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Short communication

Influence of InN epilayers on structural, electrical and optical properties of NiO films grown by magnetron sputtering

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ABSTRACT

The NiO films were prepared on GaN substrate by depositing an InN epilayer on GaN by plasma-assisted molecular beam epitaxy (PAMBE) and then growing NiO films on InN epilayer by radio frequency (rf) magnetron sputtering. We studied the effect of InN epilayers on structure, surface morphology, electrical and optical properties of NiO films using X-ray diffraction (XRD), scanning electron microscopy (SEM), Hall and optical absorption measurement. It was found that the NiO films grown with InN epilayer exhibited better crystalline qualities with more coalescent surface morphologies and an enhancement of the electrical properties. Moreover, the effect of vacuum annealing on the crystalline qualities of the NiO films was also investigated.

The NiO films were prepared on GaN substrate by depositing an InN epilayer on GaN by plasma-assisted molecular beam epitaxy (PAMBE) and then growing NiO films on InN epilayer by radio frequency (rf) magnetron sputtering. We studied the effect of InN epilayers on structure, surface morphology, electrical and optical properties of NiO films using X-ray diffraction (XRD), scanning electron microscopy (SEM), Hall and optical absorption measurement. It was found that the NiO films grown with InN epilayer exhibited better crystalline qualities with more coalescent surface morphologies and an enhancement of the electrical properties. Moreover, the effect of vacuum annealing on the crystalline qualities of the NiO films was also investigated.

Nickel oxide (NiO), a natural p-type material with a large direct band gap of 3.7 eV [1] and low resistivity, has been drawing much attention in the fields of optoelectronic devices, gas sensors, UV detectors, and cathode material for display devices [2–5]. It has been recognized as a good p-type candidate for the fabrication of heterojunction LEDs and LDs [6–8]. The attractiveness of NiO as a p-type conducting material lies in the fact that the NiO films has excellent chemical stability and low cost compared to the high-quality p-type ZnO and GaN materials, which are difficult to achieve due to the less stability and high resistance [9–12]. In resent years, there are many reports on the heterojunction light-emitting diodes based on NiO films with Si [13], Al_2O_3 [14], ZnO [15], and GaN [16], but there are few reports on the heterostructure of NiO/InN or InN/NiO. Furthermore, it is meaningful to explore a new p-type material for the fabrication of InN-based light-emitting diodes due to the immature fabrication process of p-InN, which hindered the development of InN-based devices. In this work, we prepared the NiO/InN heterostructures on GaN/sapphire substrates by PAMBE combined with rf-magnetron sputtering. We studied the influence of InN epilayers on the crystallographic, morphological, electrical and optical properties of NiO films. Moreover, the effect of vacuum annealing on the crystalline qualities of NiO films was also investigated and the energy band-gap of the NiO films was determined by the optical absorption measurement and found to be around 3.75–3.91 eV.

The InN epilayer was grown on GaN/sapphire substrate by plasma-assisted molecular beam epitaxy. Detailed growth process has been introduced in our earlier work [17]. In short, a thin InN buffer layer with thickness of about 20 nm was beforehand deposited at a low temperature of 400 °C followed by ~200 nm thick InN epilayer at 460 °C. Afterwards, the NiO films was

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deposited on the InN epilayer by rf-magnetron sputtering from a NiO target of 99.99% purity under Ar and O_2 atmosphere at room temperature. Sputtering deposition was performed under a gas pressure of 1 Pa. The RF power on the target was kept at a constant of 110 W. In addition, the NiO film deposited directly on GaN/sapphire without InN epilayers was also prepared as a comparison. Mention that other conditions were remained unchanged. The crystal structures and surface morphologies of the samples were carried out by X-ray Diffracrometer (XRD) and field emission scanning electron microscope (FE-SEM). The films' electrical and optical properties were measured by Hall system and SHIMADZU UV-360 Spectrophotometer. All the measurements were performed at room temperature.

In order to investigate the crystal quality of the NiO films, X-ray diffraction measurements of θ−2θ scan were performed on the samples. Fig. 1(a) showed the XRD patterns of the NiO films grown directly on GaN/sapphire substrate. It was found that the NiO films displayed a strong NiO (111) and a weak NiO (200) diffraction except for the GaN/Al_2O_3 substrate reflections. As a comparison, the NiO films grown with InN epilayers, as shown in Fig. 1(b), displayed only one diffraction of NiO (111) plane and nearly no NiO (200) diffraction was detected, which indicated a strong (111)-orientated crystal structure and good quality of crystallinity. Moreover, the only sharp diffraction peak around 2Theta ~31.3° comes from the diffraction of InN (002) plane and no Indium droplets diffraction was detected, which indicated the InN epilayers has a high crystalline quality according to the fact that the NiO films could not grow on InN layers covered by Indium droplets [18]. Furthermore, the full width at half maximum (FWHM) of the NiO (111) reflection for NiO films grown with InN epilayer was smaller than that of NiO films grown directly on GaN, which were ~2.25° and 2.67°, respectively. These results indicate that the crystalline qualities have been improved for NiO films grown with InN epilayers. According to Y. Pan et al. [18] the mechanism of improvement of properties of Cu_2O films grown under InN epilayers is a in-plane rotation between Cu_2O and InN, which indicates less lattice mismatch for the subsequent growth of epilayers. On the other hand, this is probably due to the increased surface mobility of the adatoms, which increases the probability of their finding lattice sites with minimum energy [19]. And this conforms to the enhancement of the electrical properties found in Hall results.

