Optimization of gallium nitride-based laser diode through transverse modes analysis

Xiaomin Jin[1], **Bei Zhang (章 蓓)**[2], **Liang Chen**[3],
Tao Dai (代 涛)[2], **and Guoyi Zhang (张国义)**[2]

[1]*Electrical Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA*
[2]*School of Physics and State Key Laboratory for Artificial Microstructures and Mesoscopic Physics,*
Peking University, Beijing 100871
[3]*RSoft Design Group, Inc., 400 Executive Boulevard, Suite 100, Ossining, NY 10562, USA*

Received July 27, 2007

We investigate the transverse mode pattern in GaN quantum-well (QW) laser diode (LD) by numerical calculation. We optimize the current GaN LD structure by varying the n-GaN layer thickness. The n-type GaN layer is an important factor to determine the optical mode. Finally, we discuss the lasing performance of the GaN LD based on the transverse optical modes.

OCIS codes: 140.0140, 140.5960, 220.0220.

The GaN-based laser diodes (LDs) have attracted a lot of attention as short-wavelength light sources in recent years. For current GaN lasers, the high threshold current and the short lifetime are the main obstacles. One of the major reasons is the anti-guided-like behavior of waveguide mode associated with the n-GaN layer because of insufficient cladding thickness[1−3], which is also called the "ghost mode" phenomena[1]. Because of the ghost mode, the higher-order mode of this multi-layer waveguide is usually the lasing mode for GaN LD. The optical confinement factor is also very low even for the lasing mode, about several percents. This leads to high lasing threshold for the designed laser. If we can optimize the optical waveguide structure and maximum confinement factor, the lasing threshold current can be greatly reduced.

In this paper, we present the two-dimensional (2D) GaN LD simulation using Rsoft LaserMOD[4] as shown in Fig. 1. The detail laser structure layer is listed in Table 1. The simulated laser structure has five quantum-wells (5QWs). A similar device was fabricated at Peking University, China. The transverse modes in GaN LD and the laser light-current (LI) characteristics are calculated and discussed. One of the project goals is to identify the current laser design issues. To avoid the meshing difficulties of the finite-element method, the classical Ritz simultaneous iteration is combined with an additional optimization to analyze the closed arbitrary dielectric waveguides[4]. To analyze the optical field in the GaN LD, the internal transfer Matrix and Ritz iteration are used to solve mode calculations. The problem has been simplified by assuming a strong index guiding and approximating Maxwell's equation with scalar Helmholtz equation, which results in real and symmetric matrices. The eigenvalue can be solved efficiently by subspace iteration using the Ritz subroutine[5].

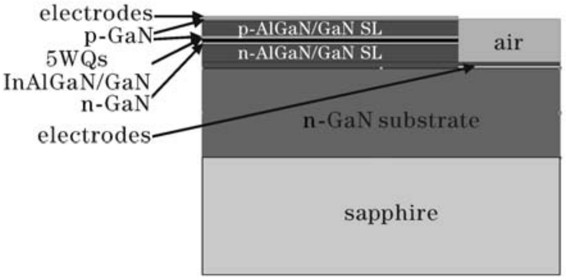

Fig. 1. 2D GaN laser model using Rsoft LaserMOD.

We calculate the first twelve transverse modes in the above GaN LD structure. Figure 2 shows several optical mode patterns of the GaN LD. Different order modes have different optical confinement factors. The strongest confined mode in the multilayer waveguide structure is the lasing mode. As shown in Fig. 3(a), the optical confinement factor for the zero-order mode with 4-μm n-GaN is only 0.0000067%. The 6th mode has the greatest overlap of optical field with the QW. Its optical confinement factor is 8.87%, which agrees with the result in Ref. [3]. This indicates that our LDs oscillate in the 6th order transverse mode. Figure 3(b) shows that the optical confinement factor varies with the n-GaN substrate thickness. Strong substrate modes compete with the lasing modes in this multi-waveguide structure. All the modes exist in the laser cavity. The lasing mode is the one which the highest optical confinement factor.

