

Lamb Wave Ultrasonic Stylus

0.1 Motivation

Stylus as an input tool is used with touchscreen-enabled devices, such as Tablet PCs, to accurately navigate interface elements, send messages, etc. They are, by today's standard, inseparable elements of any touch technology. The purpose of this chapter is to introduce novel ultrasound stylus sensors with a wide dynamic range, low hardware complexity and manufacturing cost, and high resolution. The main and desired feature of a stylus is quite different from a smooth touch contact such as a human finger. Thus, almost all mainstream touch technologies have an accompanying stylus design with possibly a different interfacing mechanism.

Depending on the underlying touch technology, different mechanisms can be used to navigate the stylus position over the screen. The mainstream technologies on the market are (1) Capacitive, (2) Electro-Magnetic Resonance Technology (e.g., Wacom Digitizer), (3) Bluetooth, and (4) Acoustic systems [?]. Stylus devices have diverse functionalities from simple tasks such as tapping icons to sophisticated ones such as artistic drawing and gaming. Devices with a higher performance generally require a higher hardware complexity, higher power consumption, and higher manufacturing cost.

A capacitive stylus pen is one of the most inexpensive one on the market. It, however, does not have pressure sensitivity, i.e., it cannot sense how hard the user is pressing on it. Many desired functionalities require a pressure-sensitive stylus [?].

Higher performance stylus technologies are significantly more expensive, e.g., Wacom digitizers [?] are specialized hardware and only found on higher-end devices as

they make the device more expensive to manufacture. They also require application support; applications must be coded to detect this information.

The proposed Lamb wave touchscreen in this dissertation essentially lays out a suitable hardware for high performance Lamb wave stylus designs. This chapter presents three different mechanisms using fundamental physical concepts such as the Hertzian contact mechanics, photoacoustic, and thermoacoustic effects. The designs are conceptually motivated and demonstrated through a set of supporting measurements as the proof of concept. The actual prototyping is left, however, for the future works.

It should be highlighted that the mechanism of the Lamb wave touchscreen works equally well for any sound absorbing or reflecting object, such as a stylus pen with a sound absorbing or reflecting tip. This, however, may not have a desirable performance as the tip should be in the order of a wavelength; and, this, for the frequency range of interest could be large (in the order of a few millimeters). A desired stylus performance should achieve a sub millimeter contact area, and this implies a sub-wavelength resolution. This fact in essence motivates Lamb wave stylus designs using the named mechanisms, whereby a sub-wavelength resolution can be obtained providing high performance ultrasound stylus devices. They, furthermore, offer a simple hardware design, consequently leading to a lower manufacturing cost compared to the existing high performance technologies.

The fundamental mechanism revolves around generating A0 Lamb waves, and to some extent, S0 waves (as opposed to perturbing the field in the touch screen design), and measuring the field at the transducers mounted on or at the perimeter of the screen. The localization step is much simpler compared to the touchscreen case since it leads to an inverse source problem, which is by nature linear and only detecting the first arrival times suffices for a successful localization. The amplitude of the arrivals can be further utilized to quantify the dynamic range of the device, a desirable feature in high performance tasks such as artistic drawing.

0.2 Generation of ultrasonic waves

0.2.1 Hertzian contact

When two solid bodies come in contact with each other, they experience mutual deformation exerted by one another. Contact mechanics has had a long history of modeling development since Hertz [?]. The underlying physical phenomena may vary under different conditions such as viscoelastic, thermal, adhesive, and dynamic properties of the contact condition. Of the simplest types is the Hertzian contact, where two elastic bodies contact each other over a nearly flat contact region [?]. The Hertzian contact model assumes: The strains are small and within the elastic limit. The surfaces are continuous and non-conforming (implying that the area of contact is much smaller than the characteristic dimensions of the contacting bodies). Each body can be considered as an elastic half-space. The surfaces are frictionless. This type of contact is non-adhesive and does not result in permanent deformation, and thus, can be used for ultrasonic energy transmission without any coupling medium. Since the ultrasonic energy is coupled through the contact, the contact size determines the aperture size of the source (or receiver). For two spherical isotropic solids with the radii R_1 and R_2 , the contact has a circular shape with the radius a (see Figure 1), which can be calculated as [?]

