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The characteristics and residual stress of aluminum nitride films grown by two-stage sputtering of mid-frequency power

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Abstract

The [0 0 2] oriented aluminum nitride has a high surface acoustic wave speed and high mechanic-electron couple coefficient. It is a potential material for manufacturing piezoelectric devices in high frequency application. The AlN films deposited onto silicon substrates were fabricated by two-stage sputtering process with mid-frequency generator. The results showed that the film did not have well [0 0 2] preferred orientation at 1.0 and 1.5 kW, and exhibited a [0 0 2] preferred orientation at 2.0 kW. The adhesion was poor when the film had a high preferred orientation because the substrate was damaged by high energetic atoms bombardment. A two-stage growth method was investigated in order to get high [0 0 2] preferred orientation and good adhesion. A good performance was obtained at the first stage power of 1.5 kW and the second stage power of 2.0 kW. The film showed a tensile stress state when the film was deposited at 1.0 kW. In contrast, the stress state was changed to compressive when the films were grown at 2.0 kW. The two-stage growth could succeed not only to get a high [0 0 2] preferred orientation but also to develop a reducing global stress film.

Keywords: Aluminum nitride; Reactive sputtering; Preferred orientation; Residual stress

1. Introduction

Aluminum nitride (AlN) has excellent properties, including high oxidation resistance, high thermal conductivity, chemical inertion and electron insulation. AlN has highly potential to apply in surface acoustic wave device (SAW) and film bulk acoustic resonator (FBAR) [1–3] due to its excellent piezoelectricity, high acoustic wave speed, good electrical isolation, stable chemical property, high acoustic wave velocity and low temperature coefficient of delay. Various deposition methods [4–7] such as conventional chemical vapor deposition (CVD), plasma enhanced CVD, molecular beam epitaxy, directive current (dc) and radio frequency (rf) reactive sputtering were used in AlN growth. A smooth surface was hardly obtained by CVD process due to fast grain growth at high temperature deposition. An arcing is generally generated in reactive sputtering using dc power for depositing dielectric films. In contrast, a low growth rate and limited coating for large areas are suffered by rf power. The mid-frequency (MF) was used in this work as the power for growing of AlN films. The MF generator has already shown many benefits of high growth rate, film denseness and a smooth surface, compared with rf and dc. The stress of AlN films is very important on device manufacturing, especially for SAW and FBAR devices. Kusaka et al. [8] tried to lower the stress by adjusting the N_2 partial pressure, the total pressure, and the sputtering power, but the *c*-axis texture becomes weaker while lowering the compressive stress. Yong and Lee [9] used H_2 gas addition to relieve the compressive stress, but the *c*-axis preferred orientation was bad. However, highly *c*-axis oriented films are necessary for devices due to the best electromechanical coupling. In this article, the relation between film characteristics and residual stress was also investigated during the two-stage growth.

2. Experiments

A p-type (1 0 0) silicon wafer was used as a substrate whose resistivity is 3–5 mΩ cm. The substrate was cleaned with a

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Table 1
The parameters of AlN deposited

Target to substrate distance	10 cm
Power	1–2 kW
Pressure	1 mTorr
Ar flow	35 cm^3/min
N_2 flow	15 cm^3/min
Sputtering time	30–60 min

standard wet process for removing contamination and oxide in order to obtain a fresh surface for achieving good adhesion and film denseness. The equipment had dual cathodes of 400 mm × 100 mm area and the MF of 300 kHz was used as power supplier. Aluminum (Al) of 99.99% purity was used as target materials. Highly purified nitrogen (N_2) and argon (Ar) were used as reactive gases. When the specimen was located on a sample holder, the chamber was first pumped to background pressure of 10^{-6} Torr by using mechanical and diffusion pump. Then pre-sputtering was performed for 15 min in argon plasma to remove the surface oxide on Al target. The substrate was not heated during deposition, except from self-heating in plasma. The parameters of depositing AlN films were listed in Table 1. According to our previous report [10], the best condition for growing a [0 0 2] preferred orientation was at N_2/Ar ratio of 30%, 1 mTorr, and a distance of 100 mm from the target to substrate.

