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Thin Solid Films 483 (2005) 16–20

thin solid films

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Microscopic investigations of aluminum nitride thin films grown by low-temperature reactive sputtering

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Received 18 May 2004; accepted in revised form 3 December 2004
Available online 13 January 2005

Abstract

Aluminum nitride (AlN) films were grown on sapphire substrates by radio frequency magnetron sputtering in plasma containing a mixture of argon and nitrogen, using a pure aluminum target. Surface morphology dependence of the AlN films on growth conditions such as substrate temperature and nitrogen concentration was investigated. c-axis preferred wurtzite AlN film with surface roughness as small as 2.9 nm was obtained at substrate temperature of 100 °C and nitrogen concentration of 20%. The surface roughness of the AlN films increased with increasing substrate temperature and nitrogen concentration. The correlation between the growth conditions and the film morphology was discussed.

PACS: 81.05Ea; 81.15.Cd
Keywords: Aluminum nitride; Low-temperature growth; Atomic force microscopy; Surface roughness

1. Introduction

Aluminum nitride (AlN), one of the III–V compound semiconductors with a wurtzite crystalline structure, is promising not only for the use of optical devices at ultraviolet spectral region, but also for the use of high power and high temperature electronic devices, because it has wide energy band gap, high breakdown voltage, and high thermal conductivity [1–4]. Recently, it has received more attention for the fabrication of GHz-band surface acoustic wave (SAW) devices due to its strong piezoelectricity, because the increase in the operation frequencies of wireless communication systems has stimulated the research and the development of high-frequency, low-cost, microelectronic filters with standard technological processes [5]. The growth of AlN films has been performed by various techniques such as reactive ion beam deposition [6], reactive evaporation [7], chemical vapor deposition [8,9] and molecular beam epitaxy [10–12]. Among all these techniques, the substrate temperatures during the growth are high and incompatible with other processing steps in device fabrications. Reactive sputtering technique, however, has the advantage of using simple apparatus and low growth temperature. Recently, we have demonstrated that highly c-axis preferred wurtzite AlN films can be obtained at a substrate temperature as low as 100 °C using the reactive sputtering technique [13]. It is well known that the microstructural factors of films such as surface morphology and roughness play important roles in functional devices such as SAW devices, because large surface roughness may lead to increased scattering and hence increased propagation losses. Therefore, in this article, we report on microscopic investigations of aluminum nitride thin films grown by the low-temperature reactive sputtering. Surface morphology dependence of these AlN films on growth conditions such as substrate temperature and nitrogen concentration has been revealed and the correlation between the growth conditions and the film morphology has also been discussed.

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0040-6090/$ - see front matter
doi:10.1016/j.tsf.2004.12.014

2. Experiment

AlN films were deposited on sapphire substrates by radio frequency magnetron sputtering in an ambient of argon and nitrogen, using an aluminum target (of purity 99.999%) with a diameter of 10 cm. The sputtering chamber was evacuated to a pressure of 10^{-5} Pa with a turbomolecular pump before introducing argon and nitrogen. The distance between the substrate and the magnetron sputtering cathode with a bonded aluminum target was fixed at 40 mm. The sapphire substrates were cleaned ultrasonically in organic solvents, chemically etched in a hot H_3PO_4:H_2SO_4 (1:3) solution, and rinsed in de-ionized water. The aluminum target was sputter-cleaned for 20 min before any growth took place on the substrate. During the growth, the radio frequency sputtering power and the gas pressure were kept constant at 100 W and 1.3 Pa, respectively. The nitrogen flow was varied from 0–100% while the total flow of nitrogen and argon was maintained at 3 sccm. The substrate temperature was monitored using a thermocouple and controlled at a given value between 100 and 700 °C using a heater behind the substrate. The deposition time was fixed at 120 min. The thicknesses of the films measured by a surface step profile analyzer were in the range of 0.28–0.46 μm. Surface morphology of the films was observed by a field emission scanning electron microscopy (SEM, PHILIPS XL-FEG 30) at 5 kV and an atomic force microscopy (AFM, SII Nanopics 1000). The AFM images were obtained in contact mode using Si tips. Root mean square (RMS) surface roughness of the films was determined over a (5 μm×5 μm) area using a dedicated software built in with the AFM instrument. Optical transmission spectra of these AlN films were measured from 190 to 1200 nm in wavelength using a dual-beam spectrophotometer (JASCO V-570) at room temperature.

