A HIGH D_{33} CMOS COMPATIBLE PROCESS FOR ALUMINUM NITRIDE ON TITANIUM

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ABSTRACT

We present a CMOS compatible fabrication process which utilizes aluminum nitride with titanium electrodes for high-speed piezoelectric actuation. Aluminum nitride film morphology was improved by maintaining vacuum between film depositions and by the inclusion of an aluminum nitride interlayer. A rocking curve full-width at half-maximum of less than 3 degrees was achieved. Unimorph actuators were fabricated from silicon cantilevers and piezoelectric coefficients of 3.0 pm/V and 1.65 pm/V were measured for d_{33} and d_{31}, respectively. This performance is comparable to reports for AlN processed without CMOS compatible electrode materials.

KEYWORDS

piezoelectric, aluminum nitride, cantilever

INTRODUCTION

High-speed, low-power actuators find numerous applications in microelectromechanical systems (MEMS). Although electrostatic parallel plate and comb drives are widely used for their simplicity, piezoelectric actuators are ideal for high frequency, low voltage applications, such as high-speed atomic force microscopy [1]. Zinc oxide (ZnO) and lead zirconium titanate (PZT) are commonly used piezoelectric materials, but each has drawbacks. Both contain fast diffusing elements in silicon and are not standard clean room materials. Careful processing is required to obtain high resistivity films with both, due to the small bandgap of ZnO (3 eV) and the cracking commonly encountered in sol-gel processing of PZT [2]. In contrast, aluminum nitride (AlN) has a large bandgap (6 eV), is CMOS compatible, and has excellent properties including high thermal conductivity, low density, and high elastic modulus. These material properties make AlN ideal for applications such as high frequency resonators. However, AlN is not widely used for cantilever actuation due to its moderate d_{33} coefficient (3.9 pm/V), which is slightly less than ZnO (5.9 pm/V) and much less than PZT (60-130 pm/V) [2]. The precise d_{33} for all materials varies with fabrication process, as will be discussed. However, AlN is ideal for applications which require sub-micron cantilever tip deflection.

The piezoelectric properties from polycrystalline AlN are derived from texture in the (002) direction. Metals that have been shown to yield reproducibly good AlN texture (Mo, Pt) are distinguished from other electrode materials (Ti, Al) partly by their degree of lattice mismatch with AlN [3]. However, the lattice mismatch of Ti is actually less than that of Pt, suggesting that surface oxidation may interrupt the growth of AlN. In addition, oxygen incorporation into the AlN lattice has been shown to increase the rocking curve FWHM and reduce the piezoelectric response of AlN previously [4].

We tested this idea by depositing the Ti electrode and AlN layers in a single vacuum step and precleaning the Si substrate in-situ to remove the native oxide. We also utilized a 100nm aluminum nitride interlayer below the bottom metal electrode as demonstrated by Kamohara et al [5], both to improve growth alignment and to reduce cross-talk in future devices which will combine sensors and actuators within the same die.

FABRICATION AND METHODS

The AlN and Ti films were deposited in a Tango Systems pulsed DC reactive sputter deposition system (Tango Systems, San Jose, CA). Power, pressure and substrate temperature for AlN deposition were held constant at 5 kW, 5 mtorr and 200 °C, respectively. The pressure was chosen to minimize instrinsic stress [6]. Target-substrate distance was fixed at 45 mm. All Ti films were sputtered at 3 kW with 40 sccm Ar for 150 seconds to yield a thickness of 100 nm or 300 seconds for 200 nm. System base pressure was 10^{-8} torr. Flow rates were set at 10 sccm and 40 sccm for Ar and N_2. The deposition rate was 13.6 nm/min. The silicon substrate was cleaned by inductively coupled plasma (ICP) at 800 W RF bias for 150 seconds to remove approximately 50 Angstroms from the surface.

