IN-AIR LONG-RANGE ENVIRONMENTAL TEMPERATURE SENSING WITH A SINGLE SCANDIUM-DOPED ALUMINUM NITRIDE PMUT ARRAY

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ABSTRACT

This paper presents, for the first time, in-air long-range temperature sensing by ultrasound using a single Scandium-doped (15%) Aluminum Nitride (ScAlN) pMUT array. The proposed temperature pulse-echo sensing setup can achieve an impressive 97% accuracy (and a respective average absolute error of 1.4°C) in temperature sensing at 30cm (corresponding to 60cm of round-trip distance) for temperatures up to 90°C. This is accomplished using a single 9mm^2 die without any signal pre/post-amplification with a range that could comfortably be extended to 1m.

KEYWORDS

pMUT, ultrasonic Time-of-Flight estimation, environmental temperature sensing.

INTRODUCTION

Ultrasonic environmental temperature sensing using pMUTs is a revolutionary approach designed to use time-of-flight (ToF) estimation in air for temperature monitoring. Its merits include the ability to deploy these devices unstaffed in harsh weather conditions and prohibitive environments, small size (enabling a compact integrated sensing solution), and fast response time in providing a temperature reading.

Although the concept of using ultrasound to measure temperature is not new [1, 2], the use of pMUTs to this end is very recent. One of the few examples has proposed non-contact surface temperature sensing using an AlN pMUT array at 8cm distance [3]. More recently, we proposed a method for short-range (~3cm) environmental temperature sensing using two separate opposite-facing pMUT chips in a pitch-catch arrangement [4].

Micromachined ultrasonic transducers (MUTs), as opposed to conventional ultrasonic transducers, are very small and are equipped with a flexural membrane for generating and receiving ultrasound waves. Since their flexural membrane is much softer than the traditional rigid ceramic, their acoustic impedance is more closely matched to the propagation medium, leading to closer impedance matching [5]. As a result, their transmitting efficiency can be much higher than conventional ultrasonic sensors [5]. There are several advantages in using AlN over PZT for pMUT fabrication towards temperature sensing; First, AlN-based pMUTs do not require polarization [6, 7] and are more linear. Secondly, AlN is lead-free compared to PZT. Thirdly, AlN pMUTs are more promising for CMOS integration due to their low deposition temperature [6, 7].

The proposed work demonstrates, for the first time, environmental temperature sensing using a single ScAlN pMUT die in a pulse-echo configuration over a distance of 30cm. This is the longest distance to date in the use of pMUTs for remote temperature sensing. Unlike [3], where an integrated analog frontend was necessary to amplify the received (RX) signals, we here attain accurate temperature estimates at long range without any electronic amplification at readout. The proposed work extends the previously presented work reported in [4], by introducing the capability of temperature measurement at long distances through a single pulse-echo measurement. These results pave the way for the use of pMUTs towards long-range environmental temperature sensing using a single die.

PMUT DESRIPTION

The sensing element considered in this work is a 3mm×3mm MEMS die with an array of 4×4 membranes, each ~600µm wide. Fig. 1 depicted a top view optical image of the 4×4 pMUT array used for temperature sensing. Each membrane is comprised of a 4µm-thick epi-polysilicon elastic layer and 1µm-thick 15% Scandium (Sc) doped Aluminum Nitride (AlN) transducer layer sandwiched between Molybdenum (Mo) electrodes.

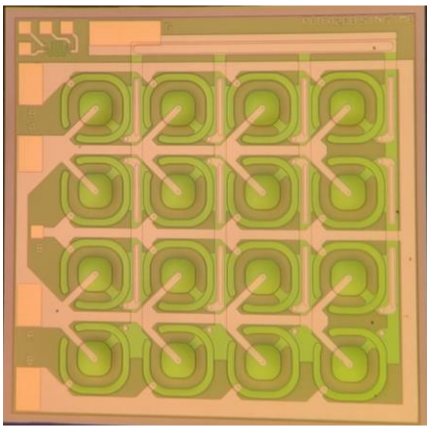

Figure 1: Top view image of a 4×4 pMUT array used for

temperature sensing.

Fig. 2 provides a schematic of the pMUT cross-section. The inner electrode, with width around half of the membrane length, was used to actuate and sense all 16 membranes in parallel. The other ring electrodes on the membrane were not used in this work and left floating.

