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A study of dislocations in AlN and GaN films grown on sapphire substrates

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Abstract

The dislocations in epitaxial AlN film directly grown on (0 0 0 1) sapphire have been investigated by transmission electron microscope and X-ray diffraction (XRD), including direct comparison with conventional GaN film grown on sapphire substrates. Unlike GaN, the threading dislocations (TDs) of AlN are almost entirely of pure-edge character, and the screw dislocation density is much less than that of GaN film, leading to a very narrow full-width-at-half-maximum of ~70 arcsec in (0 0 0 2) XRD of AlN film. The origin of screw TDs in GaN is found to be primarily related to the highly faulted layer at the interface region, which is introduced by using a low temperature (LT) nucleation layer. The high temperature AlN growth without any LT initial layer leads to the dramatic reduction of screw dislocations in AlN. Simultaneously, the AlN growth is dominated by two-dimensional step-flow mode while the island growth that occurs for GaN film on sapphire is suppressed. Moreover, we obtained a very low dark current density of 1.1×10^{-9} A/cm^2 at a 5 V bias on AlN metal-semiconductor-metal diodes, which indicates a lower defect density and good material quality of our AlN thin film.

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1. Introduction

Recently, there has been an increasing demand for deep ultraviolet (UV) emitters at wavelengths down to 280 nm [1,2]. III–V nitrides are the best

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candidates to realize these devices. So far, most of III–V nitrides are grown on sapphire substrates. In this case, the general growth procedure is that a thick GaN buffer layer has to be grown prior to any further device structures. In order to avoid the extremely large lattice mismatch between GaN and sapphire (~13.6%), a thin low-temperature (LT) GaN nucleation layer must be initially grown before the thick GaN buffer layer grown at high temperature, which has been widely used to grow a variety of nitride-based optoelectronics devices. However, when the emission wavelength of the emitter is required to move down to short wavelengths that are at higher energy than the bandgap of GaN, there exists a strong internal absorption. Therefore, it is necessary to develop GaN-free technology on sapphire substrates, namely, high quality AlN buffer layer as an underlying layer for the subsequent growth of Al-rich III–V nitride UV emitters and detectors on sapphire substrates. Another advantage of an AlN buffer over a GaN buffer is its higher thermal conductivity [3–5]. Furthermore, the compressive stress induced by the AlN underlying layer, which is opposite to the case of using GaN as an underlying layer, is expected to have effects in restraint of crack generation and reduction of dislocation density [6–8]. However, the deposition of smooth and low defect density AlN film is a difficult task. Up to date, there are only a few reports on the growth of AlN films directly on sapphire substrates. The X-ray diffraction (XRD) measurements showed a very narrow full-width at half-maximum (FWHM) of ~100 arcsec in (0 0 0 2) scan mode but a very wide FWHM in $(1 0 \bar{1} 2)$ scan mode [3–5,8], which is completely different from GaN films. This implies a different defect nature due to the different growth mechanism. Therefore, it is necessary to investigate this issue in order to further improve the crystal quality of AlN epitaxial films grown on sapphire substrates.

Recently, we have succeeded in developing a single-step technology for growth of AlN film directly on sapphire substrates. (0 0 0 2) XRD shows a very narrow FWHM of about 70 arcsec although the FWHM of $(1 0 \bar{1} 2)$ XRD rocking curve is quite large. By transmission electron microscopy (TEM) investigation, the nature and origin of threading dislocations (TDs) in AlN was investigated and compared to those in GaN. Our studies manifest that the growth mechanism of AlN is different from that of GaN grown on sapphire substrates currently using a LT GaN nucleation layer.

2. Experiments

Epitaxial films of AlN 1 μm thick were directly grown on a (0 0 0 1)-faced sapphire substrate using vertical low-pressure metal-organic chemical vapor deposition (MOCVD) without any LT nucleation layer, generally used for the growth of almost all GaN-based optoelectronics on sapphire substrates. The detailed growth conditions will be published elsewhere. The excellent surface morphology and crystal quality were characterized by atomic force microscopy (AFM) and XRD measurements, which were compared to a GaN film grown based on the technology of the LT buffer layer.

TEM observations were performed by a Philips EM420 transmission electron microscope operating at a voltage of 120 kV and a high-resolution field emission JEOL 2010F TEM operating at 200 kV. The specimens for TEM measurements were prepared by a standard procedure, i.e., mechanical thinning, followed by Ar^+ ion milling at 6.0 kV.

The dark current–voltage (*I– V*) and breakdown voltage measurements were carried out on AlN metal–semiconductor–metal (MSM) diodes with a semiconductor parameter analyzer. Schottky contacts were Ni (20 nm)/Au (200 nm), deposited by standard lithography and lift-off techniques.

3. Results and discussion

Fig. 1 shows the typical XRD rocking curves of epitaxial AlN in (0 0 0 2) and $(1 0 \bar{1} 2)$ scan modes. The (0 0 0 2) FWHM of AlN is only 68 arcsec, which is much narrower than that of current GaN, typically between 250–300 arcsec [9]. However, in the case of $(1 0 \bar{1} 2)$ scanning mode, there is a dramatic change. Generally, the typical $(1 0 \bar{1} 2)$