ABSTRACT
A fully-integrated ultrasonic fingerprint sensor based on pulse-echo imaging is presented. The device consists of a 24x8 Piezoelectric Micromachined Ultrasonic Transducer (PMUT) array bonded at the wafer level to custom readout electronics fabricated in a 180-nm CMOS process. The proposed top-driving bottom-sensing technique minimizes signal attenuation due to the large parasitics associated with high-voltage transistors. With 12V driving signal strength, the sensor takes 24µs to image a 2.3mm by 0.7mm section of a fingerprint.

KEYWORDS
Fingerprint sensor, Ultrasound transducer, MEMS-CMOS integration, PMUT

INTRODUCTION
Recurrent security breaches in the public and private sector set a pressing need for improved standards that go beyond easily compromised passwords. Biometrics and especially fingerprints are an attractive approach that can be incorporated into a wide variety of devices including smart phones, watches, or door-knobs to provide naturally secure access without inconveniencing the user.

Present fingerprint recognizers fail to meet the reliability, size, and cost constraints of consumer applications. Optical sensors are difficult to miniaturize and easily spoofed. Capacitive approaches meet the size and cost targets but suffer from susceptibility to humidity and contamination. Ultrasonic fingerprint sensors, on the other hand, achieve resilience to contamination.

Conventional ultrasonic fingerprint sensors employing bulk piezoceramic transducers and XY mechanical scanning [1] fail to meet the size and cost constraints for portable devices. A recent result [2] based on a capacitive micromachined ultrasonic transducer (CMUT) 2D array eliminates the need of mechanical scanning, but the complex interface between the large sensor array and the signal-processing electronics fails to meet the size target. Short-range imaging has been demonstrated using piezoelectric micromachined ultrasonic transducer (PMUT) arrays [3], but without integrated electronics, individual read-out of the PMUTs in an array is daunting.

This paper presents the first implementation of a fully integrated pulse-echo ultrasonic fingerprint sensor realized by bonding MEMS and CMOS wafers to achieve compact size, high signal fidelity, low power dissipation and a low-voltage electronic interface for a wide range of applications.

SENSOR OVERVIEW
Aluminum Nitride (AIN) PMUTs with 50-µm diameter and 100-µm pitch are fabricated on a MEMS wafer as the sensing element. Fig. 1 shows the complete 24x8 array bonded at the wafer level to evaluation electronics fabricated in a standard 180-nm CMOS process. Fig. 2 shows an SEM photo of the sensor stack after the bonding process. Conductive standoffs provide electrical connectivity and mechanical support. The tight integration of MEMS with electronics enables high density interconnects with low interface parasitics.
A 220-µm deep recess etched into the MEMS wafer after the bonding process exposes the PMUT transducer elements. Fluorinert FC-70 inside the open port serves as a coupling layer between the PMUT and finger as well as an acoustic delay line that separates the transmitted acoustic pulse from the echo. A 100-µm PVC lid seals the Fluorinert and protects the sensor.

The PMUTs are piezoelectric unimorphs. Voltage applied between the top and bottom electrodes results in a transverse stress in the 0.8-µm thick AlN layer. The resulting vertical stress gradient between the active AlN layer and the passive 5-µm Si elastic layer causes the membrane to deflect vertically and emit an ultrasonic wave into the Fluorinert. Similarly, an incident pressure wave deflects the membrane resulting in a charge between the electrodes that is detected by the integrated electronic amplifiers.

**SENSOR MODEL**

Fig. 3 shows the electrical-mechanical-acoustic model for the PMUT adapted from [4]. With the 22-µm electrode diameter and 0.8-µm AlN layer, each PMUT has a capacitance $C_{PMUT} \cong 100\text{fF}$. The first transformer with coupling coefficient $\eta = 3\text{µN/V}$ converts applied voltage to mechanical force that actsuates the membrane. The membrane deflects into a parabolic shape, creating a non-uniform pressure wave with peak pressure $P_{\text{out}}$, which can be approximated by a piston with area $A_{\text{eff}} = (1/3)A_{PMUT} = 650\mu m^2$ generating a uniform pressure $P_{\text{out}}$ [4]. The equivalent membrane stiffness and mass are $k_m = 180\text{kN/m}$ and $m_m = 12\text{ng}$, respectively, resulting in a 20MHz resonance frequency.

