A Study on PVD PZT and $Sc_{0.2}Al_{0.8}N$ PMUTS in Series and Parallel Connection for Optimizing Acoustic Performance

David Sze Wai Choong[1], Daniel Ssu-Han Chen[1], Mantalena Sarafianou[1], Duan Jian Goh[1], Jihang Liu[1], Srinivas Merugu[1], Sagnik Ghosh[1], Prakasha Ramegowda[1], Qing Xin Zhang[1], Peter Chang[1], Joshua En-Yuan Lee[1†], Jason Jia[2], Alberto Leotti[2], Luigi Baretta[3], Domenico Giusti[3], Alessandro Savoia[4], Yul Koh[1]

[1] Institute of Microelectronics (IME), Agency for Science, Technology and Research (A*STAR),

2 Fusionopolis Way, Innovis #08-20, Singapore, 138634, Republic of Singapore

[2]STMicroelectronics, Singapore; [3]STMicroelectronics, Italy, [4]Roma Tre University, Rome, Italy

[†]Currently at University of Technology Sydney, Australia

Email: david_choong@ime.a-star.edu.sg, koh_yul@ime.a-star.edu.sg

***Abstract*—This work presents an experimental comparative analysis of acoustic performance for series and parallel connected piezoelectric micromachined ultrasonic transducers (PMUTs) designed and fabricated in physical vapor deposition (PVD) lead zirconate titanate (PZT) and 20% scandium (Sc)-doped aluminum nitride (AlN). The aim of this research is to provide insights for optimizing PMUT array design by the choice of electrical connections in relation to material selection. In parallel connection, the current generated by PMUTs is merged and the output impedance of the device becomes lower than the output impedance of single PMUT. In series connection, the output impedance and the voltage output of PMUTs increase with the number of series connections. From the experimental results of a PMUT array with 16-membranes (each membrane represents single PMUT element), series connection shows better receive (RX) sensitivity for PZT with 4.6 mV/ Pa as compared to 2.05 mV/Pa for parallel connection, while ScAlN fared better in parallel connection with 46 mV/Pa as compared to 36 mV/Pa for series connection which are closely matched to simulated values.**

Keywords—PMUT array design, receive (RX) sensitivity, transmit (TX) sensitivity, series, parallel, PZT, ScAlN.

I. INTRODUCTION

In designing Piezoelectric Micromachined Ultrasonic Transducers (PMUTs), choice of the piezoelectric material plays an important role in determining the optimal performance for end-user applications. PZT PMUTs may be used if the priority of the application is dependent on acoustic transmission power due to its high piezoelectric coefficient [1] while scandium-doped aluminum nitride (ScAlN) may be used if the application is based primarily on imaging or sensing due to its low dielectric constant and piezoelectric voltage coefficient [2]. Furthermore, pharmaceutical or medical based applications tend to favor lead-free devices which will further stray the piezoelectric thin film choice away from PZT.

Current methods of improving the performance of the devices mainly focus on the piezoelectric material properties and stress optimization in the PMUT membrane. Direct current (DC) bias to electro-mechanically tune the tension of PMUT membranes, and enhance the electromechanical coupling significantly [3]. This effect is obvious for PZT PMUTs but ScAlN may have similar effect when high DC bias is applied [4]. For piezoelectric material properties, the transmission performance can be improved by increasing the scandium doping concentration in ScAlN [5]. Various additives have been studied as well to improve the properties of PZT [6].

Even though extensive research has been conducted to improve PMUT performance, the majority of these efforts have focused primarily on material development and individual PMUT design. In this work, we aim to improve the device performance of both PZT and ScAlN PMUTs by comparing the performance of PMUT arrays according to the electrical connection and analyze the best possible configuration specific to each piezoelectric material.

II. DEVICE AND FABRICATION

Each ScAlN PMUT element from the array was formed on a 4 µm thick epitaxial polysilicon membrane of diameter 600 µm. The actuation stack (diameter: 420 µm) in the center of the membrane was formed by 1 µm thick 20% scandium-doped AlN piezoelectric film stacked between top and bottom molybdenum (Mo) electrodes. The membrane of each pMUT was released via back-port etching through the substrate.

