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Towards a Digital Sound Reconstruction MEMS Device: Characterization of a Single PZT Based Piezoelectric Actuator

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***Abstract*—In this paper we report the fabrication and characterization of a single piezoelectric actuator for digital sound reconstruction. This work is the first step towards the implementation of a true digital micro-loudspeaker by means of an array of acoustic actuators. These actuators consist of a flexible membrane fabricated using polyimide, which is actuated using a Lead-Zirconate-Titanate (PZT) piezoelectric ceramic layer working in the d31 actuation mode. The dimensions of the membrane are of $1\,mm$ diameter and $4\,\mu m$ in thickness, which is capable of being symmetrically actuated in both upward and downward directions, due to the back etch step releasing the membrane. Our electrical characterization shows an improvement in the polarization of the piezoelectric material after its final etch patterning step, and our mechanical characterization shows the natural modes of resonance of the stacked membrane.**

I. Introduction

The constant evolution of the consumer electronics industry has an important role in today's life and the desire for higher quality products increases year after year. Improvements of components such as speakers, microphones, humidity sensors, accelerometers, gyroscopes, and cameras are in high demand and in constant evolution. These components require improved characteristics in order to keep up with the technological evolution (i.e. smaller dimensions, low power consumption and better quality).

Regarding the audio technology, an interesting approach to improve the performance of acoustic transducers is the elimination of components that introduce noise when digital signals are converted to analog signals, which are normally reproduced by commercial speaker drivers. The idea behind this approach is the development of a system that allows direct communication from the digital audio signal to a digital acoustic transducer without the need of a digital-to-analog converter (DAC), see Fig. 1. A solution to this challenge is the concept known as "Digital Sound Reconstruction", where a Digital Transducer Array Loudspeaker (DTAL) can be used to reproduce binary pulses that can be added together to reconstruct an analog audio signal.

Through the implementation of such concept, existing problems associated to conventional analog speakers (e.g. frequency response and linearity), could be diminished [1]–[3], and the development of a true Digital μLoudspeaker that does not require DAC, can be achieved.

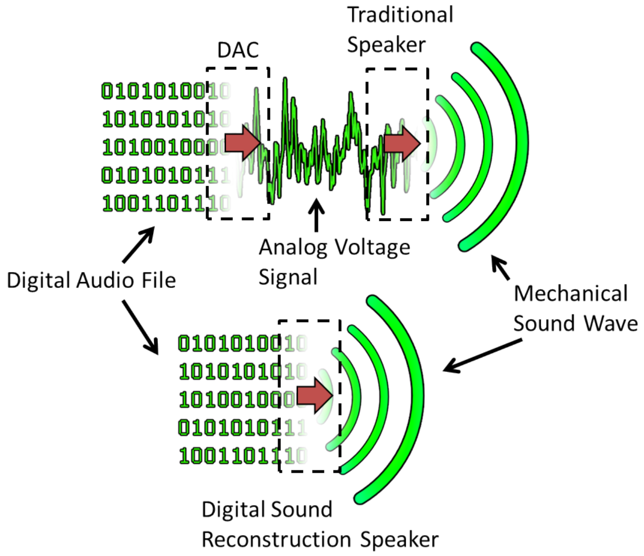

Fig. 1. Sound reproduction cycle a) typical configuation b) proposed configuration using a DTAL (which removed the space needed on a chip for a DAC which could also demand power)

The DTAL was first proposed by Huang et al. in [4]. This transducer array is organized by sets of transducers that are associated with the number of bits used to reconstruct the analog signal in a digital μLoudspeaker. Therefore, this configuration is referred as "binary weighted group". For example, a 3 bit speaker will have three sets of transducer actuators. The first set is comprised of 4 transducer actuators, that represent the most significant bit (MSB). The second set of transducers has two actuators for the second most significant bit and the third set is just a single transducer that counts for the least significant bit (LSB). So basically, in a DTAL the weight of each implemented configuration is given by the number of transducers in each bit group (i.e. $1, 2, 4, 8, ..., 2^n$).

