

Chapter 7

Characterization of AlN Photonic Crystal Nanocavities with GaN Quantum Dots

7.1 Introduction

The optical characteristics of semiconductor photonic crystal nanocavities have been generally discussed from the viewpoint of their quality-factor (Q -factor) as a decisive and obvious index for the cavity. Microscopic photoluminescence measurements are the most popular method for investigating the optical characteristics. The Q -factor of a cavity is defined by the rate τ_{cav} at which the energy stored inside the cavity $U(t_0)$ at a instant t_0 consumed or decayed:

$$Q = \omega_0 \tau_{\text{cav}} \quad (7.1)$$

$$U(t) = U(t_0) \exp\left(-\frac{t}{\tau_{\text{cav}}}\right) = U(t_0) \exp\left(-\frac{\omega_0 t}{Q}\right), \quad (7.2)$$

where ω_0 stands for the frequency of the cavity mode. Fourier transform of the above equation (7.2) gives Lorentzian curve of width $\delta\omega = 1/\tau_{\text{cav}} = \omega_0/Q$. Hence one can evaluate the Q -factor of a specific cavity mode by simply measuring the linewidth of the mode.

As described in the previous chapter, the author fabricated AlN photonic crystal nanocavities by utilizing novel process. In this chapter, experimental results are given on optical characterization of AlN photonic crystal nanocavities with GaN quantum dots. Microscopic photoluminescence measurements are performed to investigate the optical properties of the nanocavities at room temperature. For the lowest-order cavity mode of a 150-nm-period nanocavity with seven missing holes, luminescence linewidth of 0.16 nm corresponding to the Q -factor of more than 2,400, which is the highest Q for nitride-based PC nanocavities ever reported, was obtained. Furthermore, the

lowest-energy mode as short as 372 nm, which is the shortest ever reported in semiconductor photonic crystal nanocavities, is achieved in a 150-nm-period nanocavity with three missing holes. Localized nature of the cavity modes is also observed directly.

7.2 Optical Characterization of AlN Photonic Crystal Nanocavities

7.2.1 Experimental Setup of Microscopic Photoluminescence Measurements

To investigate optical properties of the nanocavities, microscopic photoluminescence (micro-PL) measurements were performed at room temperature. Figure 7.1 illustrates schematics of the measurement system. The sample was set in a cryostat. In order to avoid photo-induced contamination and deterioration, the sample chamber was pumped down to a vacuum. A continuous-wave frequency-doubled solid-state laser was used as an excitation source. The excitation wavelength was 266 nm, which was well below the bandgap of AlN. Since no appropriate focusing lens simultaneously used as an objective lens was available for this wavelength, the laser was used in grazing-incidence configuration. The excitation spot was over several ten times larger than the PC area (typical: $\sim 4 \times 4 \mu\text{m}^2$), hence the whole PC region was uniformly excited. The excitation power density was estimated to be around 10 kW/cm^2 . A $40\times$ objective lens (NA 0.6) was used to detect photoluminescence from the sample. An additional pinhole inserted between the objective lens and detector spatially limited the investigation area down to $\sim 5 \mu\text{m}^2$. A cooled charge-coupled device (CCD) photodetector array was equipped to a monochromator. For imaging purposes, there were two CCD cameras in the system. One was used to roughly position the sample to an appropriate location. It worked like a standard confocal microscope. A white light illuminates the sample through the objective lens, while the illuminated surface image was detected by the CCD camera. The other camera, set after the removable pinhole, was used only for imaging luminescence from the sample. A mirror located just after the object lens was also removable, allowing one to switch the two imaging paths alternatively. In addition, the mirror located just before the luminescence-imaging CCD was removable too. Photoluminescence spectra were taken with the mirror, while luminescence images were observed without the mirror.