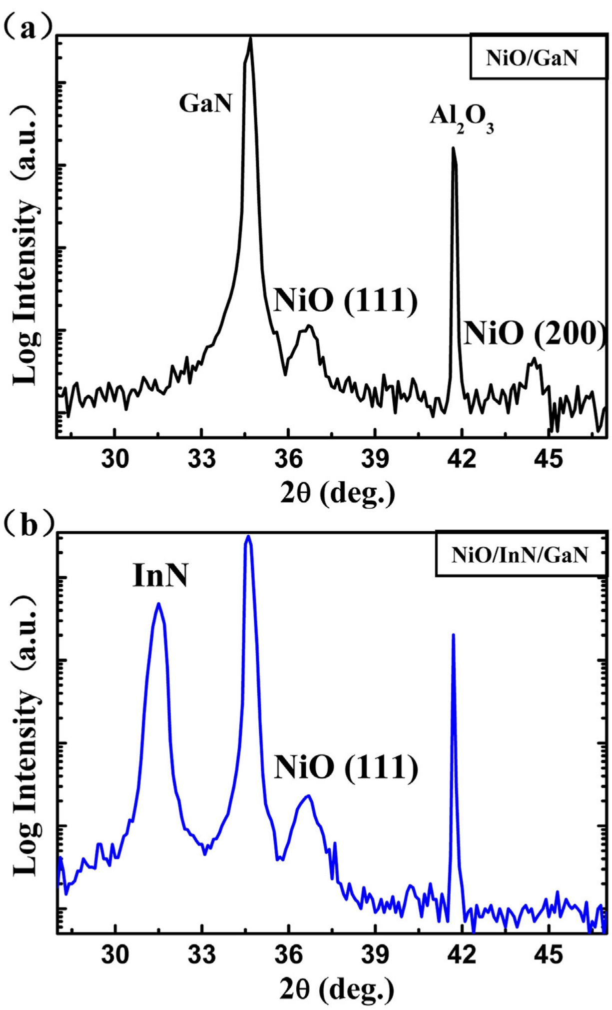

Fig. 1. XRD patterns of the NiO films deposited on: (a) GaN, (b) InN/GaN.

The surface morphologies of NiO samples were shown in Fig. 2(a) and Fig. 2(b). It was evident that the InN epilayers had a significant influence on the surface morphologies of the NiO films. On the one hand, the NiO sample grown directly on GaN showed a columnar grain structure with growth perpendicular to the film surface, and was dense, smooth and homogeneous. However, the grains with a size of ~100 nm were not coalesced to form a continuous film due to the low mobilities of the NiO layers. On the other hand, the NiO sample grown with InN epilayers showed a better coalescent surface and some of the area has coalesced to continuous films, which was probably attributed to the better crystalline quality and larger surface mobility of the adatoms [20]. The insets in Fig. 2(a) and (b) showed the cross-sectional images of the samples. The thickness of the NiO samples for NiO/GaN and NiO/InN/GaN was about 220 and 200 nm, respectively. Furthermore, the 3D morphology of the samples were also carried out by atomic force microscopy (AFM) as shown in Fig. 2(c) and (d), which was in agreement with the SEM results. The RMS roughness of the NiO surface for samples NiO/GaN and NiO/InN/GaN, calculated from 1×1 um^2 AFM scans, were 3.18 and 9.73 nm, respectively.

The optical band gap (E_g) of NiO samples was determined by optical absorption measurement. And it can be estimated using the relation of the absorption coefficient α with E_g near the band gap:

$$\alpha h\upsilon = A\left(h\upsilon - E_g\right)^{1/2} \tag{1}$$

Where A is a constant and $h\upsilon$ is the photon energy. The optical band gap of the NiO films can be determined through extrapolating the liner part of the absorption down to the photon energy axis as shown in Fig. 3. We figured out that the optical band gap of the NiO films for samples NiO/GaN and NiO/InN/GaN were around 3.75 and 3.91 eV, respectively, which is in good agreement with the earlier reports on the band gap of NiO films from 3.6 to 4.0 eV [21,22].

The effect of vacuum annealing on the crystalline qualities of NiO samples were investigated by carrying out the NiO (111) rocking curve measurements and the results were shown in Fig. 4. It was found that both the FWHMs of the two groups of samples decreased with the increase of the annealing temperature. However, the NiO films grown with InN epilayers began to deteriorate at 500 °C and decompose completely at 600 °C due to the low decomposition temperature of InN [23]. What's more, it was noted that the FWHMs of NiO films grown with InN epilayers was always smaller than that grown directly on GaN, and the vacuum annealing could improve the crystalline qualities of the NiO films.

The electrical properties of NiO samples were investigated by the room temperature Hall measurements as shown in Table 1. It was found that the NiO layers for both the samples showed p-type conductivity with carrier concentrations varied from 2.077×10^{18} to 1.976×10^{17} cm^{-3}. The carrier concentration of NiO films grown with InN epilayers was lower than that of NiO films grown directly