Cantilevers were fabricated from four-inch (100) silicon-on-insulator (SOI) wafers (5 µm device layer, 500 nm buried oxide, 500 µm handle). After defining the alignment marks, the piezoelectric film stack was blanket deposited, consisting of a 100 nm thick aluminum nitride interlayer, followed by a 100 nm thick titanium bottom electrode, variable thickness aluminum nitride actuation layer, and 200 nm thick titanium top electrode. The top titanium electrode was lithographically patterned (Shipley 3612) and then etched by a standard wet etch (50:1 H_2O:HF). The photoresist was removed in PRX-127 and the top titanium electrode was used as a hard mask for the subsequent aluminum nitride etch in 25% TMAH at room temperature, as in [7]. The bottom electrode layer, which was designed to provide access for wirebonding yet protect

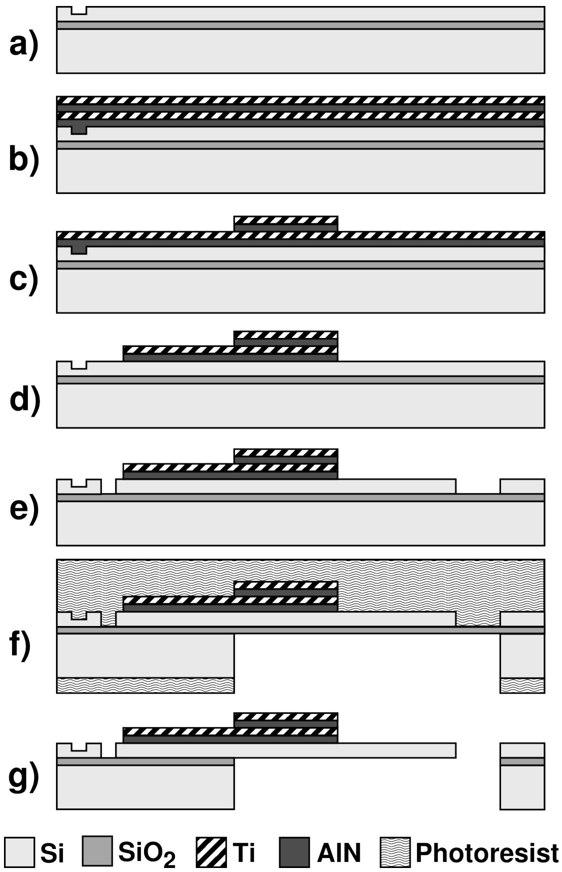

Figure 1. Fabrication process. After alignment marks (a), the piezoelectric stack is deposited (b). The top Ti electrode is etched and used as a hard mask for the next AlN layer (c), and the process is repeated for the next two layers (d). The SOI device layer is patterned via RIE (e) and the backside is patterned and etched via DRIE after a frontside protection step (f). The buried oxide is etched via RIE, releasing the cantilever (g).

the top titanium electrode from the subsequent etch, was then lithographically patterned. Identical etch processes were used to pattern the bottom titanium electrode and aluminum nitride interlayer.

The cantilever was patterned (50 µm wide, 200 µm long) and etched from the frontside using deep reactive ion etching (DRIE), stopping on the buried oxide. The frontside of the wafer was protected with a thick photoresist layer and the backside of the wafer was patterned and etched with DRIE. All lithography, including backside alignment and exposure, was performed on an ASML PAS 5500 stepper with 3D align. The cantilever was released from the buried oxide by a CHF_3/O_2 RIE step. The fabrication process is shown in Figure 1 and a finished device is shown in Figure 2.

The piezoelectric films were characterized using three techniques: x-ray diffraction two-theta and rocking curves (Philips X'Pert Pro, 45 kV, 40mA), and measurement of the d_{33} coefficient at the wafer scale and d_{31} at the device scale using laser doppler velocimetry (LDV) (Polytec OFV-2500).

Rocking curves were performed by first performing a θ-2θ scan to find the AlN (002) reflection peak (2θ = 36.04°) and then with 2θ fixed, rotating the wafer (ω) to measure the degree of grain alignment normal to the wafer. The reflected x-ray intensity was measured with a parallel plate collimator and sealed proportional detector.

Although double-beam interferometry is typically used to measure d_{33} directly, LDV was recently demonstrated [8]. However, wafer bending during measurement complicates data interpretation and a comparison between wafer and device data using LDV has not been made to date.

The d_{33} coefficients at the wafer scale were measured by applying by biasing the aluminum nitride film across its thickness and measuring the induced deflection of the top surface. The bias was applied by attaching alligator clips to the wafer and insulating one side of the teeth with foam tape. We opted to drive the wafer at high frequency (800 kHz – 1.2 MHz) at significantly higher frequencies than previous work (8 kHz) [9] in order to avoid exciting the wafer bending modes and to improve the LDV displacement resolution. Wafers were firmly attached to a flat surface with double-stick tape. The wafers were coated with an additional layer of titanium on the backside to improve electrical contact. The d_{31} coefficients were extracted by driving the unimorph cantilever actuators below resonance, measuring the tip deflection and applied voltage, and determining the d_{31} from the multilayered cantilever structure based upon reference [10].

