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Stimulated Emission from the MBE Grown Homoepitaxial InGaN Based Multiple Quantum Wells Structures

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We report on photoluminescence characterization of InGaN based laser structures grown by homoepitaxial radio frequency plasma-assisted molecular beam epitaxy. Owing to Si doped barriers, the structures show a negligible impact of the built-in electric field, which was proved by excitation intensity dependent and quantum well width dependent luminescence experiments. Relatively low variation in band potential due to inhomogeneous distribution of In was quantitatively estimated from the photoluminescence temperature behavior using Monte Carlo simulation of in-plane carrier hopping and optically detected cyclotron resonance experiments. Efficient stimulated emission with a low threshold for optically pumped laser structures was observed.

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1. Introduction

Heteroepitaxially grown InGaN-based multiple quantum wells (MQWs) are basic structures for blue and UV laser diodes (LDs) [1, 2]. Despite of rapid commercialization of these structures, InGaN-based LDs are still of high cost, have low output power, and relatively short lifetimes. This is most likely due to a large density of threading dislocations and reduction of the density of extended states caused by compositional disorder. Application of substrates with a reduced dislocation density as well as molecular beam epitaxy with a precise control of growth parameters can result in MQWs of improved compositional uniformity [2–6]. Superior quality of MQW structures grown on dislocation-free GaN crystals grown by high-pressure method has been already demonstrated [7].

Here we report results of comprehensive studies of excitation density dependent photoluminescence (PL), temperature dependent and time-resolved PL, optically detected cyclotron resonance (ODCR) as well as optically pumped lasing of the InGaN/InGaN MQW structures grown by homoepitaxial radio frequency plasma-assisted molecular beam epitaxy (RF-MBE).

2. Experimental

The structures were formed on bulk GaN substrate of 0.1 mm thickness grown by high-pressure and high-temperature method [7]. 390 nm thick silicon doped (of 10^{19} cm^{-3}) GaN buffer layer was grown on Ga-face of the GaN crystal, followed by a 30 nm InGaN epilayer. The active region was formed by 6 pairs of InGaN wells of 4 nm thickness (In content approximately 9%) and silicon doped (10^{19} cm^{-3}) InGaN barriers of 7 nm thickness (In content approximately 3%). The structures were covered by a 70 nm InGaN:Si capping layer (In content approximately 3%).

3. Results and discussion

Luminescence properties of highly excited InGaN based MQWs can be interpreted as resulting from recombination of partly localized carriers under screened built-in electric field [8]. Luminescence excitation dynamics and transient behavior provide information on the density of states within randomly fluctuating potential profile due to variation in the In content and correlative changes in the well width [8]. Figure 1a depicts some typical time-integrated luminescence spectra of the RF-MBE grown MQWs, measured at various excitation density (excited by 20 ps pulses of the fourth harmonic of YAG:Nd laser) and recorded in a backward geometry. At moderate excitation ($I_{\rm p} < 0.1$ mJ/cm^2), the spectra show one broad luminescence band originating from the QW region and peaking at 3.04 eV. Additionally, a luminescence band related to the barrier emission can be resolved at about 3.28 eV. The QWs related luminescence band slightly blueshifts with pump (by about 20 meV, see Fig. 1 and Fig. 2a). The blueshift is mainly due to filling of the local states, since a similar blueshift was observed for MQWs having thinner (2.5 nm) wells. Thus, our MBE-grown structures show negligible impact of the built-in electric field, which was achieved by doping the barriers by silicon. With an increase in excitation density ($I_{\rm p} > 0.1$ mJ/cm^2), an onset of stimulated emission from both the QWs and the barrier regions is evident (indicated in Fig. 1a by solid arrows). In disordered InGaN, variation in energy potential results in a smeared density of states at the band edge. Therefore, stimulated emission usually occurs on the high-energy side of the spontaneous band. The energy difference between the peaks of stimulated and spontaneous emission reflects the variation in band energy potential [8]. However, in our RF-MBE grown MQWs, stimulated emission appears at 3.03 eV, i.e. below the peak of spontaneous emission band. Such a behavior is typical of high quality semiconductor crystals, indicating a rather uniform distribution of constituents in InGaN epilayer. Efficient stimulated emission from the barrier region at about 3.16 eV indicates even better quality of the barrier InGaN layers. Figure 1b shows luminescence transients recorded in the spectral regions of the QW and barrier emission. A rapid initial relaxation stage is due to stimulated emission, while the slow late-decay stage is related to carrier recombination and migration in corresponding layers. At high excitation, the luminescence lifetime on the late relaxation stage is controlled by nonradiative capture of delocalized carriers. The high value of the QW emission decay time of $\tau = 600$ ps indicates a high quality of the material as well. The barrier regions show a smaller value of the lifetime, $\tau = 370$ ps, due to carrier capture to the well regions.

