Fabrication, characterization and modelling of multilayered cantilevers with piezoelectric AlN ceramic as actuator.

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Abstract:

This paper treats a wide range of subjects related to the use of AlN as actuation layer in MEMS, from its deposition conditions to accurate interferometric device characterization and physical parameter extraction. Parameters concerning the AlN films such as Young’s modulus, residual thin film stresses, thermal expansion coefficient $\alpha$ and piezoelectric coefficient $d_{31}$ have been calculated using non approximated equations capable of taking into account multiple film stacking (electrode/AlN/electrode/Si substrate).

Résumé:

Ce papier présente les potentialités de films d’AlN piézoélectriques comme éléments actionneurs pour les MEMS. Le cas de micro-poutres constituées d’un empilement de différents films (electrode/AlN/electrode/substrat de Si) est présenté. Un dispositif interférométrique de type Twyman-Green permet de quantifier précisément les déformées et les déplacements ce qui permet de calculer différentes grandeurs physiques des films d’AlN, par exemple le module d’Young, les contraintes résiduelles liées à l’élaboration, le coefficient de dilatation $\alpha$ ainsi que le coefficient piézoélectrique $d_{31}$.

Key-words: Piezoelectric; AlN ceramic; cantilevers

1 Introduction

Aluminium nitride (AlN) films have piezoelectric properties that are already used for acoustic wave propagation in miniature high frequency bypass filters for the ever-growing wireless communication market, J.H. Kim \textit{et al.} (2002), K.M. Lakin \textit{et al.} (2001). This is a promising material also for MEMS applications and sensors using surface acoustic waves have already been proposed, A. Choujaa \textit{et al.} (1995), T. Laurent \textit{et al.} (2000). For actuation purposes, even if PZT films are most of the time used for their better piezoelectric properties, H.P. Löbl \textit{et al.} (1999), AlN still represents an alternative that has been explored, D. Ruffieux \textit{et al.} (2000). The objective of the present work is to develop high quality AlN cantilevers that will serve as reliable actuation elements in more complex MEMS. After presenting the fabrication process of the AlN driven cantilevers, the rest of the paper will focus on these device characterization and physical parameter extraction.

2 Experimental work

2.1 Sample fabrication

The AlN driven micro-beams were fabricated on 380 $\mu$m thick, 3” (100) oriented Si wafers. The process flow is shown in Fig.1. After realizing a 15 $\mu$m thick Si membrane by KOH etch of bottom side of the wafer (step 1), on the top side are successively deposited three thin layers: two CrNi PVD metal layers (0.15 $\mu$m at step 2 and 0.35 $\mu$m at step 4) that have between...
them the AlN film. The Cr50%Ni50% alloy has been sputtered on a heated substrate (200°C) at 230 watt (0.5 A) using a 0.93 Pa Ar gas. The AlN has been deposited (step 3) in a pulsed reactive DC sputtering machine on a non heated substrate with an input power of 650 watt, a Ar / N2 gas ratio of 0.65 sccm / 6 sccm and a pressure of 0.65 Pa. These conditions led to a deposition rate around 17 nm /mn. Two different wafers have been processed, having a final AlN thickness of 1 μm and 1.4 μm. The top CrNi electrode patterned at step 4, has been used as a hard mask during AlN and silicon etching (steps 5 and 7). An intermediary process step allowed the deposition and patterning of 0.5 μm thick Aluminium pads that were used for wire bonding. The last RIE step removed the silicon which was not protected by the CrNi hard mask, transforming the initial Si membranes into an array of free standing cantilevers. They had a constant width of 50 μm and variable lengths from 200 μm up to 900 μm. The layout of the cantilever array is shown in Fig.2.

Prior the fabrication of the devices, a series of test structures has been realized. They allowed the measurement of the stress in the films and the influence of the bottom electrode nature over the stress in the AlN film. These test structures were arrays of 13 μm thick silicon cantilevers, 5 mm wide, width lengths varying from 0.5 mm up to 3.5 mm. Two bottom electrodes have been tested: 0.16 μm thick CrNi and 0.24 μm thick Pt films. The CrNi has been deposited using the same conditions that for the devices, while the Pt has been sputtered on a non biased, non heated substrate at 120 watt (0.22 A) using a 1.1 Pa Ar gas. After measuring the cantilever bending, a 0.8 μm thick AlN layer has been deposited using the same conditions that for the devices.

