Japanese Journal of Applied Physics

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To cite this article: Kuniyoshi Okamoto *et al* 2007 *Jpn. J. Appl. Phys.* **46** L187

Japanese Journal of Applied Physics
Vol. 46, No. 9, 2007, pp. L187–L189

JJAP Express Letter

Continuous-Wave Operation of *m*-Plane InGaN Multiple Quantum Well Laser Diodes

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(Received February 4, 2007; accepted February 6, 2007; published online February 23, 2007)

Continuous-wave (CW) operation of nonpolar *m*-plane InGaN/GaN laser diodes (LDs) with the lasing wavelengths approximately 400 nm was demonstrated. The threshold current was 36 mA (4.0 kA/cm^2) for the CW operation [28 mA (3.1 kA/cm^2) for pulsed mode], being comparable to that of conventional *c*-plane violet LDs. Both the LDs with the stripes parallel to *a*- and *c*-axes showed TE mode operation, according to the polarization selection rules of the transitions in strained InGaN. The *c*-axis stripe LDs exhibited lower threshold current density, since the lowest energy transition is allowed. As is the case with the *m*-plane light emitting diodes fabricated on the free-standing *m*-plane GaN bulk crystals [Okamoto *et al.*: Jpn. J. Appl. Phys. **45** (2006) L1197], the LDs shown in this paper did not have distinct dislocations, stacking faults, or macroscopic cracks. Nonpolar *m*-plane GaN-based materials are coming into general use. [DOI: 10.1143/JJAP.46.L187]

KEYWORDS: nonpolar, *m*-plane, InGaN, laser diode, GaN bulk substrate, polarized light

Development of GaN and related III–nitride semiconductors (Al,Ga,In)N has been initiated with the growth of planar *c*-plane wurtzite crystals, particularly on *c*-plane sapphire substrates. In 1993, high brightness InGaN blue light-emitting diodes (LEDs) have been put into practical use.[1)] Subsequently, fabrication of InGaN-based laser diodes (LDs) has been demonstrated[2)] and the LD performance has been improved so far.[3–5)] In this way, *c*-plane GaN has become commercial products such as UV, blue, and green LEDs, white LEDs with a yellow phosphor, and violet and blue LDs.

However, polar *c*-plane LEDs are theoretically predicted to be inferior to nonpolar or semipolar ones because there exist spontaneous and piezoelectric polarizations along the *c*-axis of strained quantum wells (QWs), which give rise to a separation of wavefunctions of electrons and holes due to the polarization fields. Another undesirable effect of the polarization is a blue shift of the QW emission peak due to the Coulomb screening of the polarization fields by the increase of injection currents.[6–14)] As a result, *c*-plane InGaN QWs of high InN molar fraction generally exhibit low quantum efficiency. Indeed, the value of green (520 nm) LEDs is several times lower than that of state-of-the-art blue LEDs (e.g., 35 mW output power and 63% external quantum efficiency at the driving current of 20 mA[15)]). Moreover, green LDs have never been fabricated yet. Therefore, optical devices fabricated on nonpolar *a*- and *m*-planes and semipolar $(10\bar{1}\bar{3})$ and $(11\bar{2}2)$ planes are expected to replace those fabricated on *c*-plane GaN. However, epitaxial growths of these planes involved difficulties in reducing stacking faults (SFs) as well as threading dislocations (TDs).[16,17)] For instance, in case of *m*-plane GaN growth on *m*-plane SiC or on GaN templates that originally contained SFs and TDs, the outbreak of SFs was quite a severe problem.[18–20)]

Recently, acceptable device performance has been demonstrated for semipolar $(11\bar{2}2)$ LEDs on the free-standing semipolar GaN substrate[21)] and nonpolar *m*-plane LEDs on the free-standing *m*-plane GaN substrate,[22)] according to the complete discrimination of TDs and SFs. In this paper, we report on the first achievement of CW operation of *m*-plane InGaN/GaN violet LDs fabricated on the free-standing substrates.

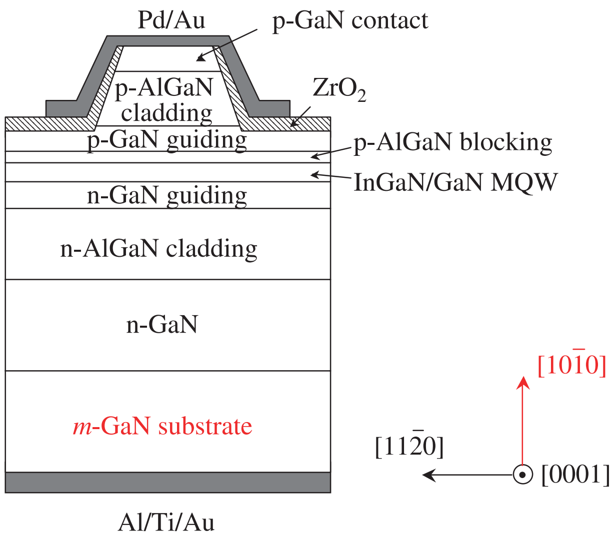

Fig. 1. Schematic drawing of the LDs with the stripe parallel to the *c*-axis.

