Journal of Crystal Growth 312 (2010) 58–63

Contents lists available at ScienceDirect

Journal of Crystal Growth

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

Seeded growth of AlN bulk crystals in *m*- and *c*-orientation

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ARTICLE INFO

Article history:
Received 22 July 2009
Received in revised form
22 September 2009
Accepted 6 October 2009
Communicated by M. Skowronski
Available online 12 October 2009

Keywords:
A1. High resolution X-ray diffraction
A1. Substrates
A1. X-ray topography
A2. Growth from vapor
A2. Seeded vapor growth
B1. Nitrides

ABSTRACT

Seeded growth of AlN boules was achieved on *m*-$(10\bar{1}0)$ and *c*-$(000\bar{1})$ orientations by physical vapor transport (PVT). The single crystalline *m*- and *c*-plane seeds were cut from freestanding AlN single crystals. AlN boules 12 mm in diameter and 7 mm in height were grown at source temperatures around 2280 °C in N_2 atmosphere at 500 Torr of total pressure. Under identical process conditions, the *m*- and *c*-plane boules exhibited the same growth rates, 150–170 μm/h, and similar expansion angles, 22–27°, which indicated that the growth was controlled by the thermal profile inside the crucible rather than by crystallographic differences. X-ray rocking curve analysis and Raman spectroscopy confirmed that both *m*- and *c*-plane grown crystals possessed high crystalline quality. The dislocation density in both crystals was non-uniform and in the range 10^2–10^5 cm^{-2}, as characterized by X-ray topography.

1. Introduction

Single crystal AlN is a promising substrate for nitride-based optoelectronic devices exploiting the deep ultraviolet (UV) spectral range. It has a similar lattice parameter and thermal expansion coefficient to that of high Al content AlGaN, which is needed for the active layers in these devices. Progress has been made in bulk crystal growth of AlN, and limited quantities of primarily *c*-plane (0001) single crystal AlN wafers are currently available for research [1–7].

Recently the non-polar planes of nitrides, i.e., *m*-$(10\bar{1}0)$ and *a*-plane $(11\bar{2}0)$, became desirable since the active layers grown in non-polar directions have certain advantages over the layers grown in the polar direction. First, the spontaneous and piezoelectric polarizations along the $[0001]$ axis in group-III nitrides generate internal electric fields causing spatial separation of electrons and holes in quantum wells, which degrades the luminous efficiency of optoelectronic devices [8]. Second, AlN and GaN have different valence band structures caused by crystal field splitting [9,10]. The light emission due to the recombination between the conduction band electrons and the holes in the valence band is polarized with $E \parallel c$ in AlN and $E \perp c$ in GaN, where E is the electric field vector of the emitted light and c is the *c*-axis of the lattice. As a consequence, the maximum emission intensity in AlN is obtained in the direction perpendicular to the *c*-axis, while the maximum intensity in GaN is obtained in the direction parallel to the *c*-axis. Owing to the above two phenomena, growing AlGaN device structures with high Al content on non-polar planes is expected to result in higher luminous efficiency of deep UV optoelectronic devices.

Although the growth of III-nitride thin films in non-polar directions has been demonstrated on SiC and sapphire [11,12], the quality of these epilayers was inferior to those grown in polar (0001) directions. Most of the AlN bulk crystal growth has been carried out in either of the two *c*-directions [3] and *m*-plane AlN wafers were harvested from the *c*-grown boules [13]. There are only a few reports discussing the properties and the growth of different orientations of AlN bulk crystals [14,15]; however, there are no systematic studies of seeded growth of AlN on non-polar AlN seeds. Due to differences in the growth surfaces, AlN crystals grown on different orientations exhibit different properties, such as different concentrations of unintentionally incorporated impurities [16]. In this article, we discuss the achievement of non-polar seeded growth of AlN, and contrast the crystallographic properties of the seeded *m*-plane $(10\bar{1}0)$ grown crystal with those of a *c*-plane $(000\bar{1})$ grown crystal.

2. Experimental: AlN bulk crystal growth

Seeded growth of AlN on *m*- and *c*-plane $(000\bar{1})$ seeds was performed by physical vapor transport (PVT) in an inductively

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doi:10.1016/j.jcrysgro.2009.10.008