In this paper we have studied a single acoustic transducer and characterized its mechanical and electrical response. In addition we developed a fabrication process that enables the realization of such devices.

II. Digital Sound Reconstruction Concept

Sound reconstruction, using a DTAL device, is produced by the addition of the small sound contributions that are created by the activation of one or more individual transducers at any discrete period of time. An example of this concept applied in a 3-bit μLoudspeaker is depicted in Fig. 2. The device is comprised of seven acoustic transducers that are activated digitally and whose individual contribution makes up for pressure change needed to represent an analog audio signal. The analog signal at Fig. 2a) is reconstructed by the actuation of all seven transducers in the 3-bit chip. The response of each individual transducer is added together in order to reproduce the equivalent sound of the analog wave. In Fig. 2b), only two transducers are needed to achieve the same amplitude as the analog wave. An example of a negative sound pressure is shown in Fig. 2c). In this point, only the transducer of the LSB is actuated but in the opposite direction to reconstruct the original signal. In the position of Fig. 2d), the four transducers of the MSB are actuated simultaneously. Likewise, the initial or idle position of the actuator is represented in Fig 2e), where the system moves from positive pressure to negative pressure, or vice versa.

In summary, the operation of the DTAL device is such that when lower pressure is needed, fewer actuators are activated and when higher pressure is required, more actuators are used. A complete digital reconstruction of an analog sound wave is shown in Fig. 2 f). Different combinations of the actuated transducers are needed to match the analog waveform at each digital point. As it can be seen each actuator displacement contributes to a small pressure change in the system, which is a portion of the total sound pressure change generated by the device.

The response of each individual transducer depends only on the digital clock that synchronizes the reconstruction process. This makes the actuation of the transducers independent of the audio's frequency being reconstructed, and therefore it enables similar sound reconstruction of high and low analog frequencies. This means that the individual transducers do not require an specific operational frequency range, as compared to the common design rules of loudspeakers.

Our work differs from previous reports [5]–[9] on the actuation principle, the dimensions of the actuator, and the general idea of the development of a complete digital acoustic transducer using an array of piezoelectric transducers.

III. Background and Proposed Design

Diamond et al. reported a direct digital method of sound reconstruction using CMOS-MEMS arrays as micro-speakers in a singles chip [10]. Such concept was previously described [1] by this group, and later further developed in other articles [10]–[13]. Their initial proof of concept was fabricated using seven large individual transducers that were wire bonded

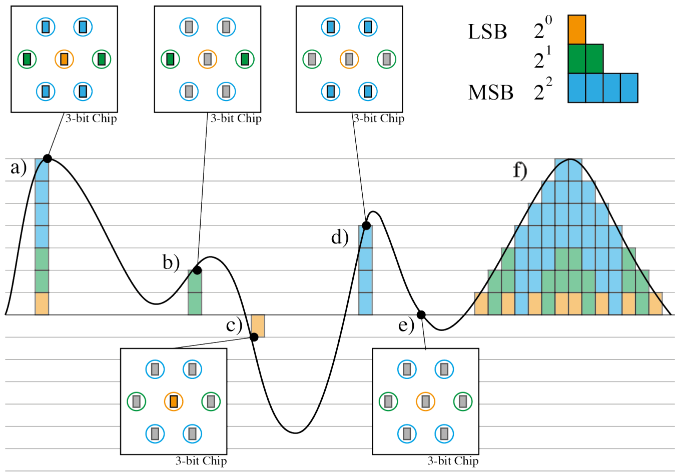

Fig. 2. Sound Reconstruction using a hypothetical 3-bit Digital Transducer Array.