The *m*-plane bulk GaN substrates were sliced from thick *c*-plane GaN substrates grown by hydride vapor phase epitaxy (HVPE). The surface exhibited smooth morphologies with monolayer atomic step structures. The miscut angle toward both the $\langle 0001\rangle$ and $\langle 11\bar{2}0\rangle$ directions were smaller than $\pm 0.3°$. The LD structures were grown by conventional low-pressure metal organic vapor phase epitaxy (MOVPE) using high group-V to group-III supply ratios (V/III ratios).[22)] There exist no distinct dislocations, SFs, or macroscopic cracks.

A schematic drawing of the LD structure is shown in Fig. 1. It consisted of an n-type GaN layer, an n-type AlGaN cladding layer, an n-type GaN waveguiding layer, a three-period InGaN multiple-QW, a p-type AlGaN electron blocking layer, a p-type GaN waveguide, a p-type AlGaN cladding layer, and a p-type GaN contact layer. After the growth, LD stripes were defined by dry etching with conventional lift-off technique. The stripes were made parallel to either

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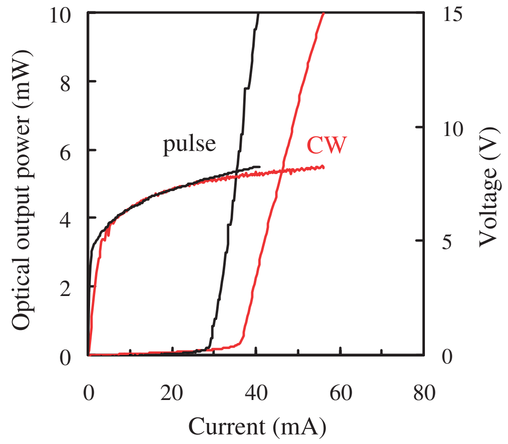

Fig. 2. Typical *L–I* and *V–I* characteristics of *m*-plane InGaN QW LDs with *c*-axis stripe under CW and pulsed operation at 20 °C.

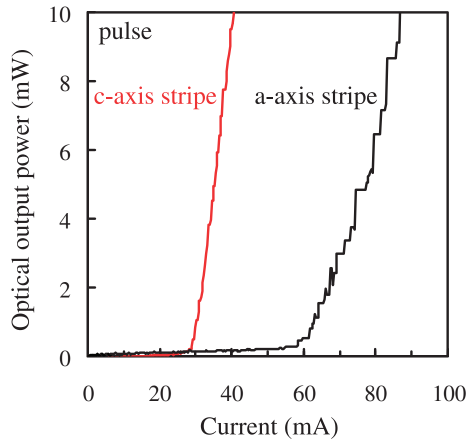

Fig. 5. *L–I* characteristics of *c*- and *a*-axes stripe LDs under pulsed operation.

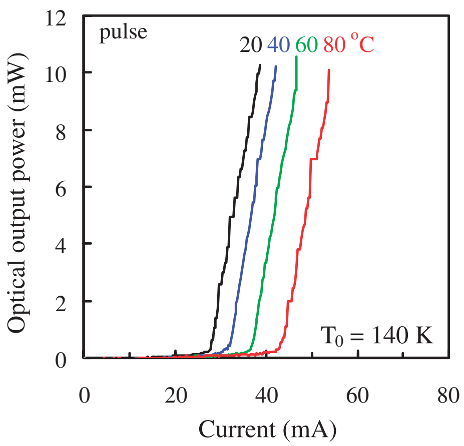

Fig. 3. Pulsed *L–I* characteristics of a *c*-axis stripe LD as a function of temperature.

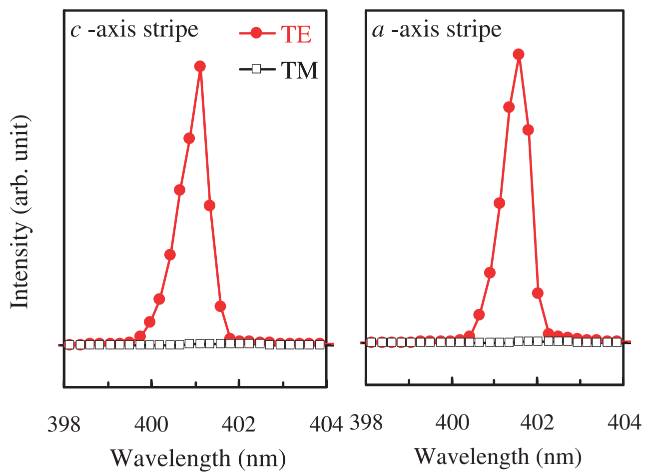

Fig. 6. Laser emission spectra of *c*- and *a*-axes stripe LDs under pulsed operation. The resolution of the monochrometer was approximately 0.2 nm.

