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Comparison of optical transitions in InGaN quantum well structures and microdisks

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$In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ multiple quantum well (MQW) microdisks 6.0 μm in diameter have been fabricated by photolithography and ion beam etching. Photoluminescence (PL) spectroscopy has been employed to study the optical transitions in these microdisks as well as in the original MQW structures prior to microdisk formation. With respect to the original MQWs, a blueshift in the PL peak position, enhancement of the PL intensity, and narrowing of the PL linewidth were observed at 10 K in the microdisks. These observations can be understood mainly in terms of a reduction of piezoelectric field strength due to partial strain relief in the microdisks. The magnitude the piezoelectric field reduction was estimated to be around 0.27 MV/cm, which is of the same order as the previously reported value of the piezoelectric field in similar MQW structures. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1355280]

I. INTRODUCTION

The group III-nitride semiconductors are recognized as very important materials for many applications in the area of optoelectronic devices and high-temperature/power electronic devices.[1–2] The emission mechanisms in InGaN alloys and multiple quantum wells (MQWs) are currently under intensive investigations[3–5] because of their applications in UV/blue light emitting diodes (LEDs) and laser diodes. Microdisk cavities have been studied intensively[6–9] since McCall *et al.* demonstrated optically pumped semiconductor microdisk lasers in 1992.[10] Microcavity lasers have many advantages over edge emitting lasers including higher quantum efficiency, a higher quality *Q* factor, and lower lasing threshold.[11–13] We have recently fabricated and studied several types of III-nitride microcavities including microdisk and microring cavities. Optical resonance modes have been observed in both GaN/AlGaN and InGaN/GaN MQW microdisks and microrings by optical pumping.[14–16] Enhancements in the intrinsic optical transition efficiency and carrier decay lifetimes were also observed in GaN/AlGaN MQW microdisks. In this article, we report a possible reduction of piezoelectric field due to partial strain relief in $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW microdisks.

II. EXPERIMENTS

The MQW structure was grown on a (0001) sapphire substrate by metal organic chemical vapor deposition (MOCVD). It consists of a buffer layer of GaN, a 2.0 μm epilayer of GaN, and an $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW structure with a total of four wells and five barriers. The well and the barrier thicknesses were 2 and 10 nm, respectively. Photolithography was employed to fabricate arrays of photoresist microdisks on top of the MQW wafer. The photoresist microdisks, with diameters of 10 μm and center-to-center spacing of 50 μm, were then used as masks in the successive ion beam etching process. A fluorescence microscope was used to observe the photoluminescence (PL) image of the sample to make sure that there was no III-nitride material present between the microdisks after etching.

PL spectra were measured for both the $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW wafer and the MQW microdisks. Excitation laser pulses with a pulse width of about 10 ps and a repetition rate of 9.5 MHz were provided by a cavity-dumped dye laser, which was pumped by an yttrium–aluminum–garnet (YAG) laser with a frequency doubler. The output from the dye laser was frequency doubled again by a second frequency doubler to provide tunability in the UV region. The laser output after the second doubler has an average power of about 20 mW and tunable photon energy up to 4.5 eV. The laser wavelength was chosen as 290 nm and the laser beam had a spot size of about 0.3 mm. The laser excitation intensity was controlled by a set of neutral density filters. The high and low excitation intensities referred to hereafter differed by a factor of about 20. The PL detection system consisted of a 1.33 m monochrometer, a fast microchannel plate photomultiplier tube (PMT), and a single photon counting system.

III. RESULTS

Figure 1 is a scanning electron microscope (SEM) image of an $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW microdisk. Because of the long-time ion beam etching, the real size of a microdisk after etching was smaller than that of the original mask, and the side of the etched microdisk was not vertical. Since

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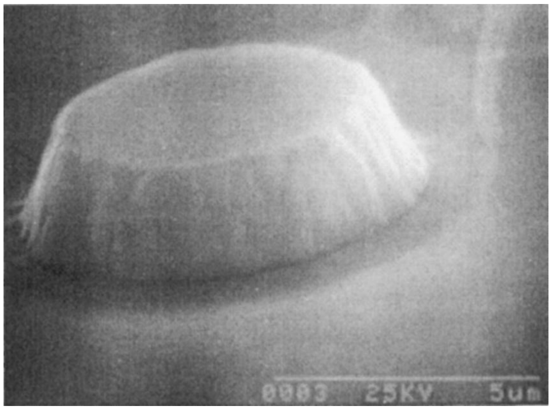

FIG. 1. SEM of an $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW microdisk with a diameter of around 6.0 μm.

the layer thickness of the entire MQW structure is very thin, the real diameter of the MQW microdisk was approximately equal to that of the top surface of the microdisk. From Fig. 1, the diameter of the MQW microdisk was estimated to be about 6 μm.

