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Anisotropic optical gain in *m*-plane $In_xGa_{1-x}N/GaN$ multiple quantum well laser diode wafers fabricated on the low defect density freestanding GaN substrates

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The threshold power density for the stimulated emission (SE) at 400 nm of *m*-plane $In_{0.05}Ga_{0.95}N/GaN$ multiple quantum well (QW) laser diode (LD) wafer excited with a stripe along the *c*-axis was found to be lower than along the *a*-axis, although the SEs exhibited transverse electric field mode for both configurations. The result was explained according to the polarization selection rules for the lowest and the second lowest energy interband transitions in anisotropically strained *m*-plane InGaN QWs. In case of the LD wafer lased at 426 nm, SE was observed only along the *c*-axis, where pronounced broadening of the gain spectrum was found. Because the equivalent internal quantum efficiency was only 44%, further reductions in nonradiative defect density and the width of gain spectrum are essential to realize longer wavelength LDs. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2978242]

Wurtzite $In_{0.08}Ga_{0.92}N$ multiple quantum well (MQW) laser diode (LD) operating at 405 nm has been placed into practical use of a high density optical storage. For future realization of LD displays and solid-state coherent light sources, pure blue and green LDs are needed. However, an abrupt increase in the threshold current density (J_{th}) with increasing lasing wavelength[1,2] prevents the operation of green LDs. Major reasons could be the increase in nonradiative defect density (DD)[3] due to the lower temperature growth and increased lattice mismatch, the broadening of gain spectrum,[4] and the quantum-confined Stark effects (QCSEs) caused by the polarization fields that reduce the oscillator strength of electron-hole pairs in *c*-plane QWs.[3,5] The use of nonpolar[6] orientations is one of the solutions since strained nonpolar (Al, In, Ga)N QWs are free from QCSE.[7]

Another potential of using nonpolar QWs is to reduce J_{th} of LDs according to the reduction in density of states near the valence band (VB) maximum. Theoretical calculations on optical gain in anisotropically strained *m*-plane GaN (Ref. 8) and GaN/AlGaN (Ref. 9) and InGaN/GaN (Ref. 10) QWs have predicted that symmetry breaking from C_{6v} to C_{2v} gave anisotropic energy splitting near the VB maximum. When an anisotropic in-plane compressive stress is induced in *m*-plane GaN, original $|X \pm iY\rangle$VB states are lifted to $|X\rangle$- and $|Y\rangle$-like ones.[11] As a result, VBs are reconstituted to $|X\rangle$-, $|Z\rangle$-, and $|Y\rangle$-like ones in the order of decreasing electron energy: the lowest energy transition (E_1) is allowed for the light polarization E perpendicular to the *c*-axis ($E \perp c$) and the second lowest energy transition (E_2) is allowed for E parallel to the *c*-axis ($E \| c$).

In this letter, amplified spontaneous emission (ASE) spectra along the *c*- and *a*-axes of *m*-plane $In_xGa_{1-x}N/GaN$ MQW LDs (Refs. 12 and 13) lased at 400 nm (LD400) and 426 nm (LD426) are shown to discuss the mechanisms responsible for the anisotropic optical gain in anisotropically strained *m*-plane InGaN MQWs.

The LD wafers[12,13] investigated were grown by metalorganic vapor phase epitaxy on the low DD *m*-plane freestanding (FS-)GaN substrates that were sliced from 1-cm-thick *c*-plane FS-GaN (Mitsubishi Chemical Co.).[14] Their active regions consisted of three-period $In_xGa_{1-x}N/GaN$ MQWs, which were pseudomorphically grown on FS-GaN. The average InN molar fraction x was thus calculated for the QWs suffering from triaxial anisotropic stress (C_{2v}),[15] where the elastic stiffness constants of $In_xGa_{1-x}N$ are assumed to obey the Vegard's law. The values obtained were $x=0.05$ for LD400 and $x=0.11$ for LD426. The thicknesses of the wells (1.9 nm) and barriers (8.3 nm) for LD426 were derived from the superlattice period and the ratio of growth times for the wells to the barriers.

