

Structural and Optical Characterization of GaN/AlGaN Single Quantum Disk Nanorods

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GaN/AlGaN single quantum disks on GaN nanorods were grown on Si (001) substrate with native SiO₂ layer by a plasma-assisted molecular-beam epitaxy under nitrogen-rich conditions. The transmission electron microscopy observations show single GaN nanorods images with an average thickness of 4 nm for the GaN single quantum disk and nanorod diameter of 15 nm. The observed photoluminescence spectra at 8 K show a peak at 3.475 eV, attributed to an exciton recombination in GaN. A strong peak was observed at 3.542 eV. This peak is attributed to the quantum confinement of excitons in the GaN quantum disks.

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1. Introduction

One-dimensional structures (nanowires or nanorods) of gallium nitride are known to have great prospects in novel technological applications. Because of the large band gap and structural confinement effects in such nanostructures, the fabrication of visible and UV optoelectronic devices with relatively low power consumption is potentially feasible [1–6]. It has been reported that dislocation- and strain-free GaN materials can be obtained by the forming nanoscale structures, such as columnar structures [7] and pyramidal hillocks [8]. The optical properties of GaN nanorods are mainly determined by the nanorods' dimensions, which are strongly affected by the growth parameters. However, the size distribution of the nanorods makes it difficult to analyze accurately their optical properties. Nano columnar heterostructures including quantum disks (QDisks) bring the new effects ensuing from quantum confinement effects in the columnar geometry [9, 10]. The typical diameter of III–N nanowires grown by the plasma-assisted molecular beam epitaxy (PAMBE) techniques is in the 20–50 nm range, which is large compared to the GaN Bohr radius 3 nm. Due to this weak lateral confinement, such heterostructures are coined as quantum wells, quantum dots, or quantum disks. Semiconducting nanowires exhibit phonon confinement due to the long length of the phonon wave vector q compared to the radius of the nanowire. Consequently light scattering within a particle of size D takes place from quasi-zone-center optical phonons with wavevector q up to π/D [11]. In this study, we report on the optical properties of the self-assembled Al_{0.12}Ga_{0.88}N/GaN/Al_{0.12}Ga_{0.88}N/GaN nanocolumnar heterostructures comprising single GaN quantum disks (SQDisks), which were grown on Si(001) substrate with native SiO₂ layer.

2. Experimental

GaN nanorods were grown on Si(001) substrates having native SiO₂ layers by PAMBE technique. The thick-

ness of the thin native SiO₂ layers is less than 2 nm. Elemental Ga, Al and rf plasma-enhanced N₂ were used as sources. After thermal cleaning of the Si substrates at 830 °C for 15 min, the low-temperature GaN buffer layers were first grown at 450 °C for 40 s. Then, annealing was performed for 10 min in the plasma-activated nitrogen atmosphere at 800 °C. On the next step, GaN nanorods were grown at 800 °C followed by the growth of AlGa_{0.12}N, GaN and AlGa_{0.12}N layers to form the AlGa_{0.12}N/GaN/AlGa_{0.12}N SQDisks. The Ga flux (1.0×10^{-8} Torr) and the N₂ flow rate (1.0 sccm) with the rf plasma power (300 W) were fixed. The growth rate is dependent on the III/V ratio, and the maximum growth rate was fixed at 1.5 $\mu\text{m/h}$.

The photoluminescence (PL) spectra were observed using a continuous wave of a He–Cd laser (325 nm (3.82 eV)) in the fixed power of 18 mW as an excitation light source. The laser-beam size is about 1 mm. The PL light was dispersed in a 1 m grating monochromator (JASCO CT-100, blazed at 300 nm). Both the entrance and exit slits of the monochromator are set to 1 mm. The records of the PL intensity were carried out through a lock-in technique. An ACTI Cryogenics closed-cycle helium cryostat was used to cool the samples from room temperature (RT) down to 8 K. A low energy pass filter was inserted in the optical line of the PL measurement to cut off the direct laser light scattered by the sample.

3. Results and discussion

Reflection high-energy electron diffraction (RHEED) patterns were recorded during growth for *in situ* monitoring of the growing surfaces. Broken-ring RHEED patterns were observed indicating that the hexagonal-GaN layers were grown with their *c*-axes perpendicular to the substrate surfaces [10]. No formation of pure metal droplets on the surfaces during growth is detected. The $\theta - 2\theta$ X-ray diffraction (XRD) rocking curves for the grown samples showed the diffraction peaks from GaN (0002) and Si (002). No other peaks were detected indi-

cating that the grown nanorods have no other orientation except the c -axis orientation.

The formation and shape of the GaN nanorods were also confirmed using a high-resolution field emission scanning electron microscope (HR-FE-SEM). The bird's-eye view of the SQDisk nanorod structure of the GaN nanorods was shown in Fig. 1. It can be seen clearly that the vertical c -oriented nanorods grow perpendicular to the SiO₂/Si substrate surfaces.

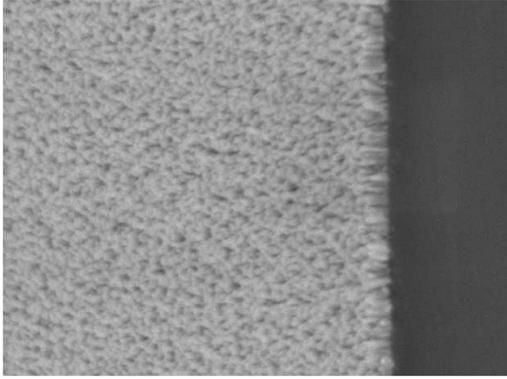


Fig. 1. Bird's-eye view by FE-SEM scans for the grown nanorods sample.