Figure 2 is low-temperature (10 K) continuous wave (cw) PL spectra of the MQW structure and microdisks under low intensity (LI) and high intensity (HI) laser excitation. In Fig. 2(a), the peak position of the dominant transition from the MQW structure is at 2.778 eV. Interference fringes between the interfaces of the top layer/air and buffer/sapphire located at the lower energy shoulder (2.683 and 2.573 eV) are quite evident in the original MQW sample. In comparison, the interference fringes in MQW microdisks are quite small, which is reasonable because of the reduced total lateral area of the microdisks. The PL peak position of the microdisks is at 2.831 eV, which was blueshifted by 53 meV with respect to that of the MQW structure. The full width at half maximum (FWHM) of the PL spectrum from the microdisks is about 123.6 meV. Taking into account the difference in the effective pumping areas between the MQW structure and the microdisks, the PL intensity in the microdisks was enhanced by a factor of about 2.5 compared with that of the MQW structure. As the setup of our PL measurement system was such that only light emitted from the top surface could be collected, the enhanced PL intensity in the microdisks is not likely due to the increased light leakage at the microdisk edges. A spectral blueshift of electroluminescence (EL) in InGaN/GaN MQW microdisk LEDs (μ-LEDs) with respect to that of the broad area InGAN/GaN MQW LEDs has been reported,[17] and is similar to the results observed here.

The peak position of the dominant transition from the MQW structure under high intensity laser excitation is at 2.798 eV, which is blueshifted by 20 meV with respect to that of the MQW structure under low intensity laser excitation in Fig. 2(a). This is most likely due to the effects of band filling and carrier screening under high intensity laser excitation, which reduces the piezoelectric field strength in the wells, an effect that has been observed and discussed previously.[18,19] The PL peak position of the microdisks under high intensity laser excitation is at 2.888 eV, which is blueshifted by 90 meV with respect to that of the MQW. This value is larger than that of 53 meV under low intensity laser excitation observed in Fig. 2(a). The FWHM of the dominant PL spectrum for microdisks reduces to about 49.7 meV under high laser power excitation. Taking into account the difference in the effective pumping areas between the MQW structure and the microdisks, the PL intensity in the microdisks was enhanced by a factor of about 10 compared with that of the MQW structure.

In summary, with respect to the original $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW structure, a blueshift of the PL peak position, enhancement of the PL intensity, and a reduction of the PL emission line FWHM have been observed in $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW microdisks. All these phenomena become more pronounced with increasing laser excitation intensity.

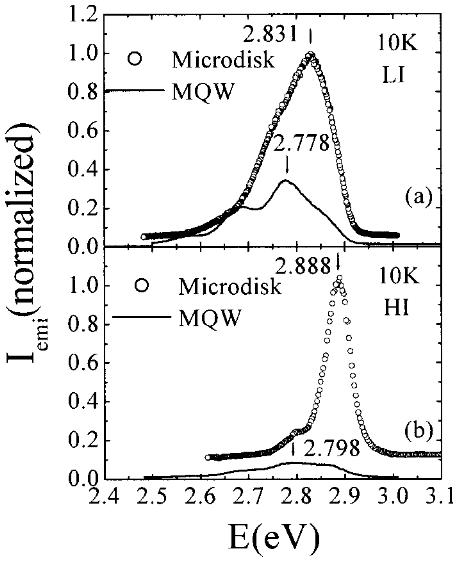

FIG. 2. Low-temperature (10 K) PL spectra of a $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW sample and a MQW microdisk under (a) low intensity and (b) high intensity laser excitation.

IV. DISCUSSIONS

Optical transitions in the InGaN MQWs at low temperatures under low intensity laser excitation are dominated by localized excitation.[4,5] The localized exciton energy is determined by (a) the energy gap of the $In_xGa_{1-x}N$ wells, (b) the quantum confinement energies of the electrons and holes, (c) the exciton binding energy, (d) the exciton localization energy, and (e) the piezoelectric or polarization field induced energy shift. Because of the polarization field resulting from the symmetry of the wurtzite structure of nitrides as well as the piezoelectric field resulting from the lattice mismatch between the wells and barriers materials, an electric field perpendicular to the plane of the wells is built up in the wurtzite III-nitride MQW material system.[1,20] The piezoelectric field, if strong enough, will induce spatial separation of the electron and hole (of an exciton) wave functions in the wells. It will then lead to a redshift in the emission spectra as well as a reduction in radiative decay rate (or PL intensity) in the MQWs with respect to that in the epilayers.

