Optimized Layers Design for AlGaN/GaN/InGaN Symmetrical Separate Confinement Heterojunction Multi-Quantum Well Laser Diode[*]

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Abstract: Waveguide characteristics of symmetrical separate confinement heterojunction multi-quantum well (SCH-MQW) AlGaN/GaN/InGaN laser diode (LD) are studied by using one dimensional (1-D) transfer-matrix waveguide approach. Aiming at photon confinement factor, threshold current, and power efficiency, layers design for SCH-MQW LD is optimized. The optimal layers parameters are 3 periods $In_{0.02}Ga_{0.98}N/In_{0.15}Ga_{0.85}N$ QW for active layer, $In_{0.1}Ga_{0.9}N$ for waveguide layer with 90nm thick, and $120 \times (2.5nm/2.5nm)$ $Al_{0.25}Ga_{0.75}N/GaN$ supper lattices for cladding layer with the laser wavelength of 396.6nm.

Key words: AlGaN/GaN/InGaN; MQW; SCH

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1 Introduction

There is considerable interest in applications of blue semiconductor lasers fabricated by the III-V nitrides. The use of compact short wavelength light sources will improve the resolution of scanners and printers as well as increase the storage density of optical disks. In the past few years, there has been rapid development of wide-band-gap nitride-based blue laser diodes, beginning with Nakamura *et al*. reporting the first pulsed injection laser[1], soon followed by continuous wave at room temperature operation[2]. For laser diodes grown on epitaxially lateral overgrown GaN, operating lifetimes now exceed 10000h at room temperature[3]. In achieving the current stage of development, the emphasis has been on material improvements such as buffer layers for epitaxial growth[4], strain-relief layers[1], lateral overgrown layers for reduction of threading dislocations[3], and modulation-doped superlattices cladding layers to prevent cracking and reduce the operating voltage[3]. Relatively little has been reported on the layer design of the LDs in order to improve both the electronic and optical properties. For optical memory applications, device design for reducing threshold current and controlling transverse mode is quite important. This paper describes the results of the optimized layer(such as MQW, waveguide layer, and cladding layer) design of the symmetrical SCH-MQW AlGaN/GaN/InGaN LD with the minimum threshold current and power efficiency.

2 Results and discussion

In this work, the LD is typical symmetrical

SCH-MQW structure. The detailed structure and optical parameters of relevant layers are shown in Table 1. Optical-field profiles in LD were calculat-ed using transfer-matrix 1-D waveguide approach[5].

Table 1   Layer structures used for simulating

Layer	Thickness(first used for simulating)/nm	$\bar{n}$(first used for simulating)	Thickness (optimized)/nm	$\bar{n}$ (optimized)
p-electrode		1. 662		
p-GaN contact	100	2. 567		
p-Al$_x$Ga$_{1-x}$N/GaN SLs cladding layer	120×(2. 5/2. 5)	2. 537	60×(2. 5/2. 5)	2. 49(x= 0. 25)
GaN/In$_x$Ga$_{1-x}$N waveguide layer	100/0	2. 567(x= 0)	0/90	2. 65(x= 0. 1)
MQW(In$_{0.02}$Ga$_{0.98}$N/In$_{0.15}$Ga$_{0.85}$N)	4QW(10. 5/3. 5)	2. 603/2. 587	3QW	2. 64
GaN/In$_x$Ga$_{1-x}$N waveguide layer	100/0	2. 567(x= 0)	0/90	2. 65(x= 0. 1)
n-Al$_x$Ga$_{1-x}$N/GaN SLs cladding layer	120×(2. 5/2. 5)	2. 537(x= 0. 14)	120×(2. 5/2. 5)	2. 49(x= 0. 25)
n-GaN	5000	2. 567	2. 567	5000
Sapphire substrate		1. 788		

The wavelength value λ used for calculation is 396. 6nm.

