Fabrication and Characterization of High Frequency Phased Arrays for NDE Imaging

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ABSTRACT

PMN-PT single crystal 1-3 composite high frequency phased arrays with center frequency of 35 MHz were fabricated and characterized for silicon carbide (SiC) NDE imaging applications. The 35 MHz 64-element array was successfully prototyped using PMN-PT single crystal and PC-MUT technology. The broad bandwidth > 90% and high sensitivity (echo amplitude > 500 mV from the impulse response with 0 gain) was observed with reasonably high uniformity. These high frequency phased arrays are promising for ceramic NDE imaging.

Keywords: single crystal piezoelectrics, high frequency ultrasound, NDE, NDT, PC-MUT, phased array.

1. INTRODUCTION

High frequency (HF) phased array ultrasound can sweep a sound beam through a range of refracted angles or along a linear path, or dynamically focus at a number of different depths, thus increasing both flexibility and capability in inspection setups [1]. But the fabrication of HF phased arrays and the beam forming electronics has been challenging [2]. Industry has therefore traditionally focused on HF single element systems, however, even these transducers utilize piezoelectric materials with relatively low properties (e.g. $k_{33} < 0.7$) due to the constraints of miniaturization. The recently developed PC-MUT technology takes advantage of high electromechanical coupling coefficients of advanced single crystal piezoelectrics ($k_{33} > 0.9$), and single element PC-MUT transducers above 40 MHz have demonstrated both broad bandwidth and high sensitivity [3]. Furthermore, precise photolithography and deep reactive ion etching (DRIE) based fine patterning of both PC-MUT composite structures and array electrode interconnections is believed to be the key to address the challenge in high frequency phased array fabrication [3].

HF phased arrays provide a specific advantage to NDE of materials such as SiC, where internal defects and anomalies can be resolved quickly. The pulse-echo method of ultrasound detection can identify voids, delaminations and inclusions, however, the high velocity within these ceramics requires a higher frequency than with medical ultrasound for comparable resolution. Single element systems must be translated in three axes for full analysis, making phased arrays a much more viable option for high-throughput analysis.

Modeling of single element impulse performance and the spatial characteristics of a 35 MHz array were reported in 2009 [4], and the progress on high frequency phased array fabrication and characterization is presented and discussed in this paper.

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2. EXPERIMENTAL DESIGN

The PC-MUT technique was used to prepare a high frequency 1-3 composite, which was then assembled with flex circuits, matching layers and a backing layer into a phased array assembly. The phased array prototype was characterized to determine pulse-echo response and element uniformity.

A. PCMUT composite fabrication

Table 1 summarizes the array specifications, and the Figure 1 shows the array layout. Due to the high phase velocity in SiC (~12 km/s), it was possible to maintain an array pitch less than a half-wavelength while maintaining a realizable dimension. The pitch of 132 um allows for flex circuit technology to be used. A larger inter-element kerf was used relative to the kerf within each element. This was defined through the composite lithography process, and was used to help streamline the alignment process for the electrode isolation step, which used a dicing saw for electrode separation.

Table 1. Phased array specifications.

Array center frequency	35 MHz
Elements in array	64
Array pitch	132 μm (0.4λ)
Total array azimuth	8.44 mm
PMN-PT post width	14 μm
Sub-"diced" kerf	4-5 μm
Inter-element kerf	9-10 μm
Composite thickness	30 μm
Array elevation	4 mm
Elevational focus	14 mm (f# 3.5)