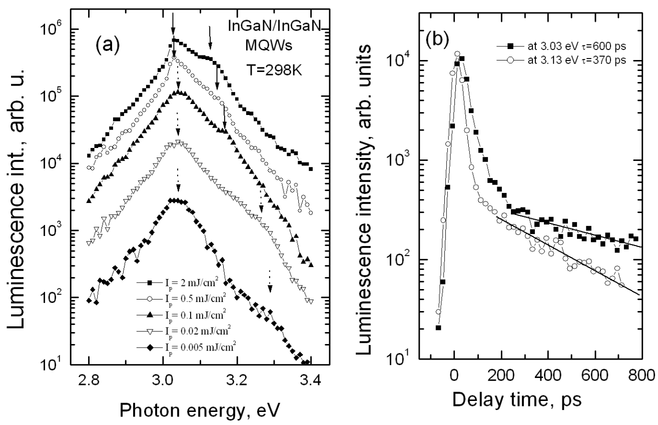

Fig. 1. (a) Time-integrated PL of highly excited MBE-grown InGaN/InGaN MQWs at various excitation densities. (b) Transients of PL recorded at 3.03 eV and 3.13 eV for 2 mJ/cm^2 excitation.

Experiments on optically detected magnetic resonance were performed at 1.6 K under cw excitation of 100 W/cm^2 by argon laser. Differential spectrum of PL with and without 60 GHz microwave irradiation was recorded. The peak of the positive ODCR signal (up to 0.5%) was observed for 0.33 T on the high--energy edge of PL spectrum. The differential spectrum was in line with the model of thermal activation of localized excitons within randomly fluctuating potential. Delocalization of excitons with microwave irradiation was observed.

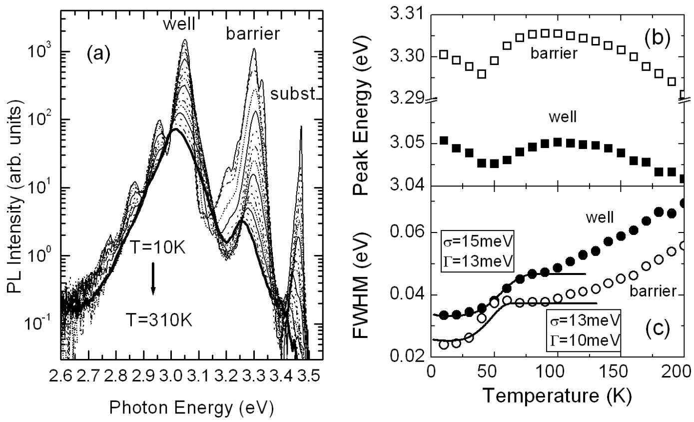

Fig. 2. (a) Variation of PL spectra vs. temperature for low intensity cw laser (2.5 W/cm^2) excitation. Variation of the energy peak position (b) and the full width at half maximum (c) vs. temperature, solid and open points — well and barrier luminescence, respectively. Solid lines represent Monte Carlo simulation results for the indicated values of the potential fluctuations roughness σ and inhomogeneous broadening Γ.

Temperature behavior of the Stokes shift and PL line width of weakly excited InGaN based structures was shown to be consistent with the model of phonon-assisted exciton hopping through the randomly distributed states confined in the band potential minima within large In-rich regions [9]. Figure 2a shows the temperature variation of the PL spectra (for cw 2.5 W/cm^2 excitation by a He–Cd laser). Low-temperature PL spectra exhibit three bands related to the QWs, barriers (and cap layer) and substrate with the corresponding phonon replicas of the excitonic emission. The characteristic S- and W-shaped temperature dependences of the PL peak (Fig. 2b) and full width at a half maximum (FWHM), respectively (Fig. 2c) were observed for the emission related to the barriers and QWs. These dependences are particularly well pronounced for the barrier material. Such a behavior indicates a certain inhomogeneity in band energy potential within InGaN layers. Monte Carlo simulation of exciton hopping (solid lines in Fig. 2c) indicates small band potential roughness, σ, and dispersion in the average band gap energy, Γ, for the QWs ($\sigma = 15$ meV, $\Gamma = 13$ meV) and barriers ($\sigma = 13$ meV, $\Gamma = 10$ meV) as compared to InGaN MQWs grown by conventional metalorganic chemical vapor deposition (MOCVD) [10]. Thus, the compositional disorder revealed by low excitation PL and ODRC was found to be relatively low, which supports the above considerations on improved uniformity of the InGaN alloy obtained by homoepitaxial MBE growth.

The lasing threshold was measured in cleaved laser structures with a 0.5 mm cavity length for optical pumping by 10 ns pulses of the third harmonic of a YAG:Nd laser. Efficient lasing was observed in a broad range of the pump density. A rather low value of the lasing threshold of 400 KW/cm^2 was estimated for the RF-MBE grown structures that compares well with record results on optical pumped lasing obtained in selected metalorganic vapor phase epitaxy (MOVPE) laser-diode structures grown on bulk GaN layer [11].

4. Conclusions

In conclusion, the performed PL characterization of RF-MBE grown homoepitaxial InGaN/InGaN MQWs indicates an excellent quality of the structures, resulting in a low threshold of stimulated emission under optical pumping. This makes the proposed growing technique promising for laser diode application.

Acknowledgments

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