30: 477

[3] Minch J, Park S H, Keating T, et al. Theory and experiment of $In_{1-x}Ga_xAs_yP_{1-y}$ and $In_{1-x-y}Ga_xAl_yAs$ long-wavelength strained quantum-well lasers. IEEE J Quantum Electron, 1999, 35: 771

[4] Huang W, et al. Analytical formulas for modulation responses of semiconductor DFB lasers. IEEE J Quantum Electron, 1995, 31: 842

[5] Zhang Y, et al. Design of the active structure of high-performance 1.55μm $In_{1-x-y}Ga_yAl_xAs$ strained MQW lasers. IEEE J Quantum Electron, 2001, 37: 923

[6] Prosyk K. A systematic empirical study of the effect of well number and length on the temperature sensitivity of the

threshold current in InGaAsP-InP MQW lasers. IEEE J Quantum Electron, 1998, 34: 535

[7] Prosyk K, Simmons J G, Evans J D. Well number, length and temperature dependence of efficiency and loss in compressively strained InGaAsP/InP ridge waveguide MQW lasers at 1.3μm. IEEE J Quantum Electron, 1997, 33: 1360

[8] Zhang Y J, Chen W Y, Jiang H, et al. Approximate well width and optical gain formulas of 1.55μm $In_{1-x-y}Ga_yAl_xAs$ compressively strained quantum-well laser. Chinese Journal of Semiconductors, 2001, 22(1): 11

应变多量子阱DFB激光器有源区的优化设计

张冶金[1] 朱 林[1] 高志国[1] 陈明华[1] 董 毅[1] 陈维友[2] 刘式墉[2] 谢世钟[1]

(1 清华大学电子工程系, 北京 100084)
(2 吉林大学电子工程系, 长春 130023)

摘要: 利用一个简单模型对1.55μm波长$In_{1-x-y}Ga_yAl_xAs$ MQW DFB激光器的阱数和腔长进行了优化,模拟得到了最高工作温度达550~560K,张弛振荡频率在30GHz以上的低阈值MQW DFB.

关键词: $In_{1-x-y}Ga_yAl_xAs$; 量子阱激光器; DFB; 微分增益; 优化设计
PACC: 4255P; 4260; 7340L; 7280
中图分类号: TN248.4 **文献标识码**: A **文章编号**: 0253-4177(2003)01-0006-05

2002-04-20收到, 2002-08-22定稿