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DC STRESS EFFECT ON CHARGE DISTRIBUTION IN SPUTTERED AlN FILMS

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Abstract: Thin films of aluminum nitride (AlN) were deposited on silicon substrates by DC reactive magnetron sputtering. Post deposition annealing of some of the deposited films was carried out at 600 °C for 30 minutes in nitrogen ambient. At higher voltage stress, the shift in flat band voltage was more in a direction of positive voltage sweep. In annealed samples the interface trap density (D_{it}) is lower than in the unannealed samples, but increases with DC voltage stress. There was no significant change in D_{it} for both unannealed and annealed samples, even after a stress of 15 V. However D_{it} reduces to 1.7×10^{11} $cm^{-2}eV^{-1}$ when the annealed samples were further subjected to post metalization annealing. In both the annealed and unannealed samples, there was a rapid increase in current up to a field of 0.1 MV/cm. Thereafter the current became quasi saturated.

Key words: AlN, Sputtering, Annealing, DC stress.

1. Introduction

Aluminum nitride (AlN) films have found widespread applications due to their excellent material properties such as wide band gap, low electrical and high thermal conductivity, high melting temperature, hardness and good chemical stability [1-4]. It is important to study the electrical properties of AlN/Si interface in view of integrating signal-processing circuits [5]. Where aluminum nitride is found to be an excellent insulating material for ICs and also enhances device lifetime and efficiency by increasing heat dissipation due to its high thermal conductivity [6]. Though AlN is technologically one of the advanced dielectric materials, not much work has been done to characterize the effect of stress voltage and effect of post deposition annealing on bulk as well interface properties of the AlN/Si. The present work is concerned with the effect of annealing as well as stress on the sputtered AlN films. AlN films have been deposited by DC reactive magnetron sputtering, because of its simplicity, low thermal budget, low cost and the ability to obtain good quality films with desired properties [7,8].

2. Experimentals

Aluminum nitride thin films were deposited by direct-current (DC) reactive magnetron sputtering (Model Alcatel SCM 450) from a pure aluminum target in a high purity argon and nitrogen gas mixture. The substrate was silicon (100), p-type, 3-5 ohm.cm. Prior to AlN deposition Si wafers were cleaned by RF discharge (100 W) for 10 minutes in argon atmosphere. The substrate temperature was kept at 250 °C during deposition and applied DC power for sputtering was 60 W. Thickness of the deposited films (S-1), measured by nondestructive optical technique with NANOSPEC AFT (model 210), was found to be 2250 Å. When the AlN film depositions were completed, some of the samples were annealed in the furnace at 600 °C for 30 minutes in presence of nitrogen gas (S-2). Slow cool down process was performed in order to avoid any increase of defect density. Subsequently the samples were metallized by aluminum with the help of shadow mask for the fabrication of Metal-Insulator-Semiconductor (MIS) structure. Post-metalization annealing (PMA) of samples S-1 and S-2 were carried at 350 ºC for 30 minutes in an inert (argon) ambient inside a chamber with 3×10^{-3} mbar pressure. Before annealing base vacuum was brought down to 2×10^{-6} mbar.

High frequency (1 MHz) C-V measurements with a HP4028A C-V meter were carried out by applying an AC signal across the sample while a DC bias was simultaneously swept from negative to positive voltages. The MIS capacitors were subjected to static (DC) voltage stress of different potentials for a duration of 10 minutes. Current-Voltage (I-V) measurements were carried out using a Keithley (Model 619) electrometer at room temperature. The experiments are carried out for both unannealed and annealed samples.

