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Membraneless Piezoelectric MEMS speakers based on AlN Thin Film

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Ahmed Fawzy[1]

Abstract
This paper reports piezoelectric aluminium nitride (AlN) based microelectromechanical systems (MEMS) speakers. We introduce a novel geometry of micro speakers based on AlN to meet the requirements of modern applications such as phones, tablets, laptops, and in-ear applications. We introduce the principle, design, and characterization results. The speakers were fabricated on cavity silicon on insulator (SOI) substrate and characterized by using an electroacoustic tester. This paper considers the acoustic performance of the speakers. The results show that the speakers gave us a high sound pressure level (SPL) of more than 78 dB for circle geometry when applying 2 volts on the electrodes. These results are equal for PZT MEMS speakers moreover AlN opens the door to integrate the speakers and the ASIC on the same chip. The size of the different geometries' speakers isn't exceeded 3mm × 3mm. These geometries offer a breakthrough in acoustic performance, a frequency response, and low power consumption

Keywords
AlN, MEMS, Micro speakers, piezoelectric.

1. Introduction

A speaker is a device used in most modern applications especially MEMS micro speaker has a tremendous candidate in new era smartphones, laptops, headphones, and in-ear applications.[1]–[3] Usually a speaker must have high SPL, low total harmonic distortion (THD), small geometry, lightweight, low power consumption, batch fabrication possibilities, and high sensitivity. All these features are desirable to achieve high-performance speakers. In addition, miniaturization and compatibility with CMOS technology are very attractive. Until now, most traditional speakers in use have been manufactured based on dynamic speakers [4], [5] which are based on magnets and suffer from big size. In another hand, electrodynamic speakers are low-priced products. There is another type of speaker called balanced armature speakers. These speakers have higher energy efficiency, good acoustic performance, and a small device size. However, these speakers are high cost, need a complicated process in fabrication [6]–[8]. The widely used piezoelectric materials include lead zirconate titanate (PZT) or organic polymers such as polyvinylidene fluoride (PVDF) due to their excellent piezoelectric coefficient and relative mature manufacture processes. The superb features of the traditional (PZT) piezoelectric speakers are their high SPL, and high sensitivity[9][10]. However, these speakers are incompatible with semiconductor batch fabrication

[1] Nanotechnology central lab, Electronics Research Institute (ERI), Cairo, Egypt (ahmed.fawzy.1986@ieee.org) (afawzy@eri.sci.eg)

and manufactured with difficult assembly steps. Due to this assembly and method of fabrication, these kinds of speakers suffer from high cost and large size and weight.
MEMS AlN thin films are used in more devices in the last five years such as piezoelectric micromachined ultrasonic transducers (PMUT)[11], [12], RF resonators[13], and MEMS microphones.[14][15][16] All previous applications depend on AlN thin film for the unique features of AlN than other piezoelectric materials such as CMOS compatibility, quality of sputtered films is very high, and free lead piezoelectric material. Piezoelectric MEMS speakers are reviewed based on a piezoelectric material, sound pressure level, and speaker size. Sol-gel and sputtered PZT materials are used widely in MEMS speakers because they have a high piezoelectric coefficient. These materials are very toxic and not easy to deal with it. ZnO and AlN are used in MEMS speakers due to nontoxic materials, but they have a low piezoelectric coefficient. The fair comparison between different speakers depends on many parameters such as (speaker geometry, size, thickness of piezoelectric layer, driving voltage, electrode material, resonance frequency, and distance between speaker and tester). These parameters must be identical to achieve fair comparison. Table 1 summarizes the key results of variant MEMS speakers.

Table 1: The key results of variant MEMS speakers

REF	Piezoelectric material	Diaphragm Configuration	Maximum SPL	Distance between speaker and tester
[17]	Sputtered PZT	1.13 mm(circular)	74.5 dB	In coupler measurement 3 cm long tube.
[18]	ZnO	Square	50 dB	Not available
[19]	ZnO	3 mm Square	76 dB	Free field measurement at 1 cm
[20]	AlN	3 mm Square	56 dB	Free field measurement

This paper introduces the design, fabrication, and characterization of MEMS piezoelectric AlN speakers. Different geometries will be studied and compared with each other to get the best geometry and high acoustic performance. The speakers were fabricated, characterized, and the results will be presented.

