Sputtering grown wide band gap AlN thin films for high power capacitors

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Abstract*— This paper reports on the characterization of optical and electrical properties of aluminum nitride (AlN) thin films, achieved by varying the N_2/Ar gas ratio during the sputtering process. Our findings reveal that AlN thin films can attain superior optical transmission in the visible spectrum compared to glass substrates, particularly at an optimal N_2/Ar ratio. Additionally, we observed that the dielectric strength and breakdown voltage of the films improve as the N_2/Ar ratio decreases, reaching a dielectric strength of approximately 4.5×10^5 V/mm under optimized conditions. The study also demonstrates an increase in capacitance with higher applied DC voltage, attributed to the piezoelectric properties of AlN. These results highlight the potential of AlN thin films for applications in dielectric layers for power capacitors and gate materials in thin-film transistors.

Keywords— Aluminum Nitride, sputtering, N_2/Ar gas ratio, electrical and optical properties

Introduction

Aluminium nitride (AlN) exhibits excellent properties: such as high optical transparency, large bandgap, good electrical insulation, high dielectric strength and remarkable piezoelectric coefficients. [1-2] These properties make it an attractive alternative in a variety of applications such as energy harvesters, sensors, resonators, UV-LEDs and laser diodes. [3-7] Due to the large bandgap and high transparency, ultrathin AlN films have also been used as surface passivation layer in LED based on III-V wide bandgap semiconductor materials [8-9] and this has a potential to shed the light on the application in emerging colloidal quantum dot LEDs and image sensors based on solution processed methods.[10-13] Common fabrication techniques for AlN include chemical vapor deposition, molecular beam deposition, and sputtering. Notably, sputtering offers the advantage of depositing AlN films at or near room temperature while achieving a high degree of c-axis orientation. [14] This study investigates the optical and electrical properties of AlN thin films by adjusting the N_2/Ar ratio during the sputtering process, focusing on parameters such as transmission, bandgap, capacitance, and dissipation factor. The findings may pave the way for utilizing sputtered AlN in power electronics applications, including capacitors and transistors.

I. EXPERIMENTS

A. Experimental methods

AlN thin films were prepared on a glass substrate by a sputtering system (Saffron Scientific Equipment Ltd, UK). In the sputtering processes, the power used was kept at 240 W, the pressure was maintained at 1.5 mtorr, and deposition time was fixed at 3600 s. The AlN target has a purification of 99.5% and the diameter is 3 inches. The distance between the centre of the substrate to the centre of the target is 155 mm with a tilting angle of 30 degrees.

II. RESULTS

A. Optical property of AlN thin films

Fig. 1(a) shows that the transmission decreases with the decrease of the ratio of N_2/Ar. Besides, the transmission is larger than the glass substrate when the ratio of N_2/Ar is larger than 57% in the visible light wavelength. When the ratios are in 14% and 7%, the transmission spectrum begins to oscillate, which is due to the thickness increase of AlN thin films. The thickness increases with the decrease of N_2/Ar ratio. This means that the increase of Ar gas will increase the sputtering rate. Fig. 1(b) shows that the bandgap of AlN material is around 5.8 eV when the ratio of N_2/Ar is larger than 0%, which is consistent with the reported value. [14]

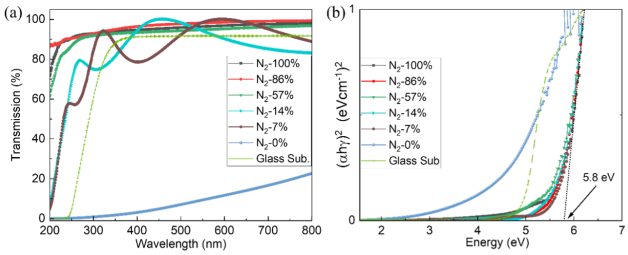

Fig. 1. (a) The transmission spectrum of the prepared AlN sample at different ratios of N_2/Ar. (b) The Tau's plot of the absorption spectrum of AlN prepared at different ratios of N_2/Ar. For comparison, the transmission spectrum and Tau's plot absorption spectrum of the glass substrate used are added as well.

