Effects of Si-doping in the barriers of InGaN multiquantum well purplish-blue laser diodes

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Optical gain spectra of InGaN multiquantum well laser diode wafers having Si-doped or undoped InGaN barriers were compared. Although evidence for effective band-gap inhomogeneity was found in both structures, the wells with the Si-doped barriers exhibited a smaller Stokes-like shift. Si doping suppressed emergence of a secondary amplified spontaneous emission peak at 3.05 eV, which was uncoupled with the primary one at 2.93 eV. Furthermore Si doping reduced the threshold power density required to obtain the stimulated emission. © *1998 American Institute of Physics.* [S0003-6951(98)00630-5]

Electrically pumped InGaN multiquantum well (MQW) blue laser diodes (LDs) grown on sapphire substrates have recently been demonstrated[1–7] and Nakamura *et al.*[1] have reported a device lifetime of more than 10 000 h for cw operation at room temperature (RT). All high performance blue/green light-emitting diodes (LEDs)[1,8] and purplish-blue or UV LDs grown on sapphire substrates[1–7] reported to date have InGaN active layers. However, very little is known about the emission mechanisms of this material. The spontaneous emission from InGaN quantum wells (QWs) has been attributed to the recombination of quantized excitons spatially localized at quantum disks (Q disks) or segmented QWs size potential minima.[9] This idea is supported by several researchers showing evidence of effective band-gap inhomogeneity in InGaN wells.[10,11] Optical gain spectra from the InGaN QWs previously reported[12] were thought to be explained by the well-known electron-hole plasma (EHP) model with Coulomb enhancement.[13] However, Deguchi *et al.*[14] showed characteristic gain emergence in the low-energy portions of the InGaN MQW LD spectra for laser material which yielded cw LDs.[1] Therefore, it is necessary to investigate mechanisms for optical gain in more detail to understand the material physics of InGaN QWs.

In this letter improvement in the optical gain of InGaN/InGaN MQW LDs[4] due to Si doping in the barriers is discussed in connection with structural, optical, and electronic measurements.

TE-polarized amplified spontaneous emission (ASE) spectra of LD wafers (lasing at 420 nm)[4] were measured at RT by means of the variable excitation-stripe length (VEL) method,[15] using a frequency-tripled 10 Hz *Q*-switched Nd^+:YAG laser with a pulse duration of 10 ns. The LD wafers were grown by metalorganic chemical vapor deposition and had ten periods of InGaN/InGaN QWs. The LD structure is given in Ref. 4. X-ray diffraction (XRD) analysis of the test MQW structures[16] showed that one sample contained 2.5-nm-thick $In_{0.15}Ga_{0.85}N$/7.0-nm-thick Si-doped $In_{0.05}Ga_{0.95}N$ MQW while the other had 2.5-nm-thick $In_{0.12}Ga_{0.88}N$/6.0-nm-thick undoped $In_{0.04}Ga_{0.96}N$ MQW. The Si-doping level was approximately 5×10^{18} cm^{-3}. To minimize light scattering, mechanically polished or reactive-ion etched facets were prepared. A 200 μm wide and 500 μm long pumping beam was directed perpendicular to the surface, but not perpendicular to the mirror facet, to obtain pure single-pass gain.

ASE spectra measured at various excitation-stripe lengths (L) and power densities (P) are shown in Fig. 1. The Si-doped barrier MQW exhibited an ASE peak at 2.937 eV, which shifted to 2.927 eV with increasing L [Fig. 1(a)(i)]. With increasing P an anomalous second peak[14] was ob-

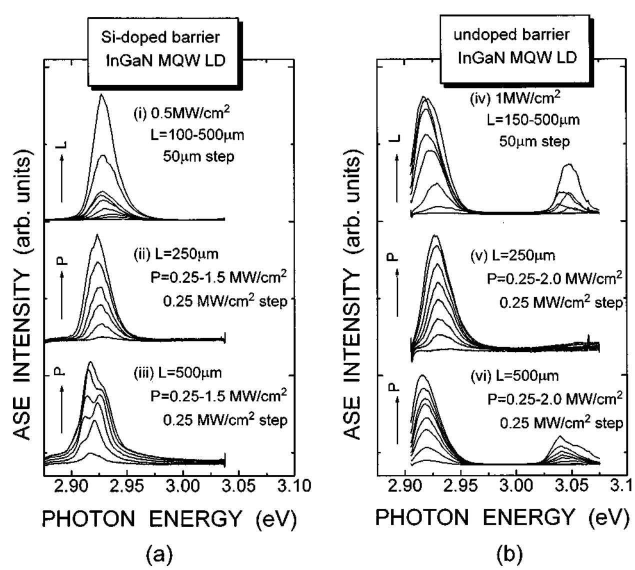

FIG. 1. ASE spectra of InGaN/InGaN MQW LD wafers having ten QWs with (a) Si-doped and (b) undoped $In_{0.04}Ga_{0.96}N$ barriers. ASE spectra were recorded for different excitation stripe lengths (L) [traces (i) and (iv)] and pumping power densities (P) [(ii), (iii), (v), and (vi)].

