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Impact of film thickness on the temperature-activated leakage current behavior of sputtered aluminum nitride thin films☆

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ABSTRACT

Aluminum nitride (AlN) is a material of significant importance in the field of micro electro-mechanical systems (MEMS) due to its piezoelectric properties and its use as passivation layer. This work provides a comprehensive study on the film thickness dependence of the temperature activated leakage current behavior of sputtered aluminum nitride thin films. The thickness ranges from 40 to 400 nm, providing insight into the electrical characteristic of AlN thin films for thickness values typically used in MEMS devices. The leakage current shows a highly symmetrical behavior for both positive and negative bias directions due to a tailored silicon substrate pre-treatment process. At low electric field strengths $E \leq 0.1$ MV/cm, the leakage current is dominated by ohmic behavior, while for $E \geq 0.3$ MV/cm, the leakage current is controlled by a Poole–Frenkel mechanism. Both the defect-related barrier height and the defect density for the Poole–Frenkel regime can be extracted from arranging the data in an Arrhenius configuration. The barrier height shows no significant influence of film thickness. However, the defect density correlates directly with the leakage current level of the film and thus dominates the electrical behavior. The defect density increases significantly with increasing film thickness. As the thin films were deposited under nominally unheated substrate conditions the substrate temperature increases with increasing sputter time. A simple model is proposed in order to provide a qualitative understanding of the observed effect by assuming a substrate temperature driven redistribution of defect states within the band gap of aluminum nitride thin films.

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1. Introduction

Aluminum nitride (AlN) is a group III-nitride material of significant importance in the field of micro electro-mechanical systems (MEMS) [1]. It is commonly applied as an active layer in sensor and actuator applications due to its piezoelectric and high temperature properties [2] as well as its compatibility toward standard CMOS processes. Besides its use as active material AlN is also often used as passivation layer due to its high thermal and chemical resistance, good thermal conductivity (~2 W/cm K) and a good thermal match to silicon [3]. The high acoustic velocity of up to 6000 m/s also facilitates the usage of AlN thin films in bulk or surface acoustic wave applications [4,5]. Different deposition techniques are applied for the synthesis of AlN thin films such as molecular beam epitaxy and plasma enhanced chemical vapor deposition [6], atomic layer deposition [7] and pulsed laser deposition [8]. In addition, reactive DC magnetron sputtering, being the most commonly used deposition technique, offers low deposition temperatures and good process control. This results in a high relevance of this process for industrial applications, making it well suited for MEMS device fabrication [9]. For all these reasons, the AlN films in this study were deposited using reactive DC magnetron sputtering.

The usage of aluminum nitride as insulation or passivation layer in MEMS devices requires low leakage currents under DC biased conditions in order to minimize crosstalk effects or energy loss and ensure proper device operation. Understanding the underlying leakage current mechanism also is of great importance in order to predict the behavior at elevated temperatures or electric field strengths. In the past, several publications addressed this issue using different substrates and device configurations such as metal–insulator–metal (MIM) or metal–insulator–semiconductor (MIS) [6,10–13]. It can be concluded from these investigations, that the dominating conduction mechanism seems to be strongly dependent on the applied electric field. At low field strengths, the leakage current is mainly of ohmic nature, while being predominantly of Poole–Frenkel type at higher field strengths [14,15]. It

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is the objective of this work to investigate the influence of film thickness on the temperature-activated leakage current behavior and to identify the dominating leakage current mechanisms in the aluminum nitride thin film. Therefore, the film thickness d is varied by one order of magnitude from 40 to 400 nm and the temperature T is increased from room temperature up to 300 °C in air. To the best of our knowledge, such a systematic investigation has not been carried out in the past and will therefore provide new insight into the electrical behavior of AlN thin films.

2. Experimental details

In order to investigate the influence of the thin film thickness on the leakage current I, six AlN samples with varying d were prepared. Monocrystalline n-type (100) silicon wafers with a resistivity of about 50 Ω cm serve as substrates providing well-defined surface characteristics as well as sufficient electrical conductivity. The AlN was deposited in a production type DC magnetron sputtering machine by "Von Ardenne" (LS 730). Using buffered hydrofluoric acid, the native surface oxide was removed prior to deposition. Previous investigations showed, that the electrical properties can be enhanced significantly by introducing a substrate-related sputter back-etch step prior to the AlN deposition [16]. For this purpose, the silicon substrates were etched for 5 min in pure argon atmosphere at a chamber pressure p = 6 μbar, a plasma power P = 500 W and a target-substrate distance d_{ST} = 65 mm. Prior to each deposition process, the 6″ aluminum target (purity 5N) was pre-sputtered at closed shutter position for 10 min at p = 6 μbar, P = 800 W and d_{ST} = 65 mm for purification purposes. An additional chamber conditioning step was applied afterwards to increase process stability using the deposition conditions while maintaining the closed shutter position. Finally, the AlN thin films were deposited at p = 4 μbar, P = 800 W, d_{ST} = 65 mm under pure nitrogen (purity 6N) atmosphere at a constant flow rate of 50 sccm. These deposition parameters were chosen, as previous investigations showed an increase in film quality at low chamber pressure and high plasma power level [17]. The sputter times t_S for the different samples were 120, 209, 299, 598, 897 and 1196 s, resulting in corresponding film thicknesses of d = 40, 70, 100, 200, 300 and 400 nm, respectively.

