Theory and Experimental Analysis of Scratch Resistant Coating for Ultrasonic Fingerprint Sensors

Stephanie Fung*, Yipeng Lu*, Hao-Yen Tang†, Julius M. Tsai‡, Michael Daneman§, Bernhard E. Boser¶, and David A. Horsley*

*Department of Mechanical and Aerospace Engineering University of California, Davis, USA
†Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, US
‡Invensense, San Jose, CA, USA

Abstract—Ultrasonic imaging for fingerprint applications offers better tolerance of external conditions and high spatial resolution compared to typical optical and solid state sensors respectively. Similar to existing fingerprint sensors, the performance of ultrasonic imagers is sensitive to physical damage. Therefore it is important to understand the theory behind transmission and reflection effects of protective coatings for ultrasonic fingerprint sensors. In this work, we present the analytical theory behind effects of transmitting ultrasound through a thin film of scratch resistant material. Experimental results indicate transmission through 1 µm of Al₂O₃ is indistinguishable from the non-coated cover substrate. Furthermore, pulse echo measurements of 5 µm thick Al₂O₃ show ultrasound pressure reflection increases in accordance with both theory and finite element simulation. Consequently, feasibility is demonstrated of ultrasonic transmission through a protective layer with greatly mismatched acoustic impedance when sufficiently thin. This provides a guide for designing sensor protection when using materials of vastly different acoustic impedance values.

Index Terms—piezoelectric micromachined ultrasound transducers, ultrasonic transmission, ultrasonic transducers.

I. INTRODUCTION

Ultrasonic fingerprint sensors have several advantages over optical and capacitive based fingerprint sensing technologies available in the market today. The image quality for both of these imaging modalities are highly sensitive to external contaminants, such as sweat or oil, which are a result of unavoidable environment conditions. In contrast, the image quality of an ultrasonic based fingerprint sensor has been shown to be unaffected when subjected to such external conditions [1].

Fingerprint sensors, regardless of the sensing method, are sensitive to aberrations and defects on the protection layers which separate the sensor and the user. Typical single-chip CMOS semiconductor fingerprint sensors use a soft thin-film protective layer which is susceptible to scratches and deformation under normal use. In time, these scratches negatively affect the image which the sensor receives causing the sensor to work improperly. Harder and thicker materials may also be used to protect the sensor, but many of these hard coatings would reflect most if not all of the ultrasound signal due to the difference in acoustic impedance of the material. However, with a sufficiently thin layer of the protective material coated on coupling material, it is possible to transmit and receive ultrasound while protecting the fingerprint sensor from performance degrading physical damage.

The ability to transmit and receive through thin protective coatings is paramount for the implementation of ultrasonic fingerprint in personal devices. Therefore it is important to understand the theory behind transmission effects of protective coatings for ultrasonic fingerprint sensors. We present the analytical theory behind the transmission effects of additional thin film layers, and simulate using a finite element model (FEM). To examine this phenomena in practice, transmission and pulse echo experiments were performed to measure the effects of a scratch resistant thin film layer. In this study, thin film Al₂O₃ was deposited via plasma vapor deposition (PVD) onto polyimide adhesive tape substrate and thin sheets of polycarbonate. The abrasion resistance of the uncoated and coated substrates were compared. Additionally, ultrasound testing was performed using a previously developed ultrasonic fingerprint sensing system based on piezoelectric micromachined ultrasound transducers (PMUT) to emulate closely the conditions for transmission and reflection of ultrasound for such applications.

![Fig. 1. Cross-section diagram showing PMUT array, coupling layer, plastic cover, and anti-scratch coating layer](image)

II. METHODOLOGY

A. Protection of Ultrasonic Fingerprint Sensors

A hard, abrasion resistant protective layer is required to guard against damage of the fingerprint sensing elements. Specific to ultrasonic sensors, the acoustic effects of the materials used in such protection layers is critical for study. The schematic drawing in Fig. 1 shows an example layer stack-up from the sensor elements to the finger. The protective layer would lie on a cover material which is coupled to the ultrasonic elements through a medium layer material with
properties specific for acoustic impedance matching. Typical hard, scratch resistant materials, such as glass, are greatly reflective to ultrasound. The use of such material requires precise control of the layer thickness, and similarly with the choice of the required matching material. In comparison, there is a plethora of existing plastic materials which could serve as the cover material and are much less reflective to ultrasound compared to glass. Despite these advantages, plastics are more susceptible to scratching and abrasion damage through regular use.