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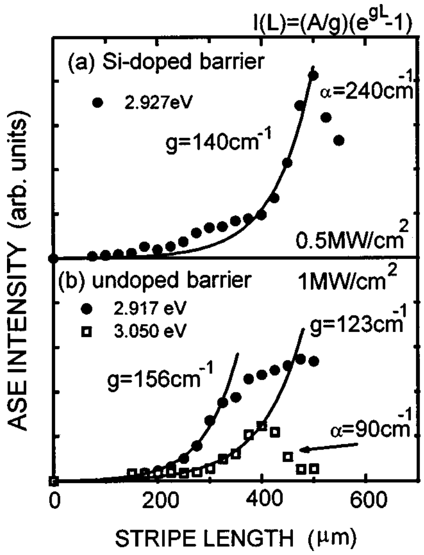

FIG. 2. ASE intensity as a function of L for MQW LD wafers with (a) Si-doped and (b) undoped barriers measured with the excitation power densities of 0.5 and 1 MW/cm^2, respectively. Net modal gain g was obtained through fitting the data using Eq. (1), the fitting curves being drawn by solid lines.

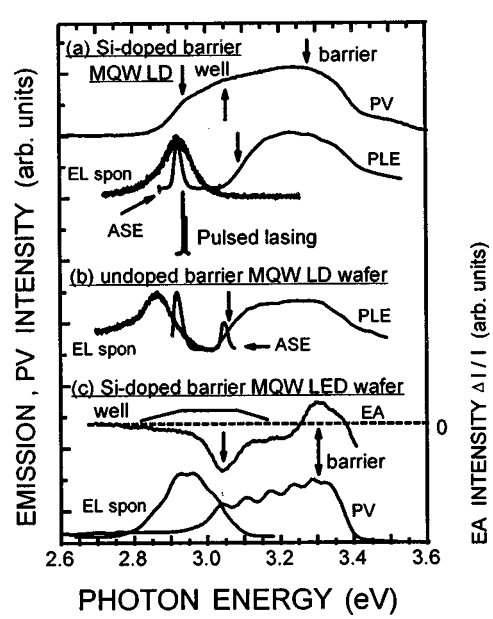

FIG. 3. Comparison of PV, PLE, spontaneous EL, EA, ASE, and lasing EL spectra for wafers of (a) Si-doped barrier MQW LD, (b) undoped barrier MQW LD, and (c) Si-doped barrier MQW LED. Respective resonance energies in the wells and barriers are indicated by arrows or an arc.

served for $L=500$ μm [Fig. 1(a)(iii)]. Within the EHP model,[13] the redshift due to the increase of P is due to bandgap renormalization. The apparent redshift with increasing L seems to be due to the combined effect of carrier depletion at the end of the pump stripe, which is due to the strong stimulated emission intensity there and the subsequent absorption of the high-energy side of the spectrum, and additional absorption of the high-energy side owing to the large effective band-gap inhomogeneity.[9]

The net modal gain g was obtained by fitting the ASE intensity $I(L)$ using the relation

$$I(L)=\frac{A}{g}(e^{gL}-1), \qquad (1)$$

where A is a constant related to the spontaneous emission intensity. The ASE intensities of the Si-doped barrier MQW pumped at 0.5 MW/cm^2 are shown as a function of L in Fig. 2(a). The data were fit giving g of 140 cm^{-1} at 2.927 eV. Since the pump stripe length was 500 μm, L greater than 500 μm left an unpumped region of increasing length, from which we obtained the absorption coefficient α of nearly 250 cm^{-1}. These values are reasonable for InGaN MQW LDs[9,11,12,14,16] according to the EHP theory.[13]

Conversely, the undoped barrier MQW structure often exhibited a secondary ASE peak at 3.05 eV in addition to the primary one, as shown in Fig. 1(b)(iv)–(vi). Although there exists macroscopic effective band-gap inhomogeneity of the order of hundreds of micrometers within the wafer, the secondary peak was found in many portions. The secondary peak at 3.05 eV appeared for $L\rangle 275$ μm at $P=1$ MW/cm^2, as shown in Fig. 1(b)(iv). For $L=250$ μm, a precursor of it is noticeable for $P\rangle 1.5$ MW/cm^2 and only 0.5 MW/cm^2 was needed to observe it for $L=500$ μm, as shown in Figs. 1(b)(v) and (vi). Once the secondary peak appeared, the primary peak redshifts to 2.917 eV, which is presumably due to depletion of carriers at the light-emitting edge owing to large optical field. Typical g values are 160 cm^{-1} for the primary peak and 120 cm^{-1} for the secondary peak, as shown in Fig. 2(b). The emergence of the secondary ASE peak indicates that there are at least two distinct density of states which are uncoupled with each other. The origin of this is unclear, but is most likely due to phase separation during the p-type overlayer growth, which may act as annealing.

