Whitepaper Series

Accelerating Ultrasonic Fingerprint Sensor R&D with Cloud Simulation

Introduction

For some time, the IC design industry has relied on electronic design automation (EDA) and electrical simulation to help achieve first pass success for prototype CMOS devices. The MEMS industry, on the other hand, has never had a codified simulation work stream. As a result, MEMS companies often require many expensive and time consuming physical prototype runs to bring ground-breaking new MEMS devices to market. Now, Cloud Simulation provides a means to rapidly virtually prototype MEMS devices like ultrasonic fingerprint sensors, saving MEMS companies millions of dollars in R&D costs and months or years of R&D effort.

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For younger technologies such as MEMS, this process in still in its early stages. Two fundamental technology advancements must be seen through, in order to reach the efficiencies of EDA. Those advancements being 1) broad standardization of MEMS manufacturing processes, and 2) the emergence of massively-scalable multiphysics simulation tools. Standardization of manufacturing processes is largely driven by market forces, where new automotive, medical, and IoT applications are expected to propel the global MEMS market beyond $30B by 2024. But even with standard processes, designing MEMS is extremely challenging due to multiple, highly-coupled physics processes. This whitepaper examines an ultrasonic sensing example, where static mechanical, thermal, piezoelectric, and acoustic wave physics all interact fundamentally to define the performance of the device.

Fingerprint Sensing Market

Human fingerprints are detailed and unique markers of human identity. Currently, fingerprint sensors can be optical, capacitive, and ultrasonic[1].

Ultrasonic sensing started to make headway into much wider application as new ultrasonic transducer technologies have reduced the power, size, and cost of the technology. With significant use in the medical and industrial markets, consumer electronics is also starting to adopt this technology. In particular, significant growth is expected to come from ultrasonic sensor adoption into mobile handsets.

A forecasted 1.6 billion smartphones will be shipped with a fingerprint sensor by 2020. Capacitive sensing has been the dominant technology since Apple introduced it in the iPhone 5s, but ultrasonic sensing technology is poised to disrupt this market now that it can capture fingerprints through a full OLED display stack. For phones with edge-to-edge displays, ultrasonic sensors are the best technology option.

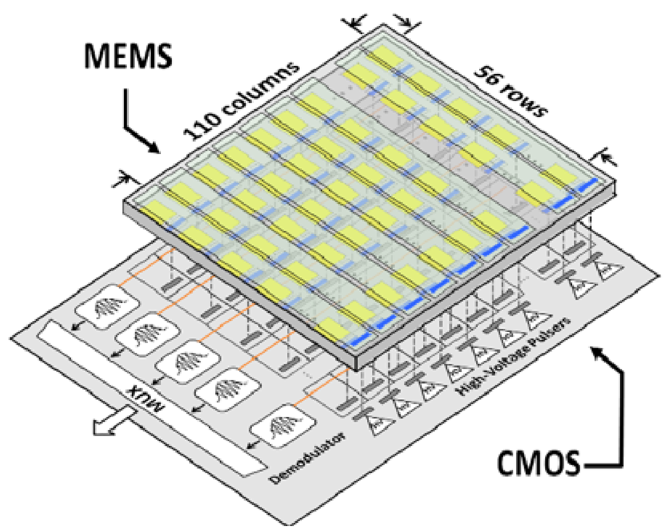

Figure 1: An integrated ultrasonic fingerprint sensor (Source: Horsley et al)[1]

Ultrasonic Fingerprint Sensing

An ultrasonic sensor, simply put, uses sound waves to detect the distance to other objects. The theory of operation is similar to radar, in that a distance is measured by analyzing reflected signals. These devices, while powerful in their capabilities, can be difficult to design.

Ultrasonic sensors use the properties of a piezoelectric material, such as lead zirconium titanate (PZT) or aluminum nitride (AlN), to convert electrical energy into mechanical energy. This mechanical energy can be used to map the detailed features of a person's fingerprint, as an example. The sensor vibrates when electrical energy is applied, and the physical vibration is tuned to create sound waves in the ultrasonic range by compressing and expanding the molecules between the sensor and the object to be detected. It sends out a sound wave and "listens" for the echo, before transmitting again.

