Using Surface Acoustic Wave Devices for Self-powered Sensing & Interaction

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Abstract
In this paper, we introduce surface acoustic wave (SAW) devices for self-powered sensing and interaction. We report on the general working principles of SAW devices, and their capability to be used as passive sensors and to operate wirelessly. We also present existing methods to manufacture SAW devices. We then provide the results of our early experiments using SAW devices for a novel sensing application and we introduce a new approach for low-cost fabrication of custom SAW devices. Finally, we present future directions for this work and its potential application in ubiquitous computing and HCI.

Author Keywords
Printed sensors, sensing, fabrication, self-powered sensors

CSS Concepts
• Hardware~Emerging technologies~Circuit substrates~Flexible and printable circuits • Human-centered computing~Ubiquitous and mobile computing~Ubiquitous and mobile computing theory, concepts and paradigms~Ubiquitous computing

Introduction

Surface acoustic wave (SAW) technology has been used widely in many industries including aerospace, telecommunication and automotive [1], [5], [6]. The most common use is via a class of electronic components known as SAW filters, which are common in radio frequency (RF) circuits. SAW devices have also been used to measure pressure, humidity, temperature and to detect the presence of certain chemicals.

SAW devices are relatively simple in their composition and due to wide adoption of SAW filters in the mobile phone industry the cost of the underlying materials has dropped in the past three decades. A wafer of SAW material that cost US$1000 in the 1990s is available today for close to US$50. At the same time, the patterning process necessary to convert this material into working SAW devices has become cheaper due to the commoditization of high volume photolithographic processing.

However, the cost and difficulty of fabricating custom SAW devices for research and prototyping has remained high because the established processes are geared towards high volume production. In particular, there are significant up-front costs associated with the machinery, clean environments and photolithographic tooling needed for patterning.

Our aim is to leverage SAW devices for new low power sensing applications that will in turn unlock new and sustainable interactive applications and scenarios. In the rest of this paper we give a more detailed background on SAW devices, describe our initial explorations with the technology, and present some more specific ideas of how we plan to develop our research.

The principle of SAW device operation

SAW devices are primarily composed of a single piece of piezoelectric material, also known as the SAW substrate. Lithium niobate ($LiNbO_3$) is a common substrate material; during production lithium niobate crystals are grown and then cut into thin circular wafers. A single wafer of crystal is used to make many SAW devices by repeating a pattern of conductive traces on top. The exact configuration of traces in this pattern will determine the SAW device characteristics. Finally, the wafer is cut into individual SAW devices and each is packaged to make it robust and suitable for integration in an electronic device. Note that unlike ICs, SAW devices consist of no active electronic components; they are purely passive.

The typical structure of a SAW device is presented in Figure 1(a) below. An RF signal is injected into the device whereupon it interacts with the patterned transducer (or IDT) and generates an acoustic wave due to the piezoelectric effect. This wave now propagates across the surface of the substrate (hence the naming of SAW, for surface acoustic wave). When the wave passes across the reflector, the piezoelectric effect again comes into play resulting in a fraction of the acoustic wave propagating back towards the transducer where it is converted back to a RF signal due to the converse piezoelectric effect. If multiple reflectors are patterned on the substrate there will be multiple reflections, and these combine to produce a return signal that is shifted in frequency, phase and/or amplitude compared to the original incoming signal.