The frequency response of a cantilever actuator was measured by driving the piezoelectric with white noise and recording the tip deflection with a spectrum analyzer (HP3562A).

RESULTS AND DISCUSSION

First, we investigated the effect of RF induced bias and AlN thickness on the degree of AlN grain alignment. The rocking curve FWHM was found to depend inversely upon the film thickness, as expected (Figure 4). Increasing the RF induced bias from 45 V to 57 V modestly improved the FWHM for a 250 nm thick film, while reducing the bias from 45 V to 40 V for a 1 µm thick film almost doubled the FWHM. A rocking curve of less than 3 degrees was measured for the 1 µm thick film, compared with greater than 7 degrees in prior work for AlN on Ti at the same thickness [11].

Next we measured the d_{33} coefficient of the AlN using whole wafers and the d_{31} using the microfabricated cantilevers (Figure 5). Both were measured for various AlN film thicknesses with a fixed RF induced bias of 45V. We found that the d_{33} coefficient was relatively independent of the main AlN film thickness whereas the d_{31} improved for thinner films. One possible explanation

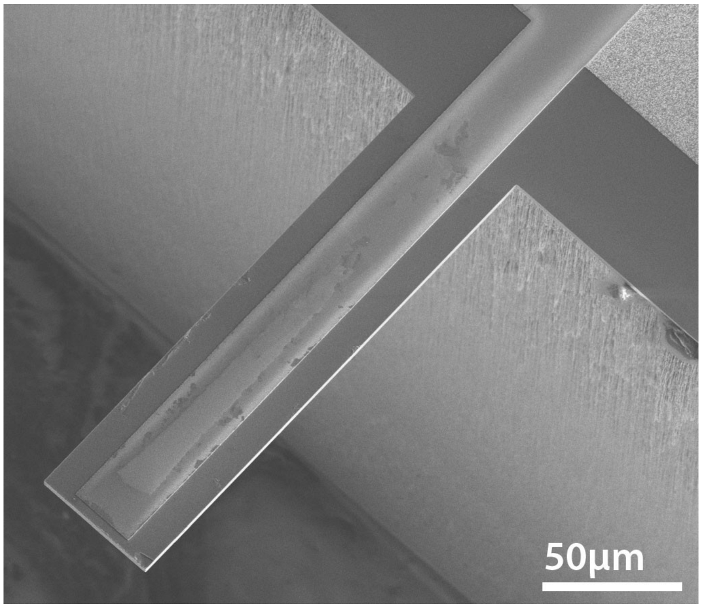

Figure 2. Scanning electron micrograph of a fabricated piezoelectric unimorph actuator. Cantilever is 5um thick x 50 um wide x 200 um long and the actuator is 30 um wide x 196 um long.

for the inferred reduction in d_{31} is increased undercutting of the AlN and Ti during the longer TMAH required for the thicker AlN films; the d_{33} measurements were performed on unpatterned wafers and so wouldn't have any undercutting. However, the AlN actuator thickness should be minimized in order to maximize tip deflection for constant voltage operation. Thus, the piezoelectric coefficient of the 100 nm thick AlN (1.65 pm/V) is the most relevant. This is the best value reported to date for AlN on Ti that we are aware of and comparable with Pt [6] but with the benefit of a CMOS compatible process.

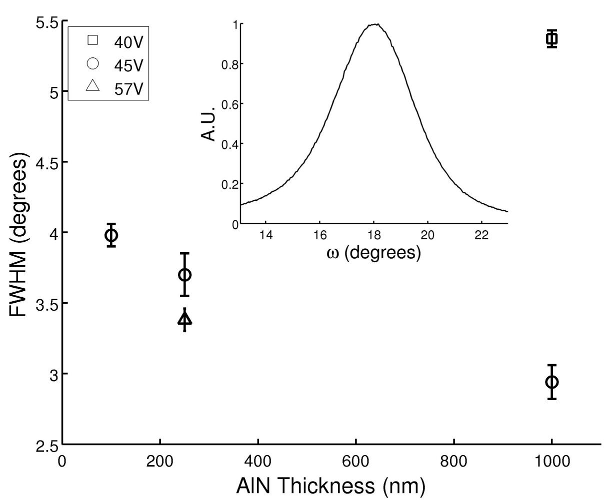

Figure 4. Variation in with aluminum nitride actuator thickness and RF induced bias. All samples were sputtered with a 100 nm AlN interlayer, 100 nm bottom Ti electrode and 200 nm top Ti electrode. RF induced bias increases structural alignment, particularly for thicker films. A typical rocking curve is inset.