2.2 AlN Young’s modulus measurement

Nano-indentation tests were performed on the AlN films of the test structures using a nanoindenter II with a Berkovich tip. The study was conducted following the continuous contact stiffness measurement procedure, W.C. Oliver et al. (1992), with a frequency of 45 Hz and an indenter vibration amplitude of 1 nm during the penetration of the tip into the sample. It allowed the determination of the M_<hkl> modulus for AlN deposited on Pt and CrNi electrodes.

2.3 Cantilever deflection measurement

Both test structures as the AlN driven cantilevers have been characterized using a previously validated measurement set-up based on a Twyman-Green interferometer, C. Gorecki et al. (2005), L. Salbut et al. (2003). Five frames of interferometric intensity data taken at 90° relative phase shifts (Fig.3 shows an example of such interferograms) are used with a phase shifting algorithm in order to obtain a highly accurate (20 nm accuracy on vertical displacement) measurement of the cantilever profile. Fig.4 shows such a measured profile of three 800 μm adjacent cantilevers. This experimental set-up allowed both static and dynamic
measurements of the samples. The use of a Thermal Control Modulus allowed us to fix the sample temperature anyway between 15°C and 60°C with 0.01°C accuracy.

![Fig.3](image1.png)

**Fig.3:** 5 phase shift interferograms used for the cantilever profile calculation.

![Fig.4](image2.png)

**Fig.4:** 3D view of the measured profile for 800 µm long cantilevers.

3 Equations for multilayered cantilevers

The use of the same metal (CrNi) for the top and bottom electrodes, allows us to consider for simplification reasons that the silicon cantilever has on its surface only two films: the AlN film and a metal electrode film with a thickness equal to the sum of the top and bottom electrodes thicknesses. The stress in the AlN and metal films are causing a mechanical deflection $\delta_m$ of the three layers cantilevers that can be written as, Q.M. Wang et al. (1999), V. Walter (2001):

$$\delta_m = \frac{3(1 - \nu)}{E_{eq} h_{eq}^2} \left( (E_i h_i + E_e h_e) (h_e + h_f) \right) L^2 \sigma_0$$

(1)

with the global stress $\sigma_0$:

$$\sigma_0 = \frac{\sigma_i h_i + \sigma_e h_e + \sigma_s h_s}{h_{eq}}$$

(2)

where $E_i$, $h_i$ and $\sigma_i$ with $i = s, f, e$ are the Young Modulus, the thickness and the stress of the silicon substrate ($s$), the AlN film ($f$) and the metal electrodes ($e$). $L$ represents the cantilever’s length and $\nu$ the Poisson coefficient considered the same for all the materials. The equivalent thickness $h_{eq}$ is equal to the sum of $h_s$, $h_f$, and $h_e$, while $E_{eq}$ represents the equivalent modulus that can be written as:

$$E_{eq} = \frac{K_1 + K_2 + K_3 + K_4 + K_5}{E_{eq} h_{eq} (h_i + h_f + E_i h_e)} h_{eq}$$

with:

$$K_1 = E_i^4 h_i^4 + E_e^4 h_e^4 + E_s^4 h_s^4$$

$$K_2 = 2 E_i E_e h_i h_s \left( 2 h_i^2 + 2 h_e^2 + 3 h_s h_i \right)$$

$$K_3 = 2 E_i E_s h_i h_s \left( 2 h_i^2 + 2 h_s^2 + 3 h_i h_s \right)$$

$$K_4 = 2 E_e E_s h_s h_e \left( 2 h_e^2 + 2 h_s^2 + 3 h_e h_s \right)$$

$$K_5 = 12 E_s^4 h_s^4 h_e h_e$$

(3)

Under an applied voltage $V$, the piezoelectric properties of the AlN film will cause an additional deflection $\delta_p$ that can be related to the AlN piezoelectric coefficient $d_{31}$ by:

$$\delta_p = \frac{3}{E_{eq} h_{eq}^2} \frac{E_i (E_i h_s + E_e h_e)}{E_i h_s + E_e h_e + E_s h_s} d_{31} L^2 V$$

(4)

