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Admittance study of MIS structures with pulsed laser deposited AlN films

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MIS structures of Al/AlN/Si have been studied by applying frequency-dependent admittance measurements at zero bias voltage. Thus, the dependence of the capacitance on the test voltage frequency has established the existence of regions of constant capacitance, where the interface and bulk electron traps do not influence the capacitance measurements. Additionally, the contributions of the hopping mechanism of charge transport and the inter-trap tunnelling have been evaluated from the alternating current conductance dispersion.

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1. Introduction

Aluminium nitride (AlN), a high-*k* semiconductor material, is considered as a potential substitute for silicon oxide as a gate dielectric in MOS electronic devices. Since bulk AlN has a dielectric constant of $10\varepsilon_0$ compared to $3.9\varepsilon_0$ for SiO_2 [1], the larger equivalent thickness of AlN ensures the reduction of leakage currents through the gate. The concentration and nature of film defects play an important role in the electro-physical properties of AlN-Si MIS structures, and they are strongly dependent on preparation methods. The most frequently used AlN thin film deposition techniques are magnetron sputtering [2], molecular beam epitaxy [3] and pulsed laser deposition (PLD) [4]. The electrical properties of MIS structures with such AlN films have been studied mainly by considering the fixed dielectric charge and estimating the specific resistivity of the AlN films in AlN-Si MIS capacitors [5] and AlN-Si MISFETs [6]. An important parameter also is the concentration of defects that are responsible for charge transport in AlN films. Due to such defects, the capacitance and dielectric loss of an AlN film increases already at considerably low frequencies. Admittance studies of Schottky and MIS structures at different frequencies of the test voltage can reveal this effect [7,8], as well as giving information about the densities of interface and bulk traps [9,10] and the current transport mechanism in MIS structures [9,11].

In this paper, we present a study on the electrical properties of AlN thin films by means of complementary measurements of capacitance and conductance at the ac test signal voltage for different frequencies. The investigated AlN films were synthesized in nitrogen ambient by PLD and were metallized to form MIS structures with AlN gates. The frequency dispersion of the film capacitance and the charge transport mechanism through the film are considered in relation to the deposition conditions.

2. Materials and methods

AlN films were prepared by pulsed laser deposition on p-type (100)Si substrates. During deposition, the substrates were heated to 800°C, the temperature at which the native SiO_2 covering the wafers is known to decompose. This temperature also proved to be high enough to promote the crystalline growth of AlN layers [12]. The target, consisting of polycrystalline AlN with 99% purity, was rotated at 0.3 Hz during multi-pulse laser irradiation, to avoid piercing. The target-substrate distance was 4 cm. A shutter was introduced between the target and the substrate once the first 1000 laser pulses had been applied. In this way, the impurities and defects still present on the target surface could be collected and removed before reaching the deposition area. The deposition of one structure was performed by applying 20,000 laser pulses generated by an UV KrF* pulsed laser source (248 nm, 7 ns) operating at a repetition rate of 2 Hz. The laser energy was set at 85 mJ/pulse. A film thickness of about 600 nm, i.e. suitable for the subsequent optical characterization, was obtained. The ambient nitrogen pressure was kept at 0.1, 5 or 10 Pa.

For the electrical measurements, metal-AlN-silicon capacitors were formed by vacuum evaporation through a metal mask of Al dots on the AlN surface, and a continuous Al film was vacuum evaporated on the Si wafer backside.

Usually, the capacitance values of the MIS structures are measured up to 1 MHz, however, we extended the upper limit to 50 MHz to establish the stability of the structure with frequency. Room temperature admittance measurements were carried out in two frequency ranges, namely 1 – 500 kHz and 500 kHz – 50 MHz, on Tesla impedance meters of types BM 507 and BM 508, respectively. No bias voltage was applied to the MIS structures. The impedance meters measured simultaneously the impedance amplitude $|Z_m|$ and the phase angle φ_m. In order to obtain the real values for the AlN MIS structure, the residual parallel impedance amplitude Z_{in} and the phase angle φ_{in} of the sample holder should be taken into account according to $1/Z_{MIS} = 1/Z_m - 1/Z_{in}$. The latter were measured before each frequency step.