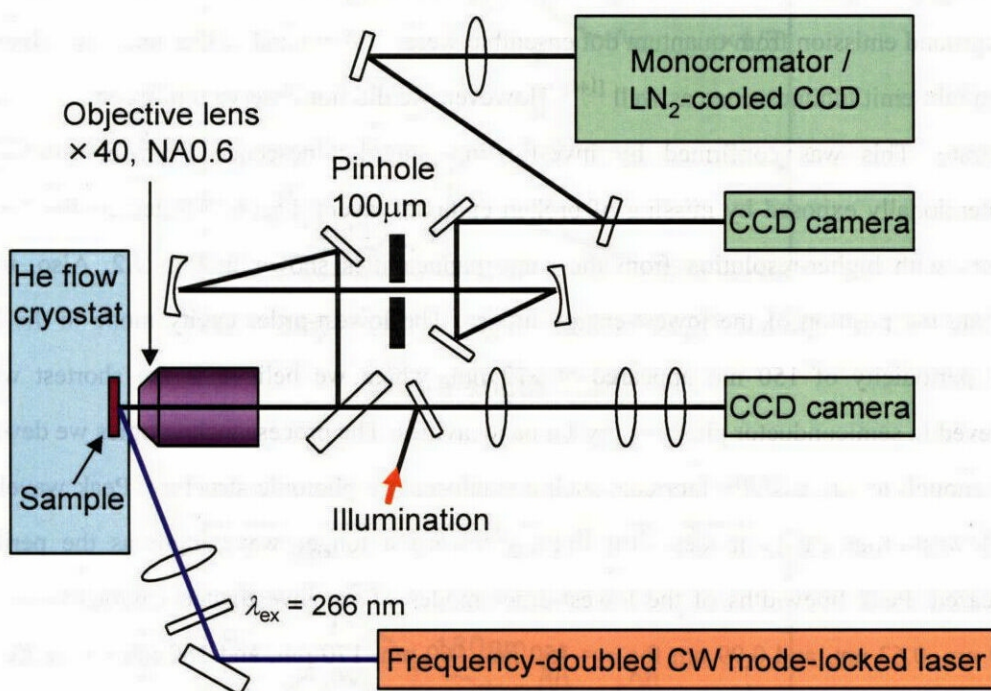


Figure 7.1 Schematic diagram of experimental setup for micro-PL measurements

7.2.2 Results of Microscopic Photoluminescence Measurements

Figure 7.2 illustrates the micro-PL spectra of nanocavities consist of three (L3, upper panel) or seven (L7, lower panel) missing holes with different periodicities and a fixed r/a ratio of 0.30. Sharp luminescence lines attributed to the cavity modes were observed from all the cavities. In this figure, arrows indicate the position of the lowest-energy modes. The cavity modes were clearly distinguishable although broad background emission, which was slightly modulated depending on the air-gap height, was also detected. Inhomogeneous linewidth and center wavelength of the background emission from quantum dot ensemble were ~ 50 nm and ~ 365 nm, respectively. Porous SiC might emit luminescence as well ^[144]. However, we did not observe much contribution from the substrate. This was confirmed by investigating photoluminescence from porous-SiC surface unintentionally exposed by missing of broken epitaxial layers. Figure 7.3 depicts the cavity mode spectra with higher-resolution from the same nanocavities shown in Fig. 7.2. Also, the arrows indicate the position of the lowest-energy modes. The lowest-order cavity mode in the L3 cavity with periodicity of 150 nm appeared at 372 nm, which we believe is the shortest wavelength achieved in semiconductor photonic crystal nanocavities. The process technologies we developed are fine enough to successfully fabricate such a small-feature photonic structure. Peak wavelengths of the lowest-order cavity modes shift linearly toward a longer wavelength as the periodicity is increased. Peak linewidths of the lowest-order modes of the investigated cavities were: 0.46 nm, 0.60 nm, 0.63 nm, and 0.99 nm for $a = 150$ nm, 160 nm, 170 nm, and 180 nm L3 cavity, and 0.16 nm, 0.27 nm, 0.33 nm, and 0.21 nm for $a = 150$ nm, 160 nm, 170 nm, and 180 nm L7 cavity, respectively.

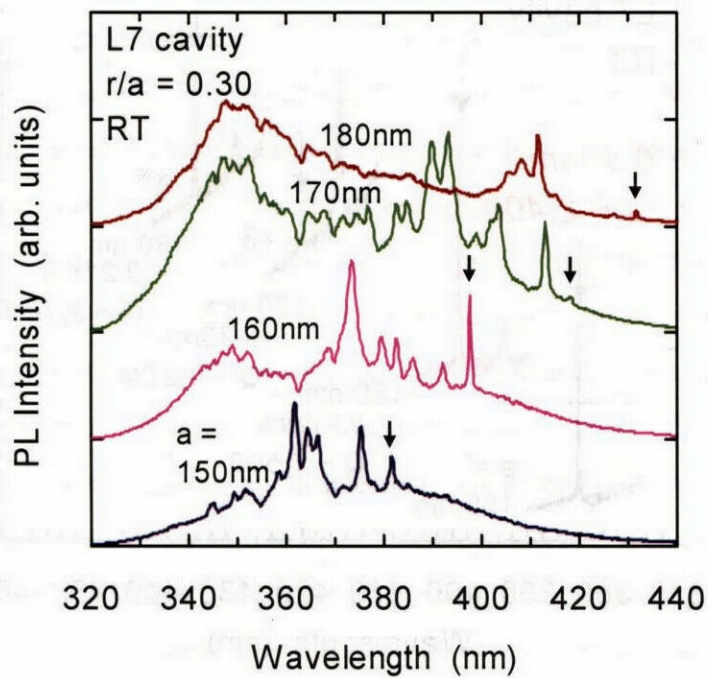
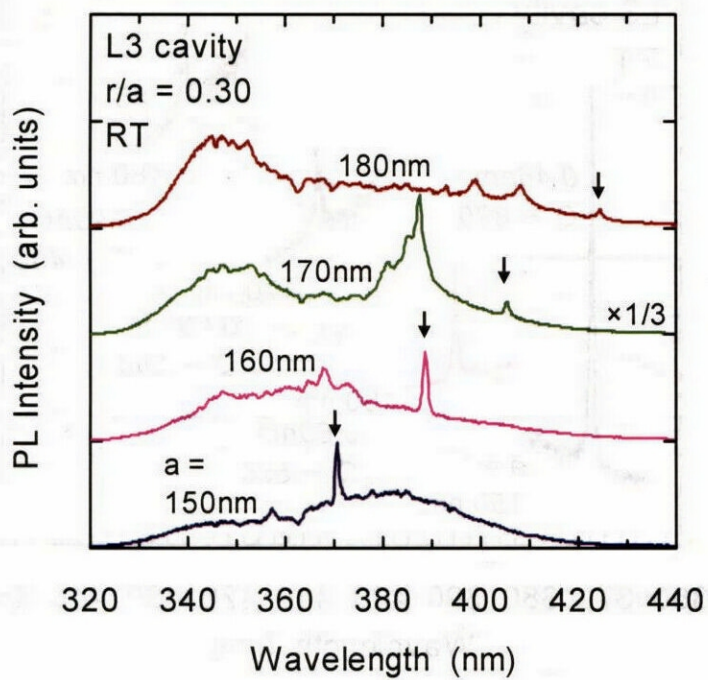