to create a 3-bit array. These transducers were fabricated separately as individual chips and later put together to produce the final device. In their last work, they proposed a set of CMOS-MEMS arrays as micro-speakers in a single chip. Each transducer in the array is comprised of a fixed bottom electrode and a suspended moving-membrane with a second electrode. When voltage was applied between the membrane's electrode and the substrate's electrode, the membrane buckles down and comes into contact with the substrate. When the voltage is removed, the membrane buckles up and springs back to its idle position. The negative pressure change was shorter than the positive pressure change since the bottom electrode stops its downwards displacement. When the membrane was released to generate a positive pressure pulse, the upwards displacement of the membrane overshoots and becomes larger than the negative displacement. In this case, the membrane is free to move by design, and the only limitation comes from the spring constant force. In addition, on the positive direction the membrane has a frequency response in which the system continues to oscillate until the vibration decreases by means of air damping. For this reason, negative and positive actuation showed an inherit asymmetry in their system. In all their work they used the electrostatic principle as the driving mechanism of their devices, but this was not sufficient to compete with modern loudspeakers due to the asymmetry described above.

In our work, we propose the use of the piezoelectric effect as the actuation mechanism for the acoustic transducer, rather than the electrostatic actuation used by Diamond et. al. [10]–[13]. Piezoelectric actuation can reduce the power consumption of the device and remove the asymmetric motion of their reported membranes. A symmetric motion, by means of piezoelectricity, can eliminate the undesirable noise of the acoustic device. Piezoelectric actuators are used as transducers in the form of cantilevers or membranes, which can generate a voltage by applying a force to the structure (direct piezoelectric effect) or a displacement by applying an electric field to the piezoelectric layer (inverse piezoelectric effect) [14].

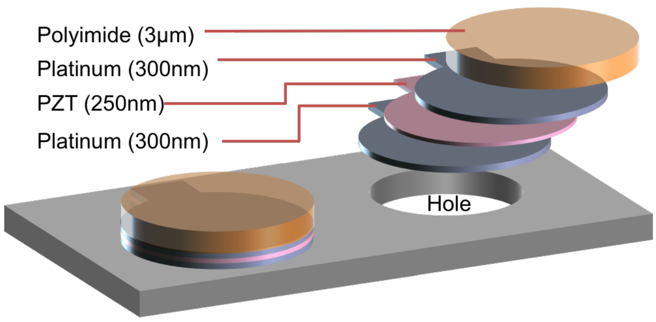

Fig. 3. Membrane design concept: four physical layers on a silicon substrate with a through etch hole

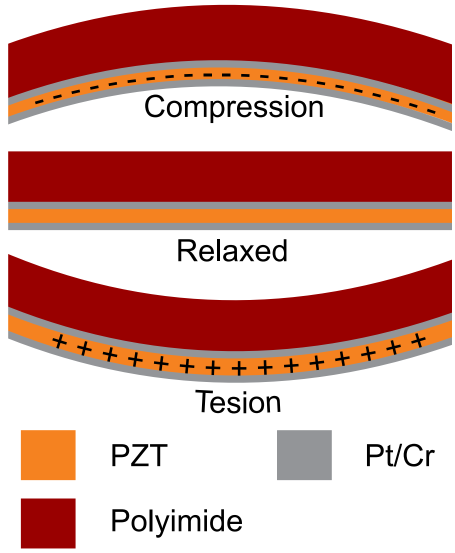

Fig. 4. Actuation principle of the proposed acoustic atuators. A tension strain of the piezoelectric film bends the piezoelectric diaphragm downwards, and similarly a compresion strain of the film bends the diaphragm upwards.

The components of the reported piezoelectric micro-speaker are: the piezoelectric actuator diaphragm and a fixed frame (substrate). Our proposed design is a circular membrane structure with a $1\,mm$ diameter and a approximately thickness of $4\,\mu m$. The membrane is processed on silicon and it is fixed from its edges to the substrate. Fig. 3 shows the design concept.