Table 1. LD Structure

Layer	Thickness (nm)
p-GaN (Contact)	50
p-$Al_{0.12}Ga_{0.88}N$/GaN p-SL (Cladding)	500
p-GaN (Waveguide)	100
n-GaN (Waveguide)	15
$In_{0.1}Ga_{0.9}N$/GaN (5QWs)	67
n-GaN (Waveguide)	100
n-$Al_{0.12}Ga_{0.88}N$/GaN n-SL (Cladding)	800
n-GaN (Substrate or Buffer)	4000
Sapphire	4000

1671-7694/2007/100588-03

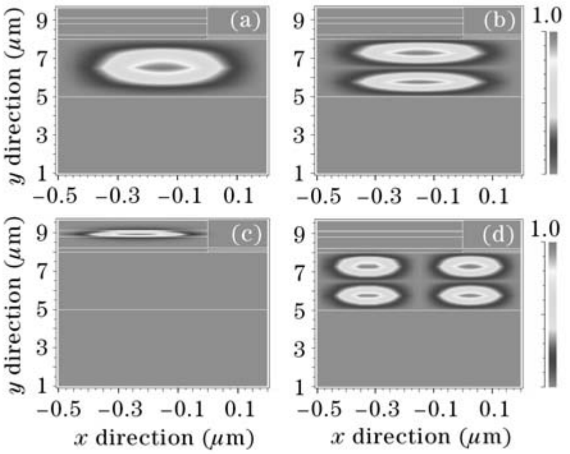

Fig. 2. Several ghost modes and lasing mode. (a) 0th order mode, (b) 1st order mode, (c) 6th order mode or the lasing mode, and (d) 8th order mode.

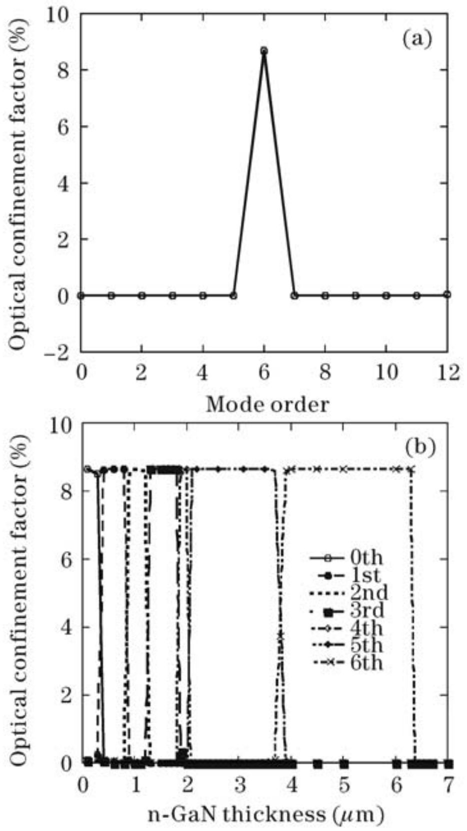

Fig. 3. Optical confinement factor versus (a) optical mode order and (b) n-GaN thickness.

Starting with fundamental mode (0th order), the lasing mode order increases with the increase of the substrate thickness. In other words, the lasing mode is not represented by a single normal mode, but by a sequence of normal modes, with the mode order increasing by one at each subsequent transverse mode coupling. Our results agree very well with that of Refs. [6] and [7]. However, the transverse mode coupling does not have fixed period compared with our 1D simulation[8]. The mode transition period increases from 0.4 to more than 2 μm when the n-GaN is around 5 μm. This comes from non-symmetry confinement of optical field in x-direction for 2D simulation. Actually, besides the modes shown in Fig. 2, most other modes are non-symmetry. The optical field is more concentrated toward $-x$ direction.