Figure7.2 Micro-PL spectrum of fabricated device

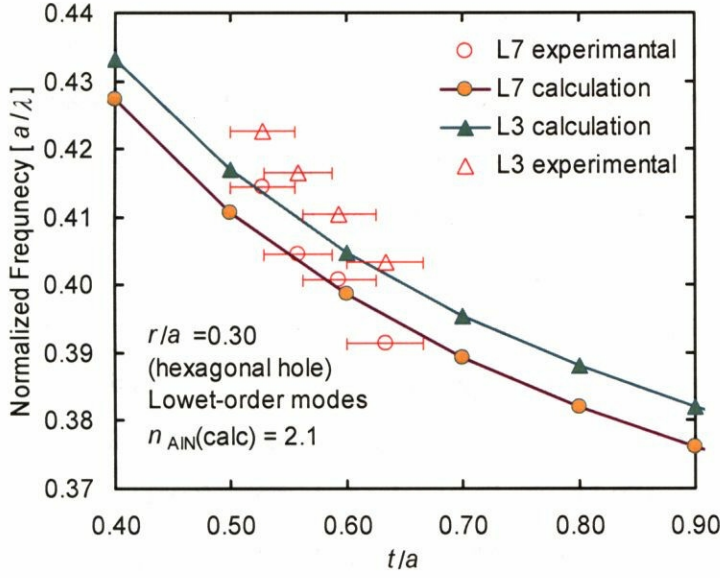


Figure 7.4 Periodicity dependence of wavelength of the lowest-order cavity modes

In Fig. 7.4, the measured and the calculated peak positions of the lowest-order modes are plotted as the normalized frequency a/λ . The calculation was performed by using three-dimensional finite-difference time-domain (3D-FDTD) method. The cell size Δx ($= \Delta y = \Delta z$) for the calculations were set to be 1/20 of the periodicity of the photonic crystal, a . Temporal resolution Δt was chosen to stabilize the calculation and $\Delta t = \Delta x/2c$, where c is speed of light in vacuum. A Gaussian-shape pulse was excited at a point with low symmetry near the cavity to investigate the cavity mode spectrum, which was deduced from fast Fourier transform of the temporal evolution of the field. In the calculation, ideal hexagonal airhole arrays with $r/a = 0.30$ were assumed. Here, the radius r was defined to be the radius of the circumscribed circle. Also, the vertices of the nearest-neighbor hexagons were assumed to be aligned with Γ -K direction, as in the fabricated PC shown in Fig. 6.13. The refractive index of AlN was assumed to be 2.1, corresponding to a published value for photon energy of ~ 3.0 eV^[90]. In addition, SEM-observed thickness of ~ 90 nm was used for the thickness t of the AlN PC slab rather than the epitaxially-grown thickness of ~ 120 nm. Since N-polarity (000-1) surfaces are less inert than Al-polarity (0001) surfaces^[145], inner surface of the convex-shaped air-bridge structure is slowly etched by HF during the PEC etching. Fairly good agreement between the experimental and the theoretical values can be obtained as shown in Fig. 7.4. Since higher

refractive index of the cavity medium gives lower resonant frequency for the cavity modes, the small discrepancy in the result can be partly explained by considering the dispersion of AlN.

From Lorentzian fitting analysis of the cavity mode of the 150-nm-period L7 cavity, linewidth of 0.157 nm (1.33 meV) was confirmed, as shown in Figure 7.5. The Q -factor of the cavity is then estimated to be more than 2,400. To the best of our knowledge, this is the highest Q -factor ever reported in nitride photonic crystals.

