WET ETCHING & UNIFORM WAFER-LEVEL THINNING OF BULK PIEZOELECTRIC CERAMICS ON SILICON

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ABSTRACT

This paper presents new micro-fabrication tools and material/process characterization for wafer-level lapping and wet-etch patterning of bulk PZT on silicon. The process enables precise control over final film thickness (5-100 μm) with high wafer-level uniformity ($\pm 0.5 \mu\text{m}$), and the lapping-rate (10-30 $\mu\text{m}/\text{min}$) and surface roughness (43 nm) are characterized. Additionally, surface micro-machining of suspended PZT structures is demonstrated by bonding and thinning over pre-patterned silicon features. Finally, a new wet-etching process is developed for low-undercut (0.6:1) patterning of $> 5 \mu\text{m}$ thick PZT films, and $d_{33-\text{EFF}}$ piezoelectric strain coefficients on thinned and patterned bulk PZT-5A and 5H films are measured as 140 and 311 pm/V, respectively.

INTRODUCTION

Recently, we introduced a micro-fabrication technology for integration of bulk PZT-5A substrates on silicon by solder bonding and thinning, to realize mm-scale diaphragm actuators [1] and energy harvesters [2]. In this paper, we report new micro-fabrication methods to achieve precise PZT film thickness with excellent wafer-level uniformity and reduced minimum film thickness ($\sim 5 \mu\text{m}$) in a reliable process. We also report here surface micro-machining of PZT diaphragms, wet-etching of thick PZT films, and integration of PZT-5H for higher piezoelectric response than PZT-5A (Fig. 1). These processes are critical to enable batch-mode fabrication of miniaturized and high-performance micro-speakers, microphones, microfluidic devices, and complex-shape actuators. The microfabrication techniques introduced here offer increased reliability, fabrication flexibility, and higher material quality over existing piezoelectric film deposition methods.

Figure 1: Bulk-PZT on Si process and SEM image of final PZT film.

UNIFORM WAFER-LEVEL THINNING

Minimizing wafer-level variation of thinned-PZT thickness is critical for batch-mode MEMS fabrication. It can be as high as $\pm 18 \mu\text{m}$ on a typical wafer, often due to increased lapping rates near the wafer edge. A new method is developed to improve wafer-scale thinning uniformity and to precisely define the final PZT thickness, by leveraging the silicon-wafer surface as a thinning-stop layer (Fig. 2). A 0.5 μm thermal-oxide layer enhances surface hardness, and the lapping rate decreases very effectively ($\sim 100\times$) upon leveling of PZT with the Si/SiO₂ surface (Fig. 3). Highly uniform film thickness ($\pm 0.5 \mu\text{m}$) is obtained across 4-inch wafers.

Figure 2: Change in the lapping rates when stop-layer is reached.

Figure 3: Flatness and thickness profile of a thinned-PZT die on Si.

For many applications, surface roughness of the final film is also a critical parameter. The average roughness on 20- μm thick lapped/polished PZT films is characterized to be 43 nm, which is acceptable for most MEMS and can be improved further by extending the polishing period (Fig. 4).

Figure 4: Surface roughness measured via AFM in tapping-mode.

For device-release purposes, PZT bonding/thinning over pre-patterned silicon features is demonstrated as an alternative to expensive and time-consuming backside through-wafer etching. Suspended structures with up to 1:40 thickness:diameter ratio are fabricated, which can be used for diaphragm actuation in acoustic, ultrasonic and microfluidic applications (Fig. 5-6). This unique surface micro-machining capability also facilitates easier packaging, and is not attainable with other piezoelectric-film deposition methods, where a flat deposition surface is required.

Figure 5: Suspended PZT layer bonded and thinned over Si cavity.

c-) Measured min. PZT thickness obtained for different membrane sizes

Figure 6: Minimum PZT thickness obtained versus diaphragm size.

LOW-UNDERCUT WET-ETCHING

Wet-etching of PZT structures is highly desirable, since it provides a cost-effective, high-throughput process, and enables lithographically-defined features. However, previous studies mostly focused on sol-gel spin-coated 1-2 μm thick films, with high-undercut ratios of 1.5:1 to 5:1 [3-6]. For etching through the complex composition of $> 5 \mu\text{m}$ thick PZT films, using the right mix of chemical reagents is critical, since residues due to reaction by-products cause unreliable etch rates and increased undercut. Here, a new mixture is utilized, $\text{BHF}:\text{HNO}_3(67\%):\text{HCl}(38\%)$ with 2:2:1 ratio, which is $14\times$ diluted by DI- H_2O to achieve a controllable etch rate and prevent photoresist-mask delamination. The solution is heated to 40°C in order to increase etching efficiency and obtain a better undercut profile. The etch process is expected to follow the below equations, where PbClF residue is converted into PbCl_2 , which has a higher solubility in water [7].

To minimize undercut, multiple cycles of lithography followed by wet-etching are used (Fig. 7). Only a portion of the total thickness is etched in each cycle (etch rate 2-3 $\mu\text{m}/\text{min}$), followed by ultrasonic cleaning. Then the photoresist mask is removed and a new photoresist layer is added to coat the previously-created undercut region. Patterning of 18 μm thick PZT in two cycles yields an undercut ratio of 0.6:1 (Fig. 8).

Figure 7: Diagram of multi-step wet-etching process.

Figure 8: Wet-etched 18 μm thick PZT layer with 0.6:1 undercut.

MEASURED PIEZOELECTRIC PROPERTIES

Preservation of bulk piezoelectric properties in the final bonded/thinned/patterned PZT-5A/5H films is confirmed via piezo-response force microscopy (Fig. 9). The d_{33} values calculated from measured $d_{33\text{eff}}$ [8] are close to the values in vendor datasheets for the bulk materials (Table 1), and are notably higher than values of existing thin-film-deposited piezoelectrics.

$$d_{33} = d_{33\text{eff}} + 2 \left(\frac{d_{31} \cdot s_{13}^E}{s_{11}^E + s_{12}^E} \right) \quad (3)$$

Figure 9: Piezoelectric response measured on $300\mu\text{m} \times 300\mu\text{m}$, 16 μm thick PZT5A/5H capacitors via piezo-force-microscopy.

Table 1: Measured longitudinal piezoelectric strain coefficients on 16 μm thick PZT-5A/5H films on Si without any repolarization.

	$d_{33\text{-EFF}}$ (Measured)	d_{33} (Calculated)	d_{33} (Vendor Datasheet)
PZT-5A	140 pm/V	398 pm/V	390 pm/V
PZT-5H	311 pm/V	772 pm/V	650 pm/V

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