In order to characterize the pMUT array, the transmit (TX) pressure output in air was experimentally measured using a condenser microphone. The microphone was placed 8cm away from the die and the pMUT array was actuated with a $4V_{pp}$ 35-cycle sinusoidal waveform with the frequency swept from 60 to 240kHz. Fig. 3 depicts the measured pressure output of the pMUT array as a function of swept frequency. The -3dB bandwidth of the pressure output frequency response is around 15.5%, where the microphone is located, with the resonant frequency identified from the graph to be approximately 150kHz.

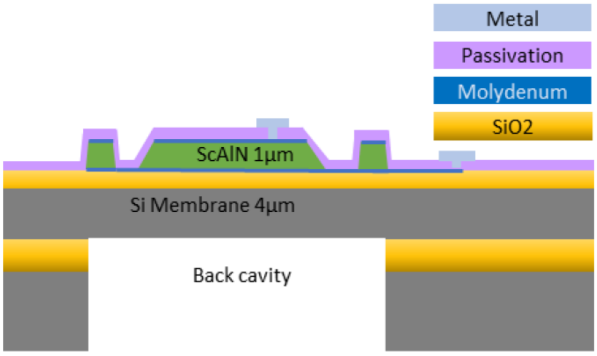

Figure 2: Schematic of the pMUT cross-section.

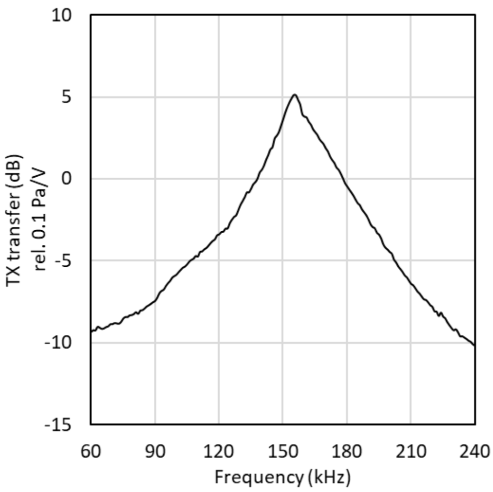

Figure 3: Transmit pressure output of the pMUT die with 16 membranes driven in parallel as a function of frequency.

METHODOLOGY FOR TEMPERATURE SENSING BY ULTRASOUND

The received signals were first windowed to remove any undesired early-time contributions (i.e., ringing from pMUT actuation and signal distortion due to switching) and then bandpass filtered around the pMUT actuation frequency. The conditioned data was fed to a matched filter implementation similar to the one discussed in [4] to estimate the updated speed of sound used to compute the temperature.

Specifically, a template signal, i.e., a received signal captured at a known environmental temperature setting, is used to compare against a received signal captured at an unknown temperature reading. Through this comparison, implemented via the matched filter, a relative time-difference between the two signals is identified and mapped to a difference in the speed of sound associated to the temperature variation in the environment at the time of the signal capture. The time-difference between the two signals is computed as described below:

- The autocorrelation of the template signal is computed.
- The cross-correlation between the template signal and the received signal of unknown temperature is calculated.
- The difference between the time values corresponding to the indices of the maximum magnitude in the autocorrelation and cross-correlation curves would refer to the desired time-of-flight (ToF) value.
- The ToF value would then be used to compute the speed of sound in the received signal of unknown temperature given the known distance between the pMUT device and the reflector.

Fig. 4 depicts the various signal processing steps for temperature estimation.

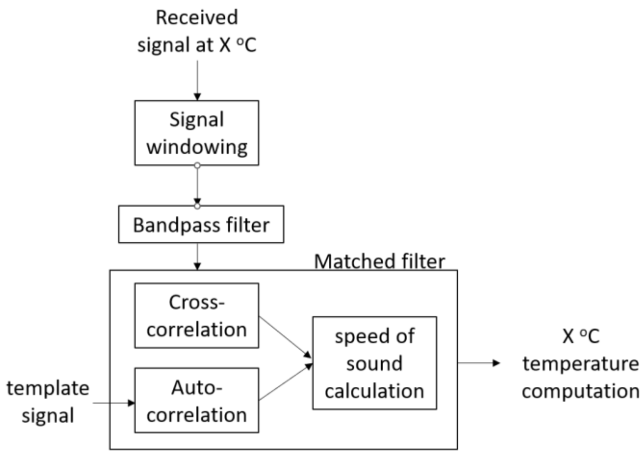

Figure 4: Block diagram of the temperature estimation algorithm.