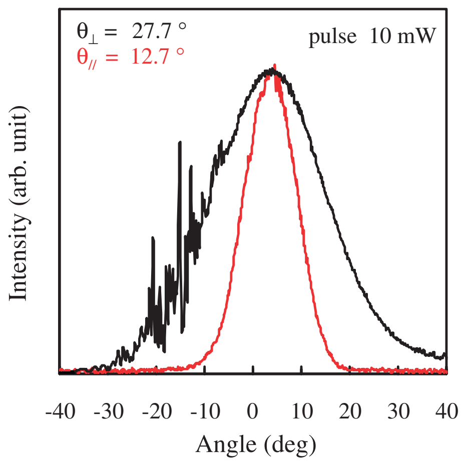

Fig. 4. Far-field patterns under pulsed operation at 10 mW.

the *a*- or *c*-axis to compare the LD performances. The bottom width of the ridge stripe was typically 1.5 µm. Sputtered ZrO_2 was used for the insulating layer. After the formation of electrodes, approximately 600-µm-long LD cavity was formed by the wafer cleavage. Typical lasing wavelength was approximately 400 nm, which will be shown later.

Representative light output power–current (*L–I*) and voltage–current (*V–I*) curves for the *c*-axis stripe LDs under the CW and pulsed operation at 20 °C are shown in Fig. 2. The operational voltage was still higher than that of *c*-plane LDs, because the process to handle the small *m*-plane GaN wafer (several millimetres around) was difficult and the contact resistance for the *p*-type layer was still high. However, CW operation of nonpolar *m*-plane LD was indeed realized. More than 10 mW outpower was confirmed in our measurement. The threshold current was 36 mA under the CW measurement and 28 mA under the pulsed operation (duty ratio is 0.1% throughout the article). The corresponding threshold current densities were 4.0 and 3.1 kA/cm^2, respectively. The differential quantum efficiencies were 16 and 30%, respectively. These values are comparable to those of *c*-plane LDs.[5)] For the *c*-axis stripe LD, characteristic temperature (T_0) of 140 K was obtained from the *L–I* curves as a function of temperature, as shown in Fig. 3. The value is also comparable to that of *c*-plane violet LDs.

Far field patterns of the *m*-plane LDs are shown in Fig. 4. The beam divergence angles perpendicular and parallel to the junction plane ($\theta_{\perp}$ and $\theta_{\parallel}$) were 27.7 and 12.7°, respectively. These values are also comparable to those of *c*-plane violet LDs, because they are principally limited by the refractive indices.

Figure 5 shows the *L–I* characteristics of the *c*-axis and *a*-axis stripe LDs under pulsed operation. The threshold current of the *c*-axis stripe LD was lower than that of the *a*-axis one. The result can be explained according to the polarization selection rules, as follows. From the pulsed lasing emission spectra of the LDs shown in Fig. 6, both the LDs are confirmed to lase with transverse electric (TE) mode (the electric field component parallel to the substrate). We note that the broad linewidth of the lasing spectra is due to the low spectral resolution of the detecting system. The results are consistent with the theoretical prediction[23] and experimental results[22,24] that the transitions from the conduction band to the highest (E_1) and the third highest (E_3) valence bands are observable from the *c*-plane edge and those from the conduction band to the second highest (E_2) and the third highest (E_3) valence bands are observable from the *a*-plane edge[22] for InGaN suffering anisotropic compressive stress. Therefore, the *c*-axis stripe LD lases with TE mode involving the highest E_1 valence band, whose transition process is polarized parallel to the $[11\bar{2}0]$ axis. On the other hand, the *a*-axis stripe LD should lase with TE mode involving the second highest E_2 valence band, which is polarized parallel to the [0001] axis. Therefore, the latter LD requires much more carriers (holes) to compensate the loss of carriers due to the emission associated with the topmost E_1 valence band. Detailed analyses on the modal gain and band structure in the QWs are necessary to fully understand the emission characteristics of nonpolar LDs.

In summary, we demonstrated the first CW operation of nonpolar *m*-plane InGaN/GaN LDs with the lasing wavelengths approximately 400 nm. The threshold current was 36 mA for the CW operation and 28 mA for the pulsed operation. These values are comparable to those of *c*-plane LDs. Due to the polarization selection rules for the transitions involving three separate valence bands in InGaN with anisotropic strain, the unique properties of nonpolar LDs were obtained: i.e., the threshold current of *c*-axis stripe LDs was lower than that of *a*-axis stripe LDs, and the operation mode of both type LDs was TE mode. To confirm the actual reduction of the polarization fields normal to the QW plane, development of InGaN LDs with high InN molar fraction such as blue and green LDs is inevitable.

The *m*-plane GaN substrates were supplied by the *Mitsubishi Chemical Corporation*.

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