The conductance, G_f, and capacitance, C_f, of the MIS structure were calculated from the equations:

$$G_f = \frac{\cos\varphi_m}{|Z_m|} - \frac{\cos\varphi_{in}}{|Z_{in}|} \tag{1a}$$

$$C_f = \frac{1}{\omega}\left(\frac{\sin\varphi_m}{|Z_m|} - \frac{\sin\varphi_{in}}{|Z_{in}|}\right) \tag{1b}$$

3. Results and discussion

Typical capacitance dispersion curves are presented in Fig. 1, where the C_f values as a function of angular frequency ($\omega=2\pi f$) are given. With increasing signal frequency the C_f value gradually decreases. Two regions of sharp decrease of the C_f values, and a steady state region, could be distinguished. The width and position of the region for a comparatively constant capacitance value depended on the nitrogen pressure in the deposition chamber - the higher the pressure the shorter this region was. In the dispersion curve, this was observed at 1-10 MHz for 0.1 Pa, 8 kHz - 1.3 MHz for 5 Pa and 20 - 100 kHz for 10 Pa. For all the MIS structures, above 16 MHz the capacitance value dropped sharply toward zero.

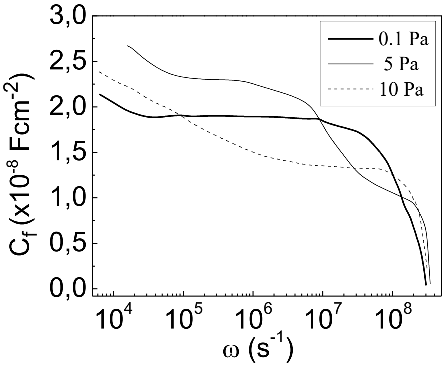

Fig. 1. Film capacitance, C_f, versus signal frequency at zero bias voltage.

The above observations clearly showed that interface and bulk traps have a strong influence on the measured capacitance. Therefore, to eliminate the influence of these traps on the measured C – V characteristics, one needs in every case to measure the admittance characteristics in an extended frequency range, in order to establish the frequencies at which interface and bulk traps do not contribute to the measured capacitance of the particular MIS structure under investigation.

The measured conductance of the structures as a function of the test frequency is shown in Fig. 2. A gradual increase in the conductance is observed with increasing the testing frequency up to 10 MHz, while above 10 MHz a sharp increase takes place.

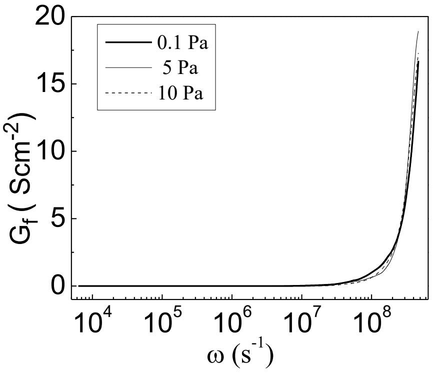

Fig. 2. Film conductance, G_f, versus signal frequency at zero bias voltage.

Additional information about the electron transport in the films can be obtained by considering the dependence of the conductivity on the angular frequency ω, given by $\sigma(\omega,T) = A\omega^s$, where A and s are temperature-dependent parameters. The appearance of a frequency dependence is an indication that ac hopping conduction takes place in the film. The index s is related to the barrier height for electrons and its value reveals the kind of carrier transport mechanism through localized states, whether it is nearest neighbor hopping or variable range hopping. The variable range hopping mechanism can be distinguished from the other one by its different temperature dependence [13]. The index s can be obtained from the slope of the linear parts of the $\ln(G_f)$ versus $\ln(\omega)$ plots.

A typical dependence is presented in Fig. 3 for structures with AlN deposited at 0.1 Pa. In the frequency range 5 - 200 kHz, the s value is equal to 1.1, indicating that in this range the conductivity is proportional to ω. Above 200 kHz, the dependence changes in slope to 2. For the films deposited at the other two nitrogen pressure values, the exponent s is also close to 1 in the 5 - 200 kHz range and tends to be higher for the higher frequencies. Similar values of the s index have been observed by other researchers, as for ceria films it is reported to be 0.95 and approaching 1, when the measurement temperature decreases [14]. For an Al/AlN$_x$/Al structure with rf magnetron sputtered AlN$_x$ films [13] the reported exponent s values are 0.62 - 1.31 in the frequency range 100 Hz – 20 kHz. In refs [14] and [11] the conduction dependence $G_f \sim \omega^s$ is explained as correlated barrier hopping of electrons from occupied traps to unoccupied states in the insulator band gap.