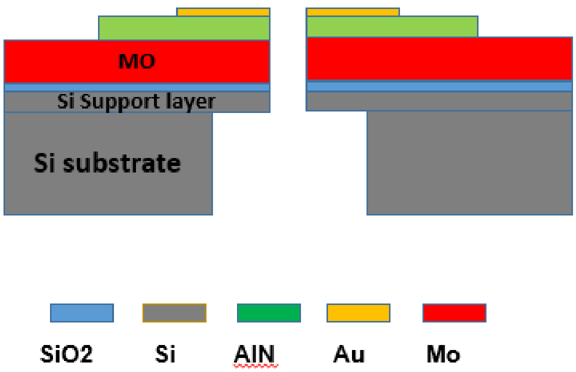

Fig. 1. Schematic cross-section of the MEMS AlN Speaker.

2. Speaker Design and Measurement

2.1 Geometry

The proposed designs of MEMS AlN speakers are based on the membrane-less concept. The concept is based on separating the speakers into pieces. Each piece is clamped on a surrounding frame and free from another side. There is a narrow gap between each piece and another. Finally, when applying a voltage on the electrodes, each piece makes an out-of-plane deflection and looks like one membrane. Moreover, these ideas can enhance the acoustic performance of the speakers.

Each piece (actuator) consists of a silicon supporting layer on which 0.5 µm piezoelectric AlN is surrounded between two electrodes as shown in Fig. 1. Finite element analysis software (FEA) has been used to study the difference between mechanical behavior, and acoustic performance. FEA can be used to determine whether changing the shape of the membrane (Square, Pentagonal, Octagonal, and Circular membranes) will affect the SPL, deflection, and THD or not. Analysis has been performed to take first the deflection in different membranes when applying 20 V, as shown in Fig. 2. The size of all membranes is equal to 3 × 3 mm2 and the thickness of the AlN is 0.5 µm. Moly is used as the bottom electrode and supporting layer with a thickness of 2 µm. Au is used as the top electrode. Thin film of Si is used as a supporting layer. Table 2 shows the material properties that used in the simulation.

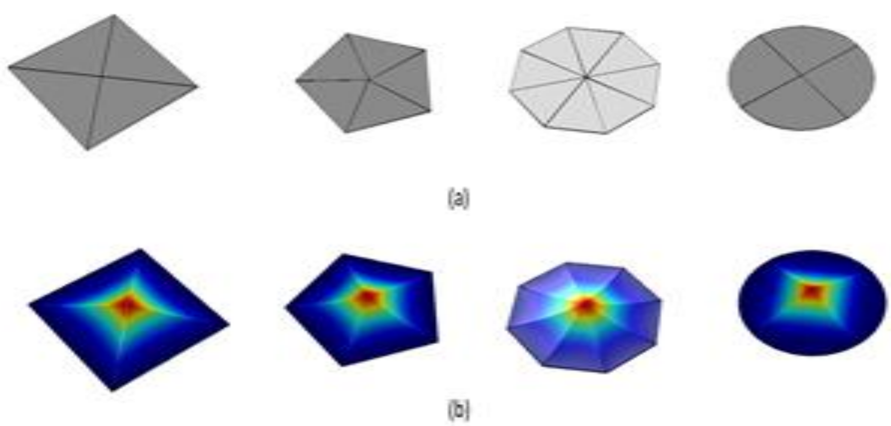

Fig. 2. (A) Different geometries of MEMS speakers with approximately equal size 3 × 3 mm2 , (b) Simulated displacement of the speakers when applied voltage on the electrodes.