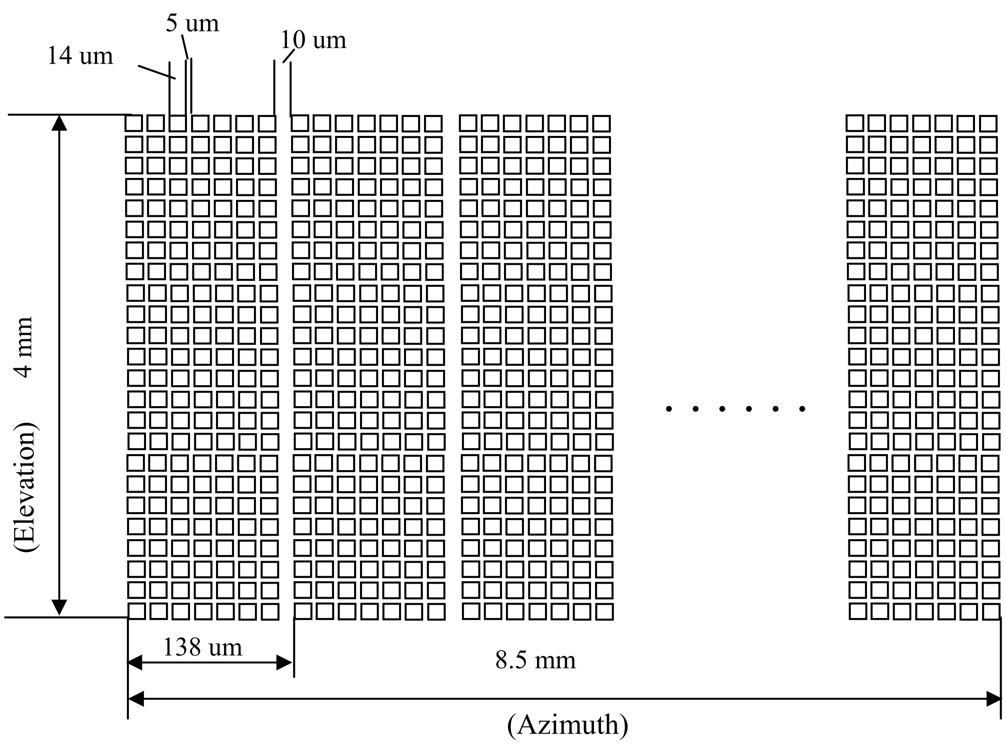

Figure 1. Layout of a 35 MHz PCMUT array.

In order to fabricate PCMUT arrays, PMN-PT single crystal/epoxy 1-3 composites need to be fabricated first. Figure 2 shows the typical process flow for PCMUT composite fabrication [3]. PMN-PT single crystal discs with dimension of D17mm x 0.7mm were fabricated and tested; the d_{33} of these discs are 1800-2200 pC/N, dielectric constant is about 5000-6500, and dielectric loss < 0.01. The crystal discs were lapped and polished on one side for lithography, followed by electroplating, deep reactive ion etching, kerf filling, lapping and electroding.

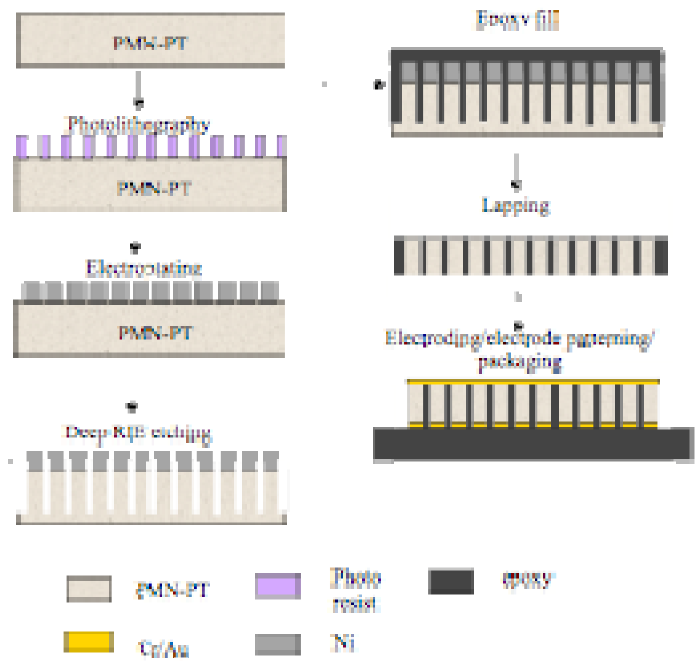

Figure 2. PCMUT Composite fabrication processes.