In optics, plastic lenses are commonly protected by thin film layers of hard material (i.e. anti-scratch coating layers on the lenses of plastic eye wear). $\text{Al}_2\text{O}_3$ is a material with known hardness and scratch resistance [2]. It can be deposited onto various substrate such as plastics and glass. Acoustic theory of layered media predicts that sufficiently thin layers of such material has little to no effect on acoustic propagation.

**B. Acoustic Propagation through Layered Media**

For fingerprint sensor protection, there are multiple discrete layers which affect the transmission and reflection of acoustic pressure wave propagation. It is necessary to take into account the effects of each layer to design a layer stack-up which provides adequate protection without too much attenuation of the pressure signal. A common approach is to model the layers in terms of acoustic impedance ($Z = \rho c$) and to find the total input impedance for the system. A general expression of transmission coefficient for an arbitrary number ($n$) of discrete layers is given in [3] as follows:

$$T = \prod_{j=1}^{n} \exp(i\varphi_j) \frac{Z_{in}^{(j)} + Z_{j}}{Z_{in}^{(j)} + Z_{j+1}} \quad (1)$$

Where $\varphi$ is the product of the thickness and the wave number ($k = \omega/c$) of the specific layer. The input impedance at the first interface, $Z_{in}^{(1)}$, is equal to $Z_1$. The input impedance of each subsequent layer is expressed as:

$$Z_{in}^{(n)} = \frac{Z_{in}^{(n-1)} - iZ_n\tan(\varphi)}{Z_n - iZ_{in}^{(n-1)}\tan(\varphi)} \quad (2)$$

The plot in Fig. 2 depicts the transmission coefficient in accordance with varying the thickness of $\text{Al}_2\text{O}_3$ in a polydimethylsiloxane (PDMS) medium. Although the acoustic impedance between $\text{Al}_2\text{O}_3$ and PDMS is greatly mismatched, the plot shows that with an adequately thin layer, ultrasound can be transmitted through the $\text{Al}_2\text{O}_3$ instead of being reflected back at the interface. While this is illustrative of the sharp drop off in transmission with the increase in $\text{Al}_2\text{O}_3$ layer thickness, deposition of hard, thin film layers on PDMS is impractical. In the experiments, $\text{Al}_2\text{O}_3$ was deposited onto plastic material, polyimide and polycarbonate, which are compatible with the deposition process as well as suitable for use as a fingerprint sensor cover layer. The analytical model was extended to account for the additional discrete layers which contribute to the total input acoustic impedance at the first layer interface encountered by the ultrasonic pressure signal.

**C. Experimental Setup**

To study the effects on acoustic transmission and reflection of a thin film of anti-scratch material, experiments were carried out to compare the transmission and reflection of ultrasound with plastic cover material. Ultrasound pressure waves were generated by an array of PMUTs driven by fully integrated CMOS circuitry. Fingerprint imaging using this system was demonstrated previously in [4]. The integrated circuitry en-

![Fig. 2. Theoretical plot of the acoustic transmission coefficient at the first interface of PDMS and $\text{Al}_2\text{O}_3$.](image)

![Fig. 3. Layer stack-up for the measurement of 508 µm polycarbonate](image)
ables each PMUT to send and receive ultrasonic pressure. This allows for pulse echo operation to measure the pressure reflection from the medium interfaces.

Two plastics were selected for heat resistance and compatibility with the deposition process: 25 μm thin polyimide adhesive tape (Nitto Denko), and two thicknesses (254 μm and 508 μm) of polycarbonate (McMaster-Carr). Nominal 1 μm and 5 μm $\text{Al}_2\text{O}_3$ thin film were respectively deposited onto the polyimide, and polycarbonate substrates. The configurations measured in the experiments are composed of discrete layers of homogeneous material. The specific layer stack-up for the 508 μm polycarbonate case is depicted in Fig. 3.

1) Transmission Measurement: A 40 μm diameter needle hydrophone probe (Precision Acoustics) is utilized for measurement of pressure transmission. The uncoated and coated polyimide substrates were submerged in FC-70 (3M), a non-conducting fluid, and affixed above the PMUT array. The needle hydrophone is positioned above the array and polyimide to measure the transmitted acoustic pressure.

