Type-II InGaN-GaNAs quantum wells for lasers applications

Ronald A. Arif, Hongping Zhao, and Nelson TanSan

Center for Optical Technologies, Department of Electrical and Computer Engineering, Lehigh University, 7 Asa Drive, Bethlehem, Pennsylvania 18015, USA

(Received 12 November 2007; accepted 6 December 2007; published online 2 January 2008)

We present a visible III-nitride gain medium based on type-II InGaN-GaNAs quantum well (QW), employing thin dilute-As (3%) GaNAs layer. The utilization of GaNAs layer shifts the hole confinement to the center of the type-II QW, which significantly reduces the charge separation effect. The optical gain and spontaneous recombination rate of the type-II InGaN-GaNAs QW are analyzed and compared with those of conventional InGaN QW emitting in the blue regime (λ ~ 450 nm), using six-band kp formalism for energy dispersion of the III-nitride wurtzite semiconductor. The use of type-II QW leads to significant improvement in the optical gain and spontaneous recombination rate. © 2008 American Institute of Physics. DOI: 10.1063/1.2829600

III-nitride active media for visible lasers and light emitting diodes (LEDs) are mainly based on type-I InGaN quantum wells (QWs). One of the major challenges for the conventional InGaN/GaN QW is the large spontaneous and piezoelectric polarization fields in QW. These lead to charge separation, which significantly reduce the optical gain of the QW. To minimize electrostatic field, nonpolar InGaN material growths have been pursued. Approaches to minimize the charge separation effect via δ-AlGaN layer in InGaN QW and staggered InGaN QW, with improved electron-hole wavefunction overlap (Γe,hh), have resulted in improvement in the efficiency and output power of LEDs. In this paper, we present a visible gain medium based on type-II InGaN-GaNAs QW with significantly enhanced transition matrix element, which will lead to large improvement in its optical gain and radiative recombination rate. Based on Fermi’s Golden Rule, the radiative recombination rate of the interband transition is proportional to the square of the Γe,hh. In conventional type-I InGaN QW, the spontaneous and piezoelectric polarization fields result in energy band-bending, which leads to charge separation in QW. By engineering the energy band lineup and polarization field using nitride-based type-II QW with improved overlap (Γe,hh), its radiative recombination rate and optical gain of III-nitride QWs can be enhanced.

The GaSb-based type-II “W” QW and dilute-nitride type-II InGaN-GaNAs QW active regions have been employed for laser applications in midinfrared and 1550 nm regimes, respectively. Our proposed type-II InGaN-GaNAs QW structure is formed by sandwiching a thin dilute-As (As < 5%) GaNAs layer with InGaN QW layers. Single-phase, hexagonal GaNAs specular thin film with up to 6.7% As content have been recently synthesized by metalorganic chemical vapor deposition (MOCVD). The studies on dilute-As incorporation into GaN show hybridization of the localized As states and the GaN valence band leads to a formation of a new valence band with transitional gap of 2.5–2.7 eV. This bandgap reduction and band lineup of N-rich GaNAs layer can then be exploited—utilizing type-II InGaN-GaNAs QW—to mitigate the impact of the polarization field to maintain a large Γe,hh. For instance, the addition of 2% As into GaN layer leads to the resulting transitional energy gap of the GaNAs alloy reduced down to ~2.7 eV, which is 700 meV lower than that of bulk GaN.

Figures 1(a) and 1(b) show the comparison of the energy band lineups at the zone center (k = 0) of the conventional

![Energy band lineup of type-I In0.19Ga0.81N QW and type-II In0.15Ga0.85N–GaN0.97As0.03 QW. Both structures are designed for λ ~ 450 nm. The 1.72× improvement in the wavefunction overlap Γe,hh in the type-II QW structure.](Image 317x79 to 557x453)

FIG. 1. (Color online) Energy band lineup of (a) type-I In0.19Ga0.81N QW and (b) type-II In0.15Ga0.85N–GaN0.97As0.03 QW. Both structures are designed for λ ~ 450 nm. Note the 1.72× improvement in the wavefunction overlap Γe,hh in the type-II QW structure.
type-I $25 \text{ Å} \text{In}_{0.19}\text{Ga}_{0.81}\text{N}$ QW ($\Gamma_{e, hh}=34.5\%$) with that of
the type-II $16 \text{ Å} \text{In}_{0.15}\text{Ga}_{0.85}\text{N}/10 \text{ Å} \text{GaN}_{0.97}\text{As}_{0.03}/5 \text{ Å} \text{In}_{0.15}\text{Ga}_{0.85}\text{N}$ QW ($\Gamma_{e, hh}=59.6\%$), with both active regions
designed to emit at $\lambda \approx 450 \text{ nm}$. The ground state electron
and hole eigenenergies and their respective wavefunctions are
also shown in Figs. 1(a) and 1(b). Although both structures
are designed for emission in the blue ($\lambda \approx 450 \text{ nm}$) regime,
the use of type-II QW leads to several advantages as
follows: (1) less amount of In content in the QW is required
than that of the conventional QW structure, and (2) it offers
improvement in the $\Gamma_{e, hh}$ by 1.72 times. By utilizing a thin
(10 Å) N-rich GaNAs layer, the hole wave function shifts to
the center of the type-II QW structure, thus, greatly reducing
the charge separation effect. The deep hole confinement
($\sim 460 \text{ meV}$) from the InGaN-GaNAs QW also leads to sup-
pression of carrier leakage.

