Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp409-410

Manipulative Polarization of a-plane InGaN/GaN Photonic Crystals for Enhanced Spontaneous Emission

Yen-Chun Lee[1], Hung-Hsun Huang [2], Yuh-Renn Wu[2], and Peichen Yu[1]

[1] Department of Photonic, National Chiao Tung University, Hsinchu, Taiwan, R.O.C
Phone: +886-3-571-2121#56354 E-mail:yup@faculty.nctu.edu.tw
[2] Institute of Photonics and Optoelectronics and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.

1. Introduction

Recently, Ⅲ-nitride-based optoelectronic devices, such as InGaN/GaN laser diodes have been used for various applications, including BD players, overhead projectors, and laser printers. However, for a c-plane InGaN/GaN quantum well (QW), there exists a strong build-in electric field due to the accumulation of spontaneous and piezoelectric polarization charges at the interface, leading to the quantum-confine Stark effect (QCSE). To avoid the internal field, the growth of non-polar InGaN/GaN quantum wells along $(11\bar{2}0)$ direction (a-plane), or along $(1\bar{1}00)$ direction (m-plane)[1] has garnered intensive research interests. As a result of eliminating QCSE, the non-polar light emitting sources exhibit not only high internal quantum efficiency, but also strong polarization[2], which must be taken into account for device design.

The development of threshold-less lasers have been proposed by raising the spontaneous emission rate through a photonic crystal (PC) microcavity with a high quality factor (Q-factor) and a small modal volume (V_m)[3,4]. However the design of PC microcavities mainly focuses on the value of Q/V_m, which was proposed by Purcell[5] first in 1968. In the ideal case, the polarization of cavity modes is assumed to be aligned with the polarization of electric charges, which is not true for strongly y-polarized emission from a-plane InGaN/GaN QWs. In this work, we demonstrate the enhanced spontaneous emission (SpE) from an a-plane InGAN/GaN QW by optimizing Q, V_m, and polarization properties of a PC microcavity slab using a finite difference time domain (FDTD) approach. The enhancement factors where the spontaneous emission coupled to the dominant cavity modes are calculated and investigated for different quantum well thicknesses and Indium compositions.

2. Cavity design

We consider a quasi-L2[5] (qL2) GaN PC microcavity slab where the refractive index (n) is ~2.5 and the thickness (d/a) ~0.7 as shown in Fig. 1(a). Because such a cavity has high Q, small V_m and only three dominant cavity modes, it is convenient to analyze the mode characteristics varying with the air holes. At the first, the air holes are set as 'A'='C'=0.3a, where 'a' is the lattice constant. The holes 'B' are first optimized. As shown in Fig.1 (b), the y-polarization electric field (Ey) of foundational mode decreases as R' decreases. The reason for this dependence is the y-polarized electric field is strongly localized around

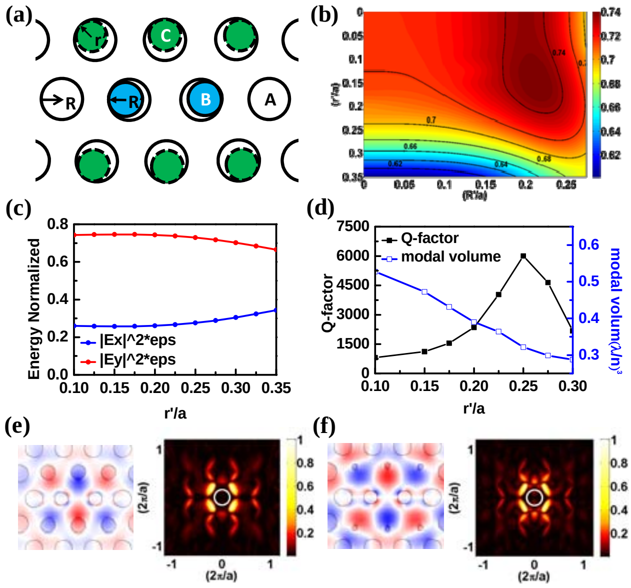

Fig. 1 The fundamental cavity mode characteristics of a modified qL2 microcavity (a)-(f). (a) Schematic of cavity configurations for a modified qL2 microcavity by varying the radiuses, R' and r' of holes near the center. (b) The degree of E_y polarization of the fundamental mode as a function of normalized R' and r'. (c) The normalized intensities of E_x and E_y polarizations of the fundamental mode vary with r'/a at a fixed R'/a=0.225. (d) The calculated quality factor, Q and modal volume, V_m of a modified qL2 cavity as a function of r'/a. The spatial distribution of electric field (E_x) (left) and the corresponding Fourier spectrum (right) for (e) r'/a=0.25 and at (f) r'/a=0.15. The central circle in k-space represents the light code, where (f) appears to have more loss than (e).

