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

Ethem Erkan Aktakka, Rebecca L. Peterson, and Khalil Najafi
Center for Wireless Integrated MicroSensing and Systems (WIMS²)
University of Michigan, Ann Arbor, MI, USA

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 (±0.5 µm), and the lapping-rate (10-30 µm/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 µm thick PZT films, and in-situ piezoelectric strain coefficients on thinned and patterned bulk PZT 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 (<5 µm) 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 high-performance microspeakers, 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.

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 ±18 µm 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 (~100×) upon leveling of PZT with the Si/SiO₂ surface (Fig. 3). Highly uniform film thickness (±0.5 µm) is obtained across 4-inch wafers.

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

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.

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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-underrcut ratios of 1.5:1 to 5:1 [3-6]. For etching through the complex composition of > 5 µm 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, BHF:HNO₃(67%):HCl(38%) with 2:2:1 ratio, which is 14× diluted by DI-H₂O to achieve a controllable etch rate and prevent photore sist-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 PbCl₂ residue is converted into PbCl₅, which has a higher solubility in water [7].

\[ Pb(Tl₂Zr₂O₇)(aq) + HCl(aq) + HF(aq) \rightarrow [TiF₄]^{4-}(aq) + [ZrF₄]^{2-}(aq) + PbCl₅^{4-}(aq) + H₂O(l) \] (1)

\[ PbCl₅^{4-}(aq) + HNO₃(aq) \rightarrow PbCl₄^{2-}(aq) + PbCl₂^{2-}(aq) + NO₃⁻(aq) + HF(aq) \] (2)

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 µm/min), followed by ultrasonic cleaning. Then the photore sist mask is removed and a new photore sist 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).

\[ d_{33} = d_{33,\text{eff}} + \frac{d_{33,\text{eff}}}{\xi_{11}} + \frac{d_{33,\text{eff}}}{\xi_{12}} \] (3)

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.

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

<table>
<thead>
<tr>
<th>PZT-5A</th>
<th>( d_{33,\text{eff}} ) (Measured)</th>
<th>( d_{33} ) (Calculated)</th>
<th>( d_{33} ) (Vendor Datasheet)</th>
</tr>
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<tbody>
<tr>
<td>140 pm/V</td>
<td>398 pm/V</td>
<td>390 pm/V</td>
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REFERENCES


CONTACT

* E. E. Aktakka, tel: +1-734-272-3170; aktakka@umich.edu
K. Najafi, tel: +1-734-763-6650; najafi@umich.edu