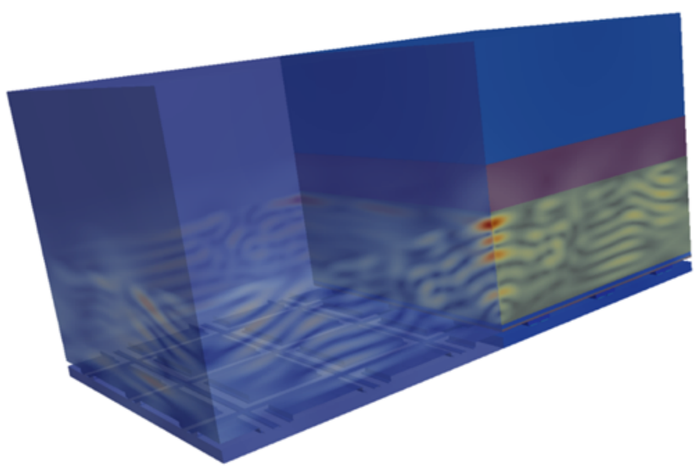

Figure 2: 3D simulation of an ultrasonic sensor fingerprint (Source: OnScale)

Acoustic fingerprint sensors have many advantages over competing technologies, most importantly, being insensitive to contamination and moisture and being usable through material stacks including glass and adhesive. In addition, ultrasonic waves used in pulse-echo imaging can penetrate the finger's epidermis, collecting images of sub-surface features[2]. Figure 3 describes the functionality of an ultrasonic fingerprint sensor.

To date, no software tools have been capable of simulating an entire ultrasonic fingerprint sensor in full-3D prior to prototyping. As a result, engineers are left with analytics alone to determine how their digital signal processing algorithms will work on the signals produced by the final device, and how packaging, material, and dimensional changes and tolerances will affect their performance. Therefore, new sensors have to be prototyped many times over to empirically solve issues related to design and manufacturing. In this paper, we will leverage the work of Prof David Horsley's group at the Berkeley Sensor & Actuator Center for the modeling and simulation of an ultrasonic fingerprint sensor in full 3D using OnScale – the only computer-aided engineering (CAE) tool capable of solving such problems today.

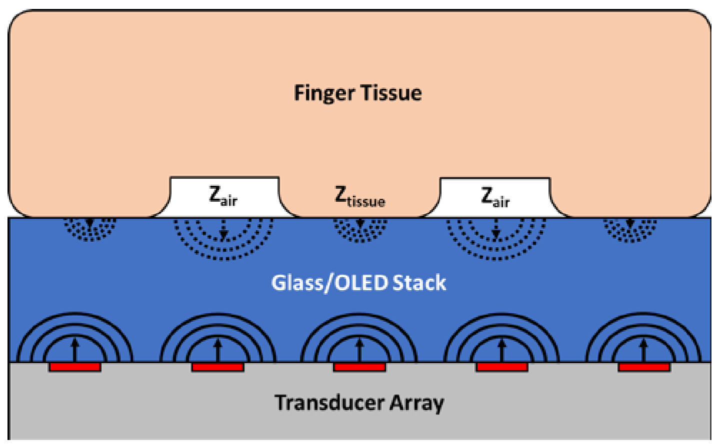

Figure 3: Ultrasonic fingerprint technology (Source: OnScale)

The PMUT

Piezoelectric micromachined ultrasonic transducers (PMUT) represent the newest entrant to the ultrasonic sensing space. Leveraging many of the advantages of other microelectromechanical systems (MEMS), PMUTs are lower power, lower cost, and significantly smaller in size than most other ultrasonic technologies on the market. This has been achieved primarily through a long history of considerable investment into silicon manufacturing processes, enabling billions of devices to be produced at costs that are in-line with the demands of consumer applications.

Recent developments have enabled PMUTs to be manufactured using many of the same tools as modern CMOS processes, allowing economies of scale that were previously out of reach.