$$a = \left(FD \frac{R_1 R_2}{R_1 + R_2} \right)^{1/3}, \quad D = \frac{3}{4} \left(\frac{1 - \nu_1^2}{E_1^2} + \frac{1 - \nu_2^2}{E_2^2} \right), \quad (1)$$

where E_1 and E_2 are the Young's moduli, and ν_1 and ν_2 are the Poisson ratios of the contacting bodies. F is the applied static force. In the case of a glass rod tapered off to have a tip radius of $100 \mu\text{m}$ in contact with a flat glass plate, a contact force of only about 5 N suffices to create a $25 \mu\text{m}$ contact radius. This mechanism has been used previously for in-situ temperature monitoring of wafers in semiconductor processing [?], and a similar mechanism can be applied to generate ultrasonic waves as a stylus.

This stylus system consists of a small piezoelectric transducer attached to a rod (e.g., a quartz pen) with a suitable mechanical impedance ratio to the transducer at

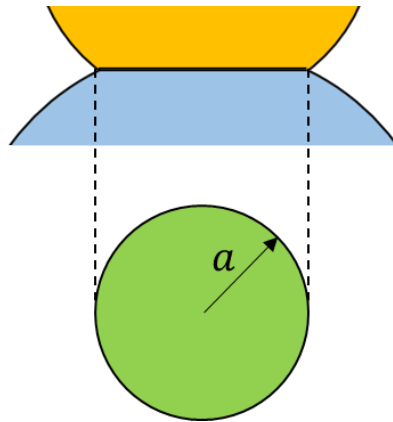


Figure 1: Geometry of a Hertzian contact.

one end. The rod at the other end is tapered off to provide a sub-wavelength Hertzian contact with the screen (see Figure 2). The transducer is pulsed repeatedly to create a propagating wave field inside the rod. The rod acts as a waveguide that directs the waves toward the pin, at which the waves are then coupled into the screen. The waves are focused at the pin, providing a high resolution contact point with the screen. The transducer design is the same as the one discussed in chapter ??, with a frequency range at around a MHz, resulting in wavelengths in the range of 2-4 mm inside the rod. The merit of the Hertzian contact is that the transmitted wave into the screen is sub-wavelength (around $25 \mu\text{m}$), providing a very high resolution that could have not been achieved otherwise. Due to the nature of the direction of the transmitted waves (pressure) and the frequency of operation, the dominant mode excited in the screen is the A0 one.

0.2.2 Thermoacoustic

This design is motivated and governed by a physical process called the thermoacoustic effect; a rapid modulation of the temperature (a fraction of a degree centigrade), at the contact with or in a close proximity of a solid object such as a screen, leads to a rapid thermoelastic expansion and contraction of the neighboring points, which in turn results in propagation of sound waves [?].

The proposed system consists of a thermoelectric material, whose temperature is

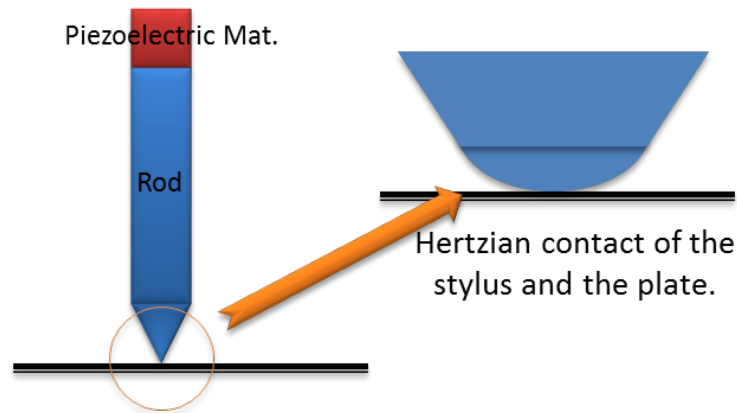


Figure 2: Hertzian contact Lamb wave stylus.