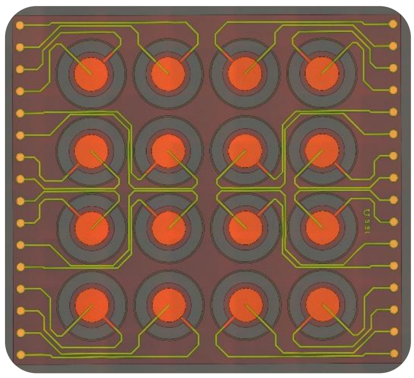

Fig. 1. Optical profiler image of the tested ScAlN device.

The (4.5 mm × 5 mm) die consists of 16 membranes. The top and bottom electrodes of each membrane have dedicated metal pads for wire bonding which allows the PMUT elements to be connected in series or parallel while the die is mounted on a printed circuit board (PCB). The PZT PMUT is of the same design as the ScAlN PMUT with the exception of 2 µm thick PVD PZT piezoelectric film being sandwiched between top and bottom platinum electrodes. The detailed fabrication process flow for the PZT PMUT is described in [3].

III. RESULTS AND DISCUSSION

For parallel connections, the top electrodes of all 16 membranes were connected to the same terminal, and the same was done for the bottom electrodes as shown in figure 1. The series-connection of the PMUT array connected the top electrode of the 1st PMUT to the bottom electrode of the 2nd PMUT, followed by the top electrode of the 2nd PMUT to the bottom electrode of the 3rd PMUT and so on until the 16th PMUT where the bottom electrode of the 1st PMUT and the top electrode of the 16th PMUT are connected to an Oscilloscope (Keysight InfiniiVision DSOX4024A), with a 10 MΩ passive probe. For the parallel configuration, the top and bottom electrodes were connected to the 10 MΩ passive probe.

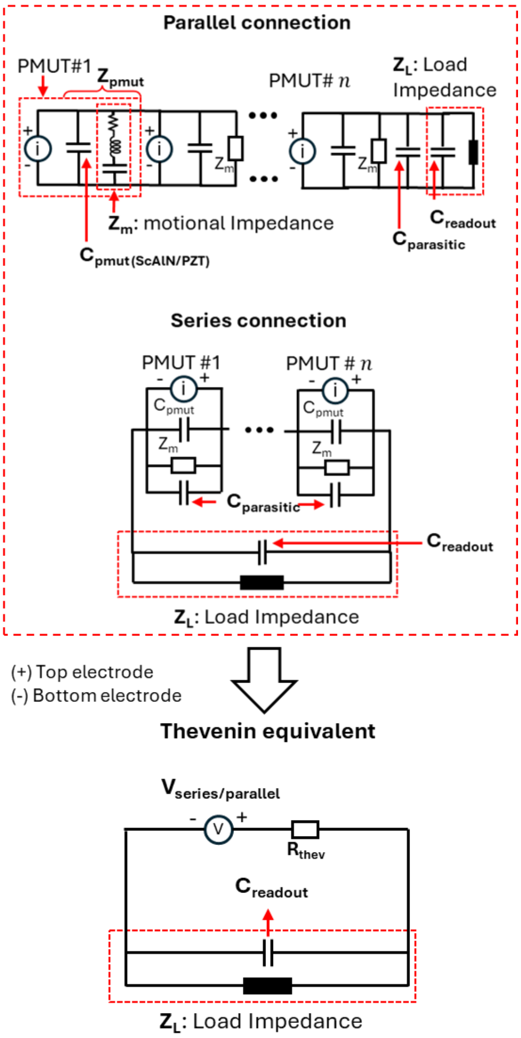

Fig. 2. Electrical diagram of test setup and simulation

Each membrane is treated as a charge source when a mechanical deformation changes the distances between positive and negative charges within the crystal lattice, causing a shift in the charge distribution. Simply, the device level configuration can be reduced to its Thevenin equivalent as defined in (1) and (2) for parallel and series connections:

