QUALIFICATION AND APPLICATIONS OF A PIEZOELECTRIC MEMS PROCESS

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Abstract: An industrializable process for manufacturing of piezoelectric ultrasound transducer elements is demonstrated. The PZT film is deposited by chemical solution deposition on SOI wafers, and standard MEMS processes are utilized to make cantilevers, bridges and membranes. The PZT film of ~50% of the devices exposed to thermal aging were found to fail at 85°C – 85%RH (relative humidity), while a real-life test of $8 \cdot 10^{10}$ cycles at resonance only gives a slight change in Q-value and resonance frequency.

Keywords: PZT, transducer, MEMS, reliability, chemical solution deposition

1. INTRODUCTION

The reliable integration of piezoelectric thin films into MEMS on an industrial scale is a key enabling technology for a wide range of future products. Examples include ultrasonic imaging transducers, pressure and flow sensors, accelerometers, acoustic wave devices, energy converters, micro-motors, micro-pumps, and micro-sensors for chemical analysis. While piezoelectric AlN can be deposited in a CMOS compatible sputter process that is easy to industrialize, the deposition techniques for PbZrTiO (PZT) are far behind in maturity. However, PZT has an electromechanical coupling that is approximately 10 times higher and this has been our main motivation for working to industrialize thin-film PZT deposition.

Ion sputter deposition has been the workhorse of the semiconductor industry for years for deposition of thin films due to its ability for high throughput and reproducible film quality. For PZT sputtering, however, the growth rate is limited due to self-heating of the sputter target, and good control of film stoichiometry is hard to achieve. We have found chemical solution deposition (CSD) of PZT to give superior material quality, with very small variations across both wafer and full batch [1]. Work is going on to take this to an automated process.

2. PROCESS FLOW

PZT is not a CMOS-compatible material and all wafer handling must take place in dedicated areas. In the devices reported here, the pattern for the bulk micro structuring is created prior to the PZT deposition while the PZT deposition and patterning is done later in a separate lab. The only traditional bulk micromachining step left is wet bulk etching and release etch of cantilevers by reactive ion etching (RIE). The process flow for the production of a cantilever is shown in Figure 1. A silicon-on-insulator (SOI) wafer is the starting point, where the buried oxide is employed as an etch stop for the back side bulk etch. Thermally grown SiO_2 serves as a barrier towards the Si, but also as a stress compensation layer as the compressive stress in the SiO_2 can be utilized to cancel the tensile stress in the deposited layers, mainly PZT.

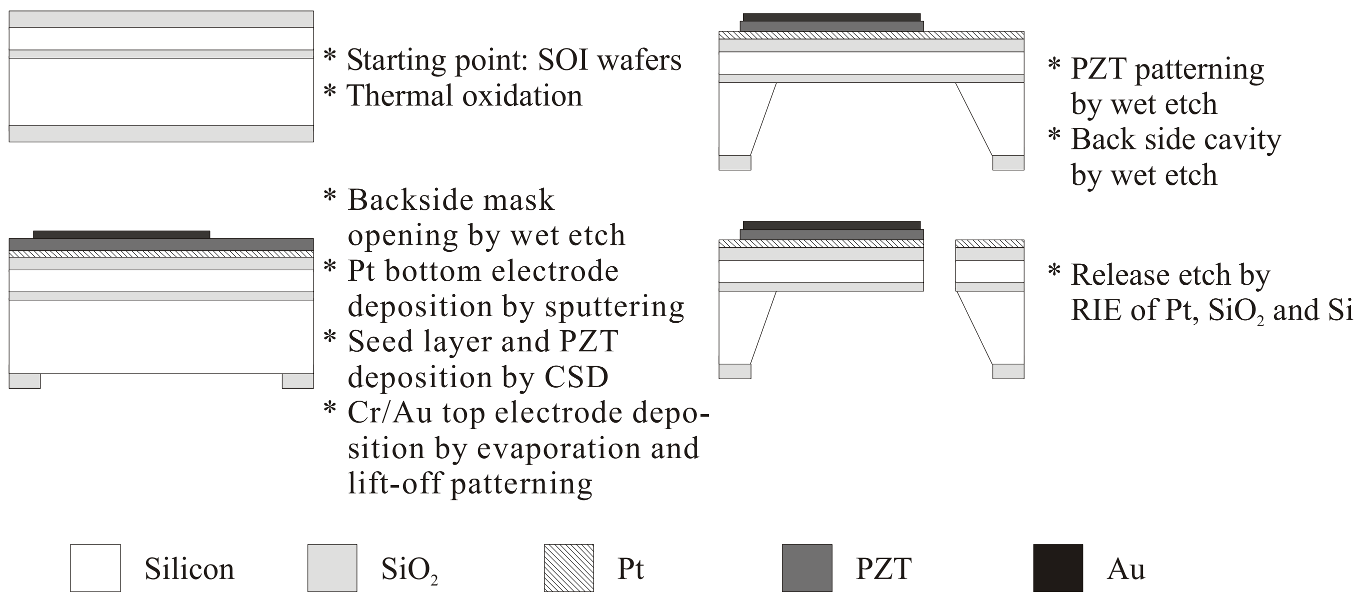

Figure 1. Process flow for manufacturing of a cantilever.