modulated by a fraction of a degree upon a repetitive voltage pulse. The heating can be generated using either the thermoelectric effect [?] or the Joule heating [?]. The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa. A thermoelectric device creates voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference. There exist three major thermoelectric effects: the Seebeck, Peltier, and Thomson effects [?]. Joule heating is the heating generated whenever a current is passed through a resistive material, and is not generally termed as a thermoelectric effect [?]. The thermoelectric effects are thermodynamically reversible whereas Joule heating is not.

For the stylus design, the thermoelectric material is mounted on a pen made of a non-thermally conductive material (see Figure 3a), such as quartz. It can operate in contact with or in a close proximity of the screen (in the order of the thermal convection length of air). Since the thermoelastic strain acts as a volumetric source, it possibly generates both symmetric and asymmetric waves.

0.2.3 Photoacoustic

Optical energy, when modulated and upon targeting at a point on a solid or fluid substrate, can create a local modulation of temperature (a fraction of a degree centigrade). This further leads to creation and propagation of ultrasonic waves. This

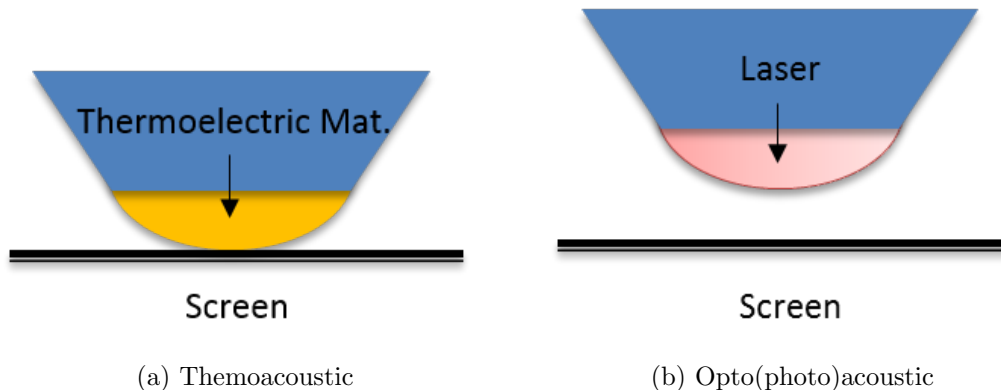


Figure 3: Structure of the thermoacoustic and opto(photo)acoustic stylus devices.

process is known as the opto(photo)acoustic effect; optical energy can be partially absorbed in a solid or fluid, which is then turned into heat (and thus temperature) by molecular vibrational modes [?]. Hence, modulating the optical energy results in the modulation of the temperature at the point of absorption, which in turn creates ultrasonic waves by the thermoacoustic mechanism. This motivates a stylus design, where a small laser device such as a laser diode at the tip of a stylus pen is pulsed repeatedly and targeted at a point on the screen (see Figure 3b). This system can operate in both contact and remote modes. The generated heat is directly proportional to the absorption of the optical energy in the target medium, which itself is a function the optical wavelength. The glass screen is very much transparent in all visible wavelengths (see Figure 4), however, with some sweet spots with less transparency that can be utilized. Nonetheless, the preliminary results prove (as presented below) that even around the visible regions (the wavelengths at around 532 nm, the green light), where the glass is over 90% transparent, the proposed mechanism gives a measurable photoacoustic response in a glass screen.