The transmission lines represent the media above and below the PMUT. Since the space between the MEMS and CMOS wafer is vacuum, the acoustic impedance $Z_{\text{bot}} = 0$ and $Z_{\text{FC-70}} = 1.33\text{MRayl}$, translating into the entire acoustic energy being transmitted towards the finger, as desired. The large acoustic impedance of Fluorinert compared to the PMUT’s stiffness and mass results in a quality factor of only 2 that is suitable for sending short pulses. At resonance, the theoretical peak surface pressure of a single PMUT with $V_{PMUT} = 12\text{V}$ peak-to-peak driving pulse is:

$$P_{\text{out}} \cong \frac{\eta \cdot V_{PMUT}}{2} \cong 27.7\text{kPa}$$

In this implementation the entire array is driven simultaneously to transmit a plane wave. Each element is modeled as a piston with area $A_{\text{pixel}} = 100\mu m \times 100\mu m$ as shown in Fig. 3. The resulting plane-wave pressure is 7kPa, equal to the surface pressure scaled by the transmitter spreading loss $L_{s,t}$.

$$L_{s,t} = \frac{A_{\text{eff}}}{A_{\text{pixel}}} \cong 0.25. \quad (2)$$

The 100-µm PVC lid with acoustic speed 2100m/s is well approximated by a transmission line with length approximately one wavelength at 20MHz. Impedances $Z_{\text{ry}}$ and $Z_{\text{rg}}$ represent fingerprint valleys and ridges, respectively. The reflected pressure $P_r$ at the Fluorinert-lid boundary is:

$$P_r \cong L_{s,t}P_{\text{out}} \frac{Z_{\text{ry}} \cdot Z_{\text{FC-70}}}{Z_{\text{ry}} + Z_{\text{FC-70}}}$$

The air inside valleys with $Z_{\text{ry}} = Z_{\text{air}} = 430\text{ Rayl}$ corresponds to a huge impedance mismatch with the Fluorinert, resulting in a strong reflected power $P_r$. For an average valley width of 150µm the reflected wave spreads again with average loss $L_{s,r} \sim 0.3$ before reaching the sensor, a value derived from experimental data. Finally the magnitude of the pressure wave that reaches the PMUT under a fingerprint valley is:

$$P_{\text{in,ry}} \cong L_{s,r}P_r = L_{s,r}L_{s,t}P_{\text{out}} \frac{Z_{\text{rg}} \cdot Z_{\text{FC-70}}}{Z_{\text{ry}} + Z_{\text{FC-70}}} \cong 2.08\text{kPa}$$

By contrast, the impedance of ridges, $Z_{\text{rg}} = Z_{\text{tissue}} = 1.5\text{MRayl}$, is close to $Z_{\text{FC-70}}$ resulting in only a weak echo. The width of a ridge ~500 µm is much larger than the pixel size, translating into negligible spreading loss, i.e. $L_{s,r} \sim 1$.

The magnitude of the resulting pressure wave picked up by a pixel under a fingerprint ridge is:

$$P_{\text{in,rg}} \cong L_{s,t}L_{s,r}P_{\text{out}} \frac{Z_{\text{rg}} \cdot Z_{\text{FC-70}}}{Z_{\text{rg}} + Z_{\text{FC-70}}} \cong 0.42\text{kPa}$$

![Figure 3: (top) Electrical-Mechanical-Acoustic model of the sensor and its environment and (bottom) corresponding physical diagram explaining effective area of PMUT and spreading loss.](image)

![Figure 4: Simplified electrical sensor model at resonance.](image)
Fig. 4 shows the simplified model adapted from Fig. 3 at resonance during reception. The transmission lines represent the pressure wave propagating in Fluorinert. The voltage received by the transducer \( V_{PMUT} \) is:

\[
V_{PMUT} = P_{in,sys} \frac{A_{eff}}{\eta} \frac{1}{1 + j \omega C_{PMUT} \frac{A_{eff}}{Z_{FCC70}}}
\]  

(6)

Together with (4) and (5), at 20MHz this yields 0.37mV for finger valleys and 0.08mV for ridges, corresponding in a contrast of approximately 5:1. In practice the acoustic cross-talk of the echo from nearby valley results in a stronger signal than the echo from a ridge, reducing the contrast to approximately 3:1.

**SYSTEM DESIGN**

**Top-electrode driving / bottom-electrode sensing**

In a conventional ultrasonic system, the transducer is operated as a single-port element as in Fig. 5a. A high-voltage switch \( SW_{RX} \) inserted between the transducer and the receiver isolates the high-voltage driving signal from the receiver during transmission. However, high-voltage circuits suffer from large parasitic capacitance \( C_{pSW} \) resulting in signal attenuation by approximately 200x for the CMOS process used.

Operating the PMUT as a two-port device, as shown in Fig. 5b, avoids this problem. The top electrode of the PMUT is permanently connected to the driver. During the transmit phase, the bottom electrode is grounded via transistor \( SW_{RX\_LV} \). Since \( SW_{RX\_LV} \) is never exposed to high voltage, a low-voltage transistor with only 20fF rather than 10pF parasitic capacitance can be used. During the receive phase, the top-electrode is grounded via \( SW_{TX\_HV} \) inside the transmitter and \( SW_{TX\_LV} \) inside the receiver is opened. Since now \( C_{TX} \) is effectively shorted, it no longer attenuates the signal. With this configuration, the PMUT itself isolates the high-voltage driving electronics from the low-voltage receiver and thus no high-voltage devices are required at the receiving port. In this work, a charge amplifier [5] is used instead of a voltage amplifier to avoid signal attenuation and the consequent higher sensitivity to capacitive feed-through.

