Thin Solid Films 519 (2011) 6797–6800

Contents lists available at ScienceDirect

Thin Solid Films

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

Pulsed-DC sputtering of molybdenum bottom electrode and piezoelectric aluminum nitride films for bulk acoustic resonator applications

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ARTICLE INFO

Available online 10 February 2011

Keywords:
Mo
AlN
Pulsed-DC sputtering
FWHM
Residual stress

ABSTRACT

Various sputtering conditions were employed to explore the feasibility of depositing a suitably textured layer of molybdenum film, as a bottom-electrode of a film bulk acoustic resonator, on a silicon substrate. A fully (110)-textured Mo film, with its full width at half maximum (FWHM) of rocking curve as low as 1.1°, could be made when a 25-nm thick primer layer of aluminum nitride (AlN) film was pre-deposited between Si and Mo. In turn, the degree of the (0002) texture of a subsequently deposited AlN piezoelectric film, about 1.4 μm in thickness, was found to be largely decided by the degree of the (110) texture of the Mo film beneath it. The residual stress of this AlN piezoelectric film also varied virtually according to the texture quality of the underlying Mo film. The optimal process condition resulted in a piezoelectric AlN thin film having a (0002) FWHM as low as 0.98°, and a slightly compressive residual stress of 439 MPa at the same time.

1. Introduction

Aluminum nitride (AlN) thin films have attracted lots of attention for applications to film bulk acoustic resonator (FBAR) [1–9]. In order to effectively utilize its promising properties such as high acoustic velocity, high electromechanical coupling coefficient [10], and high breakdown voltage [11], AlN has to be fully (0002)-oriented with a narrow enough rocking curve [12] and a well-controlled residual stress [13]. Among various manufacturing techniques, reactive sputtering has been the most frequently used to fabricate piezoelectric AlN films, since a careful control of its processing parameters allows us to tailor film properties both efficiently and economically. Performing DC magnetron sputtering from an aluminum target in an ambient of nitrogen with/without argon may result in the formation of aluminum nitride coating not only on the substrate but also on the target, which causes target poisoning [14], arcing, and deterioration of film quality. Switching the choice of power supply from DC to RF, and using a compound target may solve this problem but at the cost of lower deposition rate and expensive yet hard-to-handle equipment. This inevitably leads to the use of pulsed-DC reactive sputtering, as we have chosen for AlN deposition, which intrinsically solves the problem of arcing and deterioration of the film quality. It brings also many advantages like higher film uniformity and higher plasma activity [15] at the same time.

While molybdenum has frequently been selected as the electrode material [16] to minimize the acoustic attenuation and provide good electrical conductivity, few articles [17–19] addressed the issue of optimizing the sputtering conditions for the Mo electrode film itself. Moreover, it has been suggested [20] that the use of a primer layer between Si substrate and Mo film might improve the qualities of the Mo electrode layer and of the AlN piezoelectric layer above it. Our preliminary study on the effects of a thin AlN primer layer confirmed this viewpoint. In this paper we thus systematically examined the effects of process conditions such as working pressure, discharge power, temperature, and primer layer thickness, for Mo deposition on the full width at half maximum (FWHM) of rocking curves for both Mo electrode and AlN piezoelectric films respectively, and on the residual stress of this AlN film as well.

2. Experimental

The sputtering system consisted of two oppositely positioned, balanced magnetrons (one for Al and the other for Mo 3″ target respectively), each powered by a 1.5 kW power supply and a pulse controller SPIK 2000A (Shenchang Electric Co., Taiwan) and separated by shields so that depositions of AlN and Mo films could be conducted successively by revolving the substrate to face each target sequentially. AlN thin films, both beneath the Mo electrode film as a primer layer and above the Mo film as a piezoelectric layer, were deposited in a N_2/Ar reactive atmosphere by pulsed-DC reactive sputtering of a pure Al (99.999% pure) target. Si (100) wafer substrates were ultrasonically cleaned with acetone and methanol and subsequently etched in dilute HF solution to remove its native oxide right before deposition. The sputtering system was pumped down to a base pressure of 5×10^{-7} Torr before depositing the primer layer. The target was pre-sputtered in pure Ar for 10 min and then in working

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doi:10.1016/j.tsf.2011.01.391

Table 1
Process parameters for sputtering Mo and AlN films.

Sputtering parameter		AlN (primer layer)	Mo (electrode layer)	AlN (piezoelectric layer)
N_2/Ar (%)		60/40	0/100	60/40
Pressure (mTorr)		2	3, 4.5 (default), 7, 9	2
Power (W)	DC		200, 400, 600, 800	
	Pulsed-DC (default)	600	100, 200, 400, 600 (default), 800	600
Pulse (μs)		$t_{on}=10$, $t_{off}=10$	$t_{on}=10$, $t_{off}=10$	$t_{on}=10$, $t_{off}=10$
Target-to-substrate distance (mm)		70	70	70
Substrate temperature (°C)		*Room* temperature	*Room* temperature (default), 100, 200, 300, 350	*Room* temperature
Thickness (nm)		12, 25 (Default), 200	*~1300*	*1500*

atmosphere for 5 min prior to each run. The sputtering sequence was set as AlN (primer layer) → Mo (electrode layer) → AlN (piezoelectric layer). Different series of deposition were performed for which the sputtering parameters for AlN were fixed, while those for Mo were adjusted so that only one sputtering parameter was varied and all the others kept constant (default) at a time. For example, the default power setting for Mo was pulsed-DC at 600 W as shown in Table 1, where all sputtering parameters are summarized. The influences of working pressure, discharge power, substrate temperature (measured by a thermocouple nearly touching the substrate), and primer layer thickness on the properties of sputtered Mo electrode and AlN piezoelectric films were investigated in this way.