B. The morphological study of AlN thin films

Fig.2 shows the morphology of AlN prepared at different ratios of N_2/Ar. With the decrease of N_2 ratio, the roughness of AlN films first increases then decreases. However, the overall roughness of all the films is less than 1 nm, which shows that AlN prepared by our sputtering system can achieve excellent surface roughness. Smooth film and low roughness are an essential parameter for thin-film semiconductors used as active layers in electronic and optoelectronic devices [15-16].

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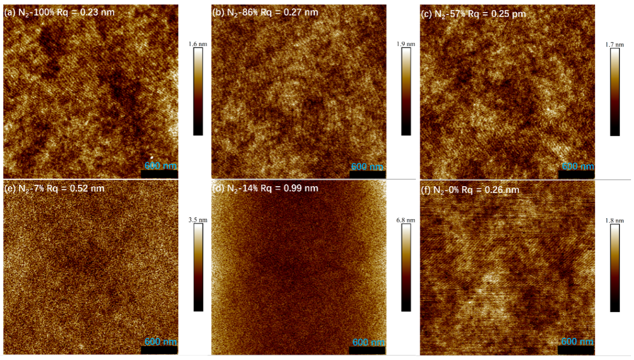

Fig. 2. (a~f) The atomic force microscopic images of AlN samples with ratios of N_2/Ar ranging from 100% to 0%.

C. Capacitors and transistors based on AlN thin films

Fig. 3(a) shows that the capacitance of the capacitor with the structure of glass/ITO/AlN/Ag decreases with the increase of frequency for all samples with the ratio of N_2/Ar larger than 0%. For the sample with the ratio of N_2/Ar equal to 0%, the AlN is a resistor instead of the property of a capacitor. The sheet resistance is 100 kΩ/□. At low frequency, with a value smaller than 100 kHz, the capacitance increases with the increase of the ratio of N_2/Ar. At a higher frequency (>700 kHz), the capacitance increases with the increase in frequency. Based on the capacitance, the thickness of AlN thin films at different conditions can be estimated by equation (1).

$$d = \frac{\varepsilon_0 \varepsilon_r S}{C} \tag{1}$$

Where d is thickness, C is capacitance, S is the area of device, ε_0 is vacuum permittivity and ε_r is relative permittivity. The thicknesses are 44 nm, 52 nm, 68 nm, 83 nm, and 167 nm, which corresponds to 100%, 86%, 57%, 14%, and 7% N_2/Ar ratio, respectively. Fig. 3(b) shows that the dissipation factor increases with the increase of frequency and the ratio of N_2/Ar.

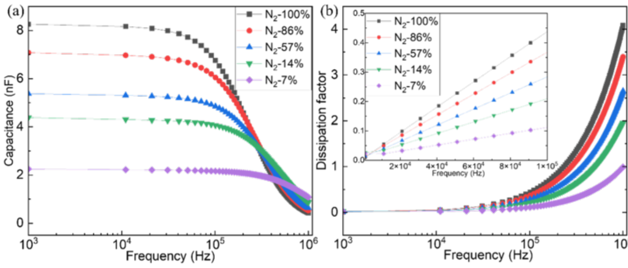

Fig. 3. (a) The relationship between capacitance and frequency for AlN thin films prepared at different ratios of N_2/Ar. (b) The relationship between dissipation factor and frequency for AlN thin films prepared at different ratios of N_2/Ar. The DC voltage was kept at 0 V for all samples.

Furthermore, electrical properties of capacitors based on AlN thin films prepared at different conditions are shown in Fig. 4(a) and the results are summarized at Table I. The breakdown voltage of as-prepared AlN capacitors is in the range of 10 to 73 V and the dielectric strength of corresponding AlN is in the range of 2.3×10^5 to 4.5×10^5 V/mm. Besides, a transistor based on AlN with N_2/Ar ratio of 7% was prepared with AlN as gate material and PEDOT:PSS as channel material. The results of drain-source characteristics under different gate voltage are shown in Fig. 4(b). The modulation under different gate voltage is obvious showing that AlN prepared by our sputtering system is feasible and effective as the gate material.