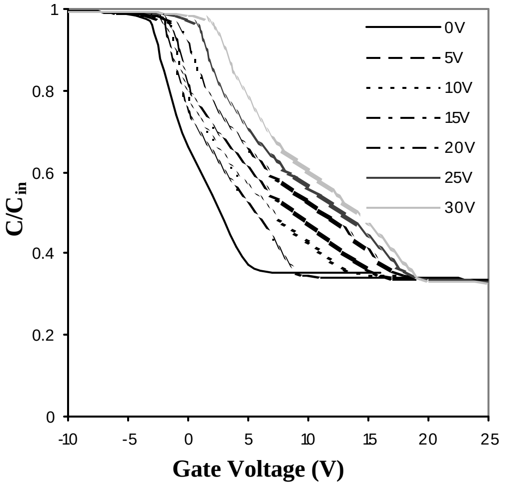
3. Results and Discussion

The C-V curves for unannealed (S-1) and annealed (S-2) samples with DC stress are shown in Fig.1 and Fig. 2, respectively. From the figures, it is quite apparent that the flatband voltage (V_{fb}) shifts towards a higher positive value with stress. The less stretch out of the C-V curve for annealed samples in comparison to the unannealed indicates a reduction of the interface trap density as a result of annealing. Fixed insulating charge (Q_{in}) densities were calculated using the standard equation [9]:

$$Q_{in} = C_{ox} (f_{ms} - V_{fb}),$$

Where C_{ox} is oxide capacitance per unit area and f_{ms} is the metal–semiconductor work function difference. As a result of annealing the changes in fixed insulating charge density can be attributed to the generation of negative charges. In addition to this, annealing results in the structural relaxation of the film, which in turn, gives rise to a further reduction in interface state density.

The variation of flat band voltage, which is always associated with the fixed insulating charges present in the bulk of the insulating layer is plotted against the applied stress voltages varying from 5 V to 30 V, in Fig. 3. The flat band shift does not show any significant variation upto a stress voltage of 20 V; varying significantly, thereafter probably due to the breaking of molecular bonds, which create additional charges inside the films as reported by Deal [10]. It is also found, the variation of flat band shift is more prominent in the annealed sample in comparison to the unannealed sample. The increase of Q_{in} in S-2 sample may be due to the incorporation of impurities from the



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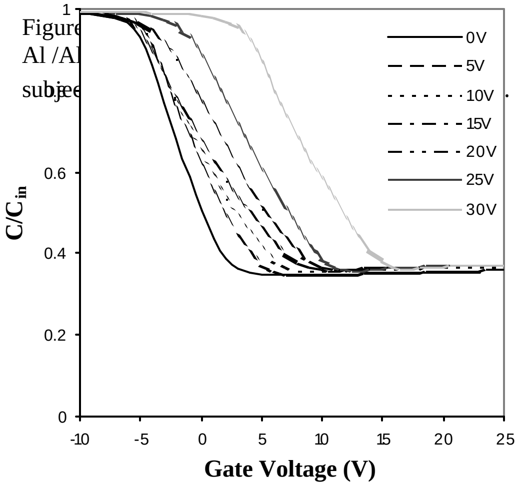

Figure 2. High frequency C-V characteristics of Al/AlN/Si (annealed, S-2) MIS capacitors subjected to voltage stress of different magnitudes.