Typically, piezoelectric devices are designed to operate in two modes: "D31mode" and "D33 mode". In the first mode of operation, an electric field is applied normal to the piezoelectric film (parallel electrodes) and produces a compression in-plane strain. In the second case, an in-plane electric field (interdigitated electrodes) is used to produce a tension in-plane strain. If the polarization is reversed the behavior of the piezoelectric material generates strain in the opposite direction. In this work, we have chosen the "D31 mode" because it is fabricated using a simpler process and design. The actuation principle for our piezoelectric actuators is shown in Fig. 4. Because the piezoelectric film is placed underneath the polyimide structural layer, a tension stress due to positive polarization bends the structure downwards. Whereas a negative polarization, causing a compression stress, bends the structure upwards.

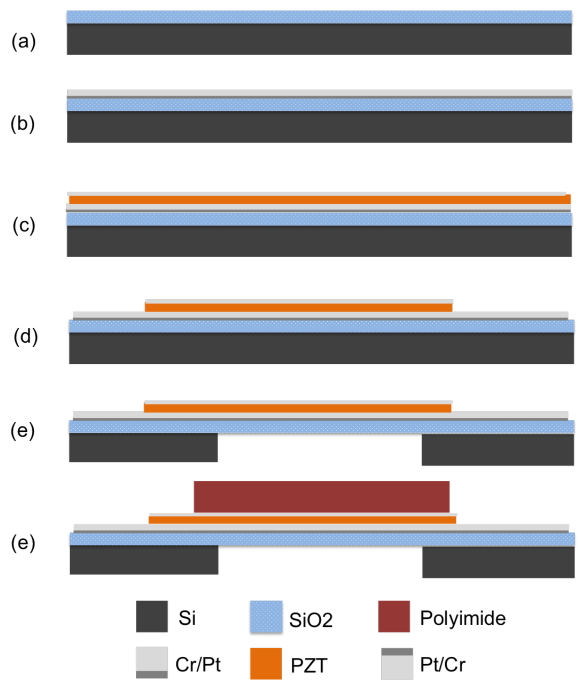

Fig. 5. Fabrication Process Sequence for the micro membrane.

IV. Description of the Fabrication Process

The acoustic membranes of this work were fabricated on $500\,nm$ of a thermally grown silicon oxide layer (SiO_2), which was used as a diffusion barrier and as an etch-stop in the last step of the fabrication process. Then a common ground layer of platinum (Pt) was deposited with a nominal thickness of $300\,nm$. This layer is used a the bottom electrode and also helps the PZT crystal to grow with the desired crystal structure.

After this, we spun a sol-gel PZT layer from Mitsubishi to a nominal thickness of $250\,nm$. This deposition was achieved through three cycles of coating and thermal annealing at $650°C$. Posterior to the annealing step, a lift-off process is used to pattern the top electrode using a platinum (Pt) layer of $300\,nm$. A hard mask of titanium nitride (TiN) is then used to etch the PZT layer.

The final piezoelectric layer has a nominal thickness of approximately $250\,nm$. Then, the polyimide layer was processed after the pyrolisys steps, due to the polyimide's decomposition temperature of $450°$ [14]–[25]. This material was processed following the procedure described in [26], [27]. Other materials such as SU-8 could be potentially used to have desired results [28], [29]. Finally, the bottom of the wafer was back-etched using deep reactive ion etching (DRIE) to release the membrane, see Fig. 5. The wafer is then diced into chips using an automatic dicer saw system or an automatic scriber [30].

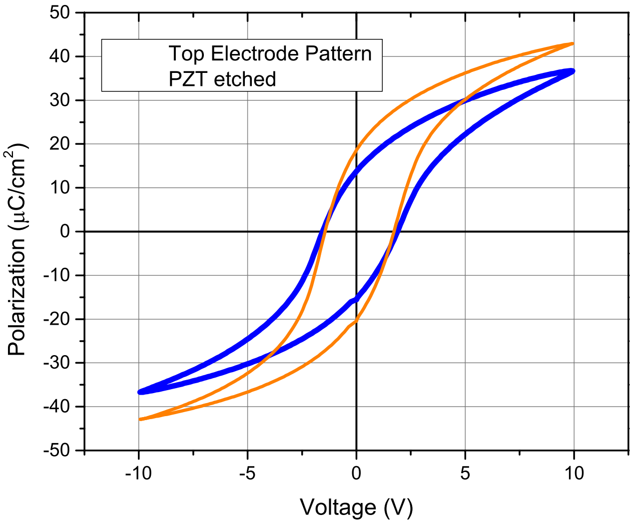

Fig. 6. Hysteresis Loop measured after the top electrode patterning and after the PZT pattern