A PMUT is a transducer that operates using the flexural mode of a thin membrane such as silicon or silicon nitride that is coupled with a thin piezoelectric film such as lead zirconium titanate (PZT) or aluminum nitride (AlN)[2,3]. When a voltage pulse is applied to the top and bottom electrodes that sandwich the piezoelectric layer, the transverse strain caused by the electric field creates a bending moment, vibrating the membrane and producing mechanical energy in the form of acoustic waves (Figure 4). In transmit (Tx) mode, the vibration sends an acoustic wave into the surrounding medium (air, water, blood, etc.). The transmitted wave hits the target object, reflects back and deflects the PMUT membrane. In receive (Rx) mode, this deflection creates strain, and subsequently charge, that can be amplified and detected using an on- or off-chip application specific integrated circuit (ASIC). This duality of function is a major contributor to the PMUT's cost and size advantages.

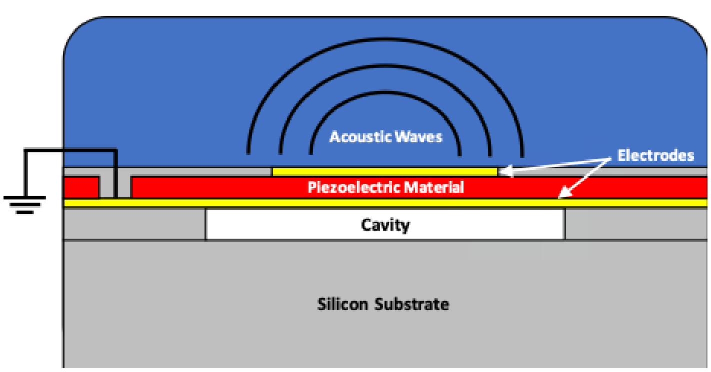

Figure 4: Basic PMUT cell structure
(Source: OnScale)

Although PZT has been widely used in piezoelectric devices due to its good piezoelectric properties, it has several disadvantages: 1) the material contains lead, making it difficult to use in some countries, 2) the material ages as a result of deformation, and 3) it requires a high annealing/deposition temperature and is therefore not compatible with standard CMOS manufacturing process flows[4]. AlN, alternatively, is lead-free, is resistant to mechanical degradation, and is compatible with standard CMOS manufacturing due to the low temperature budget of its deposition process. The combination of these advantages has led to its recent use in a variety of application areas despite its inferior piezoelectric response compared to PZT[5].

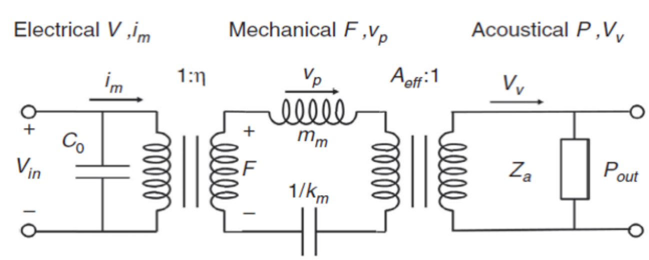

Figure 5: Lumped-element small signal PMUT model
(Source: Jiang et al)[5]

In the small signal domain, PMUTs can be modeled as shown in Figure 5. The electrical domain is described by the voltage and current while the mechanical domain is described by the force and velocity. These domains are linked by a positive quantity called the *transformer ratio* (η). The acoustical domain (right) is modeled by pressure and volume velocity and links with the mechanical domain (middle) through a quantity called *effective area* (A_{eff}). The acoustical domain output is calculated as:

$$P_{out} = V_V * Z_a \qquad (1)$$

where P_{out} is the *transmitted pressure*, V_V is the *volume velocity*, and Z_a is the *radiation impedance*[5].