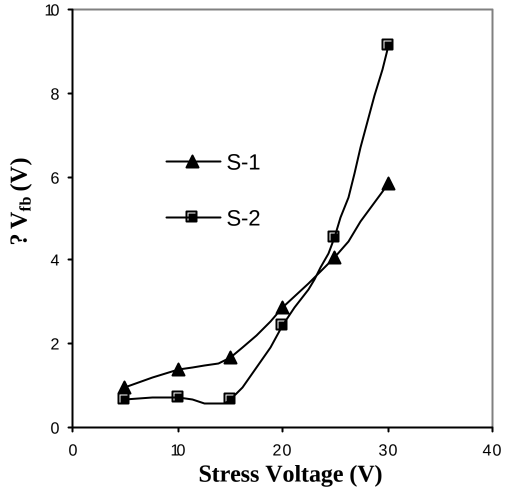

Fig. 3. Shift in flat band voltage with stress voltage

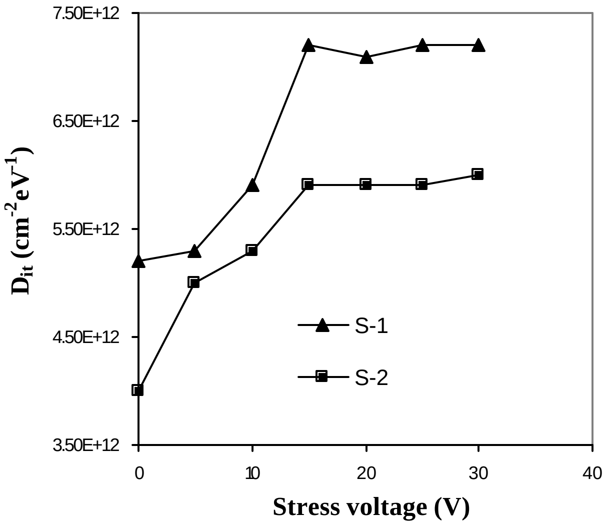

Figure 4. Interface state density versus the stress voltage for unannealed (S-1) and annealed (S-2) samples.

furnace prior to annealing. On the other hand, from Fig.4 the interface electronic state densities were found to be 5.2×10^{12} cm^{-2}eV^{-1} and 4×10^{12} cm^{-2}eV^{-1}, for unannealed (S-1) and annealed (S-2) samples, respectively. The large density of trapped charges at the interface (D_{it}) may be due to the "ion cleaning" prior to film deposition [11]. The increase in D_{it} during stress may be due to the presence of more structural defects at the Si/AlN the interface also at higher stress potentials (> 15 V), there is hardly any change in the interface trap density. This can be inferred from measured saturated current density discussed later in the text.

Fig. 5. shows the C-V plots, which represents the various annealing effects such as post deposition and post metalization annealing. It is evident from calculation that magnitude of the fixed charge density (Q_{in}), which was less than 1.7×10^{11} cm^{-2}, increased after annealing. In unannealed sample, the interface electronic state density decreases from 5.2 × 10^{12} cm^{-2}eV^{-1} (S-1) to 4.2 × 10^{11} cm^{-2}eV^{-1} (S-1P) and for annealed sample, it changes from 4 × 10^{12} cm^{-2}eV^{-1} (S-2) to 1.7 × 10^{12} cm^{-2}eV^{-1} (S-2P) after PMA. This may be due to the saturation of dangling bonds by diffused hydrogen at the AlN/Si interface. Hydrogen may come from the moisture during post metalization annealing process [9].

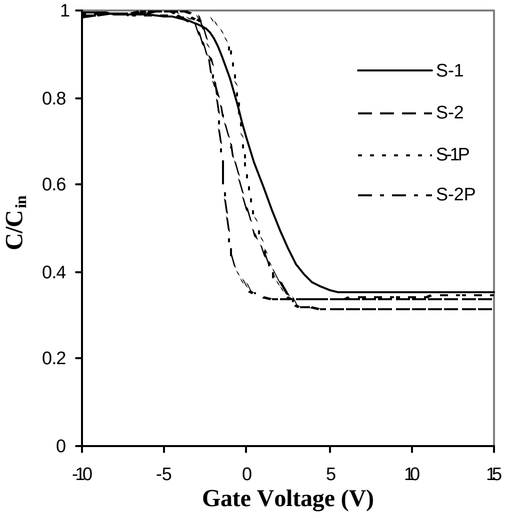

Figure 5. High frequency C-V plot of Al/AlN/Si structure after different heat treatments. (S-1P and S-2P stands for PMA of samples S-1 and S-2 respectively).

