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Tailored wafer holder for a reliable deposition of sputtered aluminium nitride thin films at low temperatures

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ABSTRACT

Active actuated resonant micro-electro-mechanical-systems (MEMS) are used for sensing purpose like topography analysis and viscosity sensors. Those applications require straight beams and they rely on controlled film stress of the involved thin films, e.g. the active piezoelectric aluminium nitride (AlN) layer. The AlN consists of aluminium and nitrogen and is deposited with a reactive sputter process. The deposition process heats up the substrate and therefore the wafer bow of the substrate causes a variation of the thermal connection between wafer and sample holder. This goes along with undefined film stress of the AlN layer. In order to minimize the derivation of film stress, the reduction of substrate temperature and the enhancement of thermal connection between substrate and substrate holder is targeted. Therefore a novel clamped substrate holder is designed. High thermal connection to the ambient equipment, equal heat distribution and clamping of wafer stabilize the deposited AlN layer. By examining the layer stress and applying an acid structuring method, an improvement of deposited film is observed. A long term study with AlN deposition with thicknesses of 0.5 µm, 1.0 µm and 2.0 µm on silicon wafers was made to confirm the enhancement.

1. Introduction

In the last decades a huge number of silicon based MEMS (micro electro-mechanical systems) sensors and actuators were developed. Based on this effort, a broad range of different application scenarios such as sensors for the detection of chemical [1–3] or physical quantities [4–7] is covered, leading to selected MEMS devices which are even commercially available today. Despite their individual and application-specific design most approaches make use of either membranes or cantilevers as functional key components. Furthermore, to increase the sensitivity, many MEMS devices are operated in resonance by applying either electro-magnetic, capacitive or piezoelectric elements for excitation [8].

When making use of the latter transducer principle, a typical design consists of an aluminium nitride layer (AlN) sputter deposited on silicon (Si) and released with a support structure from the substrate [9–11]. Despite moderate piezoelectric constants [12,13], AlN is often preferred compared to zinc oxide (ZnO) or lead zirconate titanate (PZT) as functional material, as it is compatible with standard complementary metal oxide semiconductor (CMOS) microfabrication processes [14] and offers a high temperature stability [15,16]. Most promising application scenarios for cantilever or membrane-type micromachined AlN devices are as density and viscosity sensors of liquids [17,18], as high frequency filters [19,20], as MEMS scanning mirrors [21] or as vibrational energy harvesters [22].

Even more challenging are AFM cantilevers with beam thickness of only a few 100 nm. If equipped with a piezoelectric layer the measurements accuracy is affected by the additional layer compared to the original device [23–25]. Functional layers on top of the cantilever with a typical thickness of 500 nm will influence its mechanical properties [26], such as an increased cantilever bow, leading to a higher static deflection of the cantilever tip [27].

The deposition of magnetron sputtered AlN layers generates heat on top of the substrate by the particle bombardment [28]. Besides the intrinsic defects in the film the introduced heat leads due to the different coefficients of thermal expansion (CTE) of substrate and deposited thin film to a specific bending. During the deposition process this results in a continuously changing thermal connection between substrate and holder, if the wafer can move freely. When targeting AlN films in relation to e.g. different film thickness or the highest degree of c-axis orientation at varying sputter deposition parameters, this effect leads to an undefined substrate temperature and hence, to a high variation of the implemented biaxial film stress [29].

Any MEMS device fabrication process comprises a specific patterning of the AlN layer. Beside dry etching of AlN [14], patterning by a lift-off process or by direct wet etching of AlN layers with phosphoric

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acid show a promising simplification of the manufacturing process, when achieving especially in the latter approach to remove the presence of any etch residues [7,30,31].

It is the objective of this study to investigate the influence of substrate clamping conditions on both mechanical properties and on the wet etching capability of AlN layers on Si wafers, so that a defined and stable thermal contact during the sputter-deposition process is ensured. For this purpose a specific wafer holder is developed and the results of these important film parameters are compared with those obtained from depositions where the silicon wafer is not clamped and could move completely free.

2. Experimental details

For studying the impact of Si wafer clamping condition on the AlN layer properties AlN films with three different thickness values (i.e. 0.5 µm, 1.0 µm, 2.0 µm) are prepared. The deposition experiments are repeated in a time period within 5 weeks. The week 1 represents the run-in period, which is reflected by the high value of the maximum process temperature T_m and by the variation of the AlN layer stress σ occurring at AlN films with thickness of 1.0 µm and 2.0 µm.

2.1. Clamped substrate holder

AlN thin films are deposited with a commercially available DC magnetron sputter equipment (Von Ardenne LS730S). The samples are placed on a molybdenum (Mo) plate (Fig. 1(a)) which again is placed on a rotary table inside the deposition vacuum chamber. Molybdenum has a high wear resistance, but a low thermal conductivity of $\lambda_{Mo} = 142\ \frac{W}{m\cdot K}$ [32]. During AlN deposition the wafer is continuously self-heated by the particles bombardment, so that the difference in thermal expansion coefficients of silicon and the deposited AlN deforms the wafer. During film growth the biaxial stress decreases from compressive stress (negative values) down to zero and changes to tensile stress (positive values) [33]. In detail, the wafer changes from convex to concave bending characteristics, as schematically illustrated in Fig. 2(a). As a consequence, the thermal contact resistance of the wafer to the substrate holder strongly varies with time, as the wafer bow inhibits the heat flow, what results in a temperature variation on the wafer surface. Basically, reactive sputter depositions have a strong dependence on temperature [34,35]. In order to reduce the variation of layer stress among different deposition runs, it has to be ensured that each wafer is exposed to the same temperature profile.