2) Pulse Echo Reflection Measurement: For the reflection measurements, the PMUT array operates in pulse echo mode, which is also used for the capture of fingerprint images. The voltage signal from the PMUT receiver was fed through a low noise voltage amplifier (Femto) for additional gain to resolve the reflection percentage differences of the measured signals. The solid materials from the layer stack-up shown in Fig. 3 is affixed to a micrometer stage (Newport) which allows for fine control of the sample position. Since acoustic pressure attenuates with increasing distances, the distance of the sample being measured to the PMUT array was carefully controlled. The thickness of PDMS layer is much greater than the sampling time period of the PMUT array so it would not add additional reflection signals to the measurement data.

III. RESULTS

A. Abrasion Resistance of Film

A baseline of abrasion resistance was established by dragging 0.3 mm diameter pencil lead (Mitsubishi) of HB hardness across the surface at a consistent angle and length. This is a standard test of film hardness based on ASTM D3363 [5]. The following micrographs in Fig. 4 show the surface before and after the testing the film and clearing of residual graphite from the pencil lead.

Before performing the hardness test, both sample areas were free of scratches due to abrasion. After the test, a clear hairline scratch can be seen as indicated on the right figure of the (a) uncoated substrate. On the (b) 1 μm $\text{Al}_2\text{O}_3$ coated substrate, no hairline scratch is observed. Slight indentation has been indicated in the figure, which is likely due to the softness of the polyimide substrate and not abrasion damage of the coating.

B. Transmission and Reflection

1) Transmission Measurement: As described in the Experimental Setup, transmitted pressure was measured with a needle hydrophone probe. The resulting transmitted pressure measurements of the 1 μm $\text{Al}_2\text{O}_3$ coated and bare polyimide were indistinguishable. This indicates that the transmission of pressure through the thin layer is approaching 100% as illustrated in the theoretical plot shown in Fig. 2. Near acoustic transparency can therefore be achieved with extremely thin layers of materials even if they have high acoustic impedance mismatch.

![Fig. 4. Before and after scratch test of (a) uncoated polyimide and (b) polyimide coated with 1 μm $\text{Al}_2\text{O}_3$.](image)

![Fig. 5. The echo from the coating (a) is greater than initial reflection from bare polycarbonate. The FC-70/air interface echo is provided as a reference for 100% reflection.](image)
(MATLAB) filtering. The initial reflection of the coated polycarbonate originates from the FC-70/Al<sub>2</sub>O<sub>3</sub> interface while the initial reflection of the bare polycarbonate originates from the FC-70/polycarbonate interface. The percentage increase in reflection relative to the uncoated substrate is measured, and matches well with theory and simulations. Furthermore, when taking the echo measurement from air as full reflection (coefficient of reflection=1), the resulting coefficient of reflection for the polycarbonate stack-up matches the values predicted by Equation 1.

C. Comparison to Theory and Simulation

A summary of experimental results along with theoretical calculation and simulated values is found in the following table. The experimental value for the 1 µm Al<sub>2</sub>O<sub>3</sub> is marked N/A due to experimental limitations and as a result, those measurement results were indistinguishable from the uncoated substrate. The results from experiment follow the theory and simulation values well.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Thickness</th>
<th>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</th>
<th>Theory</th>
<th>FEM</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>polyimide</td>
<td>25 µm</td>
<td>1 µm</td>
<td>5%</td>
<td>–</td>
<td>N/A</td>
</tr>
<tr>
<td>polycarbonate</td>
<td>254 µm</td>
<td>5 µm</td>
<td>23%</td>
<td>35%</td>
<td>32%</td>
</tr>
<tr>
<td>polycarbonate</td>
<td>508 µm</td>
<td>5 µm</td>
<td>22%</td>
<td>24%</td>
<td>20%</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

The theory of ultrasound transmission and reflection is presented as a systematic analysis of acoustic impedance. This analysis method can be adapted for use with various sensor protection configurations. Hardness testing of the 1 µm Al<sub>2</sub>O<sub>3</sub> shows the film coating retains the scratch resistant properties even when it is very thin. Experimental measurements of ultrasound reflection, varying the substrate thickness, yielded results that match well with values obtained from both analytical solution and simulation. The results from measurement of transmitted pressure indicate that extremely thin layers of material with large impedance mismatch, such as 1 µm Al<sub>2</sub>O<sub>3</sub>, follows theory and is nearly acoustically transparent.

ACKNOWLEDGMENT

The authors would like to thank Hionix Inc. for thin film deposition.

REFERENCES