Design and analysis of piezoelectric MEMS micro-speaker based on scandium-doped AlN thin film

1 | INTRODUCTION

MEMS loudspeakers are widely used in smartphones, in-ear applications, head phones, or other consumer goods [1–5]. In recent years, lead zirconium titanate (PZT) piezoelectric micro speakers are dominant on the research trend. Aluminium nitride (AlN) can be another way where AlN has ≈10x lower transmitting efficiency compared with PZT [6, 7]. Scandium aluminium nitride (ScAlN) is a better choice because (ScAlN) retains many features of AlN (e.g. CMOS compatibility, ease of deposition/etching) but possesses significantly increased piezoelectric properties compared with AlN [7–10]. However, most of the devices published to date have used PZT.

The popular types of speaker are electrodynamic, balanced armature and piezoelectric [9]. The electrodynamic loudspeakers consist of a coil, magnet and a membrane [9, 11, 12]. This arrangement of the components cannot go under a certain height to host all the parts. The mechanic behaviour of this type can be controlled depending on the suspension. Coil position and compliance depend on the membrane. While conventional electrodynamic speakers are mainly employed in lower priced products, balanced armature speakers are more targeted at high fidelity in-ear applications as well as wireless systems [13–17]. Initially designed for hearing aids, these speakers feature higher energy efficiency and are capable of delivering good acoustic performance at relatively small device dimension. However, due to their extremely elaborate manufacturing, balanced armature speakers are high priced and limited regarding further miniaturization. Moreover, due to certain restrictions, the reproduction range is limited, necessitating even more expensive and bulkier multi-way speaker systems. Piezoelectric MEMS transducers have a lot of advantages like easy to fabricate, workable over a large dynamic range, and free from the polarization voltage requirement [1–4]. While the tensile residual stress in the transducer diaphragm is the main problem in these transducers. This problem appears as a relatively low sensitivity and low sound output pressure in microphone and microspeaker respectively. Here, we introduce piezoelectric MEMS speaker based on 9% Sc-doped AlN films. We try to increase piezoelectric coefficient compared with AlN [10]. Increase of piezoelectric coefficient will lead to improved mechanical design, efficiency and acoustic performance.

2 | SPEAKER DESIGN AND SIMULATION

As shown in Figure 1, a simple square membrane shape divided into four triangular was selected for the speaker design in this work. The four triangular or actuators are separated by small gap. Each triangular act as a cantilever where it is clamped with surrounding frame. The thicknesses of membrane stack layers were optimized using the analytical model. According to the optimization, thickness of layers would be leaded to zero value. Very thin AlN tends to have a reduced piezoelectric coupling coefficient and a large loss angle. For this reason, these relationships must be included in the optimization. In this model, an artificial neural network (ANN) has been applied to get these data from the experimental data. The ANN helped to extract
FIGURE 2  Simulated displacement field when applying 20 V driving voltage. (a) The thickness of the ScAlN is 0.5 μm. (b) The thickness of the ScAlN is 1 μm. (c) The shape of the simulated speaker when applying voltage looks like closed membrane.

TABLE 1  Material properties as a function of layer thickness

| Thickness in μm | 0.2 | 0.5 | 1  | 1.5 | 2   |
|-----------------|-----|-----|----|-----|-----|
| AlN loss angle as a function of AlN film thickness concluded from measurements. | 6.5 | 3.2 | 1.9 | 1.2 | 1.0 |
| AlN piezoelectric coupling coefficient | 1.8 | 2.4 | 2.5 | 2.6 | 2.6 |

piezoelectric coupling coefficient ($d_{31}$), and the loss angle ($\tan \delta$) of the AlN as shown in Table 1. The prediction of any value related to the $d_{31}$ and dissipation factor of AlN as a function of thickness can be done easily using ANN.

Increasing the membrane thickness results in reduced deflection, and thus we optimized the thickness to 1 μm. The thickness of the top electrode was optimized to 100 nm. Mo was used as the supporting layer and bottom electrode with thickness of 2 μm.