A thin seed layer of $PbTiO_3$ was deposited by CSD using spin coating and subsequent pyrolysis. The purpose of the seed layer was to obtain {100} oriented PZT as this orientation has been reported to give the highest transversal piezoelectric coefficient, $e_{31,f}$ [2]. A 2 µm PZT film with Zr/Ti ratio of 53/47 was deposited on the seeded wafer using 32 sequential spin-on depositions and 8 heat treatments at 650°C. The PZT thickness was chosen as an industrially relevant compromise between cost (limited number of depositions) and performance (sufficient layer thickness).

In this design the device layer of the SOI wafer decides the thickness of resonating structures, and hence a major impact on resonance frequency. A thickness of 10 µm is found to be a good compromise between stiffness of resonators and mechanical strength during manufacturing.

After dicing, the wafer dies were packaged on ceramic substrates with access to the back side. Such a package is shown in Figure 2.

3. MEASUREMENTS

3.1 Film characterization

Films and devices are characterized electrically by measuring the electrical permittivity, and the transversal piezoelectric charge coefficient $e_{31,f}$ is measured in a 4-point bending measurement setup [3]. The average relative permittivity is found to be 1130 with a standard deviation of 4.5% [4]. The $e_{31,f}$ is measured from 0.1 to 10 Hz, and varies from -15.1 to -14.1 C/m^2 [3]. A review by Trolier-McKinstry and Muralt [5] reported the overall accepted value of $e_{31,f}$ for PZT thin films as -12 C/m2. We believe the superior film quality is related to the use of CSD seeding layers compared to sputtered seed layers. An SEM image of a multimorph cross section is shown in Figure 3.

3.2 Film reliability

Bridge and cantilever structures will be exposed to the operating environment while used in ultrasound applications. The influence of humidity and temperature is tested in a controlled climate chamber, according the test plan in Table 1. Leakage current was monitored continuously at 5V operating voltage on 18 connected devices on one die during testing. Two devices was damaged during packaging, 9 devices experienced an

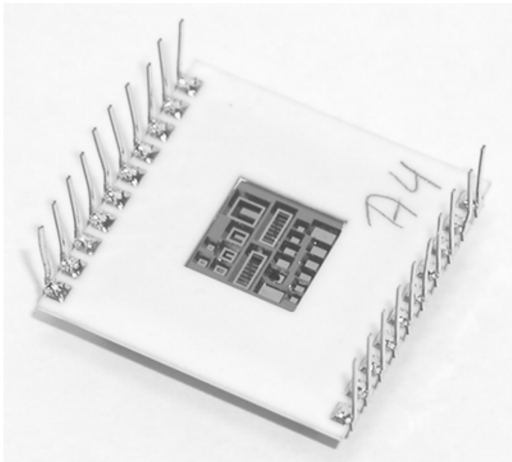

Figure 2. Backside of a packaged die with cantilevers. The ceramic substrate back opening is 10x10 mm^2.

increase in the leakage current leading to failure during the 85°C – 85%RH part of the test, while the remaining 7 devices did not show any significant change. The exact nature of the breakdown mechanism is not known at the moment, but further investigation of the PZT structure is required.

Fatigue tests with real-life parameters are performed by exciting structures at resonance. 0.5V amplitude is used, and the frequency locked at

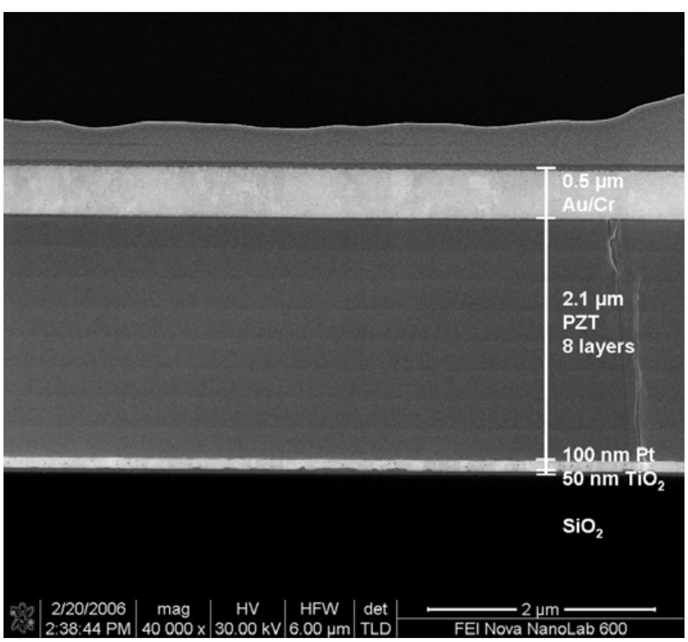

Figure 3. SEM image of a multimorph cross section milled by focus ion beam.

resonance. After $8 \cdot 10^{10}$ cycles the resonance the largest observed shift in frequency is 0.08%, while the Q value changes from nearly 80 to approx 65. The data is plotted in Figure 4.