$$Z_{thev\_parallel} = \frac{1}{j(\omega * C_{pmut} * N_{pmut} + \omega * C_{parasitic})} \quad (1)$$

$$Z_{thev\_series} = \frac{1}{j\left(\frac{\omega * C_{pmut}}{N_{pmut}} + \omega * C_{parasitic}\right)} \quad (2)$$

where the measured static capacitance of the PMUT membrane, C_{pmut}, was measured using an impedance analyzer (Keysight E4990A). The overall parasitic capacitance of PCB board, electrical wires, and PMUT is $C_{parasitic}$, which was measured before and after integration with the PCB via wire bonding. The resonant frequency was used to determine the angular frequency, ω, of the device. The RX voltage output per unit pressure of a single PMUT, V_{pmut} was estimated to be 2 mV/Pa [1]. The series and parallel voltage output of the PMUT can then be defined as (3) and (4):

$$V_{series} = V_{pmut} * N_{pmut} \quad (3)$$

$$V_{parallel} = V_{pmut} \quad (4)$$

When connected to the 10 MΩ passive probe and oscilloscope, the load impedance, Z_L, is calculated by taking the sum of the reciprocal of the load resistance, 10 MΩ, and the reciprocal of the impedance caused by the readout capacitance from PCB, probe connections and the oscilloscope, $C_{readout}$, as defined in (5):

$$Z_L = \frac{1}{\left(\frac{1}{10^7} + j\omega * C_{readout}\right)} \quad (5)$$

Finally, the readout voltage, V_{out} for parallel and series may be determined by voltage divider rule between the Thevenin equivalent impedance and overall load impedance in (6) and (7) :

$$V_{out\_parallel} = V_{parallel} * \frac{Z_L}{(Z_L + Z_{thev\_parallel})} \quad (6)$$

$$V_{out\_series} = V_{series} * \frac{Z_L}{(Z_L + Z_{thev\_series})} \quad (7)$$

While the RX output of a single PZT PMUT can be measured, the RX output of a single ScAlN PMUT is highly prone to parasitic interference due to its much lower capacitance of 14 pF which may severely diminish the RX signal. Thus, the potential RX output is estimated using the voltage coefficient, $h_{31,f}$, which is determined by $e_{31,f}$ and ε_r of ScAlN. The piezoelectric coefficient and permittivity are estimated to be -2.3 C/m^2 [7] and 11.42 respectively for ScAlN based on (8) and (9):

$$h_{31,f} = \frac{e_{31,f}}{\varepsilon_r} \quad (8)$$

$$\varepsilon_r = \frac{C_{pmut} * t_{piezo}}{A * \varepsilon_0} \quad (9)$$

The $h_{31,f}$ piezoelectric coefficient of PZT is referenced to be 0.006 C/m^2 without any bias voltage application [2] which can be used to infer the estimated voltage output from a single ScAlN PMUT per unit pressure, V_{ScAlN}, to be 67 mV/ Pa as defined in (10)

$$V_{ScAlN} = V_{PZT} * \frac{h_{31,f\ sc}}{h_{31,f\ PZT}} \quad (10)$$

Further varying the number of PMUTs from 1 to 16 while maintaining the constant values mentioned in Table-1, estimated RX sensitivity from equations (6) and (7) can be simulated for both PZT in parallel and series as can be seen in figure 3. 16-membrane based PZT PMUT can be estimated to produce RX sensitivities of 5.48 mV/Pa in series and 1.94 mV/Pa in parallel. With further increase in the number of parallel connected PMUT elements, the RX sensitivity saturates at 2 mV/ Pa.

