

CHAPTER FIVE

MICROSCOPIC PHOTOLUMINESCENCE OF III-NITRIDE PHOTONIC CRYSTAL WITH GaN QUANTUM DOTS

5.1 Introduction

In this chapter, micro-photoluminescence measurement for air-bridge photonic crystals with GaN QDs will be demonstrated. The samples were fabricated utilizing the process established in chapter 4. First, the experimental setup will be demonstrated in section 5.2.1, followed by the observation results from the sample without / with air-bridge structure in section 5.2.2 and 5.2.3, respectively. Finally, the conclusion remarks will be made in section 5.3.

Figure 5.1 (a) and (b) give the schematic demonstrations of the sample without / with air-bridge structure used for optical characterization in this study. Stranski-Krastanow mode GaN QDs were grown on n-type (0001)-oriented 6H-SiC substrate by low-pressure MOCVD. A 100 nm thick AlN layer was deposited on SiC substrate, followed by GaN QDs growth. Finally the growth was terminated by a 20 nm thick AlN cap layer. Two dimensional photonic crystal patterns with periodicity and r/a ratio ranging from 140 nm to 200 nm and 0.25 to 0.325, covering the essential periodicities tuning photonic band gap to the emission wavelength of QDs, were subsequently fabricated into the as-grown samples (shown in fig. 5.1 (a)). Photoelectrochemical etching of SiC was employed to fabricate the air-bridge structure between III-nitrides layer and SiC substrate (shown in fig. 5.1 (b)). The experimental results as well as the discussion will be demonstrated in the following section 5.2.

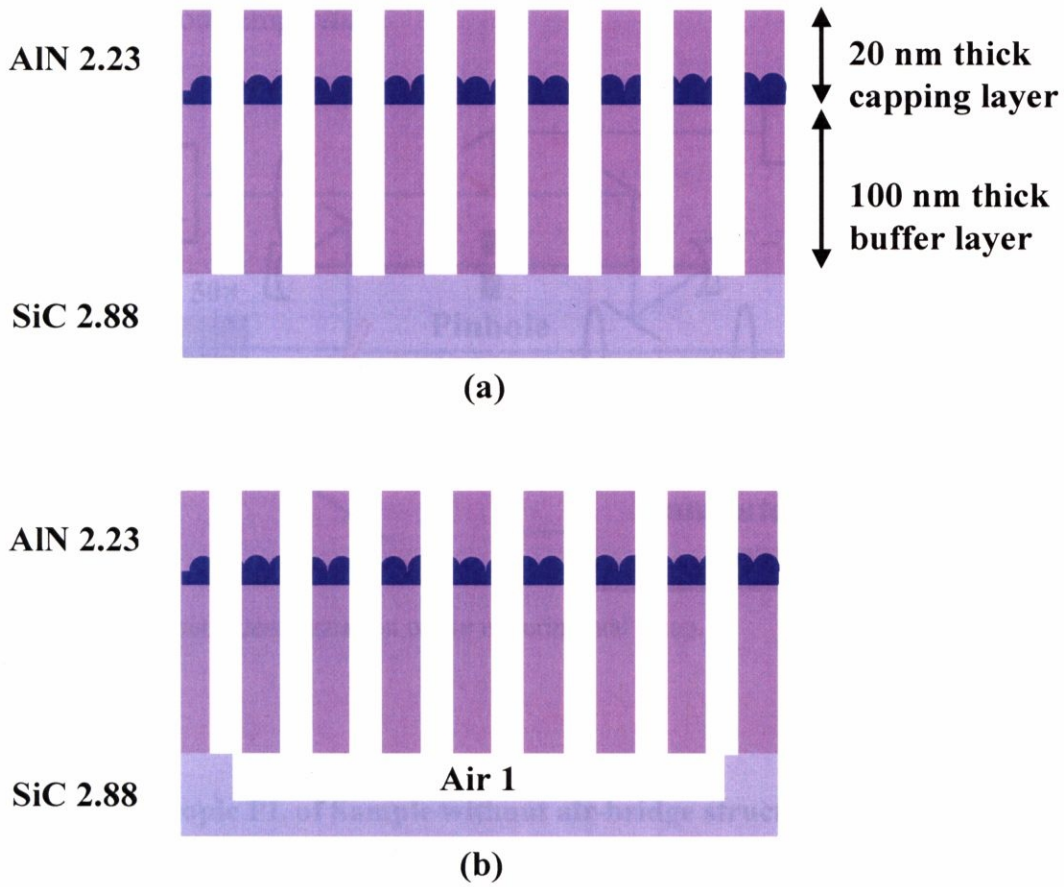


Fig. 5.1 Schematic demonstration of sample (a) without and (b) with air-bridge structure consisting of GaN QDs for optical characterization.