holes 'B'. The radius R' of the air holes 'B' is fixed at R'=0.225a for the highest Q/V_m. The modal volume is about 0.28(λ/n)^3 with Q~2000 for the foundational mode. To further increase cavity Q while supressing the Ex field, we consider tuning the radius of air holes 'C'. The PC microcavity is therefore denoted as a modified qL2 (MqL2) cavity. Figure 1(c) shows E_y and E_x for foundational mode varying with r' from 0. 35a to 0a at R'=0.225a. The E_y of foundational mode increase slightly as the radius r' of the air holes 'C' decreases due to weak boundary influence in the y direction. When r' is changed from 0.3a to 0.25a in Fig. 1(d), the Q-factor also enhances three-fold , compared to that of a qL2 microcavity. The polarization ratio of E_y intensity is increased from 0.7% to 0.72%, despite that the

V_m becomes slightly large from 0.28(λ/n)^3 to 0.31(λ/n)^3. The Q-factor of MqL2 is better than that of qL2 due to the change in the y-direction boundary, i.e. tuning air holes 'C', The boundary tuning impact E_x field due to the localization of Ex field around air hole 'C'. As shown in Fig. 1(e) and 1(f). The right pictures of Fig. 1(e) and 1(f) show the spatial Fourier transformation (FT) spectrum of the in-plane E_x field. In the FT maps the white circle represents the light cone, where he light can be localized better by the total internal refection (TIR) for the cavity with r'=0.25a than r'=0.10a. Therefore, Ex field is decreased and Ey is increased as r' become smaller. The quality factor is also higher at r'=0.25a due to better confinement.

3. Result and discussion

The light source is chosen to be an a-plane $In_{0.2}Ga_{0.8}N$/GaN quantum well embedded in the middle of the PC slab. To calculate the light emits and couples to the cavity mode that overlaps with the emission spectrum, we apply a self-consistent Poisson and 6X6 $\boldsymbol{k}\cdot\boldsymbol{p}$ Schödinger method to solve the band structure, energy sub-bands and wave functions. Within the dipole approximation, the transition matrix element, $|M_{mn}|^2$, for $(11\bar{2}0)$ direction (a-plane) can be expressed as

$$\begin{aligned}|M_{mn}|^2 &= \left|\left\langle \Psi_f \left| A\hat{a}\cdot\vec{p} \right| \Psi_i \right\rangle\right|^2 \\ &= \left|\left\langle \sum_{n=1}^{6} u_n \phi_n^{(f)} \left| A\hat{a}\cdot\vec{p} \right| \sum_{m=1}^{6} u_m \phi_m^{(i)} \right\rangle\right|^2 \\ &= (A_x F_{fi}^x + A_y F_{fi}^y + A_z F_{fi}^z) P_{cv} \qquad (1)\end{aligned}$$

where A denotes the averaged electric field amplitude of the cavity mode in SQW, $\vec{\boldsymbol{p}}$ is the momentum matrix ment, $\hat{\boldsymbol{a}}$ is unit polarization vector, $\boldsymbol{u_n}$ denote the six Bloch function, $\boldsymbol{\phi_n}$ the corresponding envelope functions, $\boldsymbol{F_{fi}}$ are envelope function overlap components from initial state to final state, and $\boldsymbol{P_{cv}}$ is a scalar optical matrix element. The S rate in the cavity can be expressed, using generally Fermi

$$\begin{aligned}Rsp_{cavity} &= \frac{2\pi}{\hbar V_m}\int d(\hbar\omega)\sum\nolimits_k \frac{e^2}{m_0^2\omega_k^2}\rho_c(\hbar\omega-\hbar\omega_k) \\ &\times \sum\nolimits_{n,m}\int \frac{2}{(2\pi)^2}d\kappa^2 |M_{fi}|^2 \frac{1}{\sigma\sqrt{2\pi}} \\ &\times \exp\left[\frac{-(E_{n,m}-\hbar\omega)^2}{2\sigma^2}\right] f_e(E_n^e(\kappa))\, f_h(E_m^h(\kappa)) \quad (2)\end{aligned}$$

