Journal of Luminescence 186 (2017) 243–246

Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Near infrared electroluminescence from p-NiO/n-InN/n-GaN light-emitting diode fabricated by PAMBE

Yang Zhao [a], Hui Wang [a,*], Xiaoyang Gong [a], Qiuze Li [a], Guoguang Wu [b], Wancheng Li [b], Xinzhong Li [a], Guotong Du [b]

[a] School of Physics and Engineering, Henan University of Science and Technology, 263 Kaiyuan Avenue, Luoyang 471003, People's Republic of China

[b] State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Qianjin Street 2699, Changchun 130012, People's Republic of China

ARTICLE INFO

Article history:
Received 2 December 2016
Received in revised form
23 February 2017
Accepted 25 February 2017
Available online 27 February 2017

Keywords:
InN
PAMBE
Light-emitting diode
Electroluminescence

ABSTRACT

Near infrared light-emitting diode (LED) based on p-NiO/n-InN/n-GaN was realized by plasma-assisted molecular beam epitaxy (PAMBE) combined with radio frequency (rf) magnetron sputtering. The device exhibited diode-like rectifying current–voltage characteristics with a turn-on voltage of 1.0 V. Under forward bias, prominent near infrared (NIR) emissions were observed at peak around 1570 nm at room temperature. The NIR emission was ascribed to the band-edge emission of InN epilayer based on the photoluminescence spectrum and band diagram of the heterojunction. Moreover, the study of the LED in terms of the stability was also discussed.

1. Introduction

Recently, indium nitride (InN) materials and devices have been paid extensive attention due to its promising properties such as lowest effective mass, highest electron mobility and narrowest band gap energy (~0.7 eV) among the III-nitride semiconductors [1–3]. Specifically, the narrow-band-gap of InN has provided a large spectral range for the III-nitride ternary alloy systems and extended their spectral range from deep ultraviolet to near infrared, which make them ideal for high efficiency solar cells, photodetectors and optoelectronic and terahertz devices [4–7]. However, up to now, the reports on electroluminescence (EL) device based on InN materials are very scarce [8–12]. Since the high-quality p-type InN materials are difficult to achieve due to the surface electron accumulation effect and less stability [13–15]. Therefore, InN-based heterojunction structure is a better choice to obtain the excellent optical properties of InN materials. Among the numerous p-type semiconductors, NiO, as a natural p-type material with a low resistivity and wide band-gap energy (3.7 eV), has been recognized a promising candidate in the fabrication of heterojunction light-emitting diodes and laser diodes [16–19]. In addition, the structure of p-NiO/n-InN heterojunction will favor electron confinement in the n-InN side due to the large conduction band offset (CBO) between NiO and InN, which contributes to the near band emission of InN epilayers.

In this work, we chose NiO as the p-type conducting layer for the hole carriers, and fabricated the p-NiO/n-InN/n-GaN heterojunction by growing an n-type InN epilayer on n-GaN/sapphire substrate by plasma-assisted molecular beam epitaxy (PAMBE) and then depositing a p-type NiO film on the InN layer by radio frequency magnetron sputtering. High quality InN epilayers have been obtained as reported in our earlier work [20,21]. As expected, the p-NiO/n-InN/n-GaN heterojunction exhibited dominant NIR emissions under higher forward bias. The mechanism of the NIR emissions was tentatively discussed in terms of the PL spectrum and band diagram of the heterojunction. Moreover, the stability of the device was also studied.

2. Experiments

The n-InN epilayer of about 180 nm was deposited on an n-GaN/sapphire substrate by plasma-assisted molecular beam epitaxy (PAMBE). The nitridation was performed at 700 °C for 30 min after thermal cleaning. Firstly, a low temperature InN buffer layer with a thickness of ~20 nm was grown at 400 °C followed by ~180 nm thick InN epilayer at 475 °C. During the entire growth sequence, the nitrogen flow rate was kept at 1.5 sccm and the forward RF-power of the plasma source was fixed at 400 W. The InN epilayer showed n-type conductivity

---

* Corresponding author.
E-mail address: lwc9442@126.com (H. Wang).

http://dx.doi.org/10.1016/j.jlumin.2017.02.053

with an electron concentration of 1.88×10^{19} cm^{-3} and mobility of 418 $cm^2 V^{-1} s^{-1}$. Afterwards, the p-NiO film of 270 nm was deposited on the InN layer by rf magnetron sputtering from a high-purity NiO target under Ar and O_2 atmosphere at room temperature. The NiO film exhibited p-type conduction characteristics with a hole concentration of 3.1×10^{19} cm^{-3} and mobility of 4.2 $cm^2 V^{-1} S^{-1}$. Then the wet-etching method was used to expose the GaN layer. The circular Au and In metal electrodes were deposited on the NiO and GaN layers respectively by the conventional thermal evaporation. The diameter of the circular device unit was about 2 mm. Lastly, the device was annealed at 350 °C for 3 min under high purity N_2 protective atmosphere to reduce the contact resistance. The schematic diagram of the LED based on the p-NiO/n-InN/n-GaN structure was shown in Fig. 1.