The role of the cavity below a PMUT membrane is to allow for mechanical deformation of the membrane under electrical impulse, so the depth is of minimal importance as long as flexure of the membrane is not impeded. Several design parameters are needed to optimize a PMUT array's performance for an application. After defining the desired working frequency for the desired transmission medium, the PMUT lateral size can be chosen as $\frac{\lambda}{2}$ to satisfy the Nyquist sampling criteria. This is required to avoid unwanted grating lobe artifacts. By considering Equation 2, the initial thickness can then be calculated as:

$$f_r \sim \frac{Thickness}{Lateral\ size^2} \qquad (2)$$

The next step is to extract the small signal variables used in Figure 5. C_0 is the PMUT *membrane capacitance. Mass* (m_m), *stiffness* (k_m), and *transformer ratio* (η), as well as *natural axis length* and *flexural rigidity* calculations are explained in detail by Jiang et al. Given that P_{out} is the radiated pressure into the medium and is proportional to radiation impedance, our goal is to maximize the real part of the radiation impedance to optimize the transferred energy into the medium. An example radiation impedance plot for a clamped radiator such as a PMUT is shown in Figure 6.

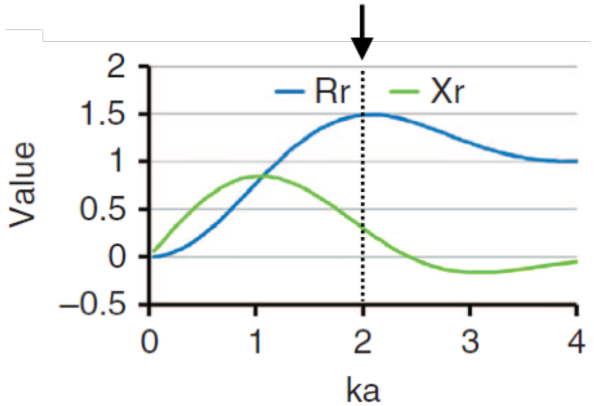

Figure 6: Radiation impedance as a function of wave number and lateral size (Source: Jiang et al)[5]

The radiation impedance at a certain frequency is a function of wavenumber *(k)* and PMUT lateral size *(a)*, such that the lateral size of this transducer is optimal when:

$$ka \sim 2 \qquad (3)$$

While the selection of these parameters should be informed by the intended application, for the purposes of this study, we will use the PMUT design parameters described by Horsley et al[6], which were selected to maximize output pressure into a Polydimethylsiloxane (PDMS) load at a center frequency of 14 MHz. When creating the model, all design dimensions for the PMUT were reproduced in order to demonstrate a faithful recreation of the empirical results in full-3D using only numerical means. The parameters are shown in Table 1.

Feature	Value
Cavity Thickness	2.0 μm
Bottom Electrode Size (x)	25 μm
Bottom Electrode Size (y)	38 μm
Piezo Layer Thickness	1.0 μm
Elastic (Si) Layer Thickness	2.0 μm
Cavity Size (x)	30 μm
Cavity Size (y)	43 μm

Table 1: PMUT Design Parameters (Source: Horsley et al)[6]

PMUT Simulation

In an effort to replicate the empirical process described by Horsley et al[6], we first simulated the pulse-echo response of a single PMUT. A 2-cycle, 1 V pulse was supplied into 50 Ω at 14 MHz with the device radiating into the PDMS load. Figure 7 shows the time-and-frequency-domain response of the PMUT. Using these parameters, we determined the transducer to have a 3-dB bandwidth of approximately 1.5 MHz and a transmit pressure of 15 kPa.

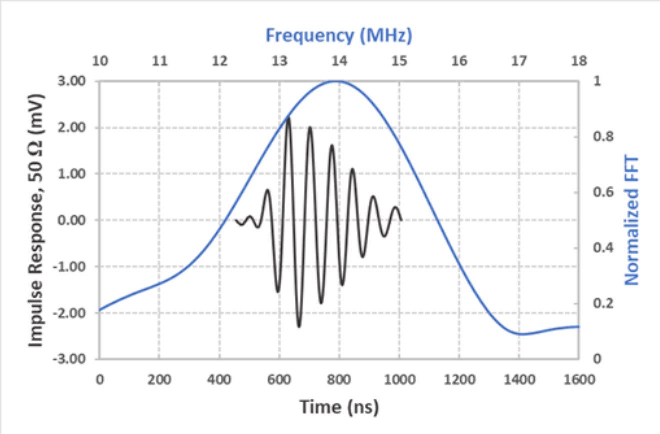

Figure 7: Pulse-echo response of a single PMUT column (Source: OnScale)

