DTIP of MEMS & MOEMS Montreux, Switzerland, 01-03 June 2005

FABRICATION OF SURFACE MICROMACHINED AlN PIEZOELECTRIC MICROSTRUCTURES AND ITS POTENTIAL APPLICATION TO RF RESONATORS

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ABSTRACT

We report on a novel microfabrication method to fabricate aluminum nitride (AlN) piezoelectric microstructures down to 2 microns size by a surface micromachining process. Highly c-axis oriented AlN thin films are deposited between thin Cr electrodes on polysilicon structural layers by rf reactive sputtering. The top Cr layer is used both as a mask to etch the AlN thin films and as an electrode to actuate the AlN piezoelectric layer. The AlN layer is patterned anisotropically by wet etching using a TMAH (25%) solution. This multilayer stack uses silicon-di-oxide as a sacrificial layer to make free-standing structures. One-port scattering paramenter measurement using a network analyzer show a resonant frequency of 1.781 GHz on a clamped-clamped beam suspended structure. The effective electromechanical coupling factor is calculated as 2.4 % and the measured bandwidth is 13.5 MHz for one such a doubly clamped beam (990x30) μm^2.

1. INTRODUCTION

Surface micromachined aluminum nitride (AlN) thin film piezoelectric microstructures find many applications in modern telecommunication devices in the form of resonators and filters. AlN properties such as piezoelectricity, high acoustic velocity and chemical stability at high temperatures are attractive for such applications. A sandwich of an AlN thin film between two electrode layers as shown in figure 1 forms a basic configuration of piezoelectric resonating structures. Applying a cyclic electric field across this piezoelectric AlN capacitor results in the AlN thin film to expand and contract alternatively causing excitation of acoustic waves. Preferentially (002) oriented AlN thin films are favourable for such piezoelectric device applications [1]. Many methods to grow AlN thin films on various substrates have been discussed in the literature [2-4]. RF reactive sputtering is one of the common methods used to deposit polycrystalline AlN thin films with preferentially (002) orientation on many kinds of substrates [5].

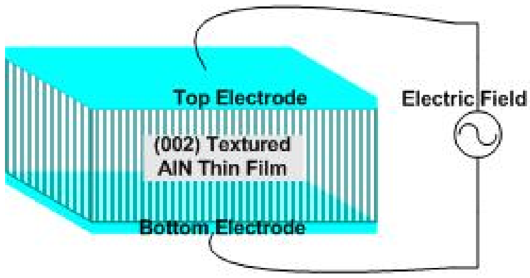

Figure 1: A simple AlN unimorph piezoelectric thin film resonating structure.

AlN thin film patterning, etch selectivity to the mask layer compatibility with surface micromachining processes and minimum feature size of free-standing piezoelectric microstructure are key factors in the fabrication process. Anisotropic AlN thin film patterning using tetra methyl ammonium hydroxide (TMAH) solution at room temperature and a Cr mask layer was already reported [6]. Fabrication of SOI based AlN thin film suspended devices involving a very thick (15 μm) silicon structural layer was reported earlier [7]. It is also known that thin structural layers cab be beneficial for certain applications, such as resonators. Also, micromachined AlN piezoelectric resonating structures on SiO_2 structural layers with germanium as a sacrificial layer has been reported recently [8].

In this paper, we discuss a new silicon based surface micromachining process for AlN thin films to make piezoelectric microstructures with feature sizes down to 2 μm and demonstrates its potential application as rf resonators.

2. EXPERIMENTS

2.1 AlN thin film deposition

Highly (002) textured AlN thin films are necessary for significant piezoelectric activity. For the fabrication of AlN piezoelectric micro structures, AlN thin films were grown on Cr/polysilicon layers using optimized sputter deposition conditions for a Nordiko 2000 multi target sputter system as shown in table 1. For piezoelectric

 ISBN:2-84813-0357-1

actuation, a stack of Cr/AlN/Cr layers was deposited in a single run without breaking the vacuum to ensure better adhesion of the Cr top layer to the AlN [5]. The deposition was done at a substrate temperature of about 400^0C.

Table 1. AlN deposition parameters

Parameters	Values
Base pressure (mbar)	$< 3 \times 10^{-7}$
Substrate	Cr/polySi/SiO_2/Si
Sputter pressure (mbar)	3.3×10^{-3}
RF power (W)	350
Ar:N_2 flow rate (sccm)	8:3
Substrate temperature (deg. C)	360
Deposition rate (nm/min)	4.2
Target-substrate distance (cm)	6