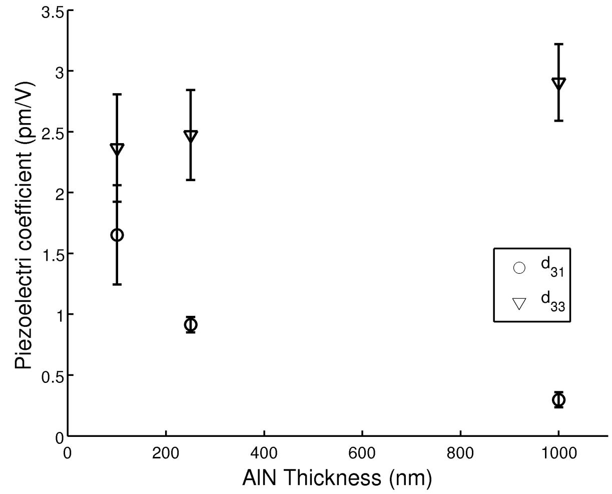

Figure 5. Dependence of piezoelectric coefficients on film thickness for a fixed RF induced bias of 45 V. The d_{31} coefficient was extracted by driving the cantilevers below resonance and measuring the tip deflection using LDV. The d_{33} coefficient was extracted by firmly attaching wafers with AlN/Ti/AlN/Ti on the frontside and Ti on the backside to an air isolation table with double stick tape to suppress wafer bending modes. An AC bias was applied across the wafer thickness, driving them between 800kHz and 1.2 MHz, and reading out deflection with LDV. d_{33} varies inversely with FWHM as expected, however d_{31} decreases for thicker films.

The frequency response for a 200 µm long, 50 µm wide cantilever are shown in Figure 6. The measured natural frequency of 152 kHz compares well with the predicted value of 165 kHz, and we measured a quality factor of 293. Tip deflections on the order of 10nm were measured for the designs evaluted; deflections on the order of 100 nm are readily achievable by increasing the bias voltage from 1-5V to 10-20V, reducing the excess width of the silicon cantilever relative to the actuator, and the combination of reducing the thickness and increasing the length of the cantilever beam.

CONCLUSIONS

We report process conditions for pulsed DC reactive sputtered AlN on a Ti electrode which yield an XRD rocking curve FWHM of less than 3 degrees for a 1 µm thick film, compared with 7 degrees in prior work. The results suggest that in-situ substrate precleaning and sequential deposition of films under vacuum limits TiO_2 formation and improves AlN alignment. We characterized the piezoelectric properties of the films with LDV on whole wafers and released cantilevers, achieving d_{33} (3.0 pm/V) and d_{31} (1.65 pm/V) values comparable with Pt, but with a low-temperature, CMOS compatible process.

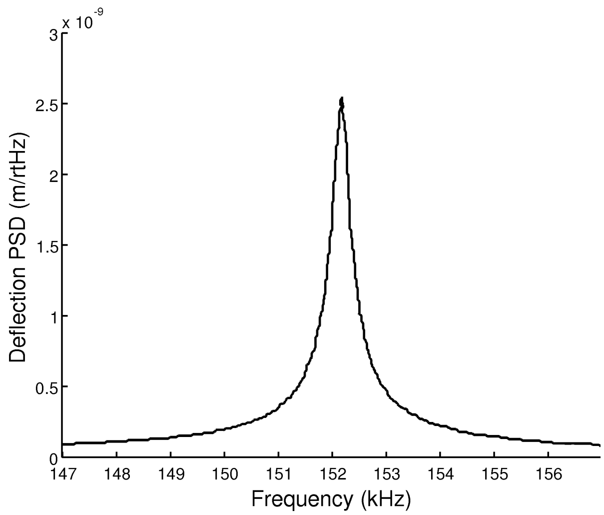

Figure 6. Cantilever frequency response to white noise at 1 V_{pk} for an aluminum nitride film thickness of 100 nm (Q = 293).

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