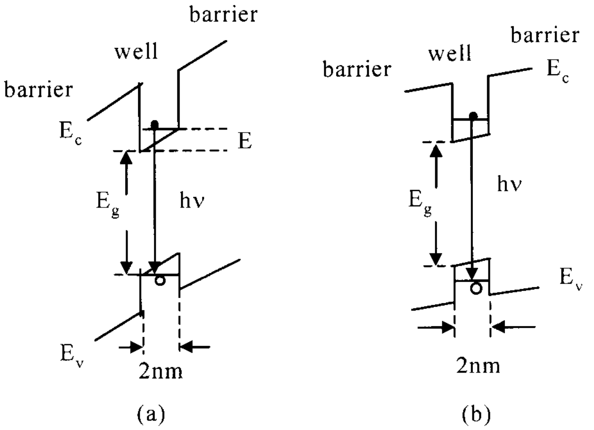

FIG. 3. Schematic diagram of the electron and hole energy levels in (a) MQWs with the original piezoelectric field and (b) a MQW microdisk with a reduced piezoelectric field.

Due to the piezoelectric field resulting from the lattice mismatch induced strain, it is conceivable that a finite size of the microdisks is required in order to sustain the lattice mismatch induced piezoelectric field. In other words, when the size of the MQW microdisk is smaller than a critical size, strain relaxation could occur, and hence the piezoelectric field would be reduced. Figure 3 shows a schematic diagram of the electron and hole energy levels in MQWs with the original piezoelectric field and a MQW microdisk with reduced piezoelectric field. Due to the presence of the piezoelectric field **E**, the emission energy of the excitons in the strained MQWs is smaller than that in the partially strain relieved MQW microdisks. If this is the case, the 53 meV blueshift of the PL peak position in the $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ microdisk observed in Fig. 2(a) would correspond to an amount of energy gained when the strain was partially relieved in the microdisks. The amount of the piezoelectric field reduced due to partial strain relief in the microdisks can thus be estimated to be around 53 mV/2 nm$=$0.27 MV/cm, where 2 nm is the well width. This value represents part of the piezoelectric field in the $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQWs since most likely the strain (the piezoelectric field) is only partially relieved (reduced) in microdisks. However, this value is of the same order as (and correctly smaller than) that reported previously in similar MQW structures.[21]

Accordingly, the increased blueshift (90 meV) in the MQW microdisks with respect to that in the MQW structure observed under high intensity laser excitation shown in Fig. 2(b) can be explained as combined effects of band filling, partial strain relief, and carrier screening. The PL peak position difference between the low and high intensities of laser excitation in the MQW structure (20 meV) is smaller than that in the microdisks (57 meV) as shown in Fig. 2. This indicates a stronger band filling effect in the microdisks than in the MQW structure, where smaller carrier density is expected due to carrier diffusion in the plane perpendicular to the growth direction, as suggested previously.[17] This will also explain enhancement of the PL intensity in the microdisks. With a reduced piezoelectric field, the electron and hole wave functions overlap and hence the radiative recombination rate will be increased,[19] which results in an increase in the PL intensity in the MQW microdisks. Our experimental results demonstrate that the optical properties in the MQW microdisks are quite different from those of the MQWs. The differences should be studied thoroughly and taken into consideration for future nitride microsize structure and device designs.

V. SUMMARY

$In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQW microdisks were fabricated by photolithography and ion beam etching. The optical properties of the microdisks were investigated by PL spectroscopy and compared with those of the original $In_{0.22}Ga_{0.78}N/In_{0.06}Ga_{0.94}N$ MQWs. Our results suggest that, in the MQW microdisks, the lattice mismatch induced strain was partially relieved and thus the piezoelectric field was reduced. This partial strain relief in the MQW microdisks leads to a blueshift of the PL peak position as well as enhanced PL intensity in microdisks. The magnitude of the piezoelectric field reduction in the MQW microdisks is estimated to be around 0.27 MV/cm. Narrowing of the PL emission linewidth together with the strong emission intensity enhancement suggest possible microcavity effects in the MQW microdisks under high intensity laser excitation. Our results also provide some useful information for the realization of future III-nitride microdisk lasers.

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