From the MOCVD growth perspective, the GaNAs film
was grown at 700–750 °C, which is compatible with the
growth temperature of InGaN QW. The x-ray diffraction
measurement comparing the 2θ peaks of [002] GaN and
[0002] GaNAs indicates that the strain $\Delta a/a$ in the
GaN$_{0.97}$As$_{0.03}$ grown on GaN is compressive at +0.78%,
which is much smaller than that typically found in the
InGaN-GaN QW ($\Delta a/a=+2.2–2.5\%$). As the proposed
type-II QW structure requires very thin (~10 Å) and mini-
num As-content (2–3%) GaNAs, the MOCVD growth
should be feasible.

For the calculation of the transition matrix element, the
energy subband dispersion is obtained by using $6 \times 6 k \cdot \mathbf{p}$
formalism for wurtzite semiconductor taking into account
valence band mixing (heavy hole, light hole, and crystal field
split off hole), strain effects, and spontaneous and piezoelec-
tric polarization fields. The spontaneous recombination rate
and optical gain can then be calculated following the treat-
ment presented in Ref. 14, using the linewidth broadening of
0.1 ps up to transverse wavevector $k_t \sim 0.2 \text{ Å}^{-1}$. The band
parameters for the III-nitride alloys were obtained from Refs.
13–19. The GaN electron effective mass constants of 0.18$m_e
and 0.2m_e$ were used for the c-axis and transverse direction,
respectively. The InN electron effective mass of 0.11$m_e
was used for both the c-axis and transverse directions. The
energy gap of the InGaN QW is calculated using bowing
parameter of 1.4 eV (Ref. 17) and InN energy gap of
0.6405 eV, with $\Delta E_{hh} = \Delta E_{oo}$ of 70:30.18,19 In developing the
valence band hybridization model of N-rich GaNAs alloy, a
flat conduction band alignment was assumed between GaN
and GaNAs. The energy gap of the dilute-As GaN$_{1-y}$As$_y$
layer can be linearly extrapolated from experiments for low
As-content ($y$) up to 6.7%, as follows (in eV):

$$E_{GaNAs}(y) = -4.565 \times y + 2.7978 \quad (0 < y < 0.067).$$

The spontaneous emission spectra and optical gain of the
conventional type-I InGaN QW and the type-II InGaN-
GaNAs QW structures have been calculated and compared
for increasing carrier density, $n=1–5 \times 10^{19} \text{ cm}^{-3}$, as shown in Figs. 2(a) and 2(b), respectively. Both gain and spontaneous
recombination rate are obtained by including all possible
transitions between electron and hole confined states. Note
that the polarization field-induced band bending in the III-
nitride QW leads to the breaking of the orthogonality condi-
tion between states with different quantum number and,

![Color online](applied-physics-lettters.png)

**FIG. 2.** (Color online) (a) Spontaneous emission spectra and (b) optical gain type-I In$_{0.19}$Ga$_{0.81}$N QW and type-II In$_{0.15}$Ga$_{0.85}$N–GaN$_{0.97}$As$_{0.03}$ QW emitting at $\sim 450 \text{ nm}$ for increasing carrier density $n=1–5 \times 10^{19} \text{ cm}^{-3}$. Therefore, these terms have to be included in the gain and spontaneous emission calculation. From our calculation, we observed that the improvements in the peak spontaneous emission spectra and peak optical gain by ~3 times were found for the type-II InGaN-GaNAs QW.

The peak material gains ($g_p$) as a function of carrier
density are shown in Fig. 3 for both the conventional and
staggered structures at room temperature. The transparency
carrier densities ($n_t$) for the type-II QW structure is found as
$1.41 \times 10^{19} \text{ cm}^{-3}$, which is slightly reduced in comparison to
that ($n_t=1.614 \times 10^{19} \text{ cm}^{-3}$) of conventional QW. The differ-

![Color online](applied-physics-lettlers.png)

**FIG. 3.** (Color online) Peak material gain ($g_p$) as a function of carrier density for type-I In$_{0.19}$Ga$_{0.81}$N QW and type-II In$_{0.15}$Ga$_{0.85}$N–GaN$_{0.97}$As$_{0.03}$ QW at room temperature.
The radiative recombination current density \( J_{\text{Rad}} \) for the InGaN–GaNAs QW leads to threshold current density reductions of 35% and 41% for In\(_{0.15}\)Ga\(_{0.85}\)N–GaN\(_{0.97}\)As\(_{0.03}\) QW at room temperature.

In our analysis, we only consider the mechanisms include both the radiative and nonradiative recombination. In particular for high carrier density operation, note that the Auger coefficient in InGaN–GaN QW system still requires further studies, due to the large discrepancies from the reported Auger coefficients \( C_{\text{Auger}} \) ranging from 0.9–1 \( \times \) 10\(^{-12} \) (Ref. 20) up to 1.4–2 \( \times \) 10\(^{-10} \) cm\(^6\) s\(^{-1}\).

However, a significant reduction in threshold carrier density achievable in the type-II QW will be crucial for suppressing the \( J_{\text{Auger}} \) as the \( J_{\text{Auger}} \) is proportional to \( n_0^3 \).

In summary, type-II InGaN–GaNAs QW active region leads to improvement in the peak optical gain and spontaneous recombination rate by \( \sim \) 3 times at 450 nm wavelength regime. In addition to significant reduction in the threshold current density by 35–40%, the type-II QW structure should also be beneficial for (1) devices that require high threshold gain for lasing operation such as microcavity lasers and (2) high-efficiency light emitting diodes for solid state lighting.

The works are supported by Department of Defense-ARL, National Science Foundation (No. 0701421), and P. C. Rossin Professorship Funds.

---