Depth Profile Analysis of Thin Multilayers with nanometric resolution by Glow Discharge Optical Emission Spectroscopy (GD-OES)

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Abstract

(Al,Ga)N-based quantum wells (QWs) and quantum dots (QDs) are key building blocks for ultraviolet (UV) optoelectronics and high-power electronics, where precise control of thickness and composition is essential.

In this work, nanostructures were fabricated by plasma-assisted molecular beam epitaxy (PA-MBE) and metal-organic chemical vapor deposition (MOCVD) on AlN templates. Quantum wells with thicknesses of 2 nm and AlN barrier layers, as well as strain-induced quantum dots, were successfully grown and encapsulated.

Depth-dependent elemental composition at the nanometer scale was performed by pulsed RF Glow Discharge Optical Emission Spectroscopy (GD-OES) demonstrating nanometric depth resolution, clearly distinguishing the Ga-containing layers and confirming the designed Al/Ga ratios across multiple samples.

Keywords

(Al,Ga)N quantum wells, Quantum dots, AlN barriers, Nanometric multilayers, Glow discharge optical emission spectroscopy (GD-OES), Depth profiling, UV optoelectronics

Issues and Challenges

(Al,Ga)N-based quantum wells (QWs) and quantum dots (QDs) are essential components in ultraviolet (UV) optoelectronic devices as well as high-temperature and high-power electronic systems. Quantum wells confine electrons and holes within layers only a few nanometers thick, enabling precise control over emission wavelength and optical properties. Quantum dots provide three-dimensional carrier localization, which enhances quantum efficiency and emission stability. Aluminum nitride (AlN) barrier layers play a crucial role in suppressing surface oxidation and preventing carrier leakage, thereby improving device reliability. Therefore, controlling precise depth in each layer is very important task.

The structure of the tested samples is represented in Figure 1. It consists of different multilayers of 2 nm of AlGaN layers repeated 4 times between AlN layers on sapphire (0001) substrate.

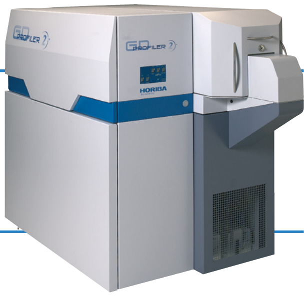
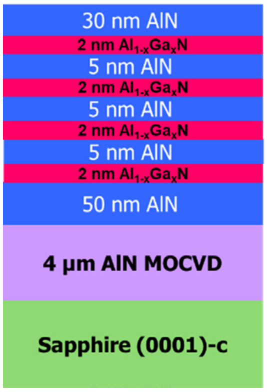


Fig. 1: GD Profiler 2: 4th generation of GD-OES



Name	Composition
Sample1	$Al_{0,90}Ga_{0,10}N$
Sample2	$Al_{0,85}Ga_{0,15}N$
Sample3	$Al_{0,80}Ga_{0,20}N$
Sample4	$Al_{0,70}Ga_{0,30}N$
Sample5	$Al_{0,40}Ga_{0,60}N$
Sample6	GaN

Fig. 2: (left) Structure of Sample, (right) different ratios of Al/Ga in 2 nm AlGaN layer

Fabrication Process

The fabrication of these nanostructures was carried out at the “Centre de Recherche sur l’Hétéro-Epitaxie et ses Applications” (CRHEA) using molecular beam epitaxy (MBE) on sapphire (0001) substrates, with a 4 µm-thick AlN buffer layer (BL) grown by metal-organic chemical vapor deposition (MOCVD). A 50 nm AlN nucleation layer was first grown on the AlN BL at approximately 900 °C to ensure high crystal quality and avoid any potential contamination from the AlN BL surface. The (Al,Ga)N QWs were deposited with aluminum compositions ranging from 0% to 90%, and their thickness was precisely controlled as 2 nm. Each quantum well was capped with a 5 nm AlN barrier to maintain strong quantum confinement.