To compare the electronic states, several optical spectra are summarized in Fig. 3. Because the potential broadening in the wells and barriers was large, static measurements like photovoltaic (PV) or photoluminescence excitation (PLE) could not distinguish the resonance signal in the wells from that of the barriers. Therefore, we measured the electroabsorption (EA) spectrum of a Si-doped barrier MQW LED[8] having an identical MQW with semitransparent electrodes to resolved the signal from the wells.

The PLE spectra of both MQW LDs exhibited tail states[9] extending more than 100 meV to lower energy from the quantized energy level, which we define as the energy at which the PLE signal intensity is half the maximum. Predominant resonance energies are found at 3.104 and 3.070 eV for the Si-doped and undoped barrier MQWs, respectively. This 34 meV blueshift could be explained by Coulomb screening of the piezoelectric field which may induce the redshift of the level due to the quantum confined Stark effect (QCSE).[9,11,17] However, QCSE does not cause the band edge broadening, which induces a Stokes-like shift, in the actual *quantum-well state*[8] when their well thickness is less than the bulk free exciton Bohr radius.[18] The electroluminescence (EL) peaks appeared at the low-energy tail of the absorption signals and the apparent Stokes-like shifts[8] are 180 and 210 meV for the Si-doped and undoped barrier MQW LDs, respectively. This result strongly supports the presence of effective band-gap inhomogeneity in the wells. The decrease of the Stokes-like shift in the Si-doped barrier MQW indicates improved band-gap homogeneity due to

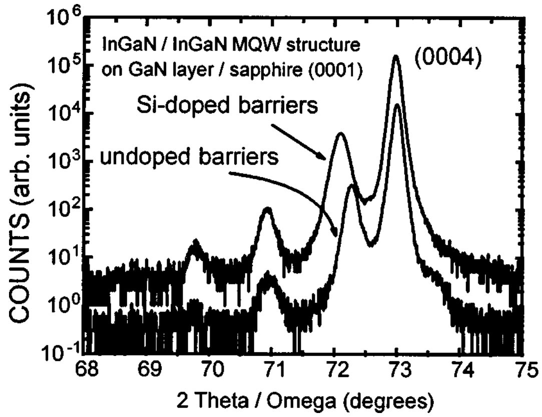

FIG. 4. Logarithmic plots of $2\theta/\omega$-scan XRD patterns for the Si-doped and undoped barrier MQW structures grown under the same conditions as LD wafers.

screening of the piezoelectric field. In addition, a Si-doped barrier MQW test structure exhibited a higher order satellite peak of the (0004) XRD pattern, as compared with an undoped barrier one as seen in Fig. 4.

It is interesting to note from Fig. 3 that while the electronic states in the wells extended from 3.2 to 2.8 eV, the primary ASE peak appeared at the same energy (2.93 eV) for both MQW LDs. This energy agreed with the lowest energy structure of the PV spectra, which are sensitive to lower energy localized tail states. The energy difference between the predominant resonance and the primary ASE peak is more than 140 meV, which is larger than the expected amount of the band-gap renormalization since the PLE resonance energy is already shifted to low energy by the many-body effect due to the Si modulation doping.[13]

Moreover, the Si-doped barrier MQW had a lower threshold power density (20 kW/cm^2) to obtain stimulated emission than that of the undoped one (50 kW/cm^2), and the net gain was very large.[16] Therefore, the primary ASE peak seems to be formed in the tail states,[14] possibly in *Q* disks or segmented QWs,[9] like one type of the Nichia cw MQW LDs.[9,14] Carriers in higher-energy states appear to relax efficiently into the lower states to provide high gain. Conversely, the secondary ASE peak at 3.05 eV in the undoped MQW seems to come from higher-energy states near the PLE resonance at 3.1 eV. It appears that this reservoir of carriers is isolated from the primary reservoir at 2.93 eV.

The role of Si doping in improving carrier transport or relaxation is still unclear. The improved gain might be due to the effect of modulation doping on the Fermi levels. The most probable explanation is that Si doping modifies the growth mode to connect electronically the InGaN nanocolumns,[19] which act as the source of *Q* disks or segmented QWs.[9]

In summary, the effects of Si doping in barriers of InGaN MQW LDs were studied. Si doping was found to eliminate the secondary ASE peak which is uncoupled with the primary one. The ASE threshold power density was decreased by Si doping. In contrast to other III-V QWs, under our growth conditions, Si doping was found to improve the structural and electronic homogeneity.

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