TABLE I. PARAMETERS FOR RX SENSITIVITY SIMULATION

Parameters	DUT(s)	
	PVD PZT	***$Sc_{0.2}Al_{0.8}N$***
C_{pmut} (pF)	620	14
$C_{parasitic}$(pF)	7	6
$C_{readout}$ (pF)	220	220
f_o (kHz)	160	210
ε_r	1011.8	11.4
$e_{31,f}$ (C/m^2)	6.1	2.3 [8]
$h_{31,f}$ (C/m^2)	0.006 [2]	0.201
Z_L (Ω)	10M	10M

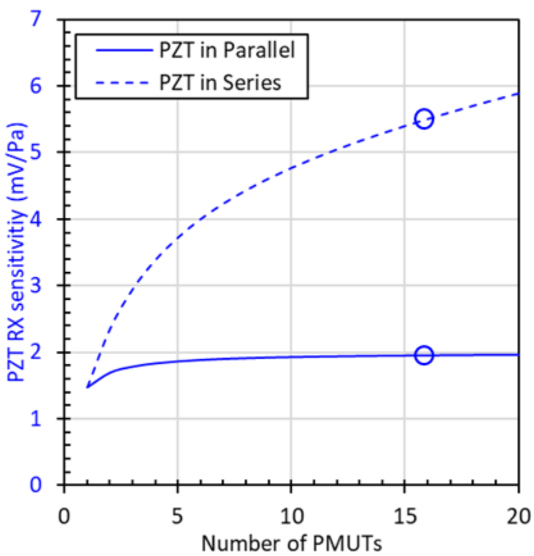

Fig. 3. Simulated RX sensitivity for PZT PMUT

The same simulation was done for a 16-membrane based ScAlN PMUT in both parallel and series configurations giving an estimated RX sensitivities of 38.9 mV/Pa for parallel and 35.5 mV/Pa for series connections in figure 4. Beyond 20 PMUT elements in series, the RX sensitivity of series connection would outperform parallel connections of the same number of ScAlN PMUTs by 4.5%.

The actual DUTs were then subjected to testing under a calibrated transmitter from 100 kHz to 260kHz and the RX response was recorded via a 10M Ω passive probe and oscilloscope. The RX sensitivity was then obtained by dividing the RX response by the known pressure from the calibrated transmitter as can be seen in figure 5.

The measured results from the PZT DUTs in parallel and series connections show RX sensitivities of 2.05 mV/Pa and 4.62 mV/Pa respectively while the ScAlN DUTs in parallel and series exhibited measured RX sensitivities of 46 mV/Pa and 36 mV/Pa respectively. The ScAlN PMUTs in parallel perform better than the PMUTs in series while the PZT PMUTs show an inverse relationship with series being the better performer. Table 2 summarizes the above comparison of the data.