The leakage current as a function of applied field for different stresses is shown in Fig. 6 and Fig. 7. Leakage current initially increases rapidly with an increase in applied electric field up to 0.1MV/cm, thereafter it increases very slowly with applied voltage. This 'quasi-saturation' of the current may be due to charge trapping leading to the creation of an internal electric field, which opposes the applied electric field and subsequently limiting the carrier conduction [12]. The conduction mechanism is driven by the electric field, which in fact reduces the barrier height on one side of the trap, by which the current carriers may escape from the trap and enter into the quasi-conduction band of the insulator, giving rise to the current [13]. After annealing the decrease in current can be attributed to the decrease in localized state density in the bandgap of the AlN layer due to crystallization [14]. A higher leakage current is observed for unannealed samples. This may due to the presence of high density of defects at the interface. After a stress of 15 V, there is no significant change in the I-V characteristics, indicating that there is no further activation of defects at the interface, which became became saturated after this stress (Fig. 3). In the large bandgap insulating materials, the mechanism of conduction is strongly dependent on the structure of the material, resulting from the deposition conditions and process parameters [15]. Deviation from the stoichiometric composition gives rise to more localized

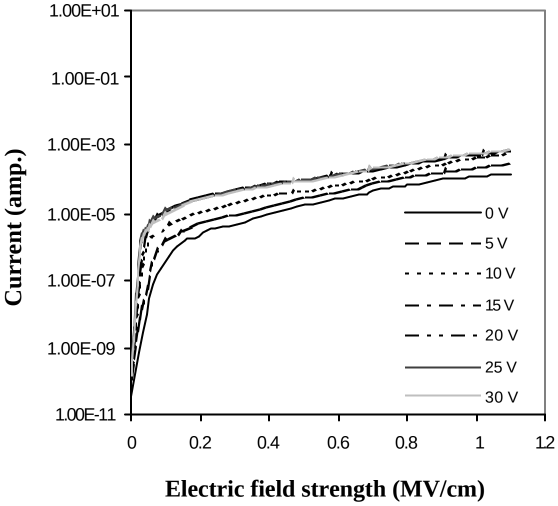

Figure 6. Current versus the electric field for the Samples (unannealed, S-1) stressed by different magnitudes of voltage. (After a stress of 15 V, the curves overlap at higher applied fields).

states through which carriers are transported, resulting in an increase in the conductivity [16]. The lower DC conductivity in case of the annealed samples (S-2) is indicative of the structural improvement of the material. Free carrier densities are extremely low in insulators and bulk limited electronic conduction takes place with the motion of electric charges through localized states. Engelmark et al. [17] reported that the current conduction is Poole-Frenkel type. The increase in leakage current with bias implies that the mechanism controlling the current through the insulating film is field-enhanced excitation of trapped charge carriers into the conduction band. The trapped charges during stress may increase the field inside the film and lower the barrier for current conduction, which results in an increase in current in stressed devices [18].

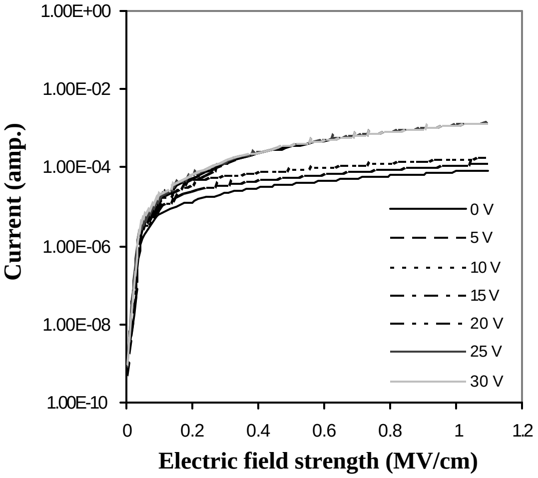

Figure 7. Current versus the electric field for the amples (annealed, S-2) stressed by different magnitudes of voltage. (After a stress of 15 V, the curves overlap at higher applied fields).

4. Conclusion

It has been experimentally shown that the electrical properties of Al/AlN/Si (MIS) structure measured by C-V and I-V techniques exhibit improvement after heat treatments. Applied voltage stress shifts the C-V plots towards the positive voltage, which is an indicative of increased bulk charge densities. The unannealed AlN film reveals large interface trap density getting reduced by annealing and further reduced by post metalization annealing. These trap density become saturated at higher stress voltages for both the annealed and unannealed samples. At lower electric field strengths, current increases rapidly and afterwards it becomes quasi-saturated.

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