In order to ensure a reproducible high degree in c-axis orientation of the AlN thin films quality, a tailored clamping fixture for 4″ wafers was developed. The requirements for the wafer holder comprise a high heat dissipation and a homogeneous force distribution when the wafer is clamped at the edge. Besides easy handling, suitability for high vacuum processing, high thermal stability for long-term usage as well as reusability are required. The deposition process heats up the wafer as well as the holder and both undergo thermally-induced expansion. To prevent any buckling of the wafer the thermal expansion coefficient of the clamped material has to be lower than of the clamping fixture. In detail, aluminium (Al) ($\alpha_{\mathrm{Al}} = 23.1\ ppm/K$ [32]) has a three times higher thermal expansion coefficient than Si ($\alpha_{\mathrm{Si}} = 7.6\ ppm/K$ [32]).

In addition, Al provides a higher thermal conductivity $\lambda_{Al} = 247\ \frac{W}{m\cdot K}$ [32] compared to Mo. Therefore, the custom build sample holder is made of an Al base plate, a clamping disk placed on top and four screws that are positioned diagonally. The screws are tightened with a torque of 4 N·m (see Fig. 1(b, c)).

Assuming that the geometrical dimensions can be regarded as constant, the ratio of thermal heat flows I of two different materials is calculated, according to Fourier's law (1)

$$I = \frac{A\cdot\lambda\cdot\Delta T}{l};\ \frac{I_{Al}}{I_{Mo}} = \frac{\lambda_{Al}}{\lambda_{Mo}} \tag{1}$$

where I represents the heat flow through a solid sample, A its area, l the sample length, ΔT the temperature difference and λ the thermal conductivity, respectively. The higher thermal conductivity λ_{Al} compared to λ_{Mo} enables an about 1.7 times higher heat flow. By clamping the wafer the thermal resistance between substrate and substrate holder is further reduced (Fig. 2(c)).

2.2. Thin film deposition of AlN

The phosphorous doped (100) wafers have a bulk resistivity of 50 Ω·cm and they are pre-conditioned with an inverse sputter etching (ISE) before the AlN is deposited to ensure a polycrystalline microstructure from the onset of film synthetization and hence, enhanced film properties [36]. The wafers are not heated before or during the deposition process. The process parameters are given in Table 1 [37].

During deposition, the maximum process temperature T_m of the substrate holder (Fig. 2(c)) is measured. A pyrometer (DIAS Pyrospot DGE 10 N) with a working range from 100 °C up to 850 °C, which is installed at the process vacuum chamber, was used. In order to reduce temperature measurement inaccuracies caused by variations of the emissivity ε of the substrate holder, an Agilent T U1241A with a type K thermocouple records the temperature after the sample was transferred out of the vacuum chamber.

2.3. Intrinsic, biaxial stress in AlN thin films

Due to the difference in volumetric thermal expansion coefficients of a 4″ Si wafer and an AlN film ($\alpha_{\mathrm{AlN}} = 4.2\ ppm/K$, [38]) a length difference of −13.0 µm at a temperature difference ΔT of 80 °C results (2). The length difference ΔL of wafer diameter L_0 at ΔT = 130 °C refers to −21 µm, respectively. Finally, with Hook's law (3) and when knowing the Young's modulus of Si ($E_{\mathrm{Si}} = 169$ GPa [39]) the resulting strain difference results in a compressive AlN layer stress σ of −21.6 MPa (80 °C) up to −35.2 MPa (130 °C), which increases the intrinsic stress component due to a high structural defect density in sputter-deposited thin films [27]. Since the intrinsic stress is an order of magnitude larger than the thermal induced stress, the thermally induced stress can be neglected.

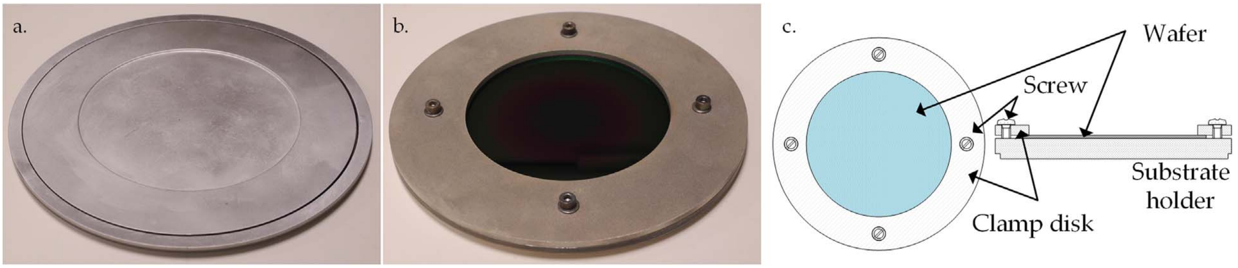

Fig. 1. Standard sample holder (a) and tailored substrate holder (b). The sample holder for clamping the wafer consists of a base plate (Al), a clamping disk (Al) and fixing screws made of stainless steel (c).