5.2 Microscopic Photoluminescence (PL) Observation

5.2.1 Experimental Setup

Figure 5.2 demonstrates the experimental setup used to perform the optical characterization in this study. The sample was set into the cryostat. A continuous-wave laser with the wavelength of 266 nm corresponding to the band edge of wetting layer was employed as the excitation light source. The laser was a frequency-doubled solid-state green laser using a resonant enhancement cavity. Excitation was performed through a $50\times$ object lens, with the laser focused to $4\text{ }\mu\text{m}$ spot on the surface. PL was collected by the same objective lens and analyzed by a 30 cm long monochromator with

a liquid-nitrogen-cooled charge coupled device camera. All the experiments were carried out at room temperature.

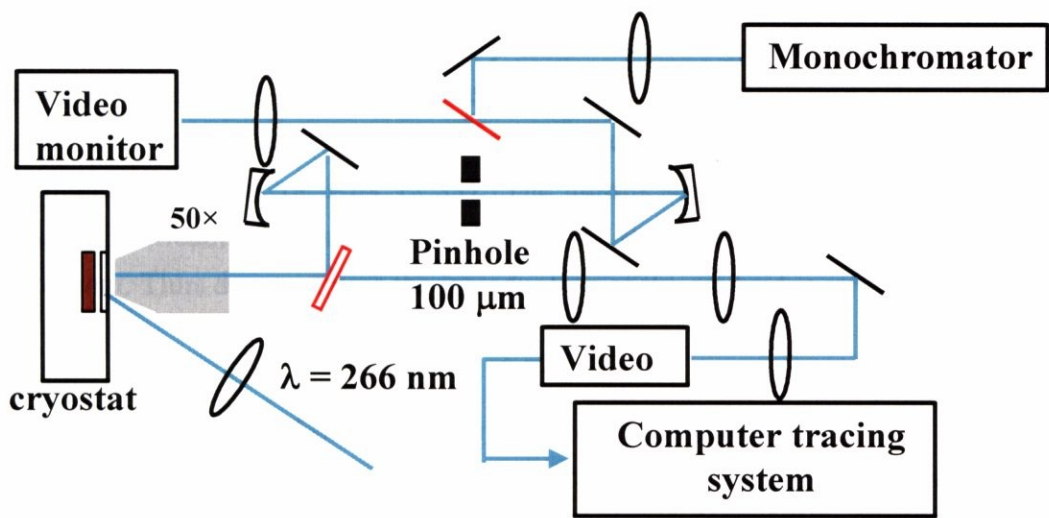


Fig. 5.2 Schematic demonstration of our experimental setup.

5.2.2 Microscopic PL of Sample without air-bridge structure

We first measured the sample without air-bridge structure. Figure 5.3 (a) shows the 3D FDTD simulation results of light enhancement for the periodicities of 160 nm, 170 nm and 180 nm. Enhancement ratio is defined as the intensity of PL from QDs with PC