Figure 1 shows electric-field profiles of the symmetrical SCH-MQW structure. It is symmetrical with single peak, which stands for guide-like waveguide mode.
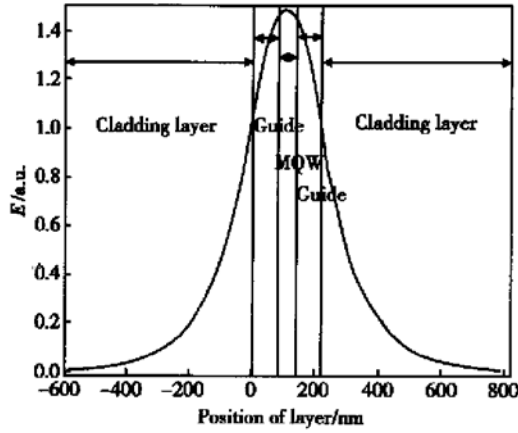

Fig. 1   Electric-field profiles of the symmetrical SCH-MQW LD

The threshold current J_{th} can be expressed[6, 7] as

$$J_{th} = B \frac{de}{r_i}(N_0 + \frac{\alpha}{a\Gamma})^2 \qquad (1)$$

$$\alpha = \alpha_i + \frac{-\ln(R_1 R_2)}{2L} \qquad (2)$$

where d, e, r_i, B, N_0, α_i, R_1, R_2, L, a, and Γ are thickness of active layer, unit charge, current confinement factor, radiation recombination coefficient, transparent carrier density (about 9.3×10^{19} cm^{-3})[8], internal loss of LD (about 43cm^{-1})[8], front facet reflectivity, rear facet reflectivity, length of LD cavity, differential gain (about 5.8×10^{-17} cm^2)[8], and photon confinement factor, respectively. α/a is about 2×10^{18} cm^{-3}. From Eqs. (1) and (2), increasing periods of MQW will raise threshold current, while lower threshold current by raising photon confinement factor from Fig. 2. So there is an optimized periods. The results are illustrated in Fig. 2, which shows 3 periods are best. Akasak-i[9] calculation result reveals the optimized well layers are less than 5 when the total loss is less than 100cm^{-1}. Nakamura[10] reported three GaInN MQW samples had the lowest pumping threshold power. Nakamura[11] experiment results show 2QW
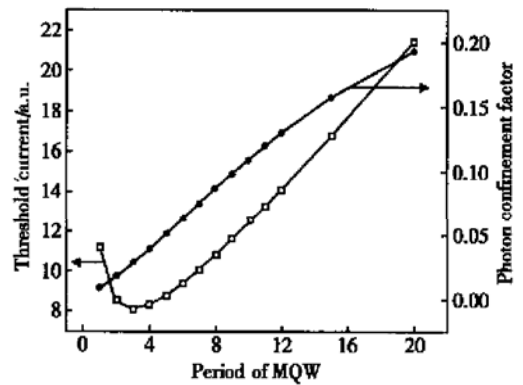

Fig. 2   Confinement factor and threshold current as functions of periods for MQW

is best with another asymmetrical LD struc-ture. Figure 3 shows photon confinement factor (Γ) and effective refractive index (n_{eff}) as func-tions of mean refractive index value of 3QW. Both Γ and n_{eff} are proportional to mean refractive index value of MQW. Because the laser wavelength limits the maximum of mean refractive index value of
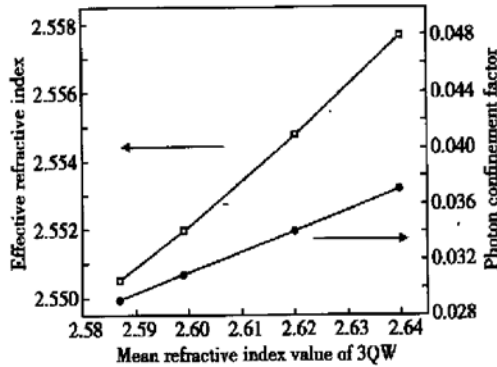

Fig. 3 Confinement factor and effective refractive index as functions of mean refractive index value of 3QW