While the value of this simulation is not insubstantial, it provides only a limited picture of the final performance of the sensor. In most cases, device OEMs must proceed with a full-loop prototype run to determine exactly how their design will perform in its intended environment and application. If the prototype does not meet specification, the analytical models must be revisited to refine the predicted performance of the PMUT array, and a new design must be prototyped. Further delay is incurred due to the fact that beamforming and signal processing algorithms cannot be optimized until the design is frozen. The cost in capital, risk, and time to market of the empirical design process cannot be overstated.

Full Sensor Simulation

It is at this point that we describe a robust numerical approach to the design process using OnScale. Without the ability to perform a full 3D simulation of the embedded sensor, the only route forward for assessing the final performance of the design is to start making prototypes and building them into test systems – a process that can take anywhere between 3-6 months per design iteration. Using OnScale, engineers can virtually prototype their sensor in realistic systems in a matter of hours.

The sensor, which was designed and built by Horsley et al[6] to meet the 500 DPI standard for consumer fingerprint sensors, is a 110 x 56 PMUT array (6,190 elements total) that achieved a fill factor of 51.7%. It was wafer-level bonded at to a complementary metal-oxide-semiconductor (CMOS) signal processing chip to produce a fully-integrated pulse-echo ultrasonic fingerprint imager. The full sensor was modeled in full-3D using OnScale with the array parameters described in Table 2.

Feature	Value
Array Pitch (x)	43 µm
Array Pitch (y)	58 µm
Array Elements	110 x 56
Array Size	4.6 x 3.2 mm

Table 2: PMUT Array Design Parameters (Source: Horsley et al)[6]

The model included a PDMS die coating and a virtual finger in order to replicate the final test-case as faithfully as possible. A virtual, pulse-echo ultrasonic imaging test was then performed using OnScale's fully-coupled piezoelectric and elastic wave solvers. Because of the closely-matched acoustic impedance of human skin and PDMS, the reflections at the fingerprint ridges are minimal, while the reflections from the PDMS-air interfaces at the fingerprint valleys are nearly 100% of the transmitted pressure waves[6].

The complete model consisted of 130M degrees of freedom and solved with Onscale (running in AWS cloud) in 29 minutes. To replicate the necessary imaging protocol, 106 parallel simulations were deployed, with each simulation representing a unique set of transmit elements. Each simulation utilized 40 processor cores and 9.2 GB of RAM, for a total computing resource allocation of 4,240 processor cores and 975 GB of RAM. The computational energy cost of each virtual image was 2,120 core hours (CH).

Beamforming Optimization & Results

Using the complete 3D model, we were able to rapidly reproduce and optimize the beamforming algorithm described by Jiang et al[7]. The PMUT array was excited in groups of 5 columns while receiving on a single column per pulse. A reference image with no finger was subtracted to reduce background noise. The image produced from the time-domain data indicated that significant grating lobes were present (Figure 8 - Left). These were easily corrected by limiting the receive beam width used by the imaging algorithim from ± 90˚ to +/- 60˚ with a Hann window (Figure 8 - Right).