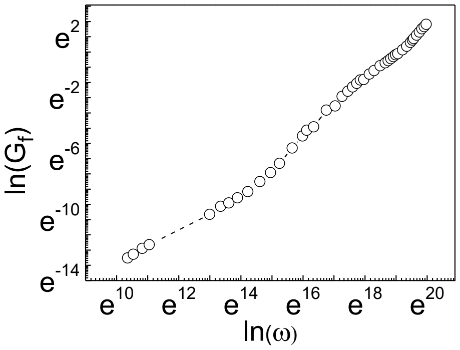

Fig. 3. Natural logarithm of film conductance, Gf, versus ln(ω) and linear approximation of the sub sections of the dispersion.

Our earlier investigations [15] of the I-V characteristics of these AlN MIS structures in accumulation have shown that their conductivity does not depend on temperature in the 77 – 300 K range. Therefore, the conductivity mechanism is of tunnelling type, more precisely inter-trap tunneling [16]. Because of the temperature independence and the proportionality of G_f to ω, we can conclude that the variable range electron hopping is transformed to the hopping toward the next nearest unoccupied trap and current through the AlN film is carried out by inter-trap tunneling.

The observed phenomenon at frequencies above 300-500 kHz, i.e. where the index s values become higher than 1, cannot be explained from the experiments presented, and needs further investigation.

4. Conclusions

From the study of the room-temperature capacitance dependence on the test frequency of MIS structures with PLD AlN films deposited at different nitrogen pressures, the existence of a wide frequency region, where the capacitance is constant, have been established. The frequency dispersion of the film conductivity has revealed that up to 200 kHz the conductance is proportional to the signal frequency, as the dependence exponent index s is close to 1. In this frequency region, the carrier transport mechanism is inter-trap tunnelling, i.e. the electron hopping is toward the next nearest unoccupied trap. The explanation of the observed high index s values ($1<s<2$) at higher frequencies (0.5 – 40 MHz) needs further investigation.

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References

[1] M. A. Dubois, P. Mulart, Appl. Phys. Lett. **74**, 3032 (1999).
[2] A. Fathimulla, A. A. Lakkani, J. Appl. Phys. **54**, 4586 (1983).
[3] Z. V. Fan, G. Rong, N. Newman, J. Smith, Appl. Phys. Lett. **76** (14), 1839 (2000).
[4] Y. E. Lu, Z. M. Ren, T. C. Chong, B. A. Cheong, S. K. Show, J. P. Wang, J. Appl. Phys. **87**, 1540 (2000).
[5] T. Adam, J. Kolodzey, C. P. Swann, M. W. Tsao, J. F. Rabolt, Appl. Surf. Science **175–176**, 428 (2001).
[6] K. S. Stevens, M. Kinnibourgh, A. F. Schvartzman, A. Ohtani, R. Beresford, Appl. Phys. Lett. **66**, 3179 (1995).
[7] M. Zhu, J. Zhu, J. M. Liu, Z. G. Liu, Appl. Phys. A **80**, 135, (2005).
[8] J. Zhu, Z. G. Liu, M. Zhu, G. L. Yua, J. M. Lin, Appl. Phys. A **80**, 321 (2005).
[9] A. A. Dakhel, Appl. Phys. A **80**, 1033 (2005)
[10] J. H. Kim, W. J. Lee, S. G Yoon, Integrated Ferroelectrics **68**, 63 (2004).
[11] F. Abdel – Wahab, J. Appl. Physics **91**, 265, (2002).
[12] W. T. Lin, L. C. Meng, G. J. Chen, H. S. Liu, Appl. Phys. Lett. **66**, 2066 (1995).
[13] R. D. Gould, S. A. Awan, Thin Solid Films **469–470**, 184, (2004).
[14] Z. T. Al-Dhan, C. A. Hogarth, Internat. J. Electron. **63**, 573 (1987).
[15] S. Simeonov, S. Bakalova, E. Kfedjiiska, A. Szekeres, S. Grigorescu, A. Popescu, C. Cojanu, F. Sirma, G. Socol, I. N. Mihailescu, 29-th Intern. Semicond. Conf. CAS, Sinaia, 2006, Vol. 2, p. 261.
[16] S. Simeonov, I. Yourukov, E. Kafedjiiska, A. Szekeres, Phys. stat sol. (a) **201**, 2966 (2004).

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