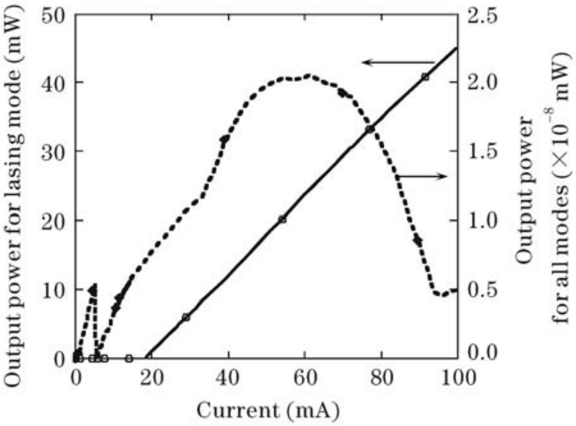

Fig. 4. LI curves of GaN LD with only the lasing mode and all the modes (ghost modes and lasing mode) considered in the calculation.

We analysis the GaN LD lasing performance with only lasing mode considered, as shown in Fig. 4. The laser has threshold around 18 mA and output power of about 30 mW at 60 mA. There is no rollover of the LI plot. The currents in the simulation are only relative values for the two-case comparison (lasing mode only case and lasing mode+ghost mode case). When we redo the simulation with twelve transverse modes, the LI plot is also shown in Fig. 4. First, the laser output power is around 10^{-8}-mW range, which means that the laser is barely lasing. We also observe several kinks at LI plots. The kinks usually represent the mode switching of the laser or the onsite of higher-order mode. In other words, it is transverses mode competition. According to our optical field analyses, the strong ghost modes compete with lasing mode in GaN Laser and prevent the laser from lasing. Actually, our detail calculation shows that, if we adjust the n-GaN thickness, we can greatly reduce the substrate modes (ghost modes) for our current laser design. Our current design is at boundary of 5th and 6th mode coupling. If the n-GaN substrate increases to 5 μm according to Fig. 3(b), we can reduce ghost modes and improve laser lasing performance. The above mode analysis is also very important for designing high-power lasers[9] and proves that the optical mode optimization is a key issue for our GaN laser design. By this work, we need to design the n-GaN layer thickness around 3 μm for 5th mode lasing or about 5 μm for 6th mode lasing to achieve low laser threshold.

In this paper, we have calculated the transverse mode distribution of InGaN/GaN QW LDs, which was developed in Peking University. We report the transverse mode in GaN LD through mode competition. Different order modes have different optical confinement factors. The strongest confined mode in the multilayer waveguide structure is the lasing mode. Strong substrate modes compete with the lasing modes in multi-waveguide structure. In most case, the lasing is higher-order mode. We also find that the n-GaN buffer thickness is an important parameter in the lasing-mode design. Finally, we simulate the lasing performance of the GaN LD to confirm our results.

We thank Wang Faculty Fellowship at Peking University, China, 2006 – 2007 through California State University (CSU) International Programs USA. This work was supported by the "973" Program of China (No. TG2007CB307004), the "863" Program of China (No. 863-2006AA03A113), and the National Natural Science Foundation of China (No. 60276034, 60577030, and 60607003). X. Jin's e-mail address is xjin@calpoly.edu.

References

1. P. G. Eliseev, G. A. Smolyakov, and M. Osinski, IEEE J. Sel. Top. Quantum Electron. **5,** 771 (1999).
2. G. A. Smolyakov, P. G. Eliseev, and M. Osiński, IEEE J. Quantum Electron. **41,** 517 (2005).
3. M. J. Bergmanna and H. C. Casey, J. Appl. Phys. **84,** 1196 (1998).
4. RSoft design Inc., *Application Notes of LaserMOD* (2006).
5. M. Grupen and K. Hess, IEEE J. Quantum Electron. **34,** 120 (1998).
6. G. Hatakosh, M. Onomura, S. Saito, K. Sasanuma, and K. Itaya, Jpn. J. Appl. Phys. **38,** 1780 (1999).
7. S. Einfeldt, S. Figge, T. Böttcher, and D. Hommel, Phys. Stat. Sol. (c) **0,** 2287 (2003).
8. X. Jin, B. Zhang, T. Dai, and G. Y. Zhang, Chin. Phys. (to be published).
9. J. Piprek and S. Nakamura, IEE Proc. Optoelectron. **149,** 145 (2002).