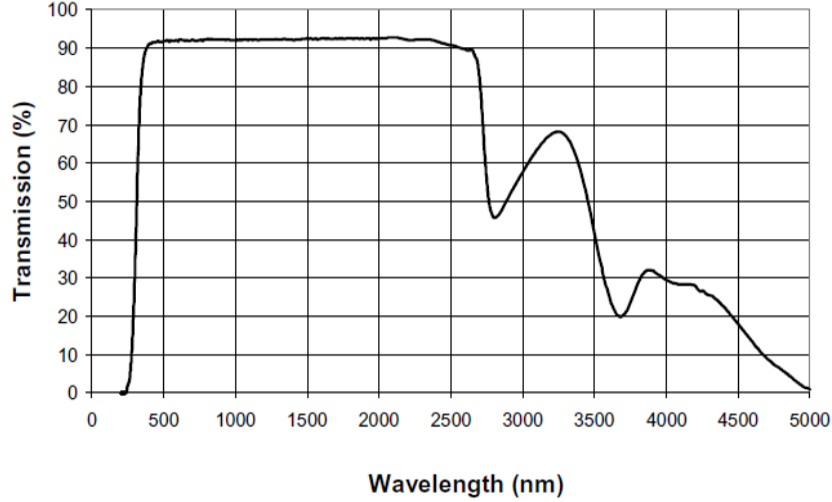


Figure 4: Optical transmission of glass.

0.3 Sensing and localization algorithm

The hardware of the Lamb wave touchscreen can be utilized to sense the wave field generated by the stylus device. The location of the stylus can be equally well estimated by means of the learning method, i.e., by tapping the screen a priori by the stylus at different locations. This approach, however, is unnecessarily complicated for the stylus localization since it is a single object and acts as a source as opposed to perturbing the field. A more practical and efficient approach is the triangulation, where the position of the stylus is inferred based upon the arrival time of the received waves.

Let $\mathbf{d}_r(t)$, $t \in [0, T_r]$, be the measured signal at the r th receiver and T_r be the time it takes for waves from the farthest point over the screen to reach out to the receiver. The location can now be estimated by the delay-sum method [?]. For this the screen should be numerically discretized using a search grid. Let x_s, y_s be the coordinates of the search grid and c_o be the effective (group) arrival speed. Then, the value of the localization map \mathcal{J} at each search point can be estimated as

$$\mathcal{J}(x_s, y_s) = \left| \sum_{r,s} d(t - t_o - \tau_{r,s}) \right|, \quad (2)$$

where $\tau_{r,s}$ is the arrival time between the receiver and the search point, i.e.,

$$\tau_{r,s} = \frac{\sqrt{(x_s - x_r)^2 + (y_s - y_r)^2}}{c_o}. \quad (3)$$

0.4 Experimental results

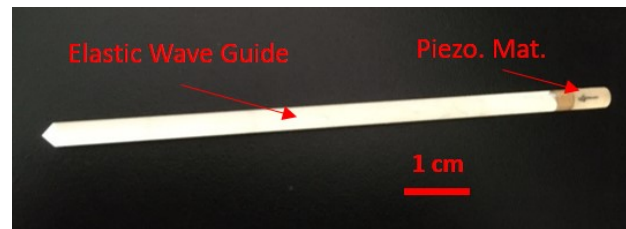
For the proof of concept, several tests are presented below. Figure 5a shows a Hertzian contact transducer designed and fabricated in the Khuri-Yakub lab [?] for in-situ temperature monitoring of wafers in semiconductor processing. It consists of a ceramic rod with a cylindrical PZT-5H transducer bonded to one end, with a center frequency at around 800 kHz. The size of tip is about 25 μm . This prototype was placed in contact with the touchscreen prototype to test the concept of the Hertzian contact stylus. The experimental setup is shown in Figure 5b. The measured waveform at one of the transducers (indicated Ch 1 in Figure 5b) is presented in Figure 6a. The localized stylus using equation 2 is presented in 6b.

In order to verify the thermoacoustic mechanism a short piece of a heating wire was wrapped around the graphite tip of a pen and connected to a function generator as shown in Figure 7a. It was then placed at around 9 cm from a transducer on a small screen prototype. Once the heating element was excited by a voltage pulser, the generated mechanical waves were detected at the sensor (see Figure 7b).

