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Inhomogeneous injection in polar and nonpolar III-nitride light-emitters

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ABSTRACT

Despite the absence of polarization-induced potential barriers, the nonpolar III-nitride multiple-quantum well (MQW) structures are shown to suffer from strongly inhomogeneous population of active QWs dominated by the QW closest to the N-side of the diode structure. This situation is the opposite of polar structures, where the extreme P-side QW always prevails in optical emission. Inhomogeneity of QW populations in nonpolar structures is supported by QW residual charges and becomes stronger in structures with deeper QWs. Indium incorporation into waveguide and/or barrier layers improves the uniformity of QW injection.

Expectations of nonpolar technology advances in III-nitride light emitters are very high [1]. The absence of internal polarization fields and lack of related quantum-confined Stark effect in nonpolar structures imply better transport and optical characteristics of nonpolar devices [2]. Nonpolar templates are expected to be especially favorable for light emitters operating in the green–yellow spectral region where the higher indium incorporation in active QWs is necessary and, therefore, higher strain-induced polarization should inhibit the characteristics of polar devices. However, the green laser diodes were first implemented practically simultaneously on both polar [3–5] and nonpolar [6] templates without any substantial advantages of the later.

High level of optical loss in existing III-nitride laser structures necessitates multiple-QW (MQW) design of the active region. In polar structures, strong built-in spontaneous and piezo-polarization fields create conditions for inhomogeneous population of different QWs and, even at high injection level, the extreme P-side QW usually dominates the optical emission [7,8]. As a result, the under-pumped QWs add their interband absorption to the total optical loss thus increasing the laser threshold. Furthermore, in polarized QWs the reduced spatial overlap between the lasing states causes insufficient optical gain and, therefore, demands more QWs in active region of the polar lasers. Taking into account inherently high transparency concentrations in wide-gap III-nitrides, the increased number of QWs should boost the lasing threshold in polar structures even further. This makes nonpolar or semipolar technology an attractive alternative to polar templates. Indeed, in the absence of internal polarization fields, after flat-band condition is reached, the QWs in nonpolar active regions should be uniformly populated thus ensuring lower threshold for nonpolar devices. However, in reality, green nonpolar/semipolar multiple-QW diode lasers have not yet revealed any drastic threshold improvement, with threshold current density often lagging around 10 kA/cm^2 [9–11], while the polar structures in this spectral range demonstrate quite comparable or even lower thresholds [3–5]. The quality of nonpolar-grown materials is still inferior to that of polar structures [12] which might best explain the present insolvency of the nonpolar devices, however, as we will point out, some physics – quite surprising for nonpolar heterostructures – can be also involved and should be taken into consideration at the stage of the device design.

In this letter, we show that even in the absence of internal polarization fields, nonpolar multiple-QW (MQW) structures with high QW indium content still suffer from strongly inhomogeneous QW injection. This inhomogeneity is induced by carrier confinement in deep QWs, which are typical for III-nitride structures, and is self-consistently supported by the residual QW charges. The non-uniformity of QW population increases with the QW depth and, therefore, becomes more pronounced in the longer-wavelength emitters. We show, however, that indium incorporation into waveguide and barrier layers can improve the QW injection uniformity by making the active QWs effectively shallower.

For carrier transport simulation we employ traditional drift–diffusion approximation widely accepted in III-nitride device modeling [13]. Special attention was paid to detailed modeling of

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carrier confinement in active QWs and thermal electron–hole redistribution among the QW subbands and barrier layers with subsequent incorporation of the microscopic modeling results into the transport simulation. III-nitride QW subband structure was calculated using Rashba–Sheka–Pikus 6×6 matrix Hamiltonian for strained wurtzite semiconductors in arbitrary crystallographic orientation including semipolar and nonpolar templates. Phenomenological boundary conditions for multi-component wave functions were used for setting up the matrix eigenvalue problem [14]. Detailed description of the model can be found in Refs. [15,16]. Injection dependence of the QW confined energy level positions, intra-QW screening of internal polarization fields, thermal carrier redistribution between QW subbands and adjacent waveguide layers were self-consistently included into the transport simulation. We assume that the carrier transport throughout the structure is supported by the extended bulk carrier states while the populations of confined states remain in thermal equilibrium with the bulk carrier subsystem [17]. Localized 2D concentrations define the QW recombination rates, residual QW charges and related Coulomb electric fields.

For our comparative analysis we choose a typical 3-QW active region layout with 3 nm wide undoped $Ga_{0.85}In_{0.15}N$ QWs, 8 nm wide N-doped GaN barriers, and 10 nm undoped GaN spacer separating MQW layers from a 15 nm $Al_{0.15}Ga_{0.85}N$ P-doped electron-blocking layer (EBL). The MQW active region is sandwiched between 100 nm N- and P-doped GaN waveguide layers. Doping levels for N-waveguide, barrier, EBL, and P-waveguide layers were adopted, respectively, as 5, 2, 500, and 100 (in 10^{17} cm^{-3}) with dopant levels of 15 meV (donor) and 170 meV (acceptor). The acceptor level in EBL deepens by 3 meV per 1% of Al contents. Details of cladding and contact layers are not pertinent to the results of this study. All microscopic parameters have been extracted from the same source [18], except for the higher value of GaInN fundamental gap bowing coefficient, 2.8 eV, which was adopted from [19]. The valence to conduction band offsets ratio is kept as 3:7 for all interfaces. It is worth noting that QW population inhomogeneity, discussed in this paper, primarily stems from the presence of deep QWs in the active region and, therefore, represents a common feature of all III-nitride long-wavelength emitters.