V. Experimental Results and Membrane Characterization

A polarization step is commonly used before testing or using piezoelectric devices, but there was no need to polarize our piezoelectric layer due to the self-polarization of PZT thin films [31] with thickness below $400\,nm$. We characterized this self-polarization effect using a TF-Analyzer 2000 as shown in Fig. 6. The blue hysteresis curve of the fabricated piezoelectric membrane was measured before the release steps and it was used as reference point to evaluate if the posterior etch processes had any effect on the behavior of the PZT polarization. The maximum polarization achieved at $10\,V$, before the PZT was etched is $P_{max} = 36.68\,\mu C/cm^2$. After the PZT and polyimide layers were patterned using RIE, the polarization was measured again (orange curve), showing a maximum polarization in our piezoelectric film of $P_{max} = 42.89\,\mu C/cm^2$. In both graphs, the polarization achieves well saturated and symmetrical P-V curves.

As it can be seen, there was an improvement after the etch of the PZT layer, which is a good characteristic for our membrane in comparison to other reported PZT processing steps used [32]–[34].

The fabricated Polyimide/PZT/SiO_2 membranes were further characterized mechanically using a Polytec Laser Doppler Vibrometer and a White Light Interferometry systems. With these tools, we were able to operate the membranes with voltages ranging from $10-25\,V$ and extract their natural frequency modes. Fig. 7 shows the first 6 resonance modes of the circular membrane and Table I summarizes these measurements. The first resonance mode was found at around $71\,kHz$, allowing these actuators to digitally reconstruct the audio signal at a frequency of at least 3 fold the maximum acoustic frequency ($20\,kHz$).

Fig. 8 A) shows an optical photograph of the wafer before PZT patterning, hence the pinkish color of the background and Fig. 8 B) shows the topology measurement using the white-light interferometry capability of the same Polytec tool. Finally, the fabricated individual membranes were subjected to a sweep voltage from $1\,kHz$ to $10\,kHz$ using a sinusoidal wave of $25\,V$. These actuators were able to reproduce the sweeping sound at a low intensity, showing promising results for the development of a truly digital μLoudspeaker with symmetrical displacement.

TABLE I
MEASRUMENTS OF THE NATURAL MODES OF RESONANCE

Mode	Natural Frequency	Composing Modes
1	71.094 kHz	0 - diameter node, 1 - circular node
2	106.938 kHz	1 - diameter node, 1 - circular node
3	110.200 kHz	1 - diameter node, 1 - circular node
4	145.359 kHz	2 - diameter node, 1 - circular node
5	147.406 kHz	0 - diameter node, 2 - circular node
6	161.375kHz	3 - diameter node, 1 - circular node

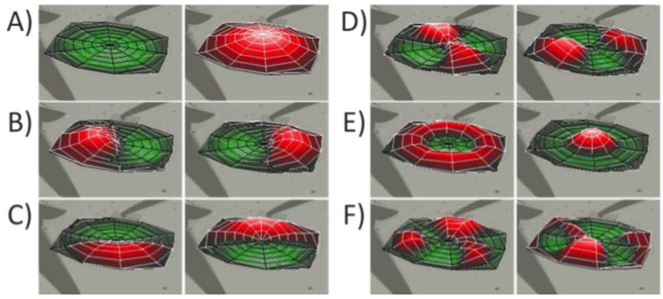

Fig. 7. Laser Doppler Vibrometry measurements of the fabricated polyimide/PZT/SiO2 membrane. The devices where stimulated with a white noise signal and a scan was performed to find the structures resonance frequency modes.

