In-situ epitaxial growth control of GaN-based vertical-cavity surface-emitting lasers

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Abstract

In-situ cavity thickness control has been carried out during the GaN-based VCSEL epitaxial growth. Clear oscillations of in-situ reflectivity intensity during the cavity growth was utilized to determine the endpoint of the cavity growth. High controllability of resonance wavelength (418 nm) within 1 nm (0.3 %) and a high light output power over 10 mW, corresponding to a wall plug efficiency over 10 %, were achieved.

INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) are semiconductor-based laser diodes emitting light in the perpendicular direction to the wafers [1]. In general, VCSELs show high performances of laser diodes and high productivity of LEDs simultaneously. So far GaAs-based infrared VCSELs have been commercialized as light sources in data centers, laser mice, and face recognition systems. Recently GaN-based blue and green VCSELs have been developed towards novel light sources in retinal scanning displays, adaptive headlights, visible light communication systems, and point-of-care testing devices.

One of the key points in VCSEL manufacturing is controls of the following three wavelengths, a center wavelength of a distributed Bragg reflector (DBR), a cavity resonance wavelength, and an emission wavelength of an active region. All of them are typically determined during the epitaxial growths. In order to monitor and control the DBR center wavelength and cavity resonance wavelength during the epitaxial growth of GaAs-based infrared VCSELs, in situ measurements, such as reflectivity spectra, have played an important role [2, 3]. On the other hand, in-situ wavelength controls during the epitaxial growth of GaN-based blue VCSELs have been rarely reported [4]. Note that a stopband width of the GaN-based (AlInN/GaN) DBR (~20 nm) is much smaller than that of the GaAs-based ($Al_{0.9}Ga_{0.1}As$/ $Al_{0.2}Ga_{0.8}As$) DBR (~70 nm). Thus, such in-situ wavelength monitor and control are more needed for the GaN-based VCSELs. In this presentation, we report an in-situ cavity resonance wavelength control during the GaN VCSEL layer growth by using an in-situ reflectivity spectra measurement.

EXPERIMENTS

We have conducted the following two experiments here. The first one is to measure a shift of an DBR center wavelength from room temperature (RT) to growth temperature (up to 1100 °C). This information is very important since all the in-situ controls are carried out at the growth temperatures. The other one is to control a cavity thickness during the GaN-based VCSEL growth toward a target cavity resonance wavelength.

Our VCSEL epitaxial layer structure is shown in Fig. 1, consisting of a 39.5-pair AlInN/GaN DBR, an n-GaN, a 30 nm n-GaInN underlayer, a 3 nm GaInN/6 nm GaN five quantum well (5QW) active region, a 20 nm p-AlGaN, and p-GaN, and a 10 nm p^{++}-GaN contact. Note that a total thickness from the n-GaN just above the DBR to the p^{++}-GaN contact corresponds to an optical thickness of 3.7λ. The reason to stop epitaxial growth at the 3.7λ is to locate an absorptive p-side ITO electrode (20 nm) at a null position of the standing wave in the 4λ cavity. The epitaxial growth was carried out on a GaN substrate in a metalorganic vapor phase epitaxy system with an in situ reflectivity spectra measurement system (EpiTT VCSEL from Laytec).

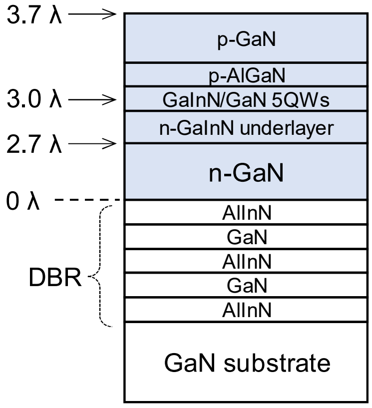

Fig. 1. GaN-based VCSEL epitaxial layers with an AlInN/GaN DBR. The epitaxial layer part of the cavity was 3.7λ and the GaInN 5QWs was located at 3λ.

In the first experiment, an already grown 40-pair AlInN/GaN DBR [5, 6] was put into the reactor. Reflectivity spectra were measured from RT to 1100 °C to obtain DBR center wavelength shift as a function of temperature.

In the other experiment, we have used the same DBR in the first experiments. We regrew the 3.7λ GaN cavity on the DBR as shown in Fig. 1. Two monitored wavelengths for the in situ cavity thickness control for the n-/p-layers and the GaInN 5QWs were selected along with the different growth temperatures. We then fabricated VCSELs using the above-mentioned epi wafer by depositing a top dielectric DBR and electrodes to measure device characteristics.

RESULTS AND DISCUSSION

We found that the wavelength was linearly redshifted to 23 nm from RT to 1100℃. The temperature dependence of the redshift was about 0.02 nm/℃ [8]. Based on the slope, now we can properly tune the monitored wavelengths along with the growth temperatures. For instance, in the following experiment we used an AlInN/GaN DBR which center wavelength at RT (in other words, a target wavelength) was 418 nm, so that the monitored wavelengths were 441 nm and 436 nm for the n-/p-layers and the GaInN 5QWs, respectively.

The reflectivity intensity profiles as a function of growth time are plotted in Fig. 2. Clear intensity oscillation was observed, corresponding to resonant cavity thicknesses observed at the bottom intensities and anti-resonant cavity thicknesses observed at the top intensities. For instance as labeled, 2.5λ and 3.5λ for 441 nm and 3λ for 436 nm correspond to the resonant cavity thicknesses.

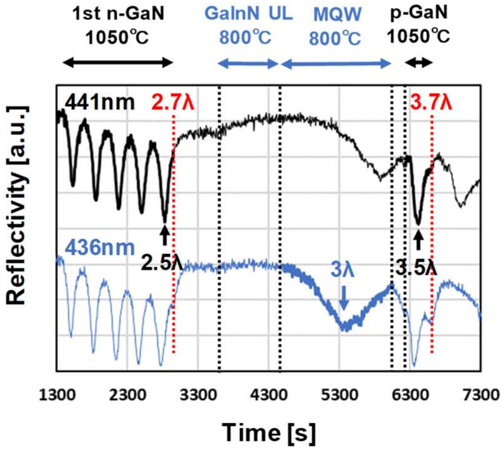

Fig. 2. In-situ reflectivity intensity profiles as a function of growth time. Two wavelengths were selected along with the growth temperatures.

We measured an emission wavelength of the VCSEL, showing 417 nm, which was within 1 nm (0.3%) of the target wavelength here, 418 nm. In addition, current-voltage-light output power (LOP) characteristics of the VCSEL fabricated here were measured under continuous-wave operation at RT. A LOP and a wall plug efficiency were over 10 mW and 10 %, which were higher than our previous best result (4.4 mW and 5%) [7].

CONCLUSIONS

We have utilized an in-situ reflectivity spectra measurement for in-situ cavity thickness control of GaN-based VCSELs. Clear oscillations of the reflectivity intensity during the cavity growth allowed us to obtain precise cavity resonance wavelength within 0.3%, leading to superior device characteristics. The in-situ reflectivity spectra measurement is a powerful tool for high reproducibility and should be useful for further developments towards commercialization.

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ACRONYMS

GaN: Gallium Nitride
AlInN: Aluminum Indium Nitride
VCSEL: Vertical-Cavity Surface-Emitting laser
DBR: Distributed Bragg Reflector
ITO: Indium-Tin Oxide
LOP: Light Output Power