InGaN-based nanocolumn light emitters in visible wavelength range

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Abstract

Light emission characteristics of bottom-up-grown GaN nanocolumns with InGaN/GaN multiple quantum wells (MQW) were investigated under high density optical excitations. Lasing emissions based on two-dimensional distributed feedback scheme in periodic structure of nanocolumns were successfully obtained in the visible wavelength range from 530 to 560 nm on the same substrate. Controllability of the wavelength by structural parameters of the nanocolumn array was demonstrated, suggesting realizability of monolithically integrated multiple-wavelength nanocolumn array lasers.

1. Introduction

InGaN-based materials attract much attention for application to visible light emitting devices. Especially, three-primary colors laser diodes for projection type displays are required to be developed, for that the development of green laser diodes with low threshold current density and high output, suitable for practical use, is indispensable [1]. However, how to suppress speckle noise caused by high coherency of laser light is the next problem to be solved for the development of laser projection displays. Coherency reduction by use of broadband laser light source, which can be attained with simultaneous driven multi-wavelength laser array [2] or random laser action [3], will introduce reduction of the speckle noise.

At the same time, InGaN-based one-dimensional nano-crystals (nanocolumns) are fabricated with the bottom-up method by rf-plasma assisted molecular beam epitaxy (rf-MBE). It is known that the dislocation free and stress reduction effects of the nanocolumn introduce superior emission properties. Furthermore, the periodic arrangement of nanocolumns, fabricated using Ti mask selective area growth (SAG) methods, functioned as nanocolumn photonic crystal, attaining green wavelength lasing operations based on two-dimensional distributed feedback (DFB) scheme [4]. The 2D-DFB scheme provides surface light emission from the nanocolumn array top and the lasing wavelength was tuned with the nanocolumn diameter and period. Using the wavelength tuning mechanism and designing the structural nanocolumn parameters from one nanocolumn arrays to the other, therefore monolithic integration of multiple-wavelength surface emitting laser diodes is highly expected. In this article, the lasing actions of InGaN-based nanocolumn photonic crystals are discussed.

2. Growth of InGaN/GaN MQW nanocolumn arrays

Using Ti-mask SAG by rf-MBE, InGaN/GaN-MQW nanocolumn arrays were grown on MOCVD-grown GaN/c-sapphire templates. Ti thin films (5 nm thick) were deposited on the GaN templates, followed by preparation of Ti nanohole mask patterns via electron beam lithography using a resist (ZEP-520A) and Ar plasma dry etching. In the growth, surfaces of Ti nanohole mask patterns were first nitrided by rf-plasma-activated nitrogen irradiation at 400 °C for 10 min; subsequently, GaN nanocolumns were grown at 900 °C for 2 hours. On tops of the nanocolumns, 3 or 15 pairs of InGaN(3nm)/GaN(12nm) MQWs were grown. Various nanocolumn arrays of triangular lattice were prepared on the same wafers changing the lattice constant (L) in the range of 200-300 nm and the nanocolumn diameter (D) from 0.6L to 0.9L.

A scanning electron microscopy (SEM) image of the nanocolumn array with L=245 nm is shown in Fig.1 (a). The nanocolumns of uniform size were periodically arranged. The corresponding photonic band diagram is calculated by two-dimensional plane wave expansion (2D-PWE) method as shown in Fig.1 (b).



Fig. 1. (a) A SEM top-surface view of the nanocolumn array of triangular lattice with period of 245 nm and diameter of 169 nm. (b) Photonic band diagram calculated by 2D-PWE) method for the nanocolumn array. The inset of (a) indicates wave vectors.

3. Optical Pumping Measurement

Optical pumping measurements were performed for the InGaN/GaN-MQW (3pairs) nanocolumn arrays with period (*L*) of 245 nm, diameter (*D*) of 169 nm. An excitation light of Nd:YAG laser (wavelength 355 nm, 5 ns pulse width, 20Hz repetition rate) was perpendicularly irradiated on the sample surface with spot size of approximately 20 µm-diameter at room temperature. Figure 2 shows emission spectra observed for the single pulse excitation for various excitation power densities. Sharp and single peak emissions were observed at 480 nm for the excitation densities over approximately 0.18 MW/cm², indicating laser action. The lasing wavelength corresponds to the photonic band edge Γ_{11} (see Fig.1 (b)), where light is strongly confined in the nanocolumn array based on 2D-DFB scheme.

The emission peak intensity for each single pulse scattered randomly and widely from one pulse to the other as a function of the excitation power density; the intensity distribution for 5000 pulses is plotted in Fig. 3. Here the mode competition and nonlinear phenomena provides random-laser-like characteristics, but the spectral wavelength range was \sim 3 nm. It is narrower than that of random lasing phenomena, which frequently spread over optical gain wavelength range and then the emission wavelength was determined by photonic band edge. Thus, this lasing phenomena should be called as "random-lasing-like photonic band-edge laser action", which provides a lower coherence than that of typical single mode lasing.

A series of InGaN/GaN-MQW (15 pairs) nanocolumn arrays having various structural parameters (period and diameter) were prepared on the same substrate and optically pumped. The lasing wavelengths shifted from 530 to 560 nm as a function of the nanocolumn parameter (L, D), as shown in Fig. 4. The 2D-PWE calculation revealed that the wavelength shift corresponded to transition of the photonic band edge determined by the nanocolumn parameter. Therefore controlling the lasing wavelength with L and D, we can achieve monolithic integration of multiple-wavelength nanocolumn laser diode array.



Fig. 2. Emission spectra from the nanocolumn array changing the excitation density. A sharp peak emission appeared at 480 nm corresponding to the photonic band edge of the nanocolumn array.



Fig. 3. Emission peak intensity as a function of excitation power density for 5000 pulse measurements. Linewidths of the each spectrum are expressed by color of symbols.



Fig. 4. Stimulated emission spectra of nanocolumn arrays with various periods L and nanocolumn diameters D.

4. Conclusions

Light emission characteristics of InGaN/GaN-MQW nanocolumn arrays were investigated with the optical pumping experiments; we observed random-lasing-like photonic band-edge lasing characteristics, basically operated on 2D-DFB scheme. The controllability of lasing wavelength with the nanocolumn parameter will contribute to monolithic integration of multiple-wavelength nanocolumn lasers suitable for low-speckle noise laser action.

Acknowledgements

This research was supported by a Grant-in-Aid for Specially Promoted Research (#24000013) from the MEXT of Japan, and the New Energy and Industrial Technology Development Organization (NEDO).

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