B. Array assembly design

The prepared PCMUT 1-3 composite was then used for phased array assembly. Acoustic matching layers were first bonded onto one side of the composite and lapped to the designed thickness. The followed array assembly procedures include: 1) the PCMUT composite was trimmed to the designed aperture size, 2) the side with patterned electrode was aligned and bonded to a flex circuit using an epoxy with low viscosity and low shrinkage and 3) the backing block was bonded to flex circuit. Figure 3 shows the schematic view of the acoustic stack for array assembly. The acoustic stack was next cleaned and prepped for interconnect termination. The terminated stack was then put into a housing and connected to a cable with required connectors.

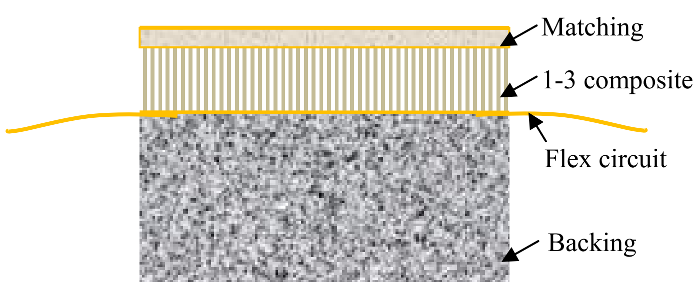

Figure 3. Schematic view of phased array acoustic stack.

C. Array characterization

The prototyped array was characterized by measuring the element capacitance, impedance and phase spectrum of elements, and impulse response of individual elements. The capacitance was measured using an impedance analyzer (HP4194A) at 1 kHz. The impedance/phase spectrum were measured using the same impedance analyzer at a frequency ranged from 10 MHz to 70 MHz. The impulse experiments were was conducted by immersing the prototyped array into a water tank, about 4 mm above a flat steel target. An Olympus 5900PR pulser/receiver was used to test each individual element ,and the echo received from the array was recorded using an oscilloscope. The sensitivity and bandwidth of each element was then be calculated from the measured impulse response.

3. EXPERIMENTAL RESULTS

A. 35 MHz PCMUT Array Prototyping

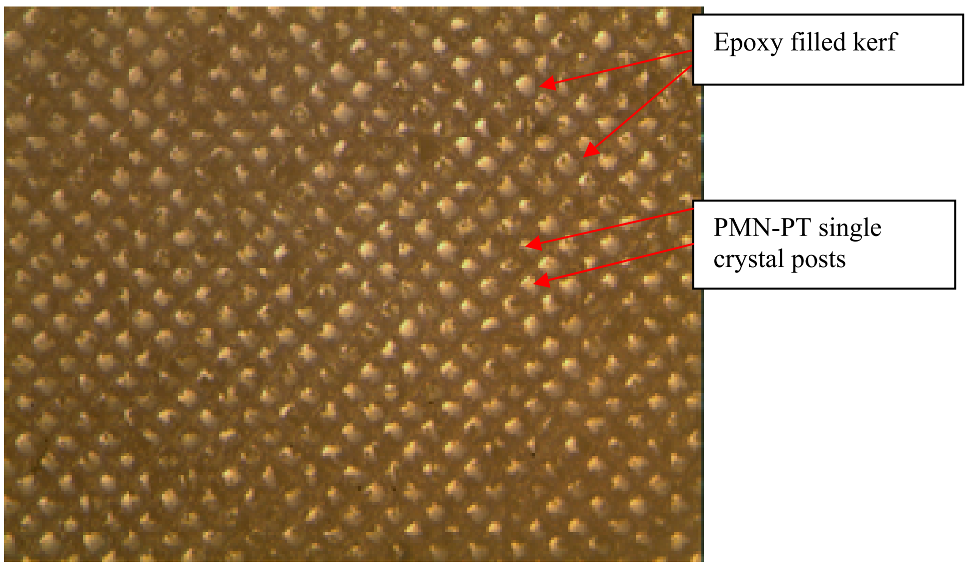

Figure 4. Photograph of the micromachined composite (after the 1^{st} side lapping).