**System Architecture**

Fig. 6 shows the system diagram. A high-voltage transmitter [6] with built-in charge pump generates a 12V \( V_{pp} \) driving signal from a 1.8V supply. Each element has a dedicated pre-amplifier followed by a 10X gain stage shared by all 24 elements in each row. In this prototype, the driver, ADCs, and control logic are off-chip.

The system operates as follows: first the switch \( SW_{RX\_LV} \) is closed in each cell and the HV transmitter drives the entire PMUT array with 3-cycles of 12-V pulses at 20MHz to emit a plane-wave. The ultrasound wave hits the finger and is reflected by the valleys and ridges. In the subsequent receive phase, \( SW_{TX\_HV} \) is closed, effectively grounding the top-plates of all PMUTs. One column is picked by closing \( SW_{col} \) and the received signals from 8 elements are read out in parallel. The echoes are amplified by the second-stage amplifier and sent off-chip for evaluation. This procedure repeats 24 times to read out all 24 columns in 24\( \mu \)s total. Because of the parallel readout enabled by the high-density electronics, the time for reading out an entire fingerprint increases only with the square root of the array size. For example, an array with 200 by 200 PMUTs at 50\( \mu \)m pitch has 10mm by 10mm area and takes only 0.2ms to read, avoiding blurring from fingertip motion.

**Signal-to-Noise Ratio**

Accurate evaluation of fingerprints requires a signal-to-noise ratio (SNR) of at least 12dB. Fig. 7 shows an equivalent circuit model for calculating the noise from the pre-amplifier and the transducer. At the output the variance of the noise is:

\[
\frac{\text{variance of noise}}{\text{variance of received signal}} = \frac{1}{\eta^2} \frac{1}{1 + \frac{j \omega C_{PMUT} A_{eff}}{Z_{FCC70}}}^2
\]
\[ \frac{v_{\text{out}}}{v_{\text{in}}} \equiv \frac{v_{\text{out}}}{v_{\text{in}}} \left( 1 + \frac{C_{\text{PMUT}} + C_{\text{P}}}{C_{\text{P}}} \right) + \frac{v_{\text{out}}^2}{(j\omega Z_{\text{in}} C_{\text{P}})^2} \]  

Since \( Z_{\text{in}} >> 1/(j\omega C_{\text{P}}) \), the noise from the transducer, \( v_{\text{out}}^2/n_{\text{i}} \), is negligible. In the 7MHz measurement bandwidth, the total noise is 102-\( \mu \)V rms at the pre-amplifier output or 0.28 kPa rms pressure noise at \( P_{\text{ac}} \).

Fig. 8 shows the measured receive signal voltage at the preamplifier output as a function of transmitter driving voltage. Since the measurement is performed without a finger present, the received signal power corresponds to its maximum value, \( P_{\text{in,12V}} \) without receiving spreading loss, i.e. \( L_{\text{a,c}} = 1 \), as shown in Fig. 8. A PMUT at the center of the array is used to pick up the echo and the result is compared with the previously described theoretical model. For a 150\( \mu \)m wide fingerprint valley this decreases due to the receive beam spreading loss of \( L_{\text{a,c}} \cong 0.3 \) as shown by the green curve which shows the estimated received echo strength from a fingerprint valley. A 7-V drive signal results in a 0.41-mV output \( V_{\text{out}} \), corresponding to 12dB SNR. Driving the array at 12-V leaves some margin for safety.

MEASUREMENT RESULT

Fig. 9a shows received echoes from 2 pixels beneath a fingerprint ridge and valley, respectively with 12V driving. The peak charge for the ridge and valley are 37aC and 16aC, respectively, resulting in 0.7mV and 0.3mV signal at the preamplifier output. The received signal from the fingerprint valley matches the model with pre-amplifier gain ~2, while the ridge echo is larger than calculated due to acoustic cross-talk from nearby valleys’ echo. Fig. 9b shows the received signal magnitude versus distance (time) for an entire row of 24 pixels. The red zones correspond to three valleys.

Fig. 10 shows a 2D fingerprint image captured with the sensor. The envelope of the pulse-echo data is extracted and plotted at a distance of 320\( \mu \)m from the transducer. The ultrasound and optical images exhibit good agreement. Two merging valleys can be clearly identified, confirming that the proposed imager is capable of resolving the minutiae used for fingerprint recognition.

![Figure 8: Measured received signal versus driving voltage.](image)

![Figure 9: Measurement result of (a) received echo for ridge and valley and (b) reconstructed image from 24 PMUTs (one row).](image)

![Figure 10: Optic fingerprint (top) and fingerprint image captured with the sensor (bottom).](image)

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REFERENCES