EXPERIMENTAL SETUP

The chip was wire-bonded on a PCB and placed in a temperature-controlled chamber (Espec SH-241). The pMUTs were actuated with a 20-Volt peak-to-peak (Vpp) 15-cycle square pulse at 140kHz, using a signal generator (Keysight 33500B) and the echoes were captured using an oscilloscope (Keysight DSOX4024A). The pMUTs were toggled between the TX and RX mode using a high-voltage switchboard. It is worth noting that all 16 membranes in the array were pulsed as a transmitter (TX) and then switched to receive (RX) the echo signals. The die was confined within a 30cm-long Perspex tube to minimize signal loss due to spreading in the absence of amplification electronics. The chamber's temperature varied from 30-90°C with 10°C increments. At every temperature increment, a 2min stabilization time was observed prior to a measurement capture. A reference temperature sensor, controlled through an Arduino kit, was used to provide baseline temperature readings. Fig. 5 provides an overview of the temperature sensing experimental setup considered in this work.

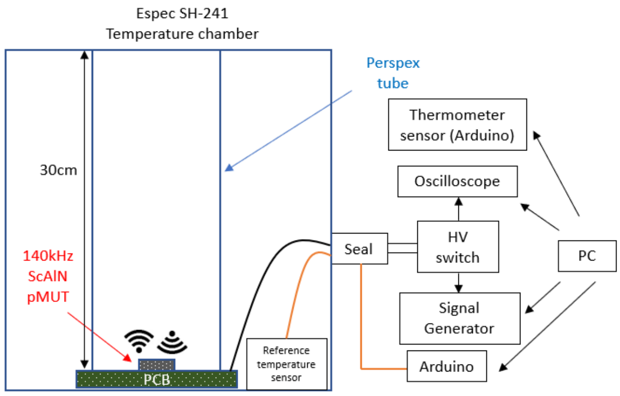

Figure 5: Temperature sensing experimental setup.

ANALYSIS OF RESULTS

Fig. 6 depicts a template signal, i.e., a received signal captured at a known temperature setting in the temperature chamber (in this case 30°C), along with a received signal captured at an unknown temperature reading. It can be observed that the early-time signal contributions can overshadow the echo signal rendering an erroneous speed of sound estimation when the two signals are passed to the matched filter. The source of the early-time signal stems from the pMUT ringing, which is further distorted by the switch. As such, the use of windowing is imperative prior to temperature computation.

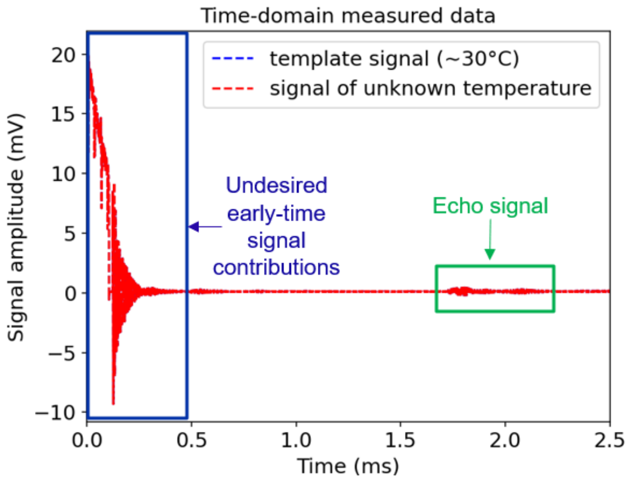

Figure 6: Undesired early-time signal contributions versus the desired echo signal highlighting the need for signal windowing prior to temperature estimation.

Despite a reduced SNR (~25dB) without the use of an amplifier at readout, the echo from the reflector (at 30cm) is still distinct with an amplitude of 0.5mV$_{pp}$ as it can be seen in Fig. 7. The relationship between temperature and speed of sound is validated from the change in ToF observed in Fig. 8: with increasing temperature, the echo signal arrives earlier due to an increase in the speed of sound in air.