Figure 4 shows the picture of a 35 MHz PMN-PT single crystal 1-3 composite with Cr/Au electrode. The composite was diced using a 20 um thick blade to form electrode separation for each element (~ 115 um x4mmx40um), the dicing depth was about 5 um. Two matching layers were attached. The acoustic impedance of the first matching layer and the 2^{nd} matching layer was 5.8 MRayl and 2.2 MRayl, respectively. The thickness of the first matching layer and the 2^{nd} matching layer was 17 µm and 20 µm, respectively. The backing layer with acoustic impedance of 6 MRayl and thickness of 0.7 mm was attached to the composite. Figure 5 shows the picture of a 64-element 35 MHz PC-MUT array without attachment of cable and housing. Figure 6 shows the finished 35 MHz PC-MUT phased array.

Figure 5. A 35 MHz 64-element PC-MUT phased array without housing and cable connection.

Figure 6. Photograph of a micromachined 35 MHz phased array (64-element).

B. Capacitance and impedance measurement

All elements were poled at 40 V (equivalent to electric field of 10 kV/cm) for a set time period, followed by capacitance and dielectric loss measurement using an impedance analyzer at 1 kHz. Figure 7 shows the capacitance of all 64 elements. A reasonably high uniformity was obtained with the capacitance of the 35 MHz PCMUT array elements. The impedance and phase sweep of all elements (without backing attached) was recorded using the impedance analyzer, and Figure 8 shows a typical spectrum of the elements. The resonances observed in Figure 8 shows that no delaminating existed in the array acoustic stack.

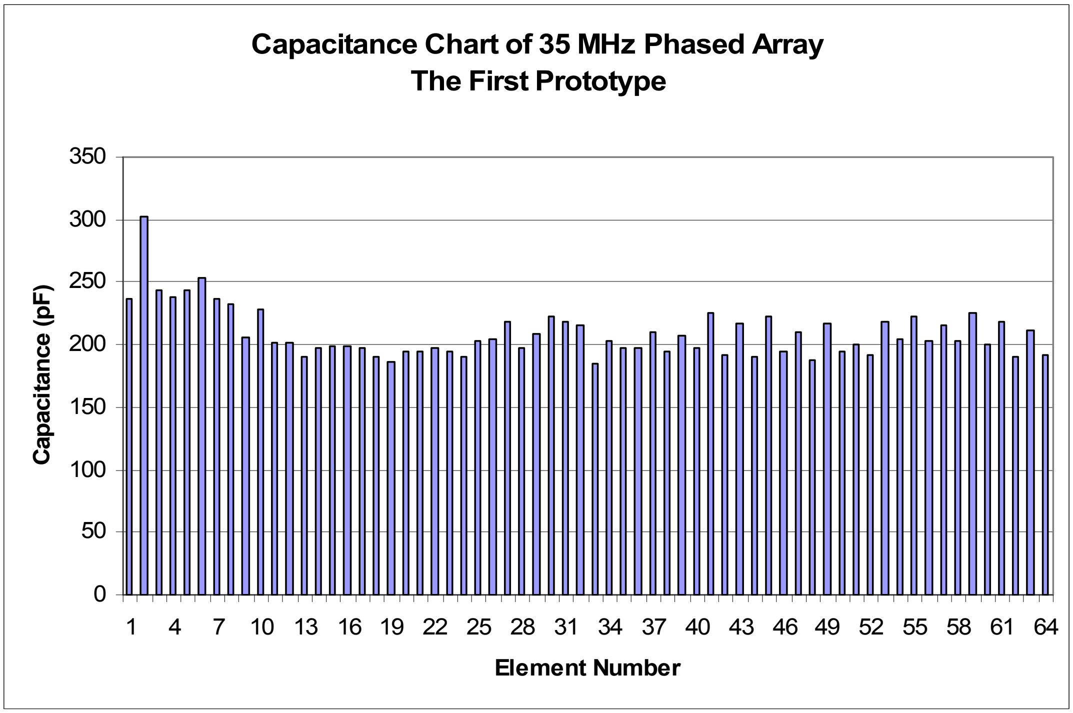

Figure 7. Capacitance measurement for 35 MHz arrays (without cable attached).

