SELF-CURVED DIAPHRAGMS BY STRESS ENGINEERING FOR HIGHLY Responsive PMUT

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ABSTRACT
A process to make self-curved diaphragms by engineering residual stress in thin films has been developed to construct highly responsive piezoelectric micromachined ultrasonic transducers (pMUT). This process enables high device fill-factor for better than 95% area utilization with controlled formation of curved membranes. The placement of a 0.65 µm-thick, low stress silicon nitride (SiN) film with 650 MPa of tensile residual stress and a low temperature oxide (LTO) film with 180 MPa of compressive stress sitting on top of a 4 µm-thick silicon film has resulted in the desirable self-curved diaphragms. A curved pMUT with 200 µm in nominal radius, 2 µm-thick aluminum nitride (AlN) piezoelectric layer, and 50% SiN coverage has resulted in a 2.7 µm deflection at the center and resonance at 647 kHz. Low frequency and resonant deformation responses of 0.58 nm/V and 40nm/V at the center of the diaphragm have been measured, respectively. This process enables foundry-compatible CMOS process and potentially large fill-factor for pMUT applications.

INTRODUCTION
Recent advancements in the pMUT technologies have attracted great attentions in potential applications in consumer electronics, such as gesture recognition, range finding, and medical imaging [1-4]. An ultrasound system consisting of a large array of pMUT elements [5] can carry out acoustic beam forming and focusing [6-7] with the assistance of microelectronics. From a system design perspective, there are two key criteria for the effective performance of ultrasonic systems: (1) optimizing the individual pMUT element for effective electromechanical coupling, and (2) designing the whole array system with high fill factor for efficient area utilization and enhanced output acoustic pressure generation [8].

Theoretical models for flat-shape pMUTs have been well reported. For example, the deflection equation of a pMUT with the circular plate and circular/ring electrode design has been explicitly derived using the approach of Green’s function [9]. The largest center plate deflection per unit input voltage was achieved when the electrode radius coverage was 60% of the whole plate radius using a central electrode [10]. Previously, the electromechanical coupling efficiency of pMUTs was investigated for the design of multiple electrode structures [11]. It is found that 100% higher acoustic output per unit input voltage could be obtained for a two-port electrode design as compared to a conventional single-port pMUT [12]. Furthermore, a bimorph pMUT design with two active AIN layers can achieve 400% higher acoustic outputs as compared to a unimorph pMUT with similar sizes [13].

Our group has developed the “curved pMUT” devices both analytically and experimentally to realize improved electromechanical coupling as compared to flat-pMUTs [14-16]. Previously, a HNA wet etching step was used to construct the curved surface before the aluminum nitride piezoelectric thin film was deposited. Since only part of the curved surface is used as the structural diaphragm, some of the wafer areas are not utilized and the device fill-factor is low. This work presents the concept of self-curved diaphragms by stress engineering instead of the wet etching process with three features: (1) fabrication of self-curved diaphragms without the wet etching process; (2) controllable designs of diaphragm curvature by the combination of residual stresses in thin films and their sizes; and (3) high fill-factor to construct self-curved pMUT arrays.

CONCEPT
Figure 1 shows the 3D schematic diagram of the stress engineered, self-curved pMUT. The curved structure is realized by a piezoelectric AlN layer sandwiched between a bottom and a top metal electrode on top of a silicon diaphragm with a self-generated curvature due to residual stresses in the films. Specifically, the silicon nitride and silicon oxide layers with known tensile and compressive stress, respectively, are introduced on top of the device layer on a SOI wafer to induce the targeted concave-shape structure. The final curvature of the diaphragm is caused by the balance of stresses in various thin films and can be adjusted by the size and properties of the thin films. In the prototype demonstrations, suspended diaphragms can bend downward as illustrated without unutilized portions as those fabricated previously by the wet etching process. As such, high fill factor can be achieved.

Figure 1: 3D cross-sectional view of a stress engineered curved pMUT fabricated in a CMOS-compatible process.
designed to achieve a desirable center deflection, a curved downward diaphragm can be self-constructed. A film with tensile residual stress at the inner portion and illustrated in Fig. 2a can be achieved by placing a thin neutral line (zero stress) or the inflection circle is located at ~0.65r position, where r is the radius of the diaphragm. Therefore, the stress-free concave-shape diaphragm as in the concave-shape structure. Analytically, if a flat, stress-free, clamped diaphragm is deflected downward, radial tensile stress is formed at the outer portion and radial compressive stress is established at the inner portion of the top surface of the diaphragm. The stress neutral line (zero stress) or the inflection circle is located at ~0.65r position, where r is the radius of the diaphragm. Therefore, the stress-free concave-shape diaphragm as illustrated in Fig. 2a can be achieved by placing a thin film with tensile residual stress at the inner portion and compressive stress in the outer portion of a flat diaphragm. Once the residual stresses are released, a curved downward diaphragm can be self-constructed.

The curvature of the self-curved diaphragm can be designed to achieve a desirable center deflection, g, by tuning the silicon nitride and oxide residual stresses, respectively; (b, bottom) After adding the bottom and top electrodes and the AlN layer to complete the stress engineered curved pMUT fabrication.

