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Properties of AlN_x thin films prepared by DC reactive magnetron sputtering

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In this paper, the results of investigation of the influence of cathode current on optical and dielectric AlN_x thin-film properties are presented. AlN_x films were prepared by pulsed DC reactive magnetron sputtering of Al target on substrates at room temperature. For characterization of fabricated test structures C-V spectroscopy, ellipsometry measurement and atomic force microscopy (AFM) were used.

Keywords: aluminum nitride (AlN), thin films, reactive magnetron sputtering, alternative dielectrics.

1. Introduction

Structures with aluminum nitride (AlN) films have been studied intensively because they could found application in electronic and optoelectronic devices. Advantages of AlN are its attractive properties, like wide direct band gap (5.9–6.2 eV) [1], high refractive index (≈ 2.0) [2] and transparence in visible light. It also has good thermal and chemical stability and high thermal conductivity (180 $Wm^{-1}K^{-1}$). Sputtered AlN films are good dielectrics with relative static permittivity of about 9 [3] and have high electrical resistivity.

So, this material is a good candidate for optical coatings (cap) or surface passivation layers of semiconductors. The AlN thin films give a better passivation effect than the Si_3N_4 films and additionally cause an increase of the mobility of carriers in two-dimensional electron gas in AlGaN/GaN heterostructures [4]. Also this dielectric is promising for application in metal–isolator–semiconductor high electron mobility transistors in the field plate configuration [5]. Applications like these give rise to a next generation of microwave power devices.

To grow dielectric AlN thin films physical or chemical vapor deposition could be used. For the purpose of our investigation pulsed DC reactive magnetron sputtering was applied. This method offers possibilities of synthesizing high quality, uniform, amorphous or polycrystalline dielectric layers.

2. Experiment

Samples used in this work were deposited on high resistivity Si (111) substrates. Metal−insulator−metal structures (MIM) were fabricated by pulsed DC reactive magnetron sputtering in Ar (99.9999%) atmosphere to form Al contacts and in Ar + N_2 (99.9999%) gaseous atmosphere for AlN_x insulator deposition. As a target Al discs (100 mm, 99.99%) were used. The holder of substrates was localized 20 cm above the target. The base vacuum in sputtering process was maintained at 10^{-6} mbar. First, the target was pre-sputtered for 1 min in Ar atmosphere to remove the surface oxide. Then, sandwich capacitors Al/AlN_x/Al were deposited through shadow mask at room temperature. Dielectric films (AlN_x) were synthesized at 2×10^{-3} mbar total pressure for 60 min. The ratio 1/5 of partial pressures of N_2 and Ar was set. AlN_x layers were deposited with cathode current in the range from 1 to 2.5 A.

The electrical properties of the dielectric films were studied on fabricating MIM capacitors by C-V spectroscopy. Measurements were carried out in the frequency range from 20 Hz to 10 MHz. The surface area A of all MIM capacitors was 16 mm^2 and thicknesses l of AlN_x layers measured by interferometeric microscopy are listed in the Table.

T a b l e. Technological parameters of thin film capacitors.

Cathode current I_C [A]	Thickness l [nm]
1	250
1.5	320
2	590
2.5	800

The surfaces of AlN_x films were examined by atomic force microscopy (AFM). For this purpose the dielectric was deposited on Si (111) substrate with 1.5 A cathode current. The topography of the film was characterized across a sample with surface area of 500×500 nm^2. To measure the refractive index of AlN_x layers a single-wavelength ellipsometry with 630 nm laser beam wavelength was used. Films were fabricated on reference glass tiles with 1.54 refractive index. The samples dedicated for AFM characterization and refractive index measurements were prepared in the same process conditions as described earlier.

3. Results

Influence of the cathode current in reactive magnetron sputtering process on optical properties was investigated by single-wavelength ellipsometry method. Experimental results of refractive index evaluation are shown in Fig. 1. The refractive index for

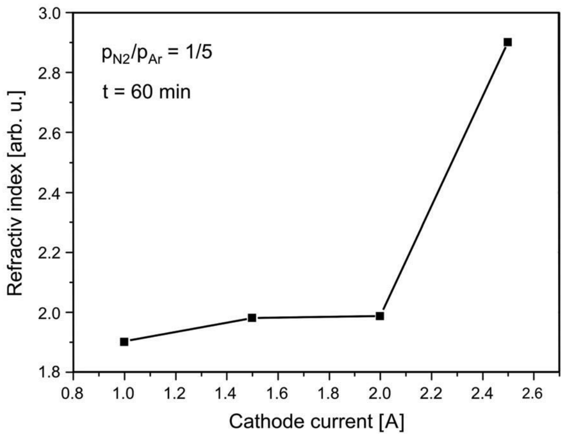


Fig. 1. Influence of cathode current in DC reactive magnetron sputtering on refractive index.

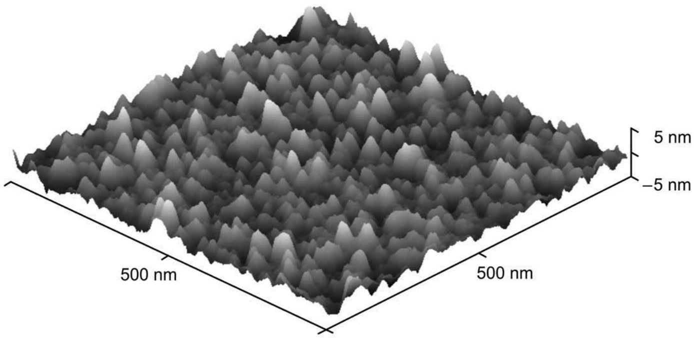


Fig. 2. The AFM image of topography of AlN thin film made with 1.5 A cathode current on Si (111) substrate.

samples deposited with cathode current lower than 2.0 A are very similar to those reported by other authors [1, 2, 6] and typical of polycrystalline AlN thin films. For cathode current higher than 2 A all samples were nontransparent for visible light and values of refractive index rapidly increased.