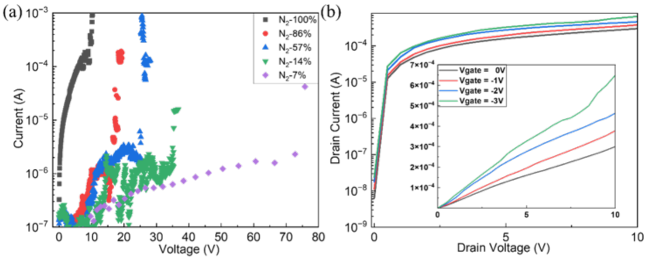

Fig. 4. (a)The leakage current versus DC voltage of capacitors based on AlN thin films prepared at different ratios of N_2/Ar. (b) The drain-source characteristics of the transistor based on AlN with N_2/Ar ratio of 7% as the gate material. The inset is the linear plot of drain-source characteristics. The channel length is 30 μm and channel width is 1000 μm. The electrodes for drain and source are aluminum prepared by thermal evaporation.

TABLE I. THE ELECTRICAL PERPERTIES OF CAPACITOR BASED ON ALN WITH DIFFERENT RATIOS VERSUS COMMERCIALIZED CERAMIC CAPACITORS.

Parameters	**N_2-100%**	**N_2-*86%***	**N_2-*57%***	**N_2-*14%***	**N_2-*7%***	***MLCC***[b]	***SLCC***[c]
Thickness between electrodes (nm)	44	52	68	83	167	3000000	34000000
Capacitance (nF)@10^3 Hz	8.3	7.1	5.4	4.4	2.2	10	1
Volumetric density (μF/mm^3)	42	30.3	17.6	11.9	2.9	0.00012	
% ΔC/V	~1.2%	~2.8%	~0.4%	~0.3%	~0.1%	-	-
ESR (Ω) @10^3 Hz	245	1329	1426	700	3600	-	-
Leakage Current (mA)[a]	0.28	0.026	0.004	0.003	0.002	-	-
Breakdown Voltage (V)	10	18	25	35	73	6000	65000

[a] Breakdown voltage at room temperature.

[b] Cited from reference [17].

[c] Cited from reference [18].

D. The effect of DC voltage on the capacitance of capacitor based on AlN thin film

Fig. 5(a) shows that at low frequencies ranging from 1 kHz to 10 kHz, the capacitance increases with the increase of applied DC voltage. Fig. 5(b) shows that variation of the applied DC voltage has little impact on the dissipation factor at the corresponding frequency range. Besides, the capacitance-voltage curve measurement further confirms the result from Fig. 5(a) as shown in the inset in Fig. 5(b). The origin of the increase of capacitance versus applied DC voltage can be attributed to the piezoelectric property of AlN.[19] Since the thickness of the AlN thin film is around 44 nm, the dipoles can be aligned once the DC voltage is applied. The number of aligned dipoles increases with the applied DC voltage.

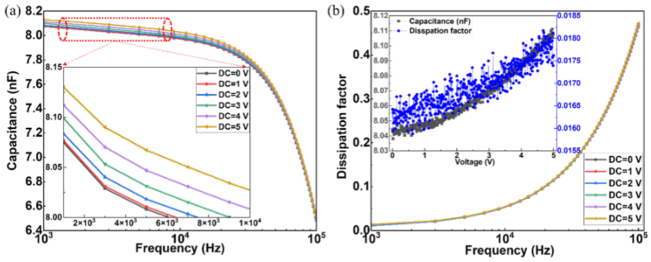

Fig. 5. (a) The relationship between capacitance and frequency for AlN thin films, measured at different applied DC voltages ranging from 0 to 5 V. The inset in Fig.5(a) shows the details of capacitance with frequency varying from 1 kHz to 10 kHz at different DC voltage. The ratio of N_2/Ar for the measured sample is 100%. (b) The relationship between the dissipation factor and frequency for AlN thin films, measured at different applied DC voltages ranging from 0 to 5 V. The inset in Fig.5(b) shows the relationship between the capacitance and dissipation factor versus the applied DC voltage.

III. CONCLUSIONS

We have successfully fabricated the AlN thin films with extremely high transmission in visible range by tuning the ratio of N_2/Ar via our sputtering system. Besides, the capacitance based on the AlN thin film can be tuned by the applied DC voltage due to the piezoelectric property. We achieved the optimal dielectric strength of the AlN thin film which is ~ 4.5×10^5 V/mm and it can be used as the gate material in transistors. The results show that the prepared AIN samples have a promising application in power capacitors as well as gate materials in thin film transistors.

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