GD-OES depth profiles

The measurements were carried out with a 2 mm anode diameter at 900 Pa and 20 W under pulsed operation at 3000 Hz with a 0.25 duty cycle.

A representative measurement is shown in Figure 3. Less than 10 s is required to pass the MQW showing the speed of the technique which also does not require UHV operation. The 2 nm thick Ga rich layers are clearly distinguished confirming the excellent depth resolution. Al being present in all layers, the Al signal is more mixed up.

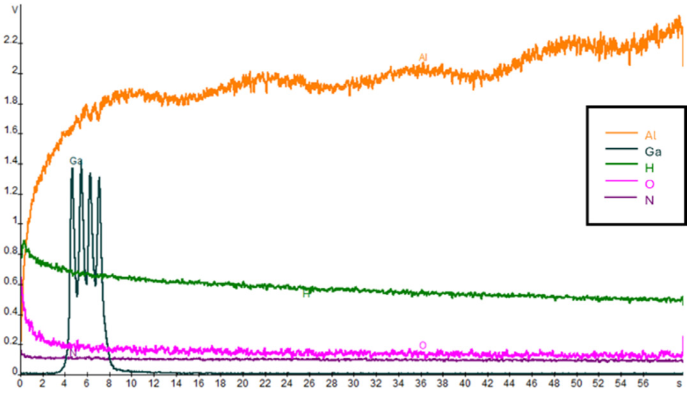


Fig. 3: GD-OES depth profile of Sample 5 including 4 cycles of 2nm of Al0.4Ga0.6N layers capped with 5nm of AlN'

In figure 4, we overlay the Ga signals of the different samples. The Ga signal intensities are perfectly correlated with the intended Ga/Al ratios in the test samples. Sample 1 (Ga0.1Al0.9) exhibited lower Ga signal intensity than Sample 2 (Ga0.15Al0.85), with the sequence continuing up to Sample 6 (Ga 100%). The increase of the Ga intensities fits with the increase of the ratio of Ga: Sample1 (Ga 10%) < Sample2 (Ga 15%) < Sample3 (Ga 20%) < Sample4 (Ga 30%) < Sample5 (Ga 60%) < Sample6 (Ga 100%). This precise correspondence between GD-OES measurements and designed compositions confirms that nanometric resolution was successfully achieved and opens door to quantification.

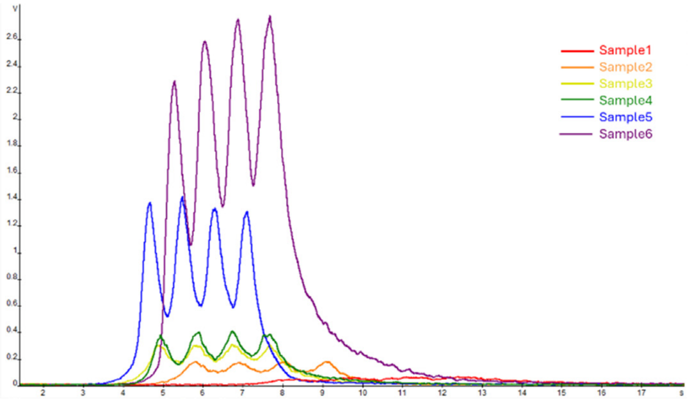


Fig. 4: Difference of intensity of 4 layers of Ga signals in 6 samples; the intensity: Sample1 (Ga 0.1) < Sample2 (Ga 0.15) < Sample3 (Ga 0.2) < Sample4 (Ga 0.3) < Sample5 (Ga 0.6) < Sample6 (Ga 1).

Summary

The ability to verify layer thickness and composition with high precision and speed is very significant for the development of UV-emitting devices, semiconductor lasers, and high-temperature power electronics. Pulsed RF GD-OES can be also applied to other nanometric multilayer systems, enabling effective quality control and performance optimization. By ensuring that each interface is well-defined and free of compositional fluctuations, device performance can be improved, and manufacturing yield can be increased.

References

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