VI. Conclusions and Future Work

The piezoelectric device presented in this work was able to achieve a competitive performance on the piezoelectric properties of the thin film as compared to previous research. We have also shown the natural resonant frequency modes of the piezoelectric actuator and determine that it is feasible to reconstruct any audio frequency bye means of digital sound reconstruction.

Future work includes the optimization and fabrication of these actuators and their acoustic characterization using an anechoic chamber provided with a specialized microphone ordered from Brüel & Kjær company. After optimizing the membranes's design, a transducer array needs to be fabricated and controlled. With these first steps we are confident that the implementation of a digital μLoudspeaker for a personal acoustical space is possible. This device can be realized on silicon with improved characteristics from the current analog acoustic transducer. The acoustical transducer will be lighter, able to have a thinner structure and be more power-efficient.

Finally, we showed a new piezoelectric actuated MEMS speaker that could potentially target hearing aid devices or

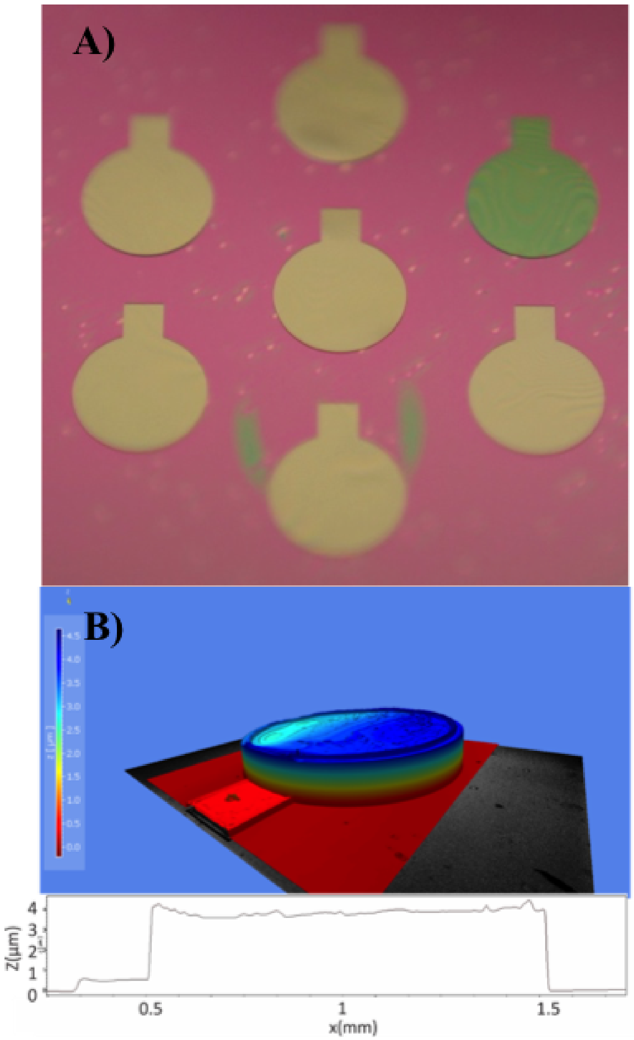

Fig. 8. A) Photograph of a 3-bit array of membranes (Note: membranes are not connected they have to be wirebonded). B) White light interferometry membrena profile.

earphones applications. Moreover, the device can be adapted to behave as a sensor (i.e.. microphone), and by modifying the design it could potentially work as an energy harvester.

REFERENCES

[1] B. M. Diamond, J. J. Neumann, Jr, and K. J. Gabriel, "Digital sound reconstruction using arrays of CMOS-MEMS microspeakers," in *Micro Electro Mechanical Systems, 2002. The Fifteenth IEEE International Conference on*, 2002, pp. 292–295.

[2] H. Kim, S. Lee, S. Lee, and K. Park, "A piezoelectric microspeaker with a high-quality PMN-PT single-crystal membrane," *Journal of Korean Physical Society*, vol. 54, p. 930, 2009.