In addition, Localized nature of the cavity modes was directly confirmed by optical microscope images of the luminescence, where a bright spot was located at the position of the defect nanocavity as shown in Figure 7.6. Here the original monotonous image is converted to a color-map in which intensity profile is represented by the linear color scale. For reference, the corresponding photonic crystal pattern ($a = 150$ nm, L3 nanocavity) is also presented in the figure as an array of white filled circles. Black scale indicates 3 μ m. Although the accurate location of the photonic crystal pattern is not determined due to the limited spatial resolution, rectangular perimeter of the pattern centered on the dominant, localized emission is clearly visible. Considering that the excitation spot is much larger than the pattern and that the captured image is spectrally integrated, background luminescence guided within the unpatterned nitride slab and leaked at the edge of the airholes is most likely attributed to the emission at the perimeter of the pattern. For better visibility, the center of the excitation spot was located well outside the pattern, which can explain the nonuniform perimeter emission in Fig. 7.6. Note that if band-edge modes are observed, whole photonic crystal region must be bright instead.

All these experimental results evidently show the observed peaks are cavity defect modes. As mentioned above, the cavity mode spectrum considering hexagonal shape of airholes was obtained by the 3D-FDTD simulations. In Fig. 7.7, the calculated mode spectrum and a measured spectrum for a 150-nm-period L7 nanocavity are compared with each other. In this figure, the calculated field distributions for several specific modes are also illustrated. Note that the measured L7 nanocavity shown in Fig. 7.7 was not the cavity of which spectra are shown in Figs 7.2 and 7.3. The micro-PL spectra were somewhat varied from one cavity to another, which is partly due to structural fluctuations induced during fabrication. Though the measured spectrum in Fig. 7.7 is chosen for clarity, the basic structure of the mode spectrum is unchanged for all the L7 cavities. From the simulations, the other peaks shown in Fig. 7.3 appeared at the higher energy side for each nanocavities are revealed to be the second-order modes.

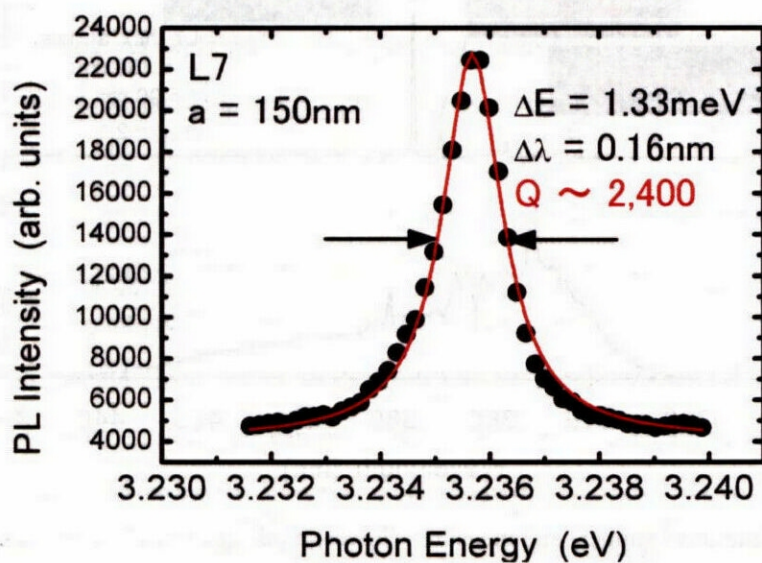


Figure 7.5 Fitting results of the lowest-order cavity mode of 150-nm-period L7 nanocavity