MQW, thicker well, thinner barrier, and smaller band gap between quantum well and barrier would have higher Γ and n_{eff}. Γ and n_{eff} versus thickness and refractive index value of waveguide layer with 3QW ($n = 2.64$) for active layers are shown in Figs. 4 and 5. Thick waveguide layer has good con-finement effect, but relatively decrease the active
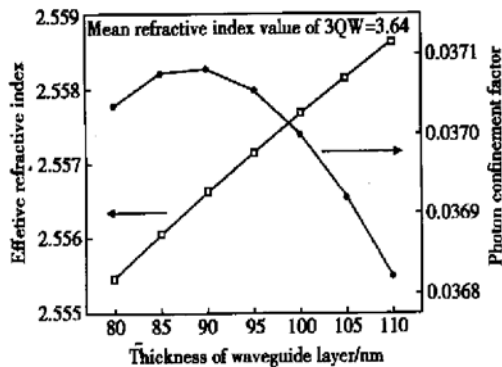

Fig. 4 Confinement factor and effective refractive index as functions of thickness of waveguide layer

region. Therefore, there is an optimal thickness of waveguide layer. In this LD, it is 90nm in Fig. 4. The reported LD[3] with 10000h lifetime used little thicker (100nm) GaN film as waveguide layer. In

Fig. 5 there is also an refractive index value ($\sim$ 2.75) of waveguide layer with maximum confine-ment factor. But when refractive index value of
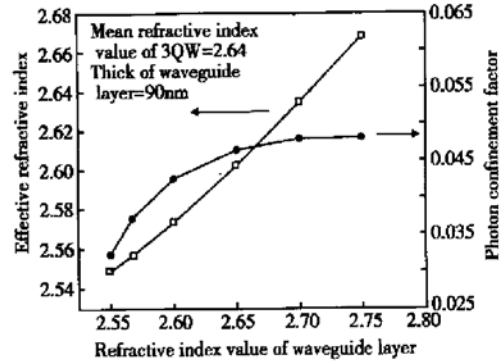

Fig. 5 Confinement factor and effective refractive index as functions of mean refractive index value of waveguide layer

waveguide layer is more than 2.65, there exists an-other anti-guide-like waveguide mode except for the guide-like waveguide mode shown in Fig. 5. The effective refractive index of such anti-guide-like waveguide mode is lower than the refractive index value of contact layer[12]. In this case, the far-field pattern is not single peak, and is not suitable for optical disk use. This result in that the optimal refractive index of waveguide layer is 2.65. This means that the waveguide layer should be GaN/In-GaN or InGaN, which is agreeable to Koike[13] ex-periment result. From Ref. [5] we can get $In_{0.1}Ga_{0.9}N$ as the optimal waveguide layer. The recip-rocal value of current confinement factor r_i^{-1} can be expressed[6] as

$$r_i^{-1} \propto 1 + \frac{A}{d_c} \qquad (3)$$

where A and d_c are one constant about 4000nm and thickness of cladding layer, respectively. Substitut-ed for expression (3), equation (1) can be written

$$J_{th} \propto \left(1 + \frac{A}{d_c}\right)\left(N_0 + \frac{\alpha}{a\Gamma}\right)^2 \qquad (4)$$

From equation (4), we got Fig. 6 showing thresh-old current versus thickness of cladding layer. The threshold current decreases quickly with increase of thickness of cladding layer. The reciprocal value of power efficiency η_P^{-1} can be written as[6]
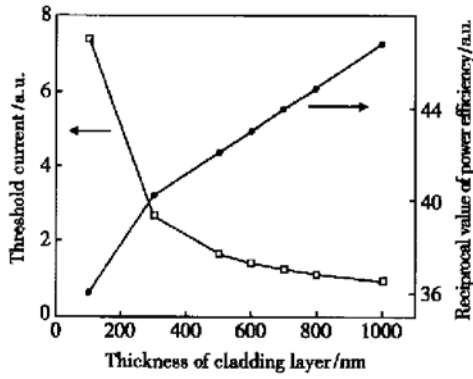
Fig. 6　Threshold current and the reciprocal value of power efficiency as functions of thickness of cladding layer

$$\frac{1}{\eta_P} = \frac{D}{r_i} + CI_{th}R + 1 \qquad (5)$$

where D, C, and R are two constant about 6, $0.3\mathrm{V}^{-1}$, and resistance of waveguide and cladding layer, respectively. R and I_{th} can be calculated using the relationships below.