Under a thermal loading $\Delta T$, the corresponding deflection $\delta_{th}$ of the bender, function of the thermal expansion coefficients of the three layers, $\alpha_s, \alpha_e, \alpha_i$, is given by:

$$\delta_{th} = 3 \frac{\left( E_i h_i^2 - (E_i h_i + E_i h_e) (h_i + h_f) \right) \times \left[ \alpha_s (E_i h_i + E_i h_e) - (E_i \alpha_i h_i + E_s \alpha_s h_s) \right]}{E_{eq} h_{eq} (E_i h_i + E_i h_e + E_s h_s)} L^2 \Delta T$$

(5)
Putting in the above equations \( h_e = 0 \) leads to the classic equations for a piezoelectric film deposited on a silicon cantilever, V. Walter et al. (2002). Furthermore, a first order development of the Eq.1 gives a generalized writing of the Stoney equation:

\[
\sigma_f = \frac{E_s h_e^2 \delta_m}{3(1-\nu)h_f L^2} \left[ 1 + 4 \frac{E_s h_f}{E_s h_f'} \left( 1 + \frac{3h_f}{2h_s} + \frac{h_s^2}{h_f^2} \right) \right]
\]

(6)

For our particular study, using the Stoney equation would have introduced a significant under-estimation of the stress in the film, since the values of the terms \( A \) and \( B \) are 0.97 and 0.11.

4 Results and discussion

4.1 Young’s modulus and stress values

The indentation modulus \( M_{\text{shik}} \) for AlN was found to be dependent of the metal electrode on which the AlN film has been deposited: \( M_{\text{shik}} = 340 \) GPa for CrNi electrode for only \( M_{\text{shik}} = 290 \) GPa for the Pt electrode. Using the elastic constants \( C_{ij} \) for AlN films given in the literature, A.F. Wright et al. (1997), G. Carlotti et al. (1995), it can be shown that the value of \( M_{\text{shik}} \) is equal to 335 GPa (maximum value for \( M_{\text{shik}} \)). Therefore, between the two metal electrodes that have been tested, the CrNi electrode proved to be the best choice since it led to a well (001) orientated AlN film. This observation is confirmed by the analysis of the X-rays diffraction spectrums which shows a perfectly (002) crystallites orientation for AlN on CrNi and a (002) orientation and amorphous part for AlN on Pt electrode.

Furthermore, the bending of the test structures cantilevers before and after the AlN deposition on their CrNi and respectively Pt electrodes, gave valuable information about the stress levels in the films. The measurements shown in Fig.5 indicated that the stress in the CrNi film is tensile, while the Pt film was under compression. The change of slope after AlN deposition indicates a compressive stress in this film. Numerical calculations using Eqs.1-3 led to values of +1110 MPa tension stress for CrNi and -700 MPa compressive stress for Pt. After its deposition on the two different metal electrodes, the stress value in the AlN film deposited on CrNi was of -220 MPa, versus -564 MPa for the one deposited on Pt. CrNi proved again to be a better choice as metal electrode since it allows the deposition of less stressed AlN. Moreover, if the thicknesses of the films are well chosen, it is possible to obtain a structure with a global stress equal to zero.

![Fig.5: Measured test structures bending before and after AlN deposition as a function of their square length.](image1)

![Fig.6: Calculated stress in the AlN films as a function of its thickness.](image2)

The compressive stress in the AlN film has been related in the literature to the high DC power input, K. Kusaka et al. (2000). W.J. Meng et al. (1993) have also shown that the stress was a function of the AlN film thickness: it had a minimum for thicknesses between 0.5 µm and 1.0 µm and it is increasing for greater thicknesses. These observations have been confirmed in our study. Fig.6 shows the calculated AlN stress in the test structures but also in the final devices that had AlN thicknesses of 1 µm (wafer1) and 1.4 µm (wafer 2). The AlN compressive stress is
significantly increasing with its thickness. Therefore, if the objective was to realize an AlN driven structure with low global stress, the CrNi electrodes thicknesses should be adjusted not only to the AlN thickness value, but also to its thickness depended stress value.