The cross-sectional diagram in Figure 2a details the stress engineering design. The combination of tensile stressed silicon nitride layer (partially covering the central region of the circular diaphragm) and the compressive stressed LTO (covering the rest of the diaphragm) results in the concave-shape structure. Analytically, if a flat, stress-free, clamped diaphragm is deflected downward, radial tensile stress is formed at the outer portion and radial compressive stress is established at the inner portion of the top surface of the diaphragm. The stress neutral line (zero stress) or the inflection circle is located at ~0.65r position, where r is the radius of the diaphragm. Therefore, the stress-free concave-shape diaphragm as illustrated in Fig. 2a can be achieved by placing a thin film with tensile residual stress at the inner portion and compressive stress in the outer portion of a flat diaphragm. Once the residual stresses are released, a curved downward diaphragm can be self-constructed.

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\[
W_j(r) = \frac{\pi \sigma_{SN} h_{SN} Z_{SN}}{rD(1-\nu_{SN})} \sum_k \frac{O_k(r_k)}{A_k \Gamma_k} \Psi_k(r)
\]

where \( r \) and \( D \) are the diaphragm nominal radius and flexural rigidity, respectively and \( O_k, \Psi_k, A_k, \) and \( \Gamma_k \) are functions defined in [17].

By adding the bottom and top electrodes and the AlN layer to complete the fabrication process after Fig. 2a, the stress engineered curved pMUT can operate as shown in Fig. 2b in the transmission mode under an AC voltage. The induced stress in the piezoelectric layer due to the \( d_{ji} \) effect stretches and compresses the diaphragm, such that it resonates in the flexural mode to emit acoustic waves. The induced stress due to \( d_{ji} \) has a vertical component in the desired vertical motion to enhance electromechanical coupling of the device.

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400µm in diameter, 50% nitride coverage, and measured center deflection of 2.7µm.

Figures 5a & 5b are SEM micrographs of two self-curved pMUTs portraying the clamped and curved diaphragm. Figure 5c shows cross-sectional view of the diaphragm stack composed of - from bottom to top, the buried oxide, silicon device, silicon nitride, and LTO layers as well as the Mo bottom electrode, AlN layer, and the top Mo electrode, respectively. Figure 5d is a close-up view on the AlN illustrating good crystal orientation.

RESULTS AND DISCUSSIONS

The center diaphragm deflection, g, versus the silicon nitride radial coverage percentage, rN, is shown in Figure 6 for a diaphragm with a nominal radius of 200 µm and silicon thickness of 4 µm. The 650 nm–thick SiN has a tensile residual stress of 650 MPa and the LTO has a compressive residual stress of 180 MPa. Results show good consistency between theory (coded in Matlab™), simulation (COMSOL), and experimental data. It is observed that the higher nitride coverage results in higher center deflection for the range of nitride coverages between 40%-55%. Since the curvature of the diaphragm can affect both the resonant frequency and the excited deformation of the devices, the SiN radial coverage ratio can be used in the design process to optimize the device performances. If the coverage percentage increases to be above the inflection circle (roughly 65%-70% of the radius of the diaphragm), the center deflection will start to reduce as compressive regions of the diaphragm can start to reduce the bending moment. The optimal design values can be analyzed or simulated with known properties and parameters of the thin films.

The dynamic responses of a fabricated curved pMUT without (blue) and with (red) the bottom silicon layer are measured using Laser Doppler Vibrometer (LDV) and presented in Figure 7. Resonant frequency reduces from 646.7 to 520 kHz while low frequency displacement remains at 0.58 nm/V after the removal of the silicon layer. It is expected from Finite Element Modeling (FEM) that the released diaphragm without silicon would have lower resonant frequency of 381 kHz and higher low-frequency displacement of 8.5 nm/V as compared to the measured values. The discrepancy between the theoretical and experimental data is attributed to the excessive residual stress in the as-deposited AlN layer (tensile 170 MPa).

Figure 4: Confocal laser scanned image of a fabricated curved pMUT (a) top view; (b) measured curvature profile; (c) 3D tilted view and the radius of curvature.

Figure 5: (a, b) Tilted and front view SEM micrographs of two self-curved pMUTs after the devices are cleaved; (c) a released diaphragm showing the stack of the pMUT layers, and (d) close-up view showing good crystal alignment of AlN on the curved diaphragm.

Figure 6: Center deflection versus nitride radial coverage (%) for devices with 200µm in nominal radii using a 650nm-thick nitride layer. Results show good consistency among simulation, theory, and experimental data.

Figure 7: Measured dynamic responses of stress-engineered curved pMUTs without (blue) and with (red) the bottom silicon layer. The pMUTs have 200µm in nominal radius and 2.7µm center deflection before release. The AlN, Si, and BOX layer thicknesses are 2µm, 4µm, and 1µm, respectively.

Figure 8 shows the effects of residual stress in AlN
on the dynamic responses of stress engineered curved pMUT devices. As the residual stress in the AIN increases, the low-frequency displacement per unit input voltage drops and the resonant frequency increases. It is expected that the device performance would match with the simulated values when the stress in the sputtered AIN is controlled to be within 30 MPa.

![Figure 8: Simulated dynamic responses of a stressed engineered curved pMUT with 200 μm in nominal radius and 2.34 μm center diaphragm displacement for -50, 0, 50, 100, and 150 MPa residual stress in the AIN layer.](https://example.com/figure8)

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