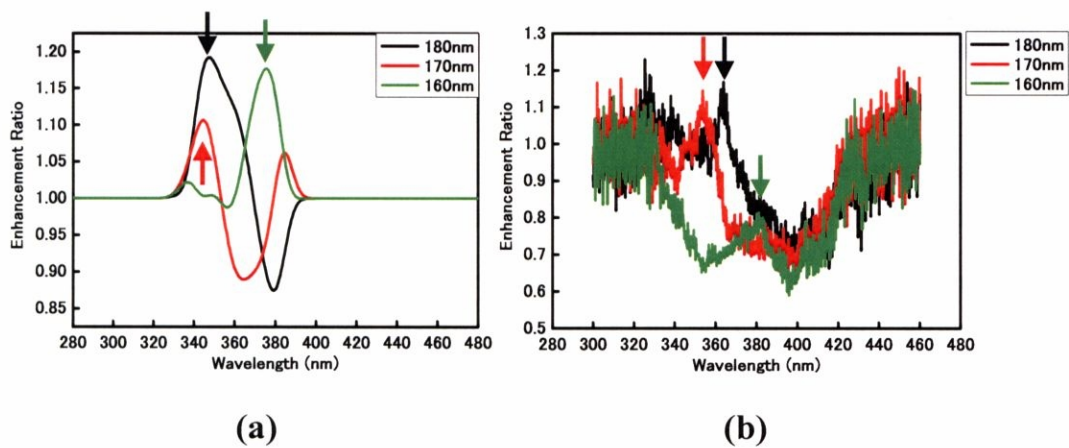


Fig. 5.3 (a) 3D FDTD simulation and (b) experimental results of the dependence of light enhancement ratio on periodicity.

patterns divided by that without PC patterns. Figure 5.3 (b) shows the light enhancement calculated from experimental results. One can observe that the experimental results show reasonable agreement with the simulation results, thus supporting the existence of photonic crystal structure. However, the enhancement is extremely weak in spite of the existence of photonic crystal structure. This is due to the refractive index problem of our sample: the refractive index of SiC substrate (2.88) is much higher than that of AlN (2.23). The luminescence from QDs was lost into substrate significantly, eventually resulting in the very poor efficiency of light enhancement. Thus demonstrates the introduction of the air-bridge structure is essential.

5.2.3 Microscopic PL of Sample with air-bridge structure

Considering the refractive index problem revealed in section 5.2.2, we fabricated samples with air-bridge structure utilizing the method demonstrated in the former chapter 4. Figure 5.4 (a) shows the optical microscope image of the fabricated sample.

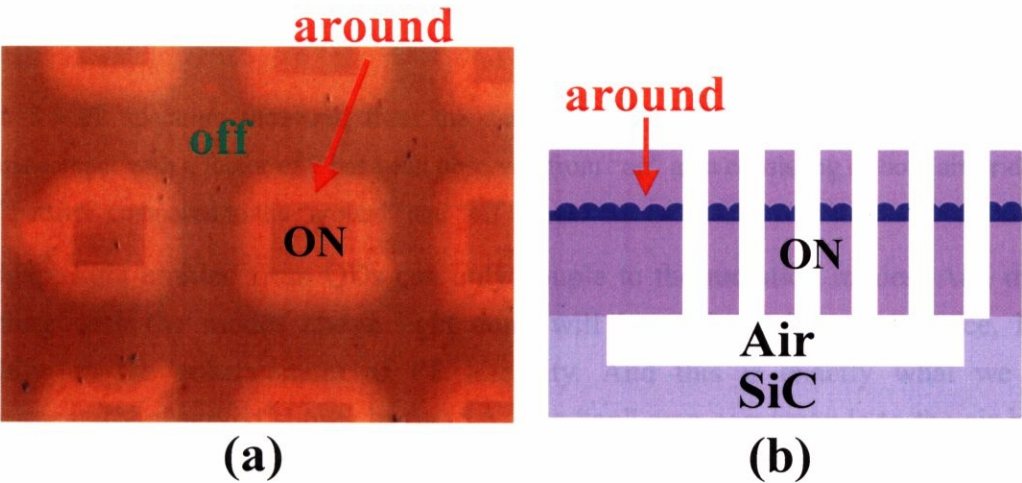


Fig. 5.4 (a) The optical microscopic image of the sample with air-bridge structure and the schematic demonstration (b) of the areas named “on”, “around” and “off” respectively.

We name the area with both photonic crystal patterns and air-bridge structures as “on” area, and the area of air-bridge as-grown structure as “around”. The “around” area is formed due to the isotropic feature of the photoelectrochemical of SiC. The as-grown sample is named as “off” area. Figure 5.4 (b) gives the schematic demonstration of the “on”, “around” and “off” areas that will help one to understand the sample structure. If the photonic band gap does exist for the in-plane waveguiding modes that correspond to the emission wavelength of GaN QDs, since the guided modes are eliminated within the