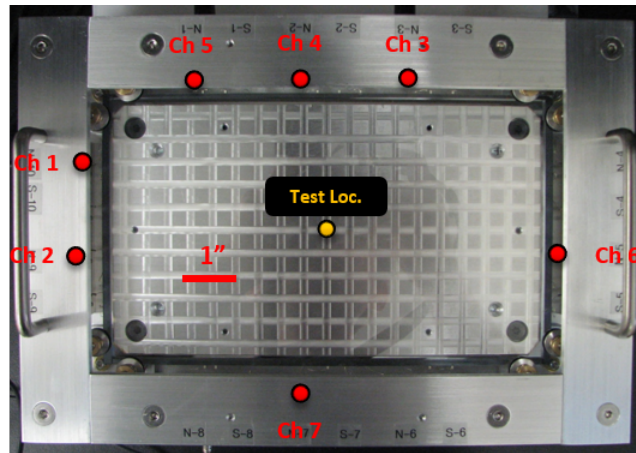
In order to verify the photoacoustic stylus concept, an in-lab laser equipment with the properties outlined in Table 1 was utilized. Figure 8a shows a screen with an ultrasonic sensor at one end and a laser beam targeted remotely at a spot on the plate. Once the laser was pulsed, the generated ultrasonic waves were detected (see figure 8b) at the sensor at about 5 cm away from the source.

Table 1: Properties of the in-lab laser device.

Power	Wavelength	Spot diameter	Q-Switch delay	Pulse width
5 mJ	532 nm	10 mm	400 μsec	10 nsec



(a)



(b)

Figure 5: (a) Pin transducer for in-situ silicon wafer temperature monitoring [?] as a candidate for the Hertzian contact stylus prototype. (b) Measured waves at the sensor Ch 1 generated by the Hertzian contact mechanism.

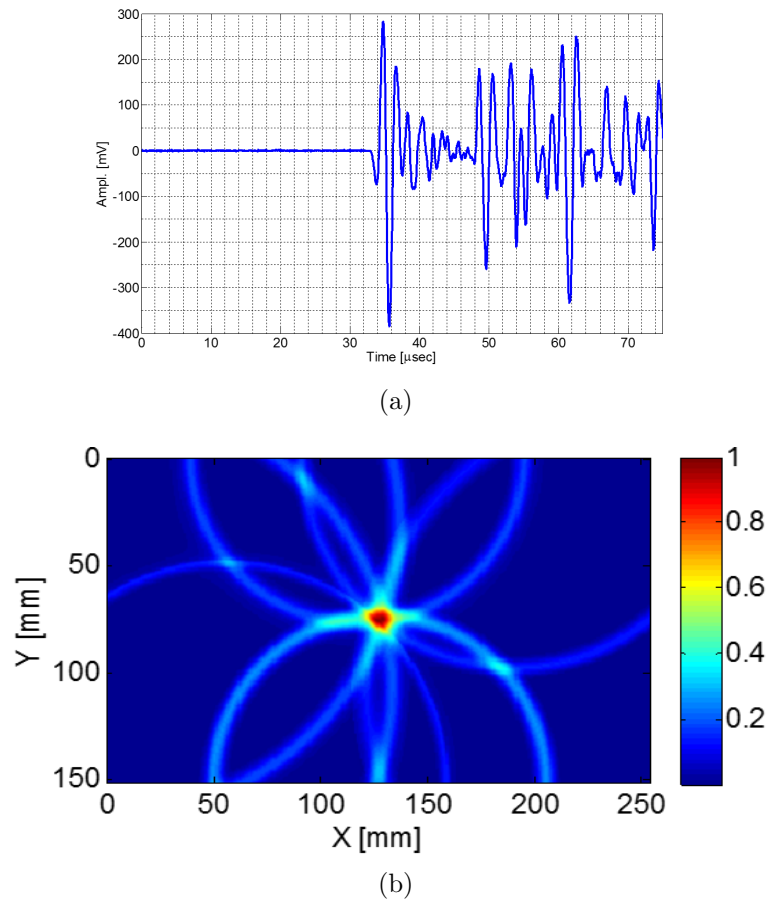
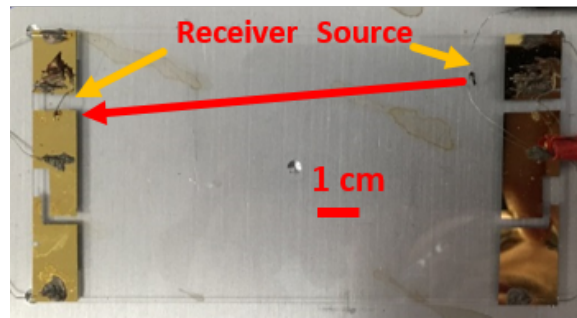
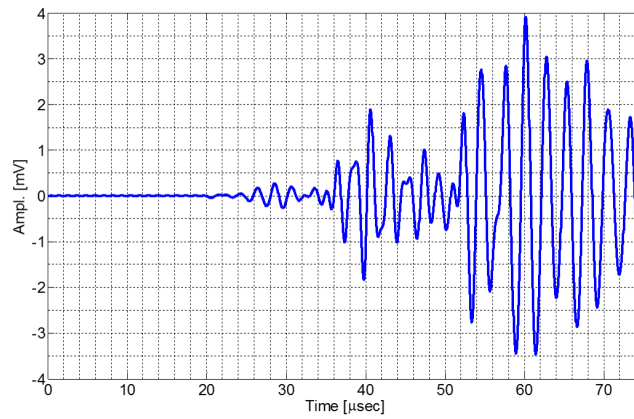