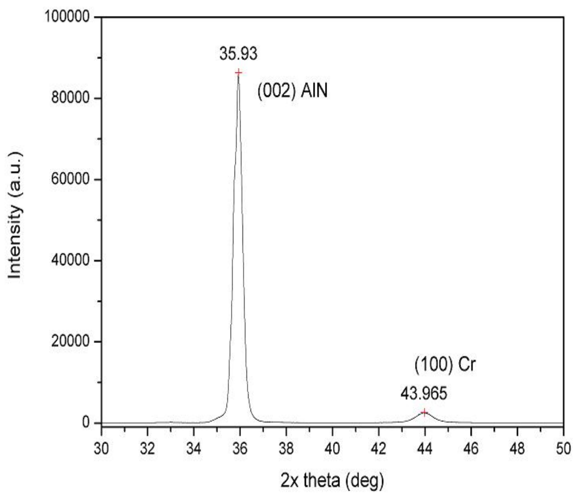

Figure 2:. XRD spectrum showing clear (002) diffraction AlN and a minor intensity peak of Cr.

Figure 2 shows a typical XRD (θ-2θ) scan results of a AlN thin film deposited on a Cr electrode. It indicates a high intensity (002) diffraction peak of AlN at 35.93^0 and its full width half maximum (FWHM) value was $<3^0$ as determined from rocking curve measurements. A narrow, sharp (002) diffraction peak indicates highly textured AlN grains with c-axis perpendicular to the substrate which is beneficial for the piezoelectric properties [1]. The crystallographic orientation and texture of the AlN thin film depend on mainly RF power, substrate temperature, target to substrate distance and sputter pressure. The optimized settings of the sputter parameters were used in the AlN deposition process for device fabrication.

2.2 Fabrication process

A schematic process description to fabricate AlN piezoelectric free standing microstructures is shown in figure 3. A stack of Cr/AlN/Cr layers forms an active area for piezoelectric actuation on the polysilicon structural layer. Three masks were used in the fabrication process. The first mask was used to define the area to be freed by sacrificial etching and the next two were used to pattern electrode area for top and bottom electrode.

An ordinary p-type (100) silicon wafer with 100 nm thick low pressure chemical vapour deposition (LPCVD) silicon nitride (SiRN) isolation layer forms a basic substrate. SiO_2 (1.2μm) and polysilicon (1μm) layers were used as a sacrificial and structural layer respectively deposited by LPCVD process. The stress in the polysilicon was reduced by annealing at 1050^0C. Now the stack of Cr/AlN/Cr layers was sputter deposited in a single run without breaking vacuum from the main chamber. This proves better adhesion of the Cr film on the AlN during sacrificial release etching. The AlN thin film of thickness more than 1μm was deposited with a sandwich of 60nm thick Cr layers. The top Cr layer serves effectively three purposes: 1) as one of electrodes to actuate the piezoelectric unimorph structure, 2) as a mask to pattern the AlN thin film and 3) as a mask to etch the polysilicon by the Bosch DRIE process.

Some additional steps were involved in this process to reduce complications with Cr etching and bottom electrode patterning. Since the Cr layer forms a sandwich for the AlN thin film, it is necessary to protect the top electrode Cr layer from over etching while patterning the bottom electrode Cr layer. It is important because the area of top electrode defines the total area under piezoelectric excitation under an applied electric field. The above problem was solved by depositing a 30 nm thick plasma enhanced chemical vapour deposition (PECVD) SiO_2 layer on the top Cr electrode layer as a protecting layer and the former layer was removed later during sacrificial etching step. Thus, over etching of top Cr layer was avoided in this process.

A cross sectional scanning electron micrograph (SEM) image of a piezoelectric microstructure before it is released by the sacrificial etching is shown in figure 4. It shows an anisotropic etched surface of the AlN thin film using TMAH 25% solution at room temperature. No external stirrer was used to stimulate the etching process. The etch rate of 22 nm/min was obtained. SEM images of fabricated typical free-standing typical piezoelectric test microstructures are shown in figures 5 and 6.