golden rule, as equation (2)

where $\boldsymbol{\rho_c}$ is a normalized Lorentzian with a finite line-width to take into account the optical loss (Q-factor) for cavity mode, and $\boldsymbol{\omega_k}$ is resonant mode frequency. $\boldsymbol{f^e}$ and $\boldsymbol{f^h}$ are Fermi-Dirac function, and $\boldsymbol{E_{n,m}}$ is the effective band-gap from state $\boldsymbol{n}$ and $\boldsymbol{m}$. $\boldsymbol{\sigma}$ is the inhomogeneous broadening function. The PC microcavity mode characteristics and the parameters are taken into count in the Fermi's golden rule. The enhancement factor is ratio of the SpE rate in the cavity to that in free space. The calculated SpE enhancement factor as a function of r' is plotted in Fig. 2 for (a) different well thicknesses and (b) different indium compositions. As seen in Fig. 2(a), the thinner well has better polarization alignment with the electric charges. Therefore the SpE enhancement factor can be as high as > 800. In Fig. 2(b), the y-polarization increases as indium increases, thus the enhancement factor is increased accordingly, up to 900 times. The ideal Purcell factor $\boldsymbol{F_p=3Q(\lambda^3)/(V_m 4\pi^2)}$ gives $\boldsymbol{F_p}$~1500, which assumes perfect polarization alignment. Our method proposes the realistic cavity engineering for enhanced SpE that is customized for the a-plane InGaN/GaN quantum well.

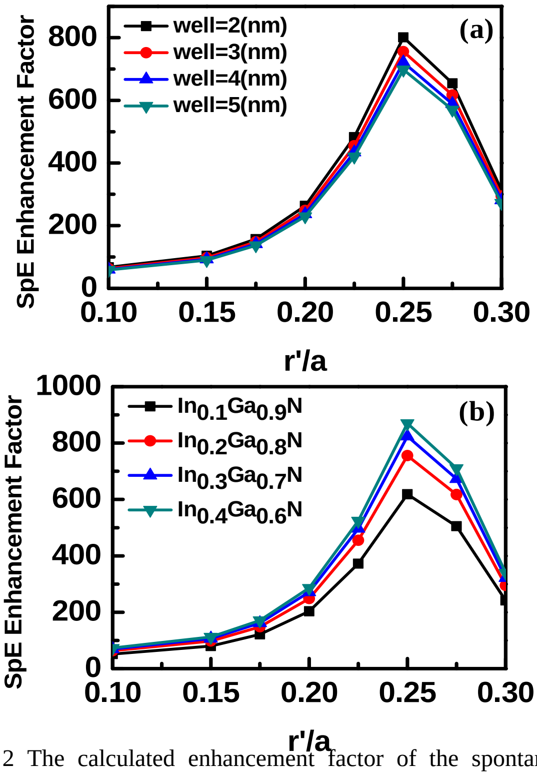

Fig. 2 The calculated enhancement factor of the spontaneous emission rate, Rsp for (a) different quantum well thickness and (b) different Indium compositions of an InGaN/GaN quantum well.

Acknowledgements

This work is founded by National Science Council in Taiwan under grant number 96-2221-E-009-095-MY3

References

[1] K. C. Kim, M. C. Schmidt, H. Sato, F. Wu, N. Fellows, Z. Jia, M. Saito, S.Nakamura, S. P. DenBaars, J. S.Speck, and K. Fujito, Appl. Phys. Lett. **91** (2007) 181120.

[2] H. H. Huang and Y. R. Wu, J. Appl. Phys. **106** (2009) 023106.

[3] E. Yablonovitch, Phys. Rev. Lett. **58** (1987) 2059.

[4] P. Yu and P. Bhattacharya, J. Appl. Phys. **93** (2003) 6173.

[5] E.M. Purcell, Phys. Rev. **69**, (1949) 681.

Appendix

E-mail: yup@faculty.nctu.edu.tw

Group : Green Photonics Laboratory

URL: http://www.ieo.nctu.edu.tw/gpl/