The crystal structure and preferred orientation were identified by X-ray powder diffraction (XRD) at a wavelength of 0.15418 nm, i.e. Cu Kα. The film thickness was measured by stylus instrument of Tencor Alpha-step 200. The average surface roughness (R_a) was determined by atomic force microscopy in the contact mode with a 5 μm × 5 μm measured area. The surface morphology of as-deposit films was observed by S-300 scanning electron microscopy (SEM). The sample was etched with a solution constitution of H_3PO_3:CH_3COOH:H_2O = 150:6:3 for 30 s in order to let a loose grain boundary etched out before SEM observation.

The residual stress was carried out by TENCO RFLX-2320 stress analyzer. The method used first to measure the curvature of 4-in. blank wafers as a reference. Then AlN film was deposited on the wafer, and the curvature of as-deposit wafer was measured again. The stress T was finally calculated by Stoney's equation [11] as follow.

$$T = \frac{Y_s t_s^2}{6(1-\nu_s)t_f}\left[\frac{1}{R} - \frac{1}{R_0}\right] \tag{1}$$

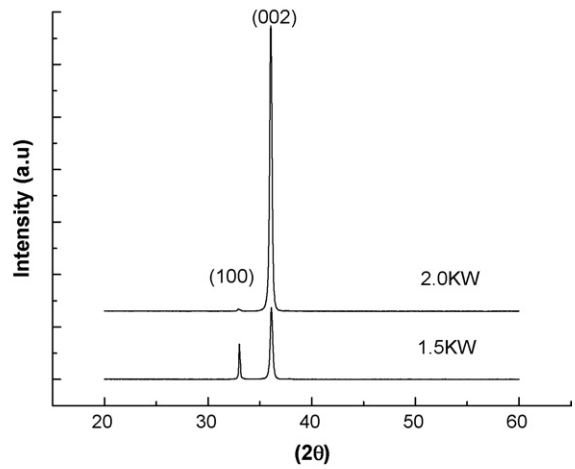

Fig. 1. XRD spectra of a single AlN layer for 1.5 and 2.0 kW.

where $Y_s/(1-\nu_s)$ is the biaxial Young's modulus of the substrate, which is 180.5 GPa for (1 0 0) silicon wafers. The t_s and t_f represent the thickness of the substrate and the film, respectively. The R_0 and R are the curvature radii of wafers measured before deposition and after deposition.

3. Results and discussion

3.1. Film growth

Fig. 1 shows XRD spectra of AlN films with single layer at 1.5 and 2.0 kW. The (1 0 0) and (0 0 2) peaks are found at 1.5 kW and the film has good adhesion. A high [0 0 2] preferred orientation appears at 2 kW, but the film exhibits bad adhesion where partly delaminated film can be examined. The reason can be explained that high power induces the interface damage by atom bombardment. This result hints that *c*-axis preferred films should be grown at high power: 2 kW, but the adhesion will be reduced. In contrast, good adhesion can be gotten at low power: 1.5 kW but the film will lose a highly preferred *c*-axis. According to the above observation, a two-stage growth method is used to improve both the *c*-axis preferred orientation and good adhesion. Two-stage growth means films are grown at two different powers during the process. The first stage is for adhesion and nucleation processed at low power such as 1.5 kW, and then the second stage is for preferred orientation at high power such as 2.0 kW. Some different two-stage power conditions are consti-

Table 2
The process parameters and the adhesive performance developed by two-stage growth

Sample no.	Sputtering power (first stage/second stage) (kW)	Deposition time (first stage/second stage) (min)	Performance
1	2.0/1.5	15/45	No adhesion
2	1.75/1.5	15/45	No adhesion
3	1.5/1.0	15/45	Peel off in part
4	1.5/2.0	15/45	Good adhesion
5	1.5/1.75	15/45	Good adhesion
6	1.5/2.0	7.5/52.5	Almost no adhesion
7	1.5/2.25	15/45	No adhesion
8	1.75/2.0	15/45	Film bulged
9	1.0/1.5	15/45	Good adhesion