Table 2: Material Properties Used in the Analysis

Material	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)
Si	160	0.22	2320
AlN	2082	0.23	3260
Mo	312	0.30	10200
Au	70	0.44	19300

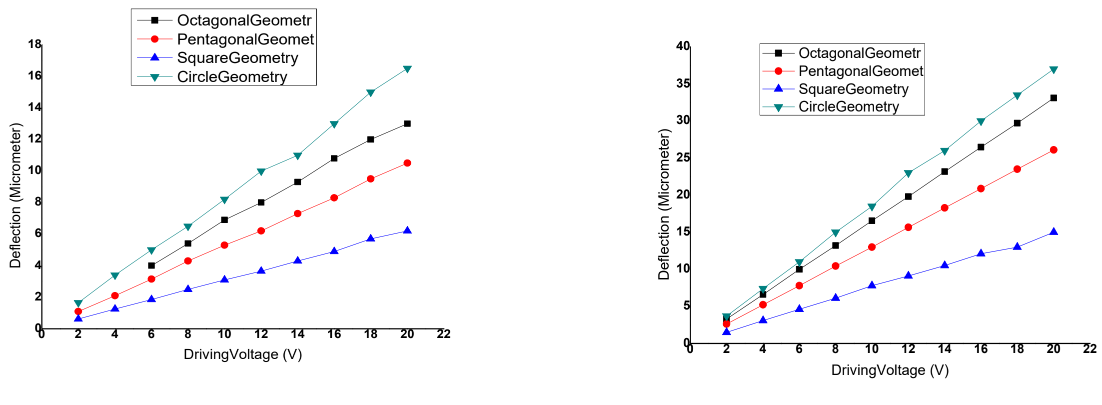

Fig. 3. Maximum deflection amplitude versus driving voltage for different geometries when (a) silicon supporting layer 5 (µm), (b) silicon supporting layer 2 (µm).

The geometry of the speakers is an important factor. As shown in Fig. 3 FEA is used to study the difference between the mechanical behaviour especially deflection of square membrane (SM), Pentagonal membrane (PM), Octagonal membrane (OM), and Circular membrane (CM), and to

prove that the geometry of the membrane can enhance the performance of the speaker. Analysis has been executed to take the maximum deflection versus different applied voltage and in two cases when using the thickness of Si support layer 5 and 2 µm. The circular membrane is the best geometry of the speakers. The deflection of CM when applying 20 V on the electrodes and using supporting layer 2, 5 µm are 37, 16.5 µm respectively. While the worst result comes from SM. The deflection of SM when applying 20 V on the electrodes and using supporting layer 2, 5 µm are 15, 6.2 µm, respectively. The speaker geometry is affected by the airflow and then the air velocity. The viscous losses and losses caused by thermal conduction are linked directly with the speaker geometries. This is the main reason that the CM, OM gives better results than PM, SM.
The residual stress is stress comes with no external load. Residual stresses can be tensile or compressive depending on the location and type of non-uniform volumetric change. The traditional membranes are constrained on all edges which leads to high membranes tension that results in the decreased acoustic performance of the speakers. Membrane less speakers can reduce the residual stress and hence increase the acoustic performance of the speakers. The residual stress of the thin film controls the resonant frequency Fn of the speakers. The thickness of the Si supporting layer plays a great role in maintaining the small Fn variations. As shown in Table 3, when changing in thickness of the supporting layer, the resonance frequency changed. In addition, FEA was used to simulate the residual stress due to the frequency variation for different speaker geometries as shown in fig. 4. From figure 4 we can see that there is no big variation in residual stress for the four geometries. CM shows smaller frequency variation compared to other geometries.