$$R = \rho \frac{d_c + d_w}{s} \qquad (6)$$

$$I_{th} = sJ_{th} \qquad (7)$$

where ρ, d_w, and s are resistivity of p-AlGaN/GaN supperlattices $(\sim 100\Omega \cdot \mathrm{cm})^{[14]}$, thickness of wavegide layer $(\sim 90\mathrm{nm})$, and surface area of LD, respectively. Substituted for Eqs. (3), (4), (6), and (7), equation (5) can be written as

$$\frac{1}{\eta_P} \propto (1 + \frac{A}{d_c})[D + (N_0 + \frac{\alpha}{a\Gamma})^2 \times$$
$$BCed\rho(d_c + d_w)] + 1 \qquad (8)$$

Supposing B is $10^{-10}\mathrm{cm}^3 \cdot \mathrm{s}^{-1}$, through expression (8), we got Fig. 6 showing power efficiency versus thickness of cladding layer. The power efficiency goes up following the decrease of thickness of cladding layer. So the moderate thickness of cladding layer is 600nm as for power efficiency and threshold current. The reported LD[3] with 10000h lifetime used 600nm supperlattices as cladding layer. Figure 7 shows Γ and n_{eff} as functions of refractive index of cladding layer. Confinement factor Γ decreases with an increase of refractive index of cladding layer, while n_{eff} increases. When refractive index value of cladding layer is less than 2.49,

there exists another anti-guide-like waveguide mode except for the guide-like waveguide mode shown in Fig. 7. As a result, the optimal refractive index of cladding layer is 2.49. By Reference[5], $120 \times (2.5/2.5)$ Al$_{0.25}$Ga$_{0.75}$N/GaN supperlattices can be got as optimal cladding layer.
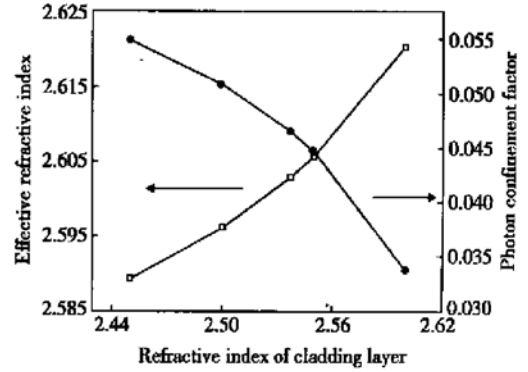

Fig. 7　Confinement factor and effective refractive index as functions of mean refractive index value of cladding layer

3　Conclusion

In summary, transfer-matrix 1-D waveguide approach was applied to simulate the characteristics of waveguide for symmetrical SCH-MQW AlGaN/GaN/InGaN LD. The layers design of the LDs was optimized to improve both the electronic and optical properties. 3QW, thicker well, thinner barrier, and smaller band gap between quantum well and barrier, In$_{0.1}$Ga$_{0.9}$N as waveguide layer with 90nm thick, and $120 \times (2.5\mathrm{nm}/2.5\mathrm{nm})$ Al$_{0.25}$Ga$_{0.75}$N/GaN supperlattices as cladding layer are the optimal structure parameters.

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AlGaN/GaN/InGaN 对称分别限制多量子阱激光器的优化设计[*]

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摘要: 采用一维传递矩阵法模拟计算了 AlGaN/GaN/InGaN 对称分别限制多量子阱激光器(发射波长为 396.6nm) 的波导特性. 以光限制因子、阈值电流密度和功率效率作为优化参量, 获得激光器的优化结构参数为: 3 周期量子阱 $In_{0.02}Ga_{0.98}N/In_{0.15}Ga_{0.85}N$(10.5nm/3.5nm) 作为有源层, 90nm $In_{0.1}Ga_{0.9}N$ 为波导层, 120 周期 $Al_{0.25}Ga_{0.75}N/GaN$ (2.5nm/2.5nm) 为限制层.

关键词: AlGaN/GaN/InGaN; MQW; SCH

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