The topography of AlN film surfaces was characterized by AFM. Figure 2 shows a 3D AFM image of AlN_x layer of 500×500 nm^2 surface area. The surface roughness of the layers root mean square R_{RMS} and arithmetic average of absolute values R_a were 1 nm and 1.32 nm, respectively. The surface of this film was smoother than that reported in the literature by other authors [2]. The observed grains have regular shape and similar diameters as well as heights.

The dielectric properties of the AlN_x films were studied on fabricated MIM capacitors. The capacitance spectra were measured by C-V spectroscopy. The results are presented in Fig. 3.

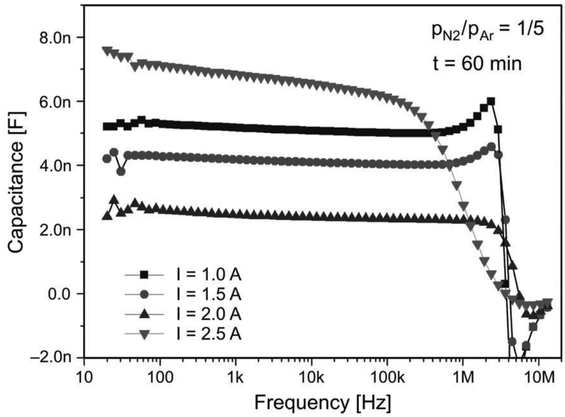
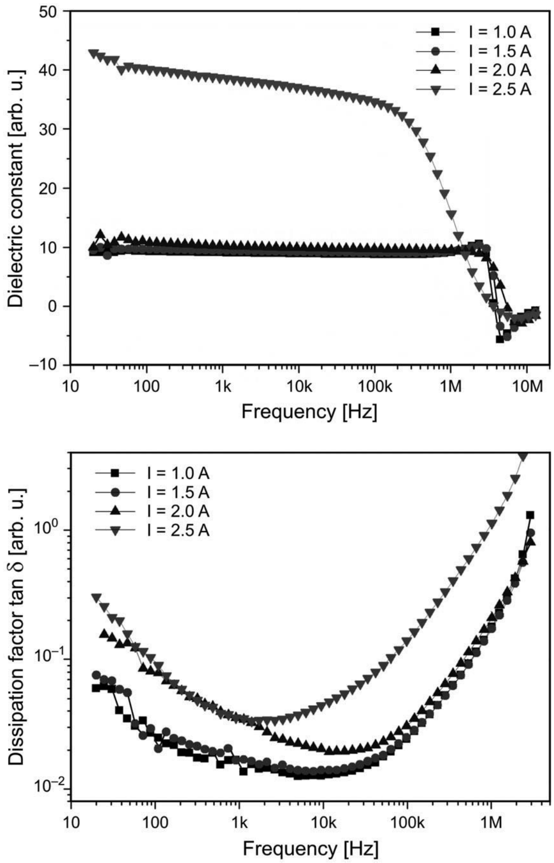


Fig. 3. Capacitance *vs*. frequency results of the AlN_x layers deposited at various cathode currents.



a

b

Fig. 4. Dielectric constant spectra of the AlN_x layer deposited at various cathode currents (**a**) and their dissipation factor spectra for various cathode currents (**b**).

The dielectric constant ε_r and dissipation factor $\tan\delta$ were calculated from the capacitance spectrum by using the formula as follows:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{l} \tag{1}$$

(where: C – capacitance, ε_r – relative dielectric constant, ε_0 – dielectric constant of vacuum, A – active area of capacitor, l – thickness of a dielectric layer) and from the conductance spectrum by the formula:

$$\tan\delta = \frac{\sigma}{\varepsilon_r \varepsilon_0 \omega} \tag{2}$$

where: $\tan\delta$ – dissipation factor, σ – conductivity, ω – pulsation.

Dielectric constant spectra are shown in Fig. 4**a**. For cathode currents 1 A, 1.5 A, 2 A, the values of relative dielectric were 9.1, 9.3, 9.5, respectively (evaluated at 1 MHz), which is comparable to dielectric AlN films [3, 6]. For a 2.5 A cathode current the relative dielectric constant rapidly increased. The dissipation factor was the lowest for 1 and 1.5 A cathode current compared to the values obtained for other cathode currents (Fig. 4**b**).

4. Conclusions

Optical and dielectric properties of AlN_x thin films fabricated by pulsed DC reactive magnetron sputtering were investigated. The refractive indexes and dielectric constants of deposited films with lower cathode current corresponded to polycrystalline AlN. Samples with the highest cathode current were not transparent for visible light and values of their refractive indexes and dielectric constants rapidly increased. This effect could arise from the modification of stoichiometry of AlN_x film. In addition, during the sputtering process with higher cathode current and constant partial pressure of reactive gas (N_2), some of the aluminum atoms in deposited layers could not be bound with nitrogen, which would explain an increase in the values of refractive index as well as dissipation factor. In these layers, additionally relaxation processes occurred, which was revealed based on equivalent circuit estimated from C-V spectroscopy measurement.

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