Table 3: Resonant Frequencies for Different Thickness of Si Supporting Layer in Different Geometries

The thickness of Si supporting layer	**Resonance Frequencies (Hz)**			
	SM	**PM**	**OM**	**CM**
5 µm	7524.8	4651.4	3759.5	2370.7
2 µm	4156.8	2559.9	2061.4	1382.9

The resonant frequency of different membrane shapes can be calculated by this equation [11][16]:

$$F_n = (\lambda/\mathrm{d}) * (\mathrm{D}/\mu)^{0.5} \quad (1)$$

where do is diameter, D is flexural rigidity of the membrane based on young modulus and passion ratio of each layer, µ is the mass per unit area, and λ is the eigenvalue. The core parameters for the characterization of MEMS speakers are THD. THD is the ratio of RMS of the harmonic frequencies to the RMS of the fundamental frequency. Simply, THD is the ratio of distortions to the pure signal.

$$THD\% = \frac{\sqrt{\sum_{i=2}^{inf} K_i^2}}{K_1} \quad (2)$$

where K_i is the harmonic frequencies, and K_1 is the fundamental frequency. The main reasons for THD in piezoelectric MEMS speakers are stiffness of the MEMS and piezo coefficient of the AlN. Due to geometrical nonlinearity, the stiffness depends on the membrane deflection. Due to the polarization effect in the AlN, its transmission coefficient depends on the input voltage.

The power consumption of dynamic speakers is measured easier than piezoelectric MEMS speakers. The impedance of the dynamic speaker is roughly constant over frequency approximately can be one of these values (4, 8, or 32 Ω). In the case of piezoelectric speakers, the measurement of power is difficult due to the strongly changing impedance over frequency. The behavior of impedance looks like the behavior of capacitor, low frequency meets high impedance and high frequency meets low impedance as shown in Fig. 5. This demonstrates that the measurement of the power consumption for piezoelectric MEMS speakers is very difficult. The only way to calculate the power is using a system-level evaluation in combination with a representative sound signal at a defined output level.

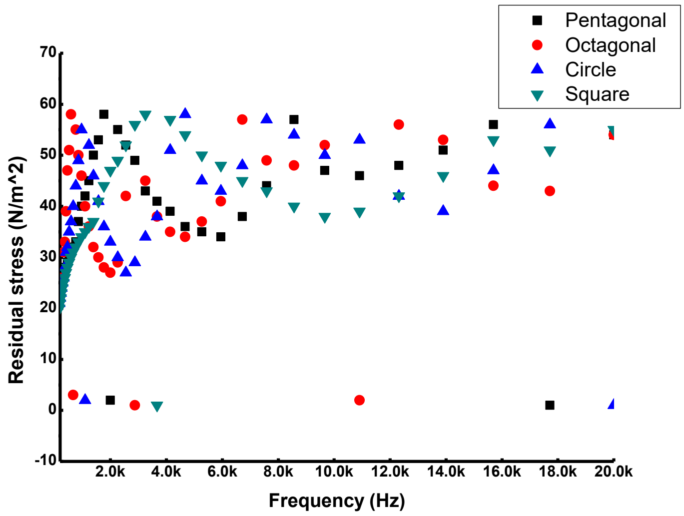

Fig. 4. The simulated residual stress versus audio range frequencies in the different speaker geometries.

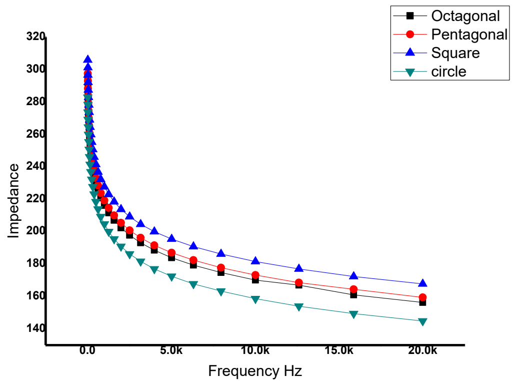

Fig. 5. Simulated results for impedance versus frequency for different geometries.