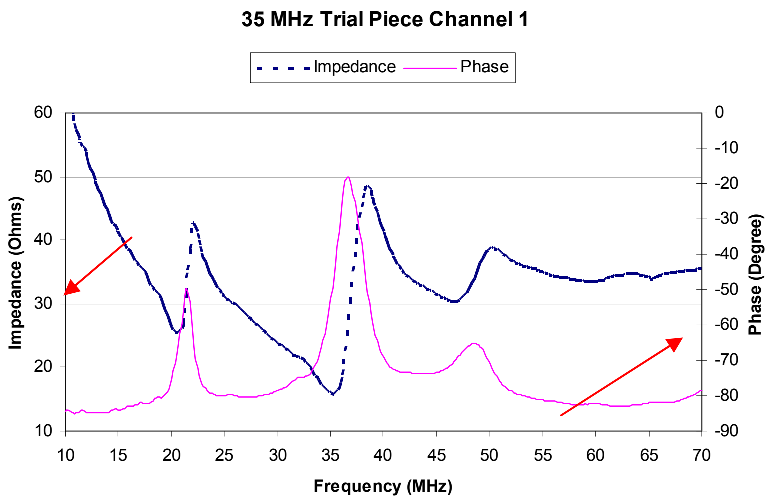

Figure 8. Impedance and phase spectrum of sub-array elements with 2-matching layer and without backing layer attached.

C. Impulse response

Pulse-echo tests were conducted using Panametrics 5900 pulser-receiver, 1 uJ energy setting, 0 gain and the distance between the transducer and target was set at 4 mm. Figure 9 shows a typical impulse response. Table 2 summarizes the performance of a few tested elements. Variations in bandwidth, sensitivity, and center frequency were noticed for the tested array elements, which may be caused by factors such as matching layer thickness non-uniformity, varied active element area, etc. A full set of sensitivity results were shown in Figure 10, where one can see that channel 63 was not functioning properly at pulse echo testing, which was likely caused by the electrical damage during the pulse- echo tests. Weak responses were found from 7 elements (element # 2, 3, 4, 16, 18, 48 and 64), which may be caused by the non-uniformity of the matching layer, which will be improved in the future prototyping.

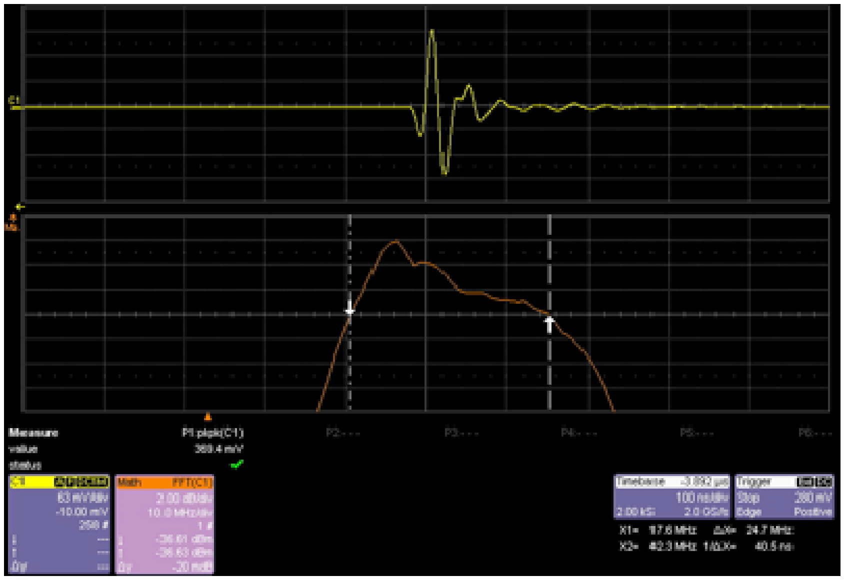

Figure 9. Impulse response of 35 MHz sub-array PC-MUT elements. Settings: Panametric 5900, Energy: 1 µJ, 26 dB Attenuation, 26 dB Gain (net =0)

Table 2. Typical element performances.