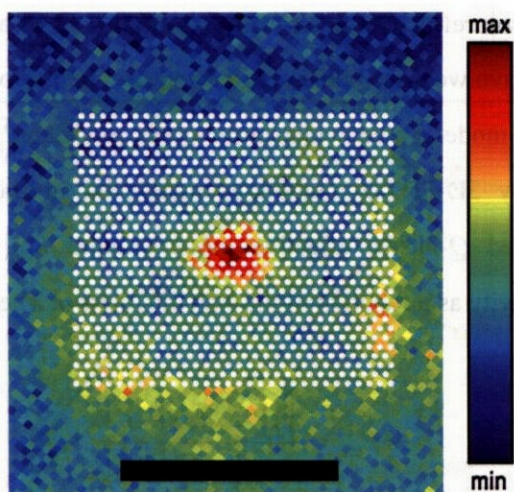


Figure 7.6 Localized luminescence of the AlN photonic crystal nanocavity

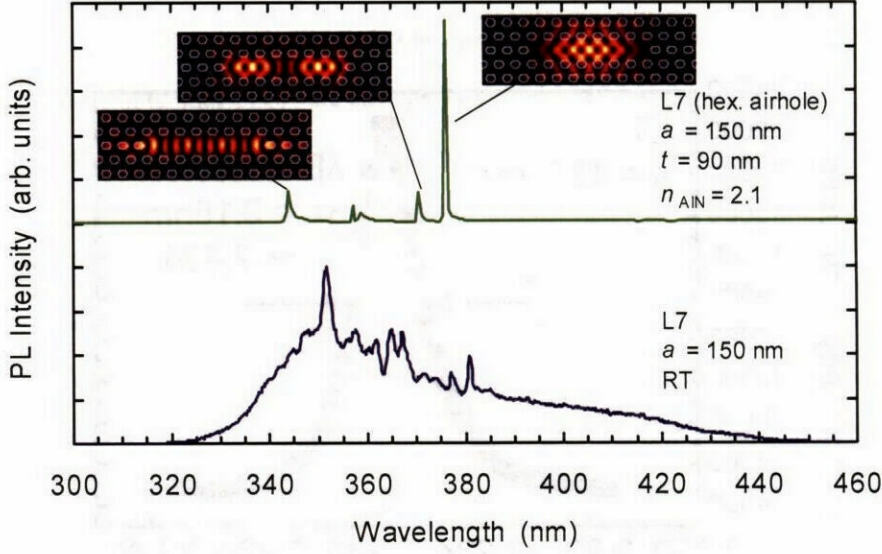


Figure 7.7 Simulated (upper) and measured (lower) mode spectra of L7 nanocavity

7.3 Discussions

In the comparison with previous report^[129], we have observed the lowest energy modes for our AlN photonic crystal nanocavities as well as the highest Q -factor of around 2,400, as described above. Since AlN has lower refractive index than that of GaN (2.54 at $\lambda = 390$ nm), AlN photonic crystal nanocavity must have weaker optical confinement and hence lower Q -factor than GaN-based one when the same cavity mode of a equivalent structure is considered. For further analysis, we have performed simulations by 3D-FDTD method as mentioned in the previous section. Fig. 7.8 summarizes the calculated Q -factor, effective mode volume V_{eff} , and the ratio Q/V_{eff} for a 150-nm-period L7 nanocavity as a function of the slab thickness a . The effective mode volume V_{eff} is defined as follows:

$$V_{\text{eff}} = \frac{\iiint \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2 d^3\mathbf{r}}{\max[\epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2]}. \quad (7.3)$$

The simulated Q -factor for the 150-nm-periodicity L7 cavity is $\sim 8 \times 10^3$, which is in fact several magnitude lower than the predicted Q -factors of GaN photonic crystal nanocavities with similar structures^[146]. Experimentally-obtained Q -factor of 2,400 is still short of the predicted value of 8×10^3 , which might be attributed to the scattering loss induced by structural disorders such as

radius deviations or hole center deviations ^[147]. As for structural imperfections, it should also be mentioned that the thickness of the fabricated AlN photonic crystal nanocavity was revealed to be thinned by HF etching. As explained earlier, (000-1) surfaces are less inert than (0001) surfaces. This fact poses a critical issue on optimizing cavity structure. One must consider the thinning effect when determining the epitaxial layer thicknesses to be grown. Actually, if the thickness of the fabricated cavity had been 120 nm as originally grown, the Q -factor could be approximately 1.5 times higher than the measured one, as can be seen from Fig. 7.8. In addition, the etched (000-1) surface shows relatively rough morphology, as shown in Fig. 7.9. In this figure, a SEM image of a flipped, broken AlN membrane after the PEC etching procedure is shown. Being etched, stable microfacets emerge on (000-1) N-polarity surface as earlier studies reported ^[145]. Unambiguously, these features deteriorate the quality of the cavity. However, a relatively high Q -factor of over 2,400 observed in an AlN-based photonic crystal nanocavity encourage us to further optimization. It should be emphasized that our fabrication technique is fine enough to observe the cavity modes of as small as 150-nm-periodicity structures. As described earlier, the lowest-order cavity mode of 372 nm for the L3 cavity with periodicity of 150 nm is the shortest wavelength in semiconductor photonic crystal nanocavities ever reported. Although uniformity of the airholes is yet to be improved, we believe it can be achieved by optimizing the fabrication process. Even higher Q -factors are also expected by introducing deliberate design such as shifted airholes or photonic heterostructures ^[148, 149].

