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Aluminum nitride thin film growth and applications for heat dissipation

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ABSTRACT

Aluminum nitride (AlN) thin film, due to its electrical and thermal properties, can be used as thermal interface material for flexible electronics. The relationship between thermal conductivity and microstructure of aluminum nitride film was studied on films grown on glass by DC magnetron reactive sputtering at room temperature. The crystal orientation, deposition rate and grain size of AlN films were affected by the deposition power. The crystallization quality and the effective thermal conductivity of the AlN films were strongly dependent on the film thickness at the optimum power of 600 W. The bulk thermal conductivity of AlN films was found to be 15.4 W/(m·K) in this study.

1. Introduction

Flexible electronics have become an important research topic in the past decades [1]. As flexible substrates, films and fibers have advantages compared to classic semiconductor materials in terms of cost, large scale fabrication and biocompatibility [2,3]. These diverse substrate materials are being investigated for displays, memory, circuitry, photovoltaic devices and MEMS sensors [2]. However, the use of these flexible materials imposes design limitations due to the heat dissipation and low thermal stability limits during device processing and operation [4].

Aluminum nitride (AlN), one of the III–V compound semiconductors with a wurtzite crystalline structure, is promising for high-frequency surface acoustic wave (SAW) devices due to its good piezoelectric performance and as a heat dissipation layer for electronic devices due to its high thermal conductivity, wide energy band gap and high breakdown voltage [5–8]. For flexible electronics AlN films combine high thermal conductivity, high optical transmittance, low expansion coefficient and low temperature preparation which are major factors favoring its use as a heat spreader material for these applications.

For several decades the thermal conductivity of AlN films has been extensively investigated [9–11]. Growth of AlN films with good crystal quality on flexible substrates is still a pending matter as the oriented growth of AlN requires specific surface conditions which are mainly achieved on metallic layers (Ir, Ru, Pt, W or Mo) or single crystal substrates such as sapphire or silicon [12]. Due to temperature limitations, differences in thermal expansion coefficients and the amorphous state of the flexible substrates, it is a technological challenge to deposit high-quality AlN films on flexible substrates [1]. In this study, glass is chosen as the substrate due to its amorphous state and relative temperature limitations similar to most flexible substrates. In this study AlN films are deposited at room temperature to simulate conditions that have the potential to be used to prevent damage to flexible substrate materials and are compatible with complementary metal oxide semiconductor (CMOS) technology [1]. AlN films can be prepared by various techniques such as chemical vapor deposition (CVD), reactive magnetron sputtering, reactive evaporation, molecular beam epitaxy (MBE), ion beam-assisted deposition, laser and plasma assisted CVD and metal organic chemical vapor deposition (MOCVD) [15–18]. Magnetron sputtering has been widely used in the industrial process of thin-film deposited on glass over the last decades due to its high rate, low cost, low temperature and ease of scaling [18]. In this paper the AlN films have been successfully deposited on amorphous glass substrates by DC magnetron reactive sputtering at room temperature. The structure, morphology and thermal conductivity of the AlN film have been investigated. There are a limited number of reports on the synthesis of AlN films on glass at room temperature to review for comparison [13,14].

2. Experimental section

AlN films were deposited on commercial glass substrates (20 mm × 20 mm) using Al (99.99% purity) target (50 mm in diameter and 4 mm in thickness) by a DC planar magnetron sputtering system. The substrates were cleaned in an ultrasonic bath with acetone, ethanol and de-ionized water, respectively. In this study, the distance between the substrate and Al target was 65 mm, which was kept constant for all depositions. The chamber was initially evacuated to a vacuum level of 5×10^{-3} Pa by using a turbo molecular pump followed by a mechanical pump and fixed as base pressure for coating. Ar (99.999%) and N_2 (99.999%) mixed gasses were used for AlN coating growth and the

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total pressure was 0.8 Pa. In order to remove the surface oxides of the target, pre-sputtering in Ar atmosphere was carried out for 10 min before AlN deposition with a pressure of 0.2 Pa. The DC power supplied was in a range of 100–700 W to meet the experimental demands. The deposition parameters of AlN films are summarized in Table 1.

3. Results and discussion

3.1. Deposition rate

Deposition rate of AlN film is an important factor to determine the adoption of this thin film method for industrial application. Fig. 1 shows the relationship between the deposition rate of the AlN films and sputtering power. The film thickness is measured using a step profiler. From Fig. 1 it is easily seen that the deposition rate of AlN films is linearly associated with power and the maximum rate of 3.3 μm/h at 600 W is higher than many other deposition methods [13,19,20]. Atul Vir Singh et al. also reported similar relationship between deposition rate and power in RF magnetron reactively sputtered AlN films [13].