4.2 Piezoelectric coefficient determination

When a DC voltage is applied between the upper and the lower metal electrodes, a supplementary displacement \( \delta_p \) (Eqs. 3-4) adds to the stress induced mechanical bending \( \delta_m \). As it is shown in Fig.7, the measured piezoelectric displacement \( \delta_p \) showed a linear behaviour with the applied voltage. The slope for the wafer 2 samples is greater, since the AlN film is much thicker than for the wafer 1 devices (the Si and metal electrodes have the same thicknesses for both wafers). However, this different slope is not only related to the different thicknesses. Using Eq.4, the piezoelectric coefficient \( d_{31} \) value for wafer 2 (1.4\( \mu \)m AlN) was found to be -2.0 pm/V, for only -1.3 pm/V for the wafer 1 samples (1\( \mu \)m AlN). The first -2.0 pm/V value is in good agreement with \( d_{31} \) coefficients measured on pulsed reactive DC sputtered AlN films, I.L. Guy et al. (1999). However, for the wafer 1, the \( d_{31} \) value is somehow small, which indicates that the AlN deposition process needs further optimization.

![Fig.7: Determination of the \( d_{31} \) piezoelectric coefficient of the AlN films.](image1)

![Fig.8: Determination of the thermal expansion coefficient \( \alpha \) of the AlN films.](image2)

4.3 Thermal expansion coefficient determination

The Thermal Control Module allowed us to fix the cantilevers temperature between 15°C and 60°C and thus to determine the thermal expansion coefficient \( \alpha \) of the AlN films (Eq.5). Fig.8 shows the variation of the total deflection \( \delta_m + \delta_{Th} \) as a function of the temperature for three different beams. The application of Eq.5 knowing the slope of these curves (\( \Delta\delta_{Th}/\Delta T \)) and the material parameters (\( L = 800 \mu \text{m}, \alpha_s = 2.44 \times 10^{-6} \text{K}^{-1}, \alpha_e = 9.5 \times 10^{-6} \text{K}^{-1} \)) allowed us to calculate \( \alpha_f = \alpha_{AlN} \). We found \( 4.3 \times 10^{-6} < \alpha_{AlN} < 4.6 \times 10^{-6} \text{K}^{-1} \), which is in good agreement with the values reported in the literature for bulk material; \( 4.4 \times 10^{-6} < \alpha_{AlN} < 5.3 \times 10^{-6} \text{K}^{-1} \).

4.4 Joule effect on some cantilevers

Impedance measurements R on all the wafer devices have been performed. They showed that some of the different cantilevers arrays present on each device were in short cut. When a voltage was applied to these cantilevers they had an important displacement \( \delta \gg \delta_p \) proportional to the square of the voltage (Fig.9), that had a Joule effect origin. Note that 15 V applied bias proved to be too high for some of the cantilevers with \( h_t = 1 \mu \text{m} \) leading to severe damage of the electrodes and the AlN beneath it. After this damage it was observed important parabolic bending related to the heating of the AlN and Si films thanks to the electrodes. From Fig.9, we can deduce the relation: \( \delta_{Th} = A_{exp} V^2 \) which combined with Eq.5 gives the relation \( \Delta T = A_{exp} V^2 \). A very simple thermal conduction model; a wall heated on one side by
an electric resistance, shows that: $\Delta T = \beta V^2 / R$ and thus $\Delta T = \beta V^2 / (1/R)$ for all the tested cantilevers in short cut (Fig.10) gives $120 < \beta < 190$ K/W.

Fig.9: Responses with $V^2$ for the beams in short cut. Fig.10: Determination of the coefficient $\beta$.

4 Conclusions
The presented process allowed the fabrication of AlN driven cantilevers that have good piezoelectrical behaviour. CrNi proved to be a better choice as bottom electrode, since the AlN deposited on it had better (002) orientation, a well defined Young’s modulus and lower stress. The influence of AlN thickness on its stress level has also been investigated, the obtained results being valuable information in designing AlN driven structures with a low global stress. The thermal expansion coefficient of these films has been determined. The devices obtained from the wafer with a thicker AlN film (1.4 µm) showed better piezoresistive properties, with a $d_{31}$ coefficient of -2.0 pm/V.

All the physical parameters have been calculated using non approximated analytical equations. From a material point of view, the important result is that the well oriented (002) AlN ceramic thin films exhibit approximately the same electro-thermo-mechanical properties, $C_{ij}$, $\alpha$, $d_{31}$ as the bulk material.

References