Two structures of the same layout, one grown on c-plane template (C1) and the other grown on m-plane template (M1), served as benchmark structures for comparison purposes. We assume pseudomorphic growth of the active region with QW layers elastically strained to fit the lattice of the waveguide material. Detailed comparison of subband structures and radiative characteristics of c-plane and m-plane grown QWs can be found in Refs. [15,16]. Dependences of confined energy levels, subband DOS, radiative recombination rates, and screened polarization fields on the QW injection level, obtained during microscopic modeling, were used in transport modeling through inter-program data interpolation procedures to ensure realistic simulation of the QW population dynamics. However, when fixed effective values of the above quantities were used instead of the interpolated data, qualitatively the same effects were consistently reproduced. For example, parameter values corresponding to the QW transparency level can be used for such simplified modeling. Some of the QW parameters at transparency concentration are presented in Table 1. Effective bulk parameters used in the modeling include radiative recombination constant $B = 0.2 \times 10^{-10}$ cm^3/s, nonradiative SRH-recombination lifetimes t_e = 10 ns and t_h = 20 ns, and Auger recombination coefficient $C = 10^{-30}$ cm^6/s. These values are close to typical experimental estimates [20] and produce the most consistent modeling results. One order of magnitude increase of SRH lifetimes in QW layers was also adopted to simulate enhancement of radiative efficiency in III-nitride QWs due to indium compositional fluctuations. Again, we emphasize that none of the above parameters, even when varied in wide range, proved to be crucial for reported results which are fundamentally determined by strong carrier confinement in III-nitride QWs.

Fig. 1 compares active region band profiles in structures C1 and M1. Surprisingly, even at high injection levels above 1 kA/cm^2 the flat-band condition is not achieved in nonpolar structure M1. This is in spite of the fact that typical adverse features of polar structures, such as polarization inter-well potential barriers and carrier accumulation in potential pockets on both sides of EBL [20], are absent in nonpolar structure. For comparable levels of injection, the internal field in the active region of nonpolar structure M1 appears quite comparable to the built-in field in polar structure C1. The internal field in nonpolar structure is supported by opposite residual charges of extreme N-side QW1 (negative) and extreme P-side QW3 (positive); see Fig. 2. Note, that in polar structure the QW charges are opposite. The QWs remain charged even at very high injection current density, when strong carrier overflow comes into play. Typical values of injection levels, when the overflow builds up, were about 1 kA/cm^2 for polar structure and 15 kA/cm^2 for nonpolar; inferior quality of the polar structure is readily explained by EBL degradation due to charge accumulation at EBL boundaries; see Fig. 1. Modeling structures without EBL confirms that carrier overflow is irrelevant for observed field build-up in the active region. Although in a non-EBL structure the leakage starts at lower injection, the active region built-in field for a given current density remains practically the same.

QW populations are expected to converge with increased electrical bias and carrier injection level. Fig. 3 shows that in polar structure C1 such convergence indeed starts at a low injection level of approximately 10 A/cm^2, though the relative population of the extreme P-side QW3 still prevails up to the very high injection in excess of 10 kA/cm^2. In nonpolar structure M1, the QW population dynamics is more complicated. The inhomogeneity of QW populations remains remarkably strong in a wide range of injection currents up to 1 kA/cm^2 and is dominated by extreme N-side QW1. However, at the highest injection levels above 10 kA/cm^2, P-side

Table 1
Microscopic characteristics of studied QWs.

QW characteristics	C1	M1	M2	M3
Band gap[a] at 300 K in eV	2.890	2.808	2.808	2.757
Band offsets (c/v) in meV	380/160	440/190	440/190	284/122
Strain components ($xx/yy/zz$) in %	−1.65/−1.65/0.92	−1.65/−1.48/1.05	−1.65/−1.48/1.05	−1.10/−0.98/0.70
Transparency concentration in 10^{12} cm^{-2}	3.6	3.9	4.3	4.9
Screened polarization[b] in C/m^2	0.015	0	0	0
Effective radiative constant[b] in 10^{-10} cm^3/s	0.022	0.17	0.17	0.11
Confined levels[b,c] in meV electrons holes	26, −116, −106	104, 370, 14, 41, 58, 80, 126, 142	51, 195, 401, 6, 24, 33, 50, 55, 78, 97, 116, 148, 162	46, 172, 5, 21, 28, 43, 50, 69, 88, 103, 115

[a] With strain effect.
[b] At the transparency injection level.
[c] Double-degenerate; counted from corresponding band position at the QW center.