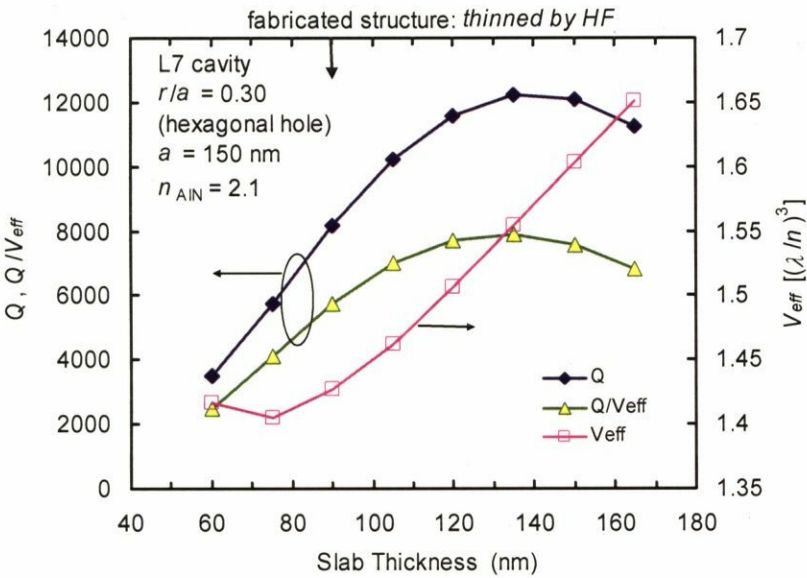


Figure7.8 Calculated Q -factor, effective mode volume V_{eff} , and their ratio Q/V_{eff} of L7 nanocavity

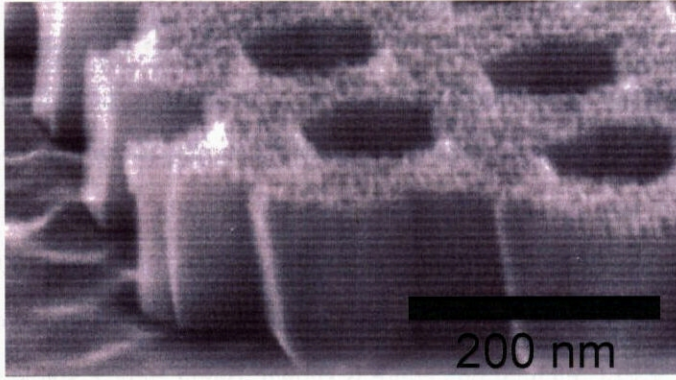


Figure 7.9 A SEM image of a flipped, broken AlN showing (000-1) surface after the PEC etching

Typical low-temperature radiative lifetime of a GaN quantum dot emitting around 400 nm light is in the range of several-tens ns, which is rather long due to large built-in electric field^[150]. Since radiative lifetime gives upper limit of the modulation frequency of single photon emitters, spontaneous emission rate enhancement is highly demanded especially in III-nitrides. Photonic band structure of photonic crystals modifies the local density of optical states and hence the spontaneous emission rate of quantum dots embedded. For cavity-coupled and uncoupled quantum dots both emitting light within photonic bandgap, spontaneous emission rate is enhanced or suppressed, respectively. Although actual spontaneous emission rate modification by photonic crystal varies significantly with both spatial and spectral matching between quantum dot exciton dipole and the cavity mode^[40], we can still expect moderate emission rate modification in our structures. Using the experimentally obtained Q -factor of 2,400 and predicted effective mode volume $V_{\text{eff}} = 1.4(\lambda/n)^3$ for the L7 nanocavity, the cavity Purcell factor $F_{\text{cav}} = 3/(4\pi^2) \cdot (\lambda/n)^3 \cdot Q/V_{\text{eff}}$ can be estimated as $F_{\text{cav}} \sim 130$. According to the discussion presented in reference 40, $Q = 1,600$ and $V_{\text{eff}} = 0.5(\lambda/n)^3$ gave experimentally observed rate enhancement factor of 8 in the case of perfect spectral resonance and moderate spatial misalignment between cavity and the quantum dot. In this case $F_{\text{cav}} \sim 240$ is deduced from the aforementioned equation. Assuming spatial and spectral distribution of GaN quantum dots in our sample are approximately equivalent to those of InAs quantum dots they studied, similar misalignment in spatial matching may result in 4 ~ 5 times enhancement of spontaneous

emission rate ^[40]. When assuming perfect spectral resonance and moderate spatial misalignment between the cavity and the quantum dot, at least one order of magnitude enhancement of spontaneous emission rate will be expected. In the near future, time-resolved photoluminescence measurements will reveal the spontaneous emission rate enhancement in the cavities.

Surface recombination of excited carriers in the sample largely affect emission rate suppression or enhancement in the nanocavity ^[151]. Quantum dots in which carriers are confined three-dimensionally have advantages compared to quantum wells for their less probability of encountering nonradiative surface states. Having observed photoluminescence from even uncapped GaN quantum dots, effects of surface recombination might not be significant in our samples as long as unprocessed, as-grown materials are considered ^[152]. Like most III-V semiconductors, III-nitride semiconductors also suffer from defective, surface states induced by process damages. Particularly, due to their inertness, high-energy ions or plasmas are bombarded to the materials in order to define microstructures. Therefore, removal of damaged crystal is demanded for nitride nanocavities. Fortunately, hydrofluoric acid used to obtain the air-bridge structure in our experiment is also beneficial to reduce surface recombination velocity in GaN ^[153]. Smooth and vertical sidewalls of the airholes are reproducibly obtained as described above, owing to crystallographic-orientation dependent chemical reactions. Concise determination of surface recombination process in the nanocavity requires further investigation. In addition to the favorable situations mentioned above, one should take into account the fact that the N-polar (000-1) surface of AlN membrane is exposed in the structure. Since the N-polar surface is less inert than the Al-polar (0001) surface, effects of contamination or any surface modifications might be prominent on the N-polar surface.