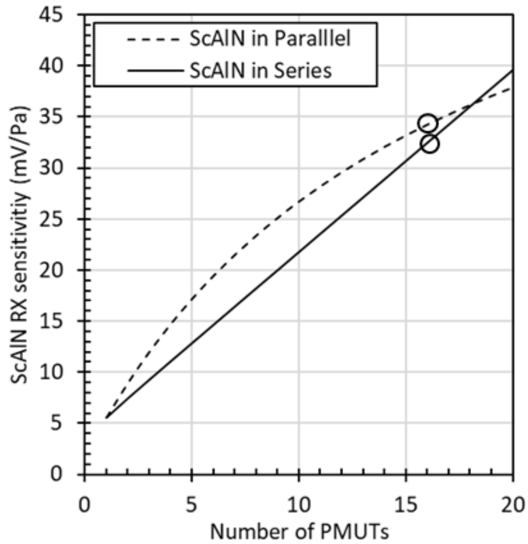

Fig. 4. Simulated RX sensitivity for ScAlN PMUT

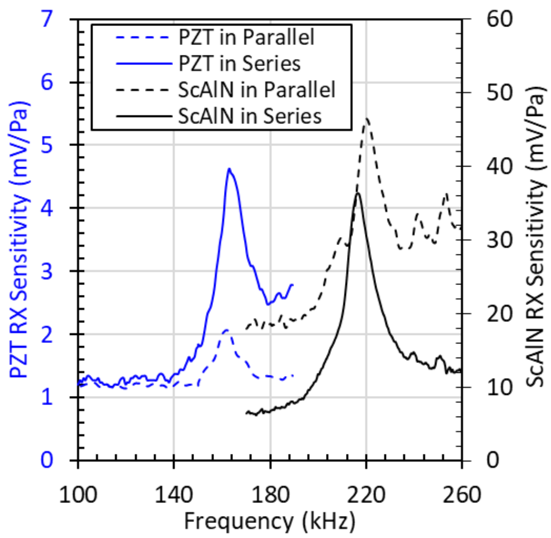

Fig. 5. Measured RX sensitivities for both PZT and ScAlN DUTs

The simulated results match the measured performance for the DUTs relatively well. The errors between simulated and measured results can be attributed to cross coupling effects which were neglected in simulations. Nevertheless, the overall trend of simulation results for series and parallel RX sensitivities still matches the experimental results. It is clear from both the simulations and measurements that parallel connection is better for ScAlN and series connection is better for PZT.

TABLE II. Comparison of RX sensitivities for different electrical configurations

DUT	Measured RX Sensitivity (mV/Pa)	Simulated RX Sensitivity (mV/Pa)	Error (%)
$Sc_{0.2}Al_{0.8}N$ Parallel	46.1	34.4	25.4
$Sc_{0.2}Al_{0.8}N$ Series	36.2	32.6	9.9
PVD PZT Parallel	2.05	1.94	5.4
PVD PZT Series	4.62	5.48	-18.6

Transmission measurements of the DUTs were performed in different electrical connections as well. However, the measurements for absolute pressure would always be in favor of parallel connection as the voltage delivered to individual PMUTs is always the same from the alternating voltage source. On the other hand, voltage delivered in series would always be divided by the number of PMUTs due to voltage divider rule, thereby reducing output effectively by the number of PMUTs in series. The efficiency of voltage converted to acoustic energy, however, can still be measured as a transfer by measuring the pressure output and dividing by the voltage across a single PMUT as seen in figure 6. The trend of voltage to acoustic energy conversion can thus be seen to be inverse to that of the trend of the RX sensitivity, where PZT in parallel performs better than PZT in series and the opposite holds true for ScAlN in parallel compared to series.

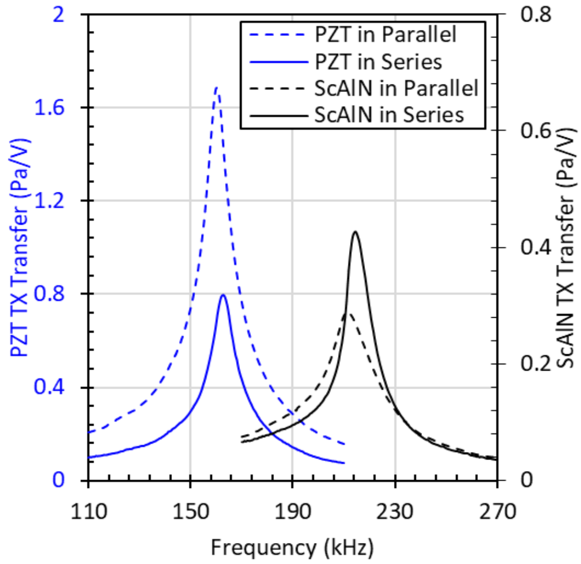

Fig. 6. Measured TX transfer of DUTs

V. CONCLUSION

We have validated a simplified model for estimating the RX sensitivities of PZT and ScAlN PMUTs, achieving between 5.4 to 25.4 % error from the measurement data. The results show that for a 16-membrane device between frequencies 100 to 260 kHz, ScAlN RX sensitivity is better in parallel as compared to series while PZT RX sensitivity is better in series as compared to parallel. However, adding PMUTs beyond 20 elements would also cause ScAlN devices to perform better in series from the simulated data. This would become a trade-off in terms of form factor as a single element would now be as big as 20 membranes or more, which could be useful if only a single channel device is needed for end-user applications.

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