Steady-state photoluminescence (PL) of the QWs was excited with the 325.0 nm line of a cw He–Cd laser (11 W/cm^2) or the 396.0 nm line of a cw InGaN LD (16 W/cm^2). The latter was used to selectively excite the wells. The ASE spectra were measured at 293 K by the variable excitation-stripe length method[16] using a frequency-tripled (354.7 nm) *Q*-switched Nd^{3+}:YAG (yttrium aluminum garnet) laser. The pulse duration and repetition rate were 5 ns and 20 Hz, respectively. A 200-μm-wide, 1-mm-long rectangular excitation-stripe was formed by mechanical slits and was irradiated parallel to the surface normal. To obtain a pure single-pass gain, the excitation-stripe was made along the *c*- or *a*-axis, but not perfectly normal to the mirror facet.

The ASE spectra of LD400 measured along the *c*-(*a*–) axis exhibited a broad MQW peak at 3.13 eV (3.16 eV) under intermediate excitation-power density (P), as shown in Fig. 1, where the excitation-stripe length (L) was 500 μm. With increasing P, the spectra became narrower for both

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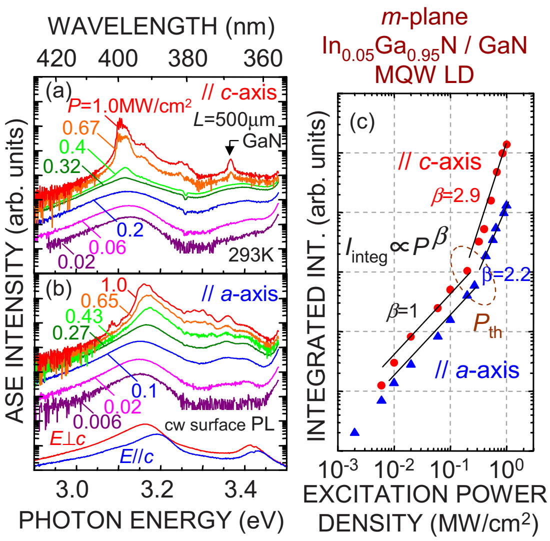

FIG. 1. (Color online) ASE spectra of m-plane $In_{0.05}Ga_{0.95}N/GaN$ wafer (LD400) along the (a) c- and (b) a-axes as a function of P ($L=500$ μm). Bottom two traces show polarized surface PL spectra. (c) Spectrally integrated ASE intensity as a function of P. Solid lines represent the fitting results using the power function P^{β}.

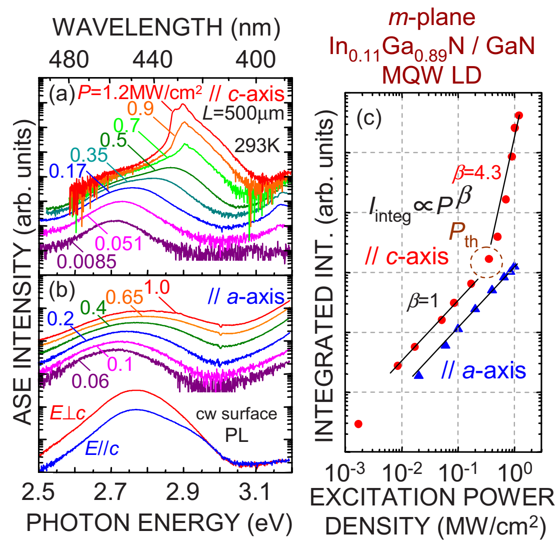

FIG. 3. (Color online) ASE spectra of m-plane $In_{0.11}Ga_{0.89}N/GaN$ wafer (LD426) along the (a) c- and (b) a-axes as a function of P ($L=500$ μm). Bottom two traces show polarized surface PL spectra. (c) Spectrally integrated ASE intensity as a function of P.

configurations, and SE peak along the c-axis appeared approximately 10–30 meV lower than the spontaneous surface emission peak [see bottom $E\perp c$ trace in Fig. 1(b)]. Additional extra peaks appeared for $P=0.65-1.0$ MW/cm^2. The peaks at 3.36–3.37 eV are attributed to SE of GaN. The peak at 3.25–3.30 eV is tentatively ascribed to the emission of GaN:Mg waveguide. Another additional peak at 3.16 (3.08 eV) along the c- (a-) axis may arise from macroscopic effective bandgap (E_g) inhomogeneity due to the variation of incorporation efficiency of In ($\eta_{\mathrm{In}}^{\mathrm{inc}}$) caused by the presence of inclined/tilted planes and facets.[7,15]