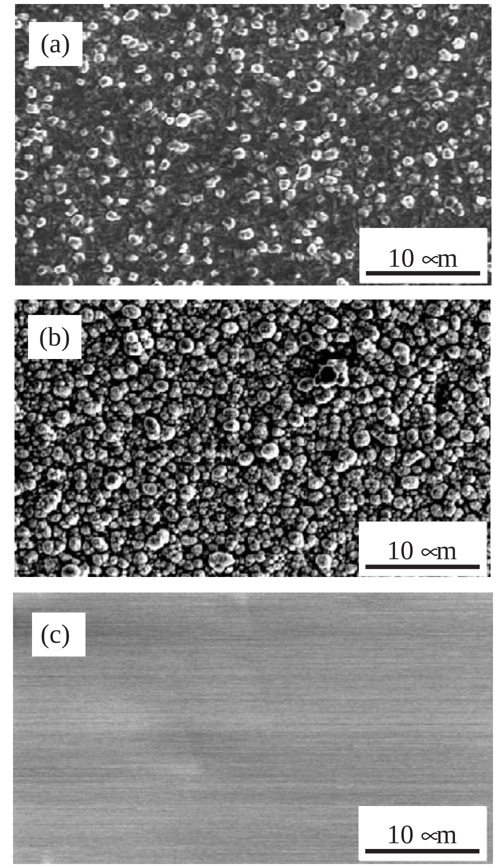

Fig. 1. SEM images of the films grown at a substrate temperature of 100 °C under nitrogen concentration of (a) 0%, (b) 10%, and (c) 20%.

3. Results and discussion

Fig. 1 shows the SEM surface morphologies of the films grown on sapphire substrates under various nitrogen concentrations at a substrate temperature of 100 °C. Fig. 2 shows the AFM images of the films grown under nitrogen concentrations from 0% to 100% at a substrate temperature of 100 °C. The AFM scan area is 5 μm×5 μm. The film grown at a nitrogen concentration of 0% (namely, in pure argon plasma) exhibits a surface morphology of aluminum grains with roughness of 295 nm as shown in Figs. 1(a) and 2(a). The roughness of the film increases with increasing nitrogen concentration (Figs. 1(b) and 2(b)). However, when the nitrogen concentration is further increased to 20%, a very smooth grown surface with roughness of 2.9 nm is obtained as shown in Figs. 1(c) and 2(c). Since only the diffraction peak corresponding to the (0002) reflection from AlN besides the peak of (0006) reflection from the sapphire substrate was observed [13], the film grown at nitrogen concentration of 20% is the highly *c*-axis oriented AlN film with smooth surface. In order to verify it, we investigated the optical transmission spectrum of the AlN film at a wavelength of 190–800 nm using a dual-beam spectrometer at room temperature. Fig. 3 shows the wavelength dependence of optical transmittance of the AlN film grown at 20% nitrogen concentration. The observation of the oscillations attests high quality of the obtained AlN film. The film exhibits approximately 75% optical transmission in the visible and ultraviolet range and shows a steep absorption edge around 200 nm corresponding to a band gap of 6.2 eV, which is close to the bulk AlN value [14]. Morita et al. [8] have grown AlN on sapphire substrates using the chemical reaction of trimethyaluminum with ammonia at a substrate temperature of 1260 °C and the surface roughness of their AlN was obtained to be 8 nm [15]. Calleja et al. [12] have grown AlN by plasma-assisted molecular beam epitaxy and have investigated surface roughness dependence on growth temperature. They found that the optimal AlN layers grown at a growth temperature of 900 °C have an average surface roughness of 4.8 nm. Based on these results, it seems that the surface roughness of the AlN films reported in this work is smaller than that of AlN films grown by other growth