[3] F. Kontomichos, J. Mourjopoulos, and N.-A. Tatlas, "Alternative Encoding Techniques for Digital Loudspeaker Arrays," *Journal of the Audio Engineering Society*, 2007.

[4] Y. Huang, S. C. Busbridge, and D. S. Gill, "Directivity and Distortion in Digital Transducer Array Loudspeaker," *Journal of the Audio Engineering Society*, 2000.

[5] Z. Wang, J. Miao, and C. W. Tan, "Acoustic transducers with a perforated damping backplate based on PZT/silicon wafer bonding technique," *Sensors and Actuators A: Physical*, vol. 149, no. 2, pp. 277–283, Feb. 2009.

[6] Y. Choe, S. Chen, and E. S. Kim, "High fidelity loud microspeaker based on PZT bimorph diaphragm," in *NSTI-Nanotech 2010*, 2010, pp. 316–319.

[7] S.-S. Je and J. Chae, "A Compact, Low-Power, and Electromagnetically Actuated Microspeaker for Hearing Aids," *Electron Device Letters, IEEE*, vol. 29, no. 8, pp. 856–858, 2008.

[8] P. Valousek, "A digital loudspeaker: experimental construction," *Acta polytechnica*, vol. 46, pp. 40–42, 2006.

[9] N.-A. Tatlas and J. N. Mourjopoulos, "Digital Loudspeaker Arrays driven by 1-bit signals," in *Audio Engineering Society Convention 116*, 2004.

[10] B. M. Diamond, J. J. Neumann, and K. J. Gabriel, "Digital sound reconstruction using arrays of CMOS-MEMS microspeakers," in *TRANSDUCERS, 12th International Conference on Solid-State Sensors, Actuators and Microsystems*, vol. 1, 2003, pp. 238–241.

[11] B. M. Diamond, "Digital Sound Reconstruction Using Arrays of SMOD-MEMS Microspeakers," Ph.D. dissertation, Carnegie Mellon, 2006.

[12] M. J. Hawksford, "Smart digital loudspeaker arrays," *J. Audio Eng. Soc*, vol. 51, no. 12, pp. 1133–1162, 2003. [Online]. Available: http://www.aes.org/e-lib/browse.cfm?elib=12189

[13] M. O. J. Hawksford, "Spatial distribution of distortion and spectrally-shaped quantization noise in digital micro-array loudspeakers," in *Audio Engineering Society Convention 120*, May 2006. [Online]. Available: http://www.aes.org/e-lib/browse.cfm?elib=13586

[14] A. Arevalo and I. G. Foulds, "Parametric Study of Polyimide-Lead Zirconate Titanate Thin Film Cantilevers for Transducer Applications," in *2013 COMSOL Conference, Rotterdam, Holland*, 2013.

[15] A. Arevalo, D. Conchouso, D. Castro, N. Jaber, M. I. Younis, and I. G. Foulds, "Towards a Digital Sound Reconstruction MEMS Device: Characterization of a Single PZT Based Piezoelectric Actuator," in *10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems NEMS2015*, Xia'an, Apr. 2015.

[16] L. Marnat, A. Arevalo Carreno, D. Conchouso, M. Galicia Martinez, I. Foulds, and A. Shamim, "New Movable Plate for Efficient Millimeter Wave Vertical on-Chip Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 1608–1615, 2013.

[17] A. Arévalo Carreño, D. Conchouso, and I. G. Foulds, "Optimized Cantilever-to-Anchor Configurations of Buckled Cantilever Plate Structures for Transducer Applications," *COMSOL Milan 2012*, 2012.

[18] A. Alfadhel, A. Carreno, I. G. Foulds, and J. Kosel, "Three-axis Magnetic Field Induction Sensor Realized on Buckled Cantilever Plate," *IEEE Transactions on Magnetics 2013*, 2013.

[19] A. Arevalo and I. G. Foulds, "MEMS Acoustic Pixel," *2014 COMSOL Conference, Cambridge, England*.