The films were characterized by X-ray diffraction (θ–2θ scan) and by measuring the rocking curves of (110) peak for Mo and of (0002) peak for AlN, respectively. Residual stress of the AlN film was evaluated according to a modified $\sin^2\psi$ method as described elsewhere [21]. Typical α-step and SEM analyses were also employed.

3. Results and discussion

3.1. Effects of working pressure

Fig. 1 shows that the (110) FWHM of Mo film decreases with decreasing working pressure, from 9 mTorr down to 4.5 mTorr. This phenomenon is understandable. As the pressure is decreased, the mean free path of the sputtered atoms becomes larger ($\lambda_{mfp}=5/P$, where λ_{mfp} is in cm and P in mTorr) [22] and they arrive on the surface of the growing film with most of their energy (half the binding energy, about several electron volts) retained. They give a substantial amount of energy transferred to the growing film, and thus increase the mobility of the adatoms to move themselves to the lattice sites towards equilibrium, i.e., to form a closer-packed (110) plane with lower surface energy. In fact, the energy delivered to the growing film is so high that fully (110)-textured (texture coefficient = 1, throughout this paper) Mo films with their FWHMs around 2° are readily obtainable without substrate heating or substrate biasing. At 3 mTorr, however, this type of "atom-assisted deposition" [12] might be enhanced to such an extent that re-sputtering occurs. Owing to this and the lower plasma concentration due to fewer ionized species at lower working pressure, the quality of Mo film thus deteriorates as evidenced by the larger FWHM value at this pressure. It should be noted at this point, however, that the aforementioned "atom-assisted deposition" is a simplistic version of the real picture. In fact, bombardment of the growing film by not only the sputtered atoms but also the ions from adjacent plasma and the neutral working gas atoms (ions that are neutralized and reflected at the target) will take place in the same time and be affected by working pressure. Moreover, lower working pressure gives higher discharge operating voltage which in turn increases the total energy per particle too. Interested readers are thus referred to the literature [23–25].

As for the AlN piezoelectric film (texture coefficient = 1, throughout this paper too, as shown in the right inset of Fig. 5), its (0002) FWHM varies in accordance with the texture quality of Mo film. In addition, the magnitude of its compressive residual stress basically follows the same trend too. These results vividly elucidate the strong dependence of the quality of AlN film on that of the underlying Mo film.

3.2. Effects of discharge power

In the case of DC sputtering, instead of the default power setting at pulsed-DC, the (110) FWHM of Mo film decreases with increasing discharge power as shown in Fig. 2. Similar behavior has been reported in the literature [26,27]. This can be attributed to the more pronounced atom-assisted deposition at higher plasma concentration, which is in turn due to a higher sputter yield (at higher discharge voltage) and more ionized species (at higher discharge current). However, this phenomenon disappears in the case of pulsed-DC sputtering, as also shown in Fig. 2, where the (110) FWHM virtually remains at the same low value of about 2° from 100 to 800 W. This is probably due to the higher plasma activity associated with pulsed-DC

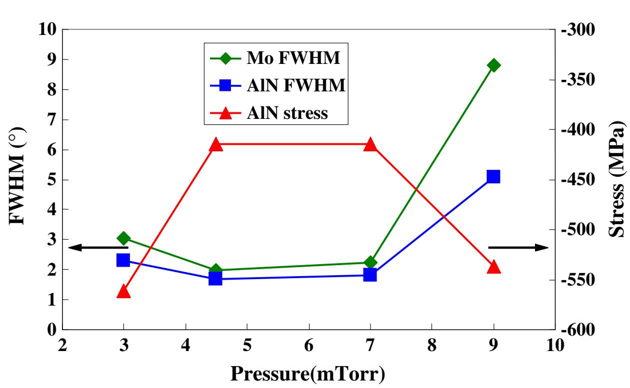

Fig. 1. Effects of working pressure (for Mo deposition) on the rocking curve FWHMs of both Mo (110) and AlN (0002), and on the residual stress of AlN film.

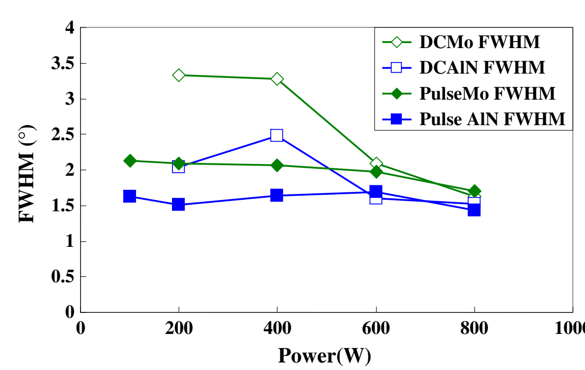

Fig. 2. Effects of discharge power (either DC or pulsed-DC, for Mo deposition) on the rocking curve FWHMs of both Mo (110) and AlN (0002).