Channel No.	Sensitivity (mV)	-6 dB Low Band Edge (MHz)	-6 dB High Band Edge (MHz)	Center Frequency (MHz)	-6 dB Fractional Bandwidth (%)
1	620	21.4	38.2	29.8	56
2	130	23.9	59.2	41.6	85
4	240	23.5	39.2	31.4	50
5	400	23.0	39	31	52
6	460	25.9	39.4	32.7	41
7	420	22.9	33.9	33.9	65
8	530	25.1	61.3	43.2	84
9	500	23.5	65.5	44.5	94
10	400	24.1	62.2	43.2	88
16	275	28.8	53.9	41.4	61
32	500	25.5	56.4	41	75

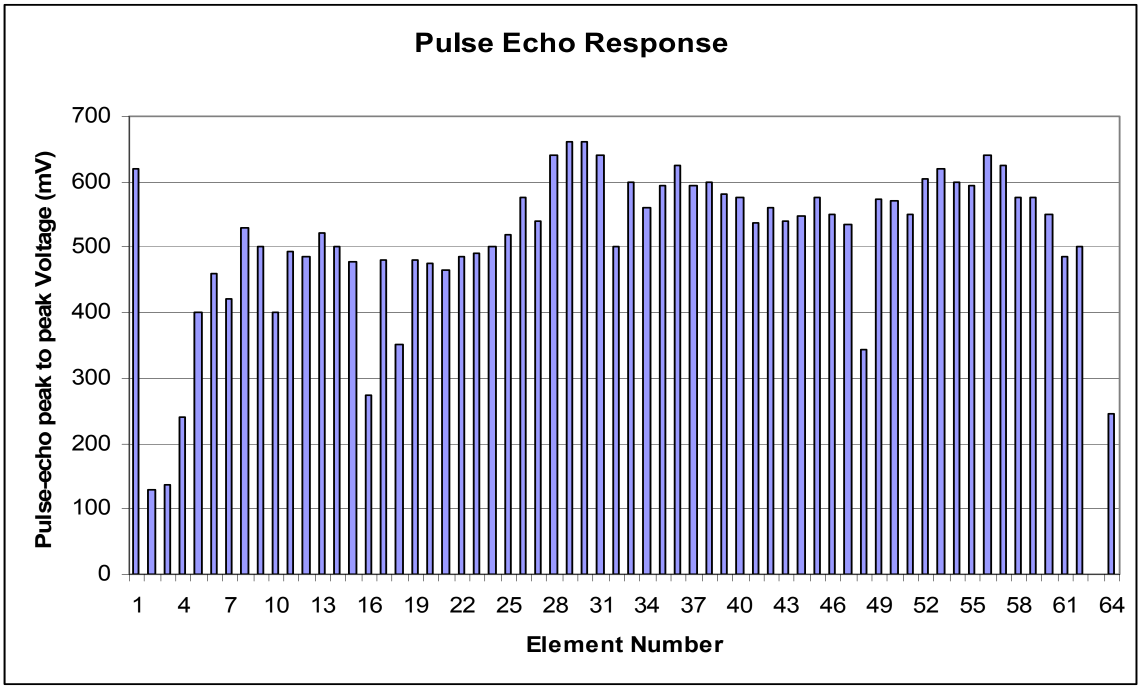

Figure 10. Pulse-echo responses for the prototyped 35 MHz Phased array.

4. SUMMARY

The first 35 MHz 64-element PC-MUT phased array was prototyped and characterized for high resolution ultrasound NDE applications. Reasonably high element uniformity can be found from the element capacitance measurement results. The broad bandwidth > 90% and high sensitivity (echo amplitude > 500 mV from the impulse response with 0 gain) was observed from the 1st prototype. More uniform impulse response can be expected by improving matching layer uniformity.

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