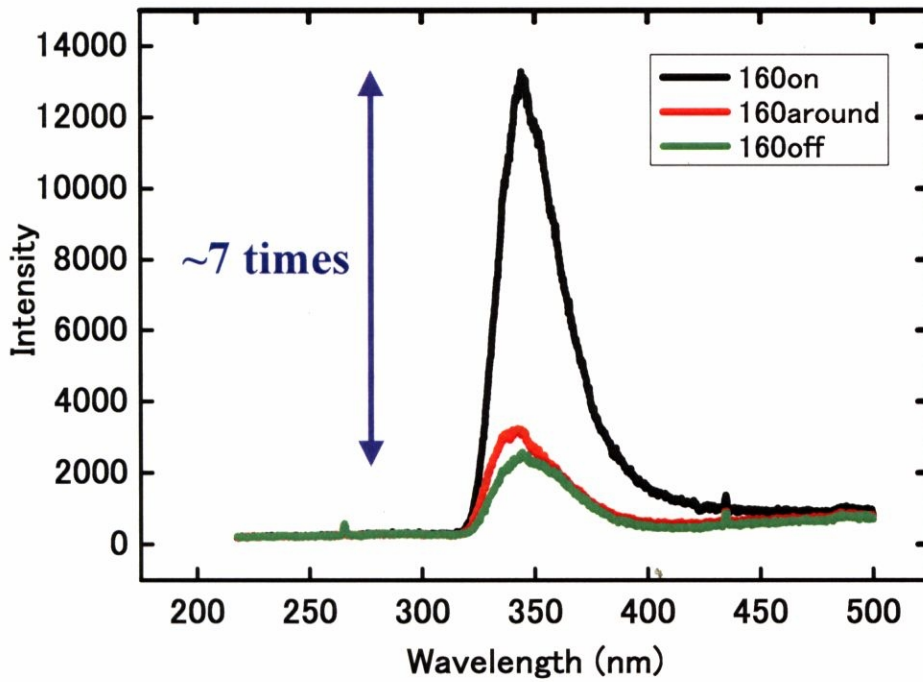


Fig. 5.5 PL spectrum measured from the named “on”, “around” and “off” areas. Strong enhancement with a factor of 7 has been observed from “on” area consisting of both air-bridge PC patterns compared to the “around” and “off” areas.

bandgap, light emitted from QDs can only couple to the radiation modes. And the PL coupling with the modes above light cone will be radiated into free space, hence resulting in the enhancement of PL intensity. And this is exactly what we have experimentally observed shown in fig. 5.5. The “on” area corresponds to the air-bridge PC pattern with the periodicity and r/a ratio of 160 nm and 0.3 respectively. And we chose the “around” and “off” areas near the PC pattern to avoid the influence yielded by size fluctuation of QDs. One can observe from fig. 5.5 that strong luminescence enhancement by a factor of 7 has been obtained. Since no significant difference occurs between the spectrum of “around” and “off” areas, we can claim that the strong enhancement observed from “on” area is due to the existence of the periodic photonic crystal structure. The coupling of PL light with photonic bands above the light cone results in the significant enhancement of light extraction efficiency. Our optical measurement results also demonstrate the good quality of air-bridge PC membrane fabricated utilizing the process established in chapter 4.

5.3 Conclusion Remarks

In this chapter, micro-photoluminescence measurement for photonic crystals without / with air-bridge structure consisting of GaN QDs has been demonstrated. For the sample without air-bridge structure, although the measured data was in good agreement with 3D FDTD simulation, supporting the existence of photonic crystal structure. The enhancement was very poor due to the extremely leaky waveguide structure with the large refractive index of SiC cladding layer (2.88) compared to that of AlN core layer (2.23). On the other hand to the sample with air-bridge structure, compared to the luminescence from GaN QDs embedded in both as-grown area and air-bridge as-grown area which results from the isotropic wet etching of SiC, strong luminescence enhancement by a factor of 7 was observed from QDs embedded in the air-bridge PC layer ($a=160$ nm). This is due to the coupling of PL light with photonic bands above the light cone, thus results in the enhanced light extraction efficiency. These results are important for the further investigation of high efficiency QDs-based emitting devices in blue and ultraviolet range.

CHAPTER SIX

CONCLUSIONS

In this master study, we focused on the fabrication and optical characterization of air-bridge III-nitride photonic crystal structures consisting of GaN QDs. The motivation of this research is the realization of high-efficiency and high-temperature operating single photon emitters in UV and blue regions. We chose GaN QDs as the material system due to the strong confinement resulting from large band discontinuity between GaN and AlN, which is promising for high-temperature operating SPEs. On the other hand we employed photonic crystal nanocavity as the device structure. Since the very small mode volumes and high quality factors of it is promising to achieve large spontaneous emissions rate enhancements. Also, large enhancement of light extraction efficiency could be achieved due to the impact of PC structure on in-plane waveguide mode. Both of these issues are essential upon the realization of high-efficiency SPEs. The numerical calculation of band structure revealed that periodicity smaller than 150 nm and r/a ratio larger than 0.25 is requisite to tune photonic band gap around the emission wavelength region of GaN QDs. Also the influence of SiC substrate has to be removed for the requirements of optical characterization.