3.3 Device examples

Three main types of devices are included in the first design; membranes, bridges and cantilevers. The main application is ultrasound transducers for air and water. All devices are designed to be used at resonance. Device types and resonance frequencies are summarized in Table 2.

The sound pressure from one packaged die with bridges and cantilevers was measured as a function of applied signal frequency. The die was placed in an anechoic chamber, together with a Bruel & Kjær microphone with 0 – 100 kHz bandwidth. The distance between microphone and chip was 5mm, and a chirp with 3V amplitude was applied to the device. The measured sound pressure is recorded, and the resulting transfer function pressure/voltage is plotted for one device in Figure 5. The device shown is a 2.0x0.8 mm^2 bridge, and the measured resonance of 19.55 kHz corresponds well with the expected resonance of 18.3 kHz. Although a cantilever will couple better to an acoustic signal than a bridge, the resonance from this device is sharp and well-defined. While this device did not

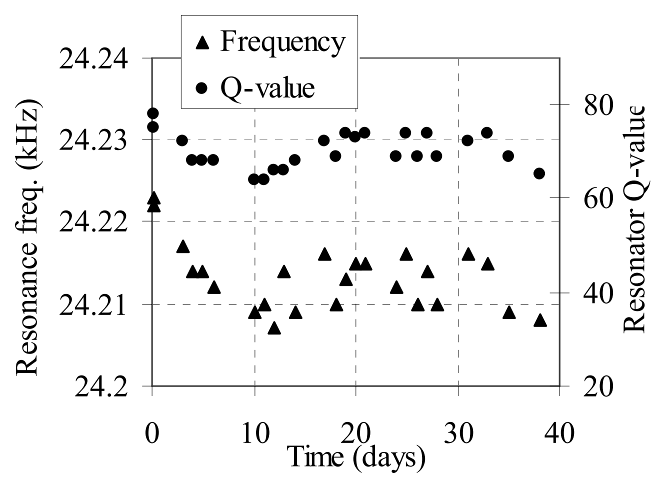

Figure 4. Resonance frequency and Q vs time for long-time fatigue test.

Table 1. Experimental plan for reliability test

Step #	Temp [°C]	Humidity [%RH]	Duration [days]	Operating voltage [V]
1	25	-	1	5
2	85	-	2	5
3	120	-	3	5
4	85	85	2	5
5	25	-	1	5

show any important higher-order modes, the phase plot shows a feature around 21 kHz that might be a higher order oscillation. Observation of devices in optical microscope during excitation shows that both transverse and buckling modes are excited for some devices.

4. CONCLUSION

An industrially capable process for thin film PZT on MEMS devices is developed. The films show very good piezoelectric performance and reproducibility across both wafer and batch. The use of a bridge structure as an ultrasound transducer element is also shown.

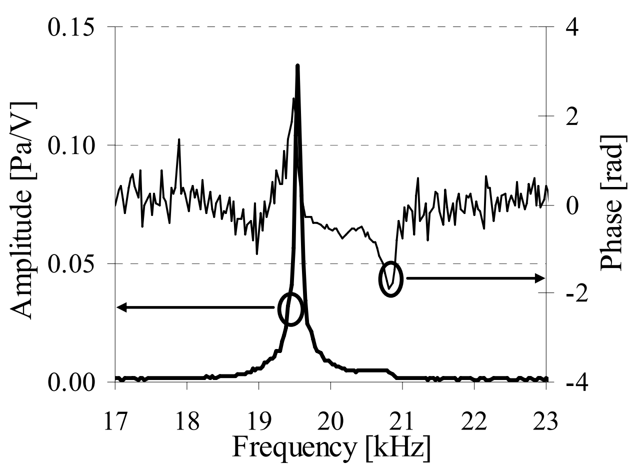

Figure 5. Amplitude and phase around resonance of the transfer function of a 2.0x0.8 mm^2 bridge.

Table 2. Devices and targeted frequencies

Type	Freq range	Use
Membranes	1 – 16 MHz	Water
Membranes	50 kHz – 1 MHz	Air
Cantilevers	5 – 500 kHz	Air
Bridges	20 – 1000 kHz	Air

5. ACKNOWLEDGEMENTS

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