7.4 Summary

In summary, we fabricated AlN air-bridge photonic crystal nanocavity with GaN quantum dots. Photoelectrochemical etching was utilized to fabricate the convex-shape air-bridge structure. We also demonstrated that our photonic crystal had high Q -factor up to 2,400 in UV region. To our best knowledge, this is the highest Q -factor ever reported in nitride-based photonic crystals. These experimental results facilitate further development of ultraviolet single photon emitters.

AlN photonic crystal nanocavities with GaN quantum dots were investigated by microscopic photoluminescence measurements. Sharp luminescence attributed to the cavity modes were observed in the fabricated structures. The peak wavelength of the lowest-energy modes depended on the

periodicity or nanocavity structure of the photonic crystal. Also, the emission was found to be localized at the location of the nanocavity. For the lowest-order cavity mode of a 150-nm-period nanocavity with seven missing holes, luminescence linewidth of 0.157 nm corresponding to the Q -factor of more than 2,400, which is the highest Q for nitride-based PC nanocavities ever reported, was obtained. Furthermore, the shortest wavelength of the lowest-order cavity modes, 372 nm, ever reported in semiconductor photonic crystal nanocavities was achieved, which clearly evidences that quite fine-feature of the structure could be fabricated with the developed processes.

Chapter 8

Concluding Remarks

8.1 Summary of This Research

In this thesis, fabrication and characterization of III-nitride semiconductor nanocavity light emitters were described. The fabricated devices are considered as fundamental structures of novel short-wavelength optical devices, namely blue/violet VCSELs and high-efficiency high-temperature single-photon emitters. The experimental results presented in this thesis facilitate the research and development of the novel short-wavelength optoelectronic devices.

In Chapter 2, basic principles of crystal growth of III-nitride semiconductors by metalorganic chemical vapor deposition (MOCVD) were presented. In order to improve the crystal quality of thin AlN layers required for the photonic crystal nanocavity, the author has developed an optimal growth sequence of buffer layers, in which alternate supply of source gases was utilized to control surface morphology and relaxation process. 70-nm-thick AlN layer with sufficient quality was able to be grown. GaN QDs were grown on the thin AlN layer and characterized. This improvement is very important for the development of III-nitride photonic crystal single-photon emitters because thinner AlN buffer layer is crucial for realizing high- Q nanocavities.

In Chapter 3, the author described MOCVD growth of electrically conductive AlGaIn/GaN DBRs. Structural, optical and electrical properties of the DBRs were studied systematically. From Si doping concentration dependence of structural and optical properties of n-DBRs, it can be concluded that reasonable reflectivity can be maintained with uniform carrier concentration profile of $1 \times 10^{18} \text{ cm}^{-3}$. The author showed that the carrier concentration in n-AlGaIn layers can be increased up to $3 \times 10^{18} \text{ cm}^{-3}$ while that of n-GaN is kept at constant value, $1 \times 10^{18} \text{ cm}^{-3}$, without further degradation of optical properties. As a result, the author demonstrated MOCVD growth of electrically conductive n-type nitride DBRs with reflectivity of near 99 %. Such high reflectivity nitride DBRs will play

very important role in fabricating nitride-based VCSELs. Also further improvements in both structural and electrical characteristics can be achieved by introducing n-AlGaIn/n-GaN short-period superlattice into the n-DBRs. The 26-period superlattice/n-GaN DBR was grown and characterized. From X-ray reciprocal lattice mapping, the GaN quarter-wave layers and the superlattice layers were revealed to be grown pseudomorphically each other. As a consequence, crack formation was prevented because of balanced strain. Reflectivity of the superlattice DBR was 94.5 %, almost equivalent to normal DBRs. Theoretical analyses were performed to shed light on the origin of the electrical conductivity of the n-DBRs. It has been suggested that electrically conductive nitride DBRs is really available when both high quality and high doping concentrations are achieved.