Taking these two challenging issues into consideration, we first carried out a systematic investigation to optimize each step of the whole nanofabrication. By changing the value of RIE parameters such as source, bias power, gas pressure and gas ratio, we could fabricate III-nitride PC structures with abrupt vertical airhole features and smooth etching surface even to the periodicity as small as 140 nm. To remove the SiC substrate, we employed the photoelectrochemical etching method. This task is extremely challenging since the removal of SiC must be carried out subsequent to the nanofabrication of PC structure and we have to remove SiC assuring the most moderate damage yield to the fabricated III-nitrides PC structure above. Until then, there has been no reported work on the air-bridge fabrication by removing SiC subsequent to device fabrication and furthermore, the mechanism of the reaction itself is not clarified yet. We started from no preliminary work, established the experiment apparatus, and investigated the influence of etching parameters such as electrolyte density and

photocurrent density on etching rate and etched surface. By solving the ‘expected’ and ‘unexpected’ problems, we succeeded for the first in fabricating air-bridge AlN-based PC structures by photoelectrochemical etching of SiC. The etching condition could promise the introduction of air-layer with thickness of 300 nm and the moderate smooth etching surface of the sample.

Finally we carried out the micro-PL measurement for the GaN QDs embedded PC nanocavity with/without air-bridge structure. For the sample without air-bridge structure, we could not observe significant change in spite of the existence of PC structures. In contrast, for the sample with air-bridge structure, compared to the luminescence from GaN QDs embedded in both as-grown area and air-bridge as-grown area which results from the isotropic wet etching of SiC, strong luminescence enhancement by a factor of 7 was observed from QDs embedded in the air-bridge PC layer ($a=160$ nm). This is due to the coupling of PL light with photonic bands above the light cone, thus results in the enhanced light extraction efficiency. On the other hand, however, we could not observe strong cavity mode. The major reason may be responsible is the roughness yield to the PC membrane due to the imperfect fabrication process of air-bridge structure. Therefore, the most urgent task is to improve the condition for photoelectrochemical etching of SiC.

Although there still remains some challenging assignments, this work is absolutely an important and successful attempt for the realization of high-efficiency and high-temperature operating SPEs in UV and blue wavelength region. Also, the knowledge obtained in this study will no-doubt contribute to the practical application of III-nitrides photonic crystal devices and GaN QDs-based devices.

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Presentation and Publication List

International

- 1) Katsuyuki Hoshino, ○Ning LI, and Yasuhiko Arakawa, “Growth of High-density GaN Self-assembled Quantum Dots by Metalorganic Chemical Vapor Deposition”, International Symposium on Quantum dots and Photonic Crystals 2005, Tokyo, Japan, March 2005.
- 2) ○Ning LI, S. Kako, M. Kitamura, S. Iwamoto, and Y. Arakawa, “Fabrication and optical characterization of III-Nitride air-bridge photonic crystal with GaN quantum dots” Submitted to 6th International Symposium on Blue Laser and Light Emitting Diodes, Montpellier, France, May 2006.

Domestic

- 1) ○李 宁, 星野勝之, 加古敏, 岩本敏, 荒川泰彦, “GaN 量子ドットを有するフォトニック結晶微小共振器の作製とその光学評価”, 第 52 回応用物理学関係連合講演会(埼玉大学), 31p-YV-1, 2005 年 3 月.
- 2) ○李 宁, 星野勝之, 荒川泰彦, “原料交互供給法による AlN エピタキシャル膜の MOCVD 成長”, 第 52 回応用物理学関係連合講演会(埼玉大学), 30p-L-6, 2005 年 3 月.
- 3) ○李 宁, 加古敏, 北村雅季, 岩本敏, 荒川泰彦, “量子ドットを有する窒化物半導体フォトニック結晶～エアブリッジ構造の作製～”, 第 53 回応用物理学関係連合講演会(徳島大学), 9a-H-7, 2005 年 9 月.

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