The morphology and crystal structure properties of the InN epilayers and the heterojunction were measured by JSM-6700F scanning electron microscopy (SEM) and Ultima IV X-ray diffractometer (XRD). The electrical properties of the films were measured by ACCENT HL5500PC Hall system. The electroluminescence (EL) and photoluminescence (PL) properties of the heterojunction were detected using a continuous wave He-Cd laser (325 nm, 30 mW) and a home-made acquisition equipment consisting of photomultiplier tube and lock-in amplifier systems. All the measurements were performed at room temperature (RT).

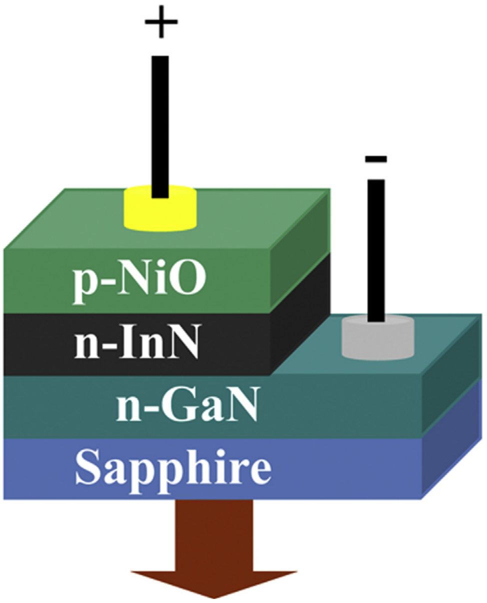

Fig. 1. Schematic diagram of the p-NiO/n-InN/n-GaN heterojunction device.

3. Results and discussion

The surface and cross-sectional morphology of the InN epilayers grown on GaN/sapphire substrate were shown in Fig. 2(a). It was noted that the InN epilayer exhibited a compact film grown with a two-dimensional mode, although some small areas were not completely coalescent. The crystal structure properties of the heterojunction were investigated by the XRD measurements as shown in Fig. 2(b). The XRD pattern revealed two main diffraction peaks at 2θ ~31.3° and 38.3°, which were corresponding to the InN (002) and NiO (111) diffractions respectively, except for the GaN (002) and Al_2O_3 (006) substrate reflection. This indicated that the as-grown InN epilayers had a c-axis preferred orientation and the NiO film had a strong (111) preferred orientation. Therefore, the materials grew with the following out of plane orientation epitaxial relationship: $(111)_{NiO} \| (001)_{InN} \| (001)_{GaN} \| (001)_{Al2O3}$. In addition, there was no diffraction peak around 2θ ~33.3° was detected, which indicated the InN epilayers had a high crystalline quality according to the fact that the NiO films could not grow on InN layers covered by Indium droplets [15].

The current-voltage (I-V) characteristics of the p-NiO/n-InN/n-GaN heterojunction were shown in Fig. 3. As seen, it revealed a typical rectification characteristic with a turn-on voltage of 1.0 V. The inset displayed the contact characteristic of the Au/NiO and In/GaN, which indicating that good ohmic contacts had been formed for both the electrodes. Moreover, the linear curves of the I-V characteristic of the InN layer with GaN substrate indicated that the rectifying characteristics came from the p-NiO/n-InN heterojunction.

The electroluminescence (EL) spectra of the p-NiO/n-InN/n-GaN heterojunction diode under different injection currents were shown in Fig. 4(a). It was noted that dominant NIR emissions peaked around 1570 nm were detected under forward injection currents. The inset showed the intensity of the emission and the full width at half-maximum (FWHM) of the NIR peak as a function of the injection current. The intensity of the NIR emission increased significantly as the injection currents increased from 25 to 70 mA. On the contrary, the FWHM of the NIR emission peak, calculated as 289, 210, 176 and 154 nm, respectively, decreased with increasing the injection currents. This indicated that the device did not reach the saturation state too early at higher injection currents, which was similar to that in Shi's report [22]. In order to explore the origin of the NIR emission, the PL

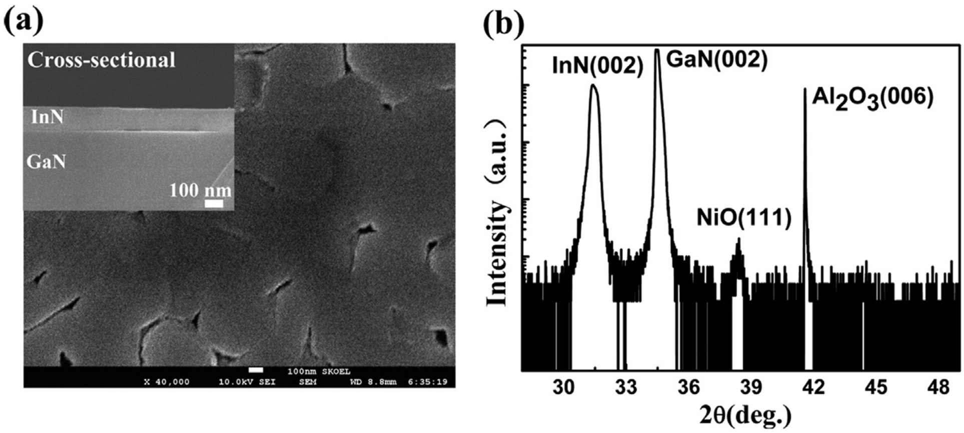

Fig. 2. (a) Surface morphology and cross-sectional images of InN epilayers grown on GaN/sapphire substrate. (b) XRD diffraction pattern of the p-NiO/n-InN/n-GaN heterojunction diode.