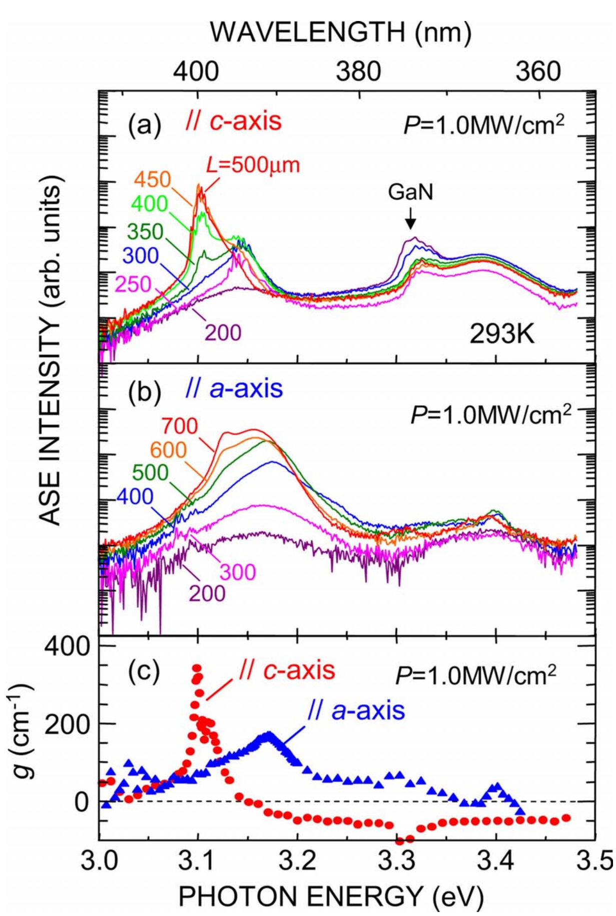

FIG. 2. (Color online) ASE spectra of LD400 wafer along the (a) c- and (b) a-axes as a function of L ($P=1$ MW/cm^2). (c) The net modal gain spectra along the c-(closed circles) and a-(closed triangles) axes.

As shown in Fig. 1(c), spectrally integrated ASE intensity (I_{integ}) linearly increased with P below the threshold power density (P_{th}) and further increased superlinearly above P_{th} ($I_{\mathrm{integ}}\propto P^{\beta}$, where $\beta=2.2-2.9$). The P_{th} value along the c-axis (170 kW/cm^2) was smaller than along the a-axis (320 kW/cm^2). We note that E of the SE was polarized parallel to the substrate plane [transverse electric (TE) field mode] for both configurations. Therefore, SE with $E\perp c$ and $E\parallel c$ were guided along the c- and a-axis, respectively. The results indicate the formation of population inversion between the conduction band and the highest (second highest) VB for the SE along the c-(a-) axis. The energy difference between E_1 and E_2 transitions was estimated from the ASE spectra and polarized surface PL spectra [bottom two traces in Fig. 1(b)] to be 30–40 meV, which nearly agrees with the value obtained by the polarized PL measurements.[17]

To compare the net modal gain (g) between the two configurations, ASE spectra of LD400 are shown as a function of L in Fig. 2 ($P=1$ MW/cm^2). As shown in Fig. 2(a), SE peak along the c-axis first appeared at 3.14 eV for $L\leq 350$ μm, but the peak energy changed to 3.10 eV for $L\geq 400$ μm. Similarly, the SE peak along the a-axis at 3.13 eV appeared in addition to the primary one (3.16 eV) for $L\geq 500$ μm. The appearance of the lower energy SE peaks for longer L may also reflect the inhomogeneity in $\eta_{\mathrm{In}}^{\mathrm{inc}}$. For example, low E_g areas absorb SE from high E_g areas, which can be the reason for the intensity decrease of 3.14 eV peak along the c-axis for $L\geq 400$ μm. The g value was thus obtained by fitting the ASE intensity $I(L)$ for $L\leq 500$ μm using the relation $I(L)=(A/g)(e^{gL}-1)$, where A is a constant related to the spontaneous emission intensity. A series of data fitting gave g spectra, as shown in Fig. 2(c). The spectrum obtained along the c-axis exhibited a sharp peak at 3.098 eV,