[20] A. Arevalo, S. Ilyas, D. Conchouso, and I. G. Foulds, "Simulation of a Polyimide Based Micromirror," *2014 COMSOL Conference*, 2014.

[21] D. Castro, A. Arevalo, E. Rawashdeh, and N. Dechev, "Simulation of a Micro-Scale Out-of-plane Compliant Mechanism," in *2014 COMSOL Cambridge, England*, 2014.

[22] A. A. Carreno, E. Byas, and I. G. Foulds, "μHeater on a Buckled Cantilever Plate for Gas Sensor Applications," *2012 COMSOL Conference, Milan, Italy*, 2012.

[23] A. Arevalo, D. Conchouso, E. Rawashdeh, D. Castro, and I. G. fould, "Platform Isolation Using Out-of-Plane Compliant Mechanisms," in *2014 COMSOL Conference, Boston, USA*, Aug. 2014. [Online]. Available: http://www.comsol.se/conference2014/usa/file/id/19569/file/23661_arevalo_paper.pdf

[24] S. Ilyas, A. Ramini, A. Arevalo, and M. I. Younis, "An Experimental and Theoretical Investigation of a Micromirror Under Mixed-Frequency Excitation," *Journal of Microelectromechanical Systems*, 2015.

[25] A. Arevalo and I. G. Foulds, "Polyimide Thermal Micro Actuator," in *2014 COMSOL Conference, Cambridge, England*, 2014.

[26] D. Conchouso, A. Arevalo, D. Castro, , and I. G. Foulds, "Out-of-plane Platforms with Bi-directional Thermal Bimorph Actuation for Transducer Applications," in *10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems NEMS2015*, Xia'an, Apr. 2015.

[27] A. Arevalo, E. Byas, D. Conchouso, D. Castro, S. Ilyas, and I. G. Foulds, "A Versatile Multi-User Polyimide Surface Micromachining Process for MEMS Applications," in *10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems NEMS2015*, Xia'an, Apr. 2015.

[28] A. A. A. Carreno, D. Conchouso, A. Zaher, I. Foulds, and J. Kosel, "Simulation of a Low Frequency Z-Axis SU-8 Accelerometer in Coven-

torWare and MEMS+," in *Computer Modelling and Simulation (UKSim), 2013 UKSim 15th International Conference on*, 2013, pp. 792–797.

[29] D. Conchouso, A. Arevalo, D. Castro, E. Rawashdeh, M. Valencia, A. Zaher, J. Kosel, and I. Foulds, "Simulation of SU-8 Frequency-Driven Scratch Drive Actuators," in *Computer Modelling and Simulation (UKSim), 2013 UKSim 15th International Conference on*, Jun. 2013, pp. 803–808.

[30] Y. Fan, A. Arevalo, H. Li, and I. G. Foulds, "Low-cost silicon wafer dicing using a craft cutter," *Microsystem Technologies*, 2014.

[31] V. P. Afanasjev, A. A. Petrov, I. P. Pronin, E. A. Tarakanov, E. J. Kaptelov, and J. Graul, "Polarization and self-polarization in thin PbZr1-xTixO3 (PZT) films," *Journal of Physics: Condensed Matter*, vol. 13, no. 39, p. 8755, 2001.

[32] H. J. Kim, "High Performance Piezoelectric Microspeakers and Thin Speaker Array System," *ETRI Journal*, vol. 31, no. 6, pp. 680–687, Dec. 2009.

[33] E. Hong, S. V. Krishnaswamy, C. B. Freidhoff, and S. Trolier-McKinstry, "Fabrication of piezoelectric diaphragm using lead zirconate titanate (PZT) films," vol. 687, p. B5. 16, 2001.

[34] I.-J. CHO, S. JANG, and H.-J. NAM, "A Piezoelectrically Actuated MEMS Speaker with Polyimide Membrane and Thin Film Pb(Zr,Ti)O3(PZT) Actuator," *Integrated Ferroelectrics*, vol. 105, no. 1, pp. 27–36, Aug. 2009.