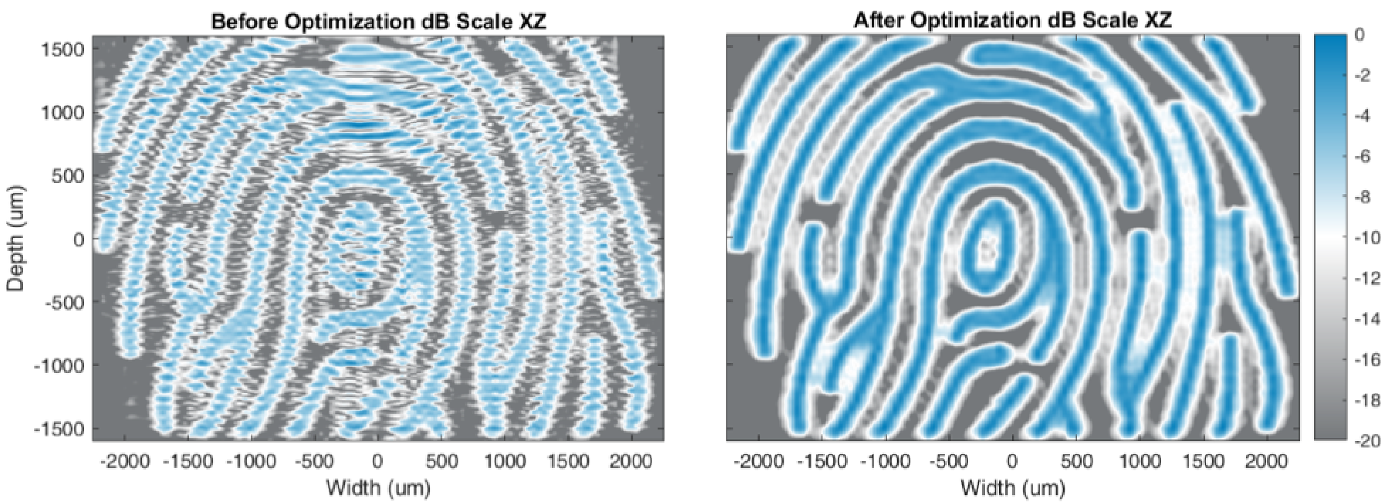

Figure 8: Virtual fingerprint image before (left) and after (right) beamforming optimization (Source: OnScale)

Summary

In this paper we describe the virtual prototyping and beamforming optimization of a 110 x 56 PMUT array fingerprint sensor first designed and prototyped by Horsley et al[6] at the Berkeley Sensor & Actuator Center. We demonstrate the powerful capabilities of OnScale's time-domain multiphysics simulation in the cloud by circumventing the legacy empirical approach to physical sensor design that imposes immense cost, risk, and delayed time to market on device OEMs. The sensor was modeled in full-3D and included the PDMS die coating and a virtual finger, resulting in a 130 million degrees of freedom model that was solved in 29 minutes per image on 106 parallel cloud nodes using a total of 4,240 processor cores. All of the simulation capabilities described herein are available in OnScale's standard simulation product, which can be downloaded for free at www.onscale.com.

About OnScale

OnScale empowers engineers to accelerate innovation across multiple industries, including next-generation technologies such as MEMS, Semiconductor, 5G, Biomedicine, and Autonomous Vehicles. OnScale combines powerful multiphysics solver technology used and validated by Fortune 50 companies for over 30 years, with the limitless speed and flexibility of cloud High Performance Computing (HPC). By removing the constraints of legacy simulation tools, OnScale allows engineers to dramatically reduce cost, risk and time to market for cutting edge technologies.

About the Authors

Dr. Ryan Diestelhorst is the VP of Strategy at OnScale. As an electrical engineer, MEMS designer, and venture-backed entrepreneur, Ryan has built his career around developing disruptive new technologies and bringing them to market.

Dr. Gerry Harvey is the VP of Engineering at OnScale. A numerical scientist, engineer, and FEA expert with over 15 years of industry experience, Gerry helps customers get up to speed with OnScale solutions and maximize the potential of OnScale Cloud.

Dr. Andrew Tweedie is the UK Director at OnScale. An expert in ultrasonic sensors and resonators, Andrew has worked in industries ranging from biomedical to sonar. He is committed to the belief that cloud-based simulation will allow engineers to unlock new design possibilities.

Dr. Amirabbas Pirouz is a Research Scientist at OnScale. He received his PhD from Georgia Tech with a focus on ultrasonic sensors. At OnScale, he is using his technical depth in MEMS to help customers leverage the incredible power of OnScale's multiphysics solvers.

Endnotes

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7 X Jiang, HY Tang, Y Lu, E Ng, J Tsai, B Boser, & D Horsley, "Ultrasonic Fingerprint Sensor with Transmit Beamforming Based on a PMUT Array Bonded to CMOS Circuitry," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control (UFFC), vol. 64, no. 9, pp. 1401-1408, 2017.