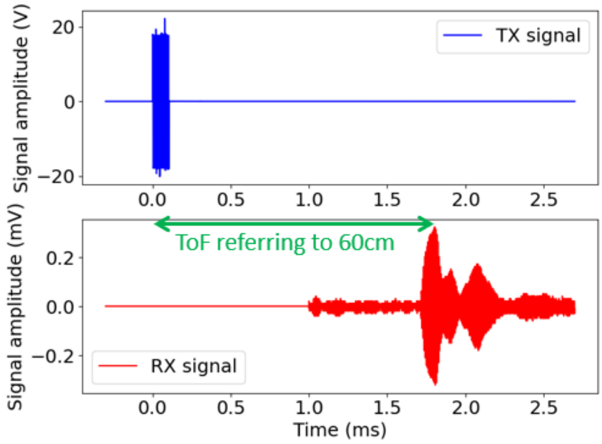

Figure 7: Time of flight (ToF) estimation corresponding to a roundtrip distance of 60cm measured at a temperature of 30°C.

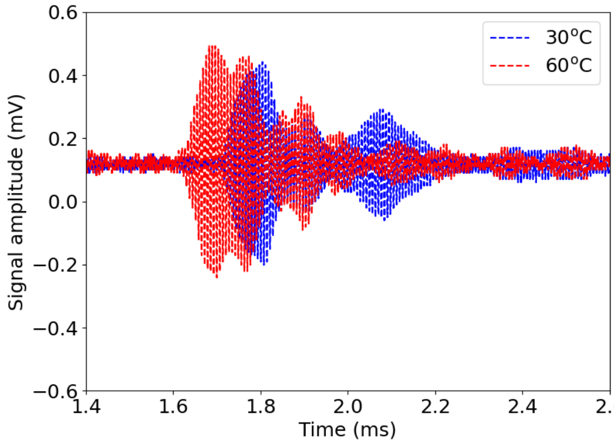

Figure 8: Contrast in arrival time of received echo signals at two different temperatures. As the speed of sound increases proportionally to the temperature, the received echo signal at 60°C arrives before the one at 30°C having travelled the same round-trip distance of 60cm.

Fig. 9 demonstrates the resulting temperature estimates from the proposed sensing system compared against the ones measured by the reference temperature sensor. It can be seen that the proposed pMUT sensing system results in a 97% accuracy at the long range of 30cm with an average absolute error of 1.4°C. These results pave the way for the use of single chip pMUTs for long-range environmental temperature sensing applications. The impressive accuracy is attributed to using a threshold rule to identify equal magnitude peaks in the cross-correlation curve for the temperature calculation.

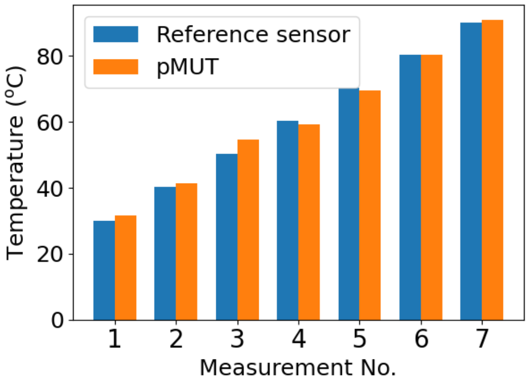

Figure 9: Estimated temperature results using the proposed pMUT sensor and a reference sensor are in good agreement.

CONCLUSIONS

This paper has demonstrated, for the first time, a successful proof-of-concept of in-air long-range temperature sensing by ultrasound using a single 15% Scandium-doped Aluminum Nitride (ScAlN) pMUT array chip. The proposed temperature pulse-echo sensing setup can achieve an impressive 97% accuracy (and a respective average absolute error of 1.4°C) in temperature sensing at 30cm (corresponding to 60cm of round-trip distance) for temperatures up to 90°C. This is accomplished using a single 9mm^2 die without any signal pre-amplification at readout, and thus the sensing range could comfortably be extended to 1m. The promising results presented by this work pave the way for the use of pMUTs for environmental temperature sensing.

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