The top and bottom electrodes are made from Au and Mo respectively and operated by applying voltage on it. The actuators perform an out of plane displacement interacting with
adjacent air. Each triangular is mechanically decoupled from each other, and then large movement can be achieved. Thus, for the device with an active area of $3 \times 3 \text{ mm}^2$, deflection of more than 39 $\mu$m can be achieved when apply 20 V driving voltage. As shown in Figure 2, one of the cantilevers that consists the speaker can achieve deflection of 39 and 24 $\mu$m when the active layers are 0.5 and 1 $\mu$m respectively at 20 V driving voltage. The first resonance mode of the speaker is 8536 Hz. This high resonance frequency helps the speaker to reproduce sounds in wide bandwidth.

The gaps between the four actuators are 4 $\mu$m which determined by the simulation. The performance of the proposed design is affected by the gap especially the SPL. The gap will affect the SPL generated by the four actuators. Based on simulation, when making gaps more than 10 $\mu$m, the acoustic losses will be significant which leading to drop in SPL. The proposed structure uses 4 $\mu$m gaps to work acoustically like a closed membrane while saving the mechanical performance of decoupled actuator. This feature allows the loudspeaker to generate higher SPL than devices with closed membranes. Figure 3 indicates the gap width influence on the SPL. The effect of the gap width appears much more in low frequency.

With respect to the acoustic performance of the full device, Figure 4 shows the total SPL as a function of frequency. The SPL is above 51 dB from 20 Hz onwards and above 56 dB at 20 kHz. With further improvement in the near future, the device promises to give typical SPL demands for in-ear applications in consumer electronics like conventional speakers. The usage of ScAlN instead of PZT will help us to integrate actuator and circuit in one package.

Moreover, the comparison between AlN and ScAlN in terms of the deflection will give us clear indication with the percentage of the enhancement and this enhancement will reflect on the acoustic performance as shown in Figure 5. The comparison shown in Figure 5 highlights that the thickness of the active layer has a great impact on the SPL when apply 20 V. When the thickness is 0.5 $\mu$m, the deflection will be 39 and 29 $\mu$m for ScAlN and AlN respectively. When the thickness is 1 $\mu$m, the deflection will be 24 $\mu$m and 18 for ScAlN and AlN respectively. 9% doping of Sc gives approximately 25% improvement in deflection than pure AlN. As shown in Figure 6, the maximum deflection versus driving voltage up to 20 V using both ScAlN and AlN when the thickness is 1 $\mu$m. When the driving voltage is increased above 10 V, the enhancement of ScAlN appear strongly. Because below 10 V the maximum deflection less than 10 $\mu$m, the 25% enhancement of Sc not appear well with small value of deflection.

3 | FABRICATION

Based on the above described design, prototypes for MEMS speaker have been fabricated by using silicon MEMS technology. First, deposition of a thermal oxide layer SiO$_2$ which used as isolation layer. 2 $\mu$m Mo layer is used as supporting layer on Si substrate. Mo also is used as a lower electrode upon the supporting layer. ScAlN film was sputtered with 1 $\mu$m thick by using a ScAl alloy target with 9% Sc. Au is used as top electrode, the speaker stack, consists of ScAlN layer sandwiched between two electrodes. Finally, DRIE is used for the etching of wafer backside to release the actuators. The fabrication process is based on four masks as shown in Figure 7. After dicing speaker chips have been assembled for acoustical characterization. First prototypes with few cm$^2$ chip size and good piezoelectric activity have been completed and assembled for characterization. The
FIGURE 5  Comparison between deflections of the speaker as a function of thickness of active layers in case of usage two materials AlN (blue) and ScAlN (yellow)

FIGURE 6  Comparison between maximum displacement amplitude versus driving voltage when the thickness of the active layer is 1 (μm) in case of usage two materials AlN (red) and ScAlN (blue)

FIGURE 7  Schematic illustration of MEMS micro speaker fabrication process
acoustic measurements work will be carried out by CRY6151 ELECTRO-ACOUSTIC ANALYSIS SYSTEM. It can measure the performance of micro speakers like SPL, total harmonic distortion THD, and sensitivity. The measurements will accomplish soon in the future works.

4 | CONCLUSION

Piezoelectric MEMS microspeaker based on 9% Sc-doped AlN were demonstrated in this paper. The ScAlN layer thicknesses were optimized based on FEM simulations to maximize the membrane deflection, which leads to higher sound pressure level. The maximum achievable displacement with 20 Vpp driving voltage reached to 39, and 24 μm for 0.5 and 1 μm thickness, respectively. This speaker will potentially make breakthrough in speaker industry due to unique features like small size, higher energy efficiency, full CMOS compatibility, lead-free and magnet-free.

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