2.2 Measurement Setup

The measurements of the MEMS speaker were executed by the Electroacoustic analysis system as shown in Fig. 6. The device can be used to measure SPL and THD. The setup is based on a shield box, MIC, and headphones. The device works in the audible range from 20 Hz to 20 kHz. The SPL measurement results for four different geometries with frequencies are shown in Table 4. These results were achieved when applied 2 V (peak-to-peak). The SPL is above 78 db. OM is less than 8% with respect to CM. The worst performance comes from SM which is less than CM with 33%. With further improvement in the near future, the device promises to give typical SPL-like dynamic speakers which can be used in consumer electronics. THD measurements have been executed based on the rules of IEEE 519-2014. The important measurement to assess the quality of sound is THD. The input voltage in these measurements is 2 Vpp. Overall, the THD is moderate, staying under 5% in all geometries in the audible range. At resonance frequencies, the THD became very high but under 10 % for all geometries. The shape of the geometry doesn't affect THD. We make our measurements based on second harmonic and third harmonic to fundamental harmonic. In the next version of these speakers, control algorithms will be added to vanish these distortions.

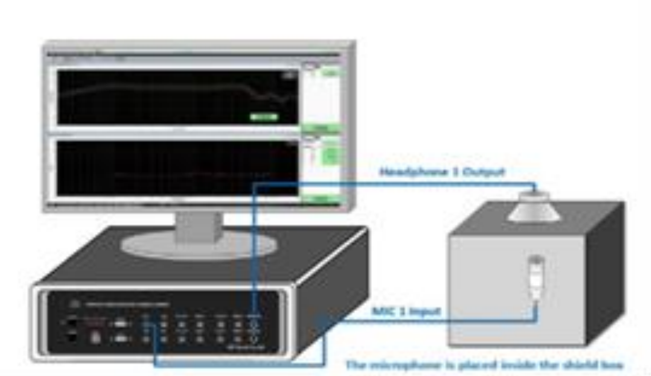

Fig. 6. Photograph for hardware connection of MEMS speaker-test

Table 4: SPL measurements for different geometries by using electroacoustic tester and 2 V peak to peak

Speaker Geometry	SPL dB
CM	78
OM	72
PM	63
SM	52

3. Conclusion

AlN MEMS speakers were demonstrated in this paper. The thickness of the AlN layer and Si supporting layer were optimized by using FEA to produce a speaker with a novel acoustic performance. Based on simulations and fabrication, the CM is the best design for speakers. The deflection and SPL will be changed by changing the shape of the membrane. It has been shown that for small gaps between membrane pieces, the membrane-like a closed membrane. This new type of piezoelectric speaker has been developed especially for modern applications.

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مكبرات الصوت الكهر ضغطية الكهروميكانيكية الدقيقة بدون أغشية اعتمادا على أفلام نيتريد الألومنيوم

الملخص

يشير هذا البحث إلى مكبرات صوت من نيتريد الألومنيوم الكهرو ضغطي (AlN) القائمة على الأنظمة الكهروميكانيكية الدقيقة (MEMS). نقدم هندسة جديدة للسماعات الصغيرة التي تعتمد على AlN لتلبية متطلبات التطبيقات الحديثة مثل الهواتف والأجهزة اللوحية وأجهزة الكمبيوتر المحمولة وتطبيقات الأذن. نقدم مبدأ التصميم ونتائج التوصيف. تم تصنيع مكبرات الصوت على تجويف سيليكون على ركيزة عازلة (SOI) واختبرت باستخدام جهاز اختبار صوتي كهربائي. تتناول هذه الورقة الأداء الصوتي للسماعات. أظهرت النتائج أن مكبرات الصوت أعطتنا مستوى ضغط صوت مرتفع (SPL) يزيد عن ٧٨ ديسيبل لهندسة الدائرة عند تطبيق ٢ فولت على الأقطاب الكهربائية. تتساوى هذه النتائج مع مكبرات الصوت PZT MEMS علاوة على ذلك، يفتح AlN الباب لدمج مكبرات الصوت وASIC على نفس الشريحة. لا يتم تجاوز حجم مكبرات الصوت ذات الأشكال الهندسية المختلفة ٣ مم × ٣ مم. تقدم هذه الأشكال الهندسية طفرة في الأداء الصوتي، واستجابة للتردد، واستهلاك منخفض للطاقة.