Figure 6: (a) Result of the localization algorithm, where the red spot shows the located stylus. (b) Localized stylus position using Equation 2.

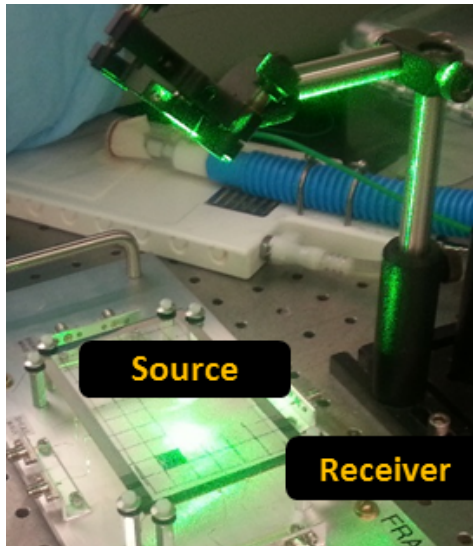


(a)

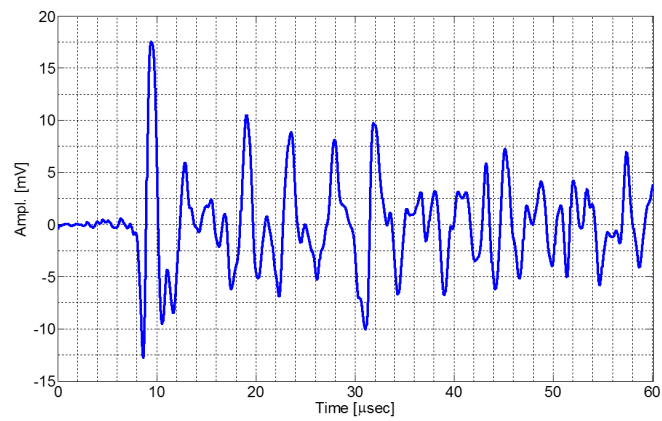


(b)

Figure 7: (a) A screen with an ultrasonic sensor on the left and a heating element as the stylus on the right. (b) Measured thermoacoustic waves at the sensor.



(a)



(b)

Figure 8: (a) A screen with an ultrasonic sensor and a laser beam targeted remotely at a spot on the plate. (b) Measured photoacoustic waves at the sensor.