3.2. XRD

Fig. 2(a) shows the XRD patterns of AlN films grown at different power levels at room temperature illustrating how the diffraction peaks of AlN films change with the power ranging from 100 to 700 W. For AlN film deposited at 100 W there is no visible diffraction peaks indicating that the deposited film is amorphous. When the power increases from 200 to 500 W the intensity of AlN (100) and (110) diffraction peaks ($2\theta = 33.2°$ and 59.3°) increases (PDF 76-0702). Particularly at 500 W the intensity of AlN (100) peak is the highest and the value of FWHM (0.215°) is the lowest which indicates that the film was grown with a preferred orientation of AlN (100). When the power increases from 500 to 700 W the intensity of AlN (100) and (110) diffraction peaks recedes significantly. AlN (002) diffraction peak ($2\theta = 36°$) emerges at 300 W and the intensity of AlN (002) peak gradually increases with increasing power from 300 to 700 W. At the power of 700 W the intensity of AlN (002) is very high and the FWHM is 0.218°, which indicates that the film has a preferred orientation of AlN (002). It is shown from Fig. 2(a) that the preferred orientation of AlN films grown on glass at room temperature has a turning point of power at 600 W. The atoms involved in the AlN (002) orientation require a higher kinetic energy to form a closely packed structure as compared to the (100) or (110) orientation [21]. For the (002) orientation the c-axis is normal to the substrate and the plane parallel to the substrate is the closely packed basal plane with either all aluminum or nitrogen atoms [22]. So the high kinetic energy and large mean free path of particles deposited on substrate caused by high power will grow c-axis AlN films.

The AlN films deposited at 700 W tend to brittle and prone to cracking from induced stress. Furthermore, the high-power deposition may increase the substrate temperature which may damage the flexible substrate [1,13]. So in this study the optimized deposition power is 600 W. Fig. 2(b) shows the XRD patterns of AlN films grown on glass at the power of 600 W with different thicknesses. It can be seen that the intensity of AlN (002) diffraction peak increases significantly when the thickness increases from 1 μm to 10 μm, and the value of FWHM (0.312°) at 10 μm is lowest. As reported [13], the oriented growth of AlN films requires specific surface condition and single crystal substrate is beneficial for preferred growth of AlN films. As the thickness increases, the crystal quality of the under layer improves, thus, affecting the preferred (002) growth of the AlN films.

Table 1
Deposition parameters of AlN films.

Substrate	Glass
Al target (purity)	99.99%
Target to substrate distance (mm)	65
Working pressure (Pa)	0.8
N_2 concentration (%)	25
Substrate temperature (°C)	RT
Power (W)	100–700
Deposition time (h)	1

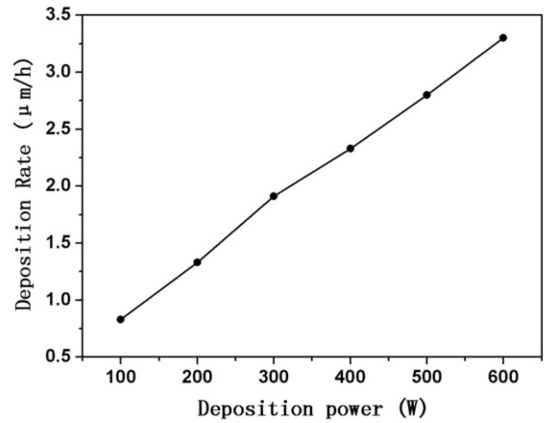

Fig. 1. The relationship between the deposition rate of the AlN films and sputtering power.

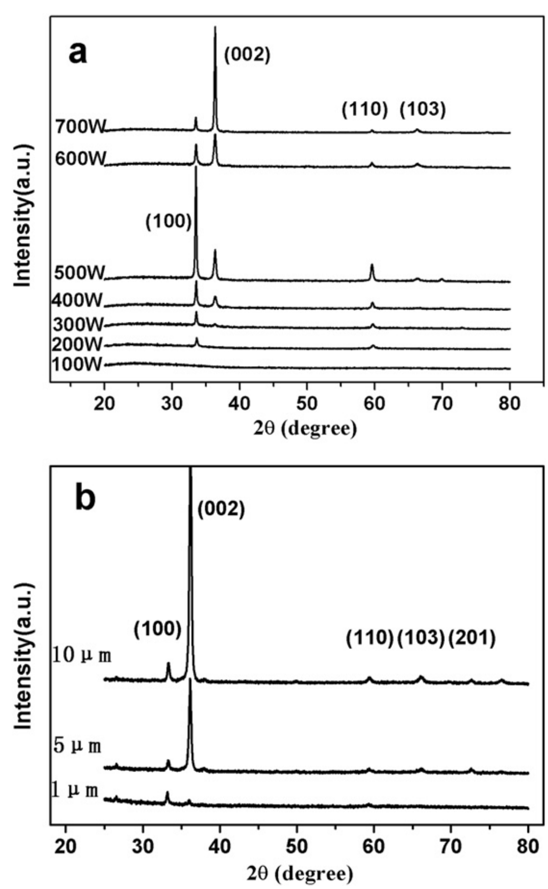

Fig. 2. (a) The XRD patterns of AlN films grown at different power levels at RT; (b) the XRD patterns of the AlN films grown on the glass at the power of 600 W with different thicknesses.