In Chapter 4, Developments of fabrication processes for nitride vertical-cavity surface-emitting devices were presented. Because at least one of cavity mirrors is made by insulating materials in practical device structures, electrical contact should be carefully prepared. Metallic ring contact had been examined, but poor current spreading due to poor hole diffusion length was observed. In order to overcome design issues concerning efficient hole current injection, the author used ITO as a transparent intracavity contact in this study. Rapid thermal annealing of sputtered ITO films under nitrogen ambient can improve both electrical and optical properties of the films. To improve process yield in photolithographic liftoff, new double-layer resist technique was developed. Undercut resist profile favorable for liftoff as well as good adhesion onto nitride (and ITO) surface was available with this technique. The author also established a substrate preparation method to prevent thick AlGaIn/GaN DBR to crack. These technological developments are highly useful to fabricate III-nitride vertical-cavity surface-emitting devices.

In Chapter 5, the author described fabrication and characterization of InGaIn vertical microcavity LEDs. As described in chapter 4, magnetron-sputtered, transparent ITO film was employed as a p-contact. The LED mesas were defined by Cl_2 -based plasma etching, followed by the deposition of 10.5-pair $\text{SiO}_2/\text{ZrO}_2$ top mirror. The top-mirror was wet-etched and finally an Al n-contact was formed. EL spectra of these LEDs exhibited narrow linewidth, which attributed to the microcavity effects. In the angle-dependent EL measurement, blue shift of main mode due to DBR resonance was clearly observed. Furthermore, directionality of the microcavity LED was dramatically improved (half angle $\sim 10^\circ$) compared with that of conventional one. The results are promising for developing blue/ultraviolet VCSELs and high performance LEDs. The author also found that the electrical properties of the device can be improved by using the superlattice DBR.

In Chapter 6, the author presented developments of fabrication processes for AlN photonic crystal nanocavities. There have been difficult issues for the fabrication of III-nitride photonic crystal nanocavities. Corresponding to the short-wavelength of GaN quantum dot emission, fine patterns as small as 150-nm-period is required. Also, the 6H-SiC substrate must be removed in order to obtain sufficient optical confinement in the nanocavities. To this end, the author developed efficient way to remove SiC substrate with photoelectrochemical etching. And he could fabricate AlN air-bridge photonic crystal nanocavity for the first time. The author found that lateral etching of 6H-SiC substrate occurred just below the AlN/SiC interface due to accumulated photogenerated holes, and that partially lifted-off AlN epitaxial layer subsequently formed convex air-bridge structures by relaxation of internal in-plane compressive strain.

In Chapter 7, optical characterization results of AlN photonic crystal nanocavities with GaN quantum dots were described. Microscopic photoluminescence measurements were performed to investigate the optical properties of the nanocavities. Sharp luminescence attributed to the cavity modes were observed in the fabricated structures. The peak wavelength of the lowest-energy modes depended on the periodicity or nanocavity structure of the photonic crystal. Also, the emission was found to be localized at the location of the nanocavity. For the lowest-order cavity mode of a 150-nm-period nanocavity with seven missing holes, luminescence linewidth of 0.16 nm corresponding to the Q -factor of more than 2,400, which is the highest Q for nitride-based PC nanocavities ever reported, was obtained.

In summary, fabrication technologies of III-nitride semiconductor nanocavity light emitters are newly developed and fundamental characteristics of the structures are demonstrated.

The author believes these experimental results facilitate further development of nitride-based ultraviolet quantum optoelectronic devices such as high-efficiency single-photon emitters.

8.2 Future Prospects

As concluding remarks, we would like to mention the future prospects of this research. For nitride-based VCSELs, optical properties of the cavity have already reached an acceptable quality. In fact, similar VCSELs were operated under optical excitation and also we confirm that our highest quality DBR has reflectivity high enough to be used as a VCSEL mirror. It should be noted that electrical properties of the devices must be further improved at present. Constant efforts to reduce resistance of the device must help to achieve current-injection operation. From theoretical analysis, it

is suggested that the electrical conductivity will be obtained if high-quality nitride DBRs with high doping concentration ($\sim 10^{19} \text{ cm}^{-3}$) can be grown, despite the relatively high conduction band discontinuity and the large internal electric field. Recently, new alloy system AlInN has been proposed to be a constituent of nitride stress-free DBRs. 18 % InN in AlInN is known to be perfectly lattice-matched to GaN ^[154]. Nearly ideal pseudomorphic growth provides thick stack of AlInN/GaN DBR without any cracking. Though its usefulness is very attractive, AlInN is still very difficult to grow high-quality crystal. When these obstacles are overcome and electrical conductivity is given, nitride VCSEL may be realized.

For nitride photonic crystal nanocavities, there still remains several fundamental issues. Current injection operation seems very difficult for the AlN-based structures. However, technological progress of nitride-based optoelectronic devices has not terminated yet. Considering an AlN LED was recently demonstrated ^[155], one can expect future development of electrically-driven AlN photonic crystal nanocavity single-photon emitters. Apparently, further optimization of the photonic crystal structure as well as further development of process technologies should be needed. Although extensive characterization of the nanocavities are also requisite to realize high-efficiency single-photon emitters, the author believes that the experimental achievement presented in this thesis will eventually result in such innovative quantum optoelectronic devices.

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