Transmission electron microscopy (TEM) observations, Fig. 2, show single GaN nanorods images with an average thickness of GaN quantum disk of 4 nm and nanorod diameter of 15 nm. These structural observations using the RHEED, XRD, HR-FE-SEM and TEM show the good c -oriented GaN (0001) fiber texture.

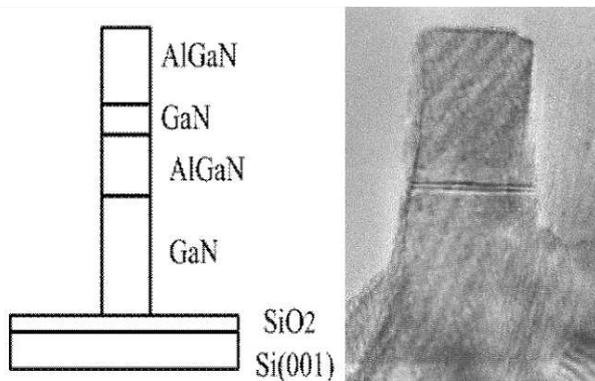


Fig. 2. The designed single quantum disk nanorod structure (a) and TEM images of AlGaIn/GaN/AlGaIn single quantum disk nanorods (b).

Figure 3 shows the photoluminescence (PL) spectra of the single quantum disk AlGaIn/GaN/AlGaIn/GaN nanorods measured at 8 K. A strong excitonic emission peak was observed at 3.475 eV. This peak can be regarded as originating from a neutral donor-bound exciton, D⁰X [9, 12, 13]. It was shown that this PL from the donor-bound excitons is radiated from the upper region of the

GaN nanorods without any extended structural defects and having high crystalline quality. On the higher energy side, a strong PL peak was observed at 3.542 eV, which is blue-shifted by 67 meV from the peak energy of the standard D⁰X at 3.475 eV. The emission line from GaN quantum disks of 3 nm thicknesses was reported at 3.530 eV at 4.2 K [14, 15]. More investigations are conducted to confirm this suggestion and will be published elsewhere. However, the peak position for AlGaIn for the designed alloy with Al/Ga ratio of 12% is expected at 3.812 eV.

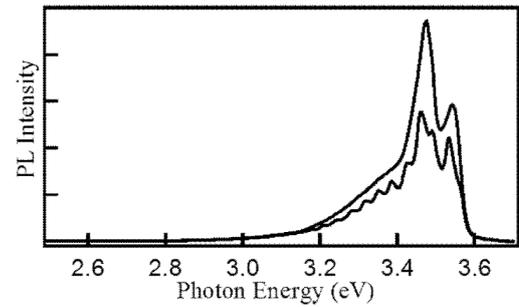


Fig. 3. PL spectrum of Al_{0.12}Ga_{0.88}N/GaN/Al_{0.12}Ga_{0.88}N/GaN/SiO₂/Si(001) measured at 8 K, higher, and 20 K, lower.

A broad PL peak centered around 3.35 eV, was observed in the low energy side of the donor bound energy. This observed peak energy can be associated with defect-related emissions from different regions in the nanorods and is consistent with previously reported peak values [16–22]. Experimentally, the GaN nanorods sampled by the laser spot have a range of diameters and distributed quality being excited and hence a range of defect-related bound-exciton emissions can be detected. Although strain-accommodating properties of the nanowires usually prevent the formation of dislocations, the strain induced by the lattice mismatch between AlGaIn and GaN can result in the creation of point defects and line defects. Indeed, different origins for structural defects were reported in previous ensemble measurements of vertically aligned GaN nanorod arrays. Densely merged GaN nanorods on the surface may result in the formation of the localized defects. Structural defects at the GaN/Si interface, GaN nanorods mis-oriented during growth and coalesced into GaN bundles, and stacking faults and dislocations located at the base of the nanorod in the interface region are expected. PL peaks associated with defect-related bound-exciton emissions are more dominant at low temperature. PL peak near 3.43 eV was reported and attributed to structural defects at the nanorod/substrate interface. A broad emission (full width at half maximum around 30 meV) at 3.417 eV was attributed to the recombination of excitons bound to extended structural defects located at the bottom of the nanorods produced during the initial phase of the growth. PL peak around 3.41 eV was correlated to

nanowire bundles presenting some degree of coalescence. PL emission at around 3.36 eV was attributed to excitons bound to the structural defects at the surface.

Satellite peaks were observed in the PL spectra at 20 K, as shown in Fig. 3. The energy separation between adjacent peaks is around 35 meV which is smaller than the phonon replicas of longitudinal optical (LO) phonon energy in GaN (92 meV). These observed satellite peaks could be attributed to optical interference from the nanorods sample, the origin of these satellite peaks is under further investigations.

4. Conclusions

The GaN single quantum disk embedded in AlGaN/GaN nanorods were grown by PAMBE techniques. The HR-FE-SEM and TEM analysis of these samples confirmed the columnar growth of the designed nanorods with the single quantum disks. The TEM images of the GaN single QDisk show an average thickness of 3 nm and a nanorod diameter of 15 nm. The PL spectra observed at 8 K show an excitonic peak at 3.475 eV which was attributed to exciton recombination in GaN. A strong peak was observed at 3.542 eV and is attributed to the quantum confinement of excitons in the GaN quantum disks.

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