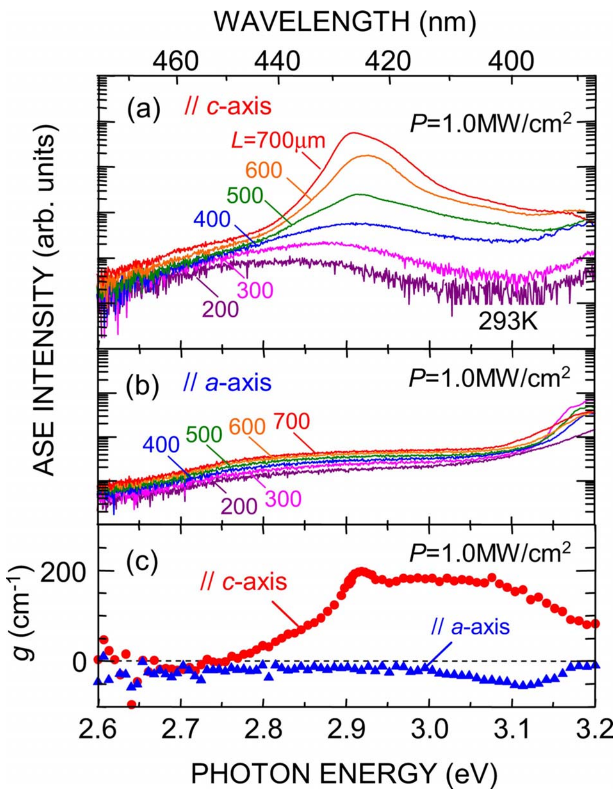

FIG. 4. (Color online) ASE spectra of LD426 wafer along the (a) c- and (b) a-axes as a function of L ($P=1$ MW/cm^2). (c) The net modal gain spectra along the c-(closed circles) and a-(closed triangles) axes.

and the peak value (342 cm^{-1}) was twice that along the a-axis (168 cm^{-1}). The results suggest that a cavity along the c-axis is preferable to reduce J_{th} under the assumption that edge mirrors are of similar quality. Indeed, a LD along the c-axis exhibited lower J_{th} than that along the a-axis.[12]

ASE spectra of LD426 are shown as a function of P in Fig. 3 ($L=500$ μm). As shown, SE was observed only along the c-axis, and P_{th} (350 kW/cm^2) was twice the LD400 (170 kW/cm^2). This tendency is consistent with the fact that J_{th} increased with the lasing wavelength (4.0 kA/cm^2 for 404 nm and 17 kA/cm^2 for 430 nm).[12,13] The ASE peak shifted to the higher energy by 190 meV with the increase in P below P_{th}, due presumably to a pronounced E_g inhomogeneity. Indeed, the value of full width at half maximum of weakly excited PL peak was 155 meV [see bottom two traces in Fig. 3(b)], which was approximately twice that of LD400 (88 meV). The value of $\beta=4.3$ above P_{th} for LD426 was larger than that of LD400 being 2.9. The result may reflect better carrier injection from the excited regions. The ASE spectra of LD426 are shown as a function of L in Fig. 4 ($P=1$ MW/cm^2). The g spectrum obtained along the c-axis [closed circles in Fig. 4(c)] was enormously broadened, as is the case with the c-plane LD lased at 423 nm (Ref. 18). Since the equivalent internal quantum efficiency η_{int}^{eq}, which was approximated as the spectrally integrated PL intensity under weak excitation regime (16 W/cm^2) at 300 K divided by that at 12 K, was only 44% for LD426, plausible major reasons for the increase in J_{th} may be the increase in DD and the broadening of g spectrum.

In summary, TE mode P_{th} of LD400 along the c-axis was found to be lower than along the a-axis. The result was explained according to the polarization selection rules in anisotropically strained m-plane InGaN QWs. In case of LD426, SE was observed only along the c-axis due to the increase in DD and the broadening of g spectrum. Because η_{int}^{eq} was only 44%, further reductions in nonradiative DD and the width of g spectrum are essential to realize m-plane green LDs.

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