To form circular electrical contact pads, a 10 nm thin chromium film serving as an adhesion promoter and a 300 nm thick gold layer were e-beam evaporated onto the AlN thin film and patterned using a lift-off process. Aluminum with a thickness of 800 nm was sputter deposited onto the wafer backside to provide an electrical back contact.

The leakage current over voltage (I–V) measurements were performed using an Agilent B2911A source-meter. After each applied voltage step, the current transient $I(t)$ is measured in order to determine the steady state current [17]. The measurement frequency was fixed at 2 Hz, which is a good compromise between a low signal-to-noise ratio and a high time resolution. The maximum applied voltage was chosen such that the maximum electric field E in the thin film is limited to 0.5 MV/cm according to $E = U/d$. The measurement procedure is divided into two parts. In each part, the voltage is first applied in positive bias direction and ramped up to the maximum voltage and down to zero again. Second, the same ramp is applied in negative bias direction. The first part consists of a fast voltage sweep for stabilization purposes [17]. The step size is 10% of the maximum voltage and the transient is measured for 10 s. In the second part, the I–V measurements are done, but the voltage step size is reduced to 2% of the maximum voltage and the corresponding dwell times are 30 s to minimize relaxation effects. The average value of the last 20 data points (last 10 s of the transient $I(t)$) gives the steady state current $I(U)$. One sample is measured for each film thickness due to the time consuming measurement procedure. However, pre-investigations showed a good reproducibility within samples from the same deposition run.

The electrodes on the front side with surface area $A = \pi \times 250^2\ \mu m^2$ were contacted using contact needles on a wafer probe station PM 8 from SÜSS Microtec and the backside was grounded. The temperature dependent measurements ranging from 25 °C up to 300 °C were performed in air using a chuck with integrated temperature control (ATT A300). The leakage current density is calculated as $J = I/A$. Within the scope of this work, the dielectric constant of AlN is assumed as $\varepsilon_r = 10$, which is reasonable as reported recently [17].

The scanning electron microscope (SEM) measurements were performed using a Hitachi SU8030 at 5 kV acceleration voltage. The samples were prepared separately at similar deposition conditions and the thickness measured from cross section micrographs. The substrate holder temperature during thin film deposition was measured in situ using a DIAS PYROSPOT Series 10 pyrometer. The pyrometer is focused on the backside of the substrate holder and is thus shielded from the plasma radiation. The actual sample temperature is probably slightly higher compared to the temperature of the substrate holder due to the e.g. the thermal resistance present at the sample-holder interface.

The analysis of the grain size was performed with the program ImageJ [18]. The grain positions were obtained by detecting local brightness maxima and the grain boundaries by following the local minima enveloping the corresponding maxima.

3. Results

Fig. 1 yields the J–E characteristics for all samples. The surface pre-treatment using a sputter-etch step results in a high symmetry of positive and negative bias direction [16]. Therefore, only the positive direction is shown in this graph. The leakage current density increases strongly with the film thickness by two orders of magnitude. This effect is addressed in more detail below and in Section 4. Samples with different film thickness d exhibit the same behavior and are basically only shifted along the J-axis. This indicates that the dominating leakage current mechanisms are independent of d. As shown in Fig. 1, the leakage current density at low electric fields $E \leq 0.1$ MV/cm can be described by an ohmic behavior according to

$$J_{\Omega}(E, T) = \sigma E \exp\left[-E_A/kT\right] \tag{1}$$

with the thermal activation energy E_A, the conductivity σ and the Boltzmann constant k [19]. At higher field strengths $E \geq 0.3$ MV/cm, J is dominated by a Poole–Frenkel type defect hopping mechanism according to

$$J_{PF}(E, T) = C_{PF} E \exp\left[-\frac{q\phi_B - \beta\sqrt{E}}{kT}\right] \tag{2}$$

with the defect-related barrier height ϕ_B. For $q\phi_B - \beta\sqrt{E} \ll kT$, the factor C_{PF} can be expressed as

$$C_{PF} = qn_0\mu \tag{3}$$

with the elementary charge q, the defect concentration n_0 and the charge carrier mobility μ [20]. The coefficient β is defined as

$$\beta = \sqrt{\frac{q^3}{\pi\varepsilon_0\varepsilon_r}} \tag{4}$$

with the dielectric constant in vacuum ε_0. Contributions to the leakage current density by tunneling effects can be neglected due to the strong temperature impact on J as shown in Fig. 1.

The temperature dependence of the mobility μ is negligible, due to the strong temperature influence of the exponential term in Eq. (2). Typical values are between 200 and 70 cm^2/V s in the

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