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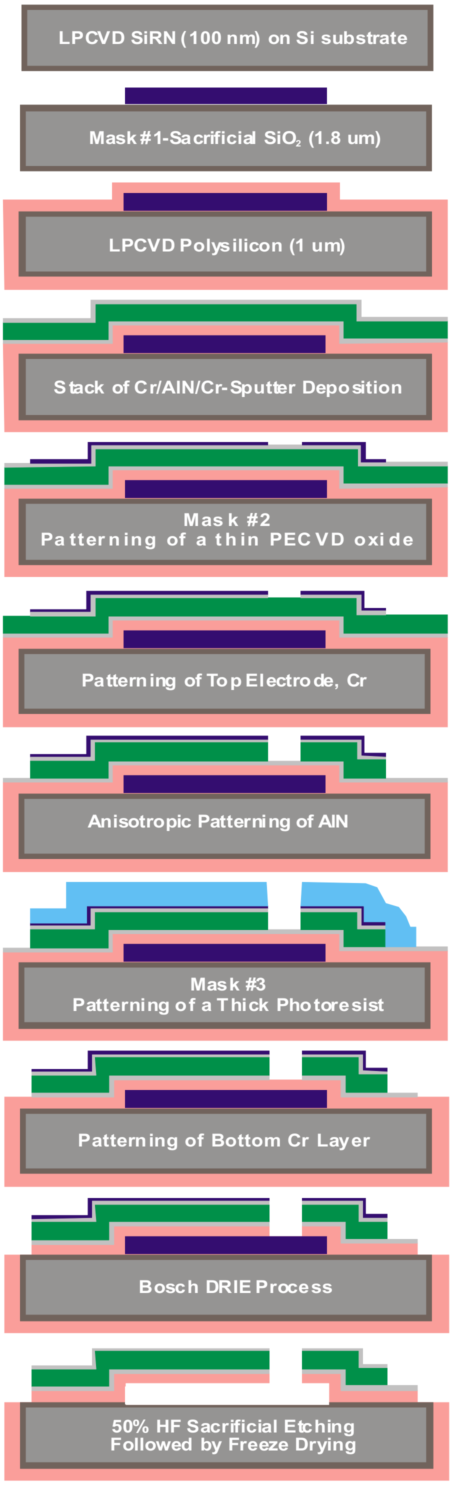

Figure 3: Fabrication process flow of the AlN thin film piezoelectric microstructures.

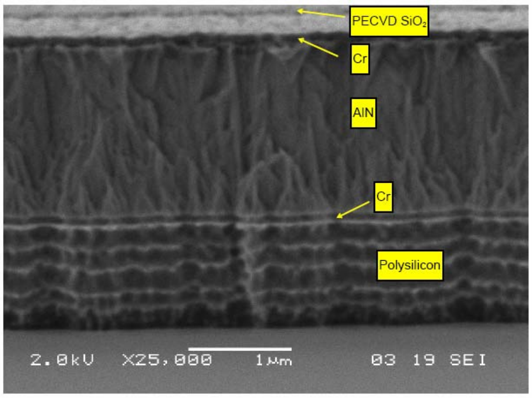

Figure 4: Anisotropically etched (002) textured AlN thin film between Cr layers after Bosch process.

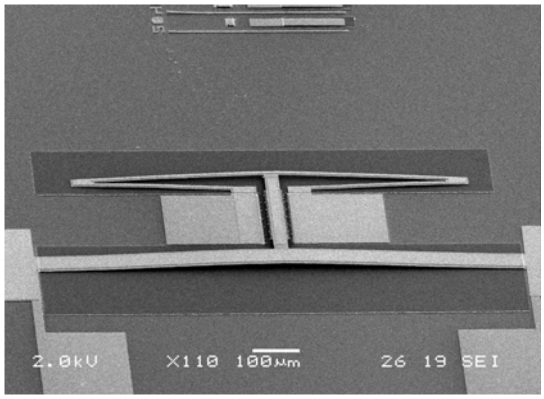

Figure 5: A doubly clamped unimorph piezoelectric microstructure with a spring element.

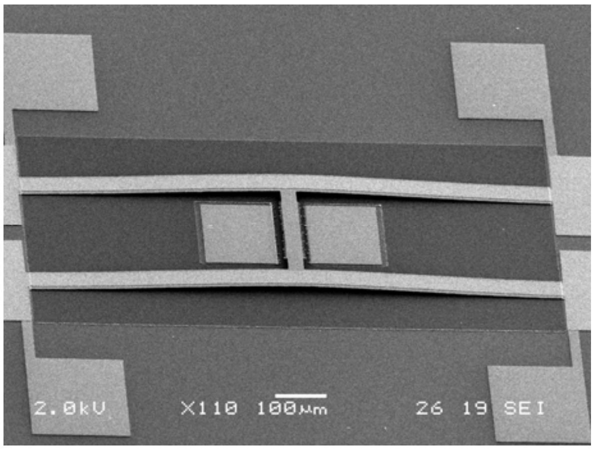

Figure 6: Doubly clamped H-shaped piezoelectric AlN thin film suspension device with patterned top and bottom Cr electrodes for electrical probing.

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The long clamped beams in figures 5 and 6 are isolated electrically from other parts of the device electrically by means of patterned top Cr electrode. The length, width and height of the piezoelectric long beam are 1000 µm, 30 µm and 2.3 µm respectively. A 3-dimensional (3-D) profile of the H-shaped piezoelectric beam is shown in figure 7. ATOS white light interferometer was used to figure out the 3-D surface profile of the freed H-shaped beam structure. It shows compressive stress in the freed structures causing an out-of-plane height about 16 µm from its fixed end for this particular H-shaped beam.

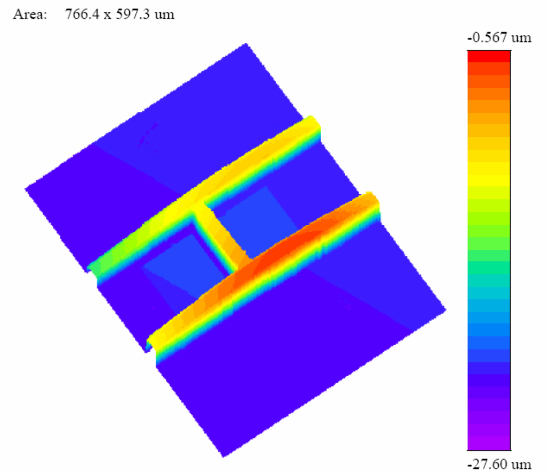

Figure 6: A 3-Dimensional surface profile of doubly clamped H-shaped piezoelectric AlN thin film suspension device using an ATOS white light interferometer.

3. RESULTS

The fabricated structures were tested in a one-port resonator configuration. RF probe station along with a HP 8510C vector network analyzer was calibrated using a standard calibration sample for a characteristic impedance of 50Ω in open, short and load modes. A G-S-G (ground-signal-ground) probe was used with a spacing of 125 µm between them. The calibration procedure was repeated for every selected frequency range of measurements. Figure 7 shows the result of a reflection coefficient measurement in a one-port resonator configuration in a narrow band frequency range from 1.6 to 1.9 GHz.

The reflection coefficient, S_{11} of -4.4 dB was obtained at the resonant frequency of 1.781 GHz. The measured input impedance of the resonating beam is shown in figure 8. The series and parallel resonant frequencies were measured at frequencies 1.771 GHz and 1.789 GHz respectively. The effective electromechanical coupling is related to the difference in series and parallel resonant frequencies [9]. For the results shown in figure 7 and 8, the effective electromechanical coupling constant, (K^2_{eff}) can be calculated using the following equation.

$$k^2_{eff} = \frac{\Pi^2}{4}\left[\frac{f_p - f_s}{f_p}\right]$$

Based on the above equations, the effective electromechanical coupling factor was found as 2.4 % and the measured bandwidth was 13.5 MHz.

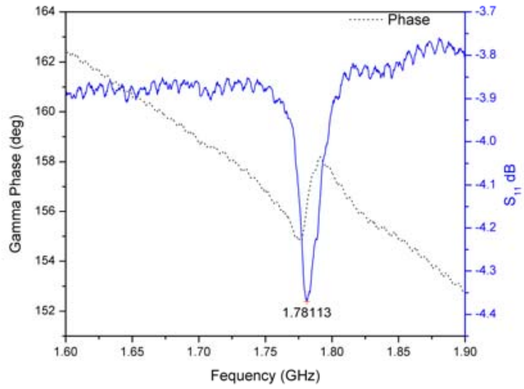

Figure 7: Measured reflection coefficient, S_{11} (-4.4 dB) on the clamped resonating beam of dimension (990 x 30) µm^2 showing a resonant frequency of 1.74GHz.

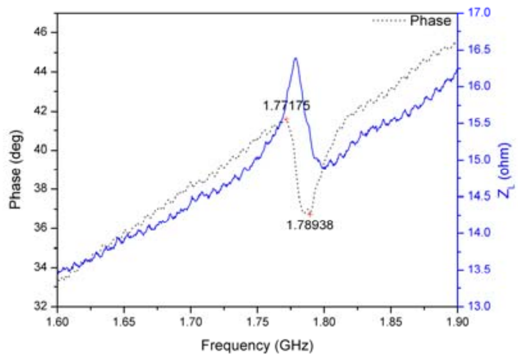

Figure 8:.Narrow band impedance and phase response with resonant and anti resonant frequencies at 1.771 and 1.789 GHz respectively with a bandwidth of 13.5MHz.

4. CONCLUSIONS

Novel silicon based surface micromachining process for AlN thin films have developed to fabricate AlN

 ISBN:2-84813-0357-1

piezoelectric microstructures on polysilicon layer. Cr layers are used as electrodes for actuation and act as high selectivity masks to wet etch the AlN thin film and to dry etch the polysilicon layer. Anisotropic etching of AlN is the unique process which is used to pattern the AlN thin film under ambient condition using 25% TMAH solution under no external influence. The 3-D surface profile from white light interferometer measurements shows the compressive stress in the freed piezoelectric structures. One-port measurement on doubly-clamped beam demonstrates its potential application as high frequency resonators above 1.7 GHz. Further work on two port measurements and modeling of such devices are in progress.

6. ACKNOWLEDGEMENTS

The authors would like to thank Mr. Henk de Vries, Mesa+ Test Facility Centre for providing RF network analyzer set up to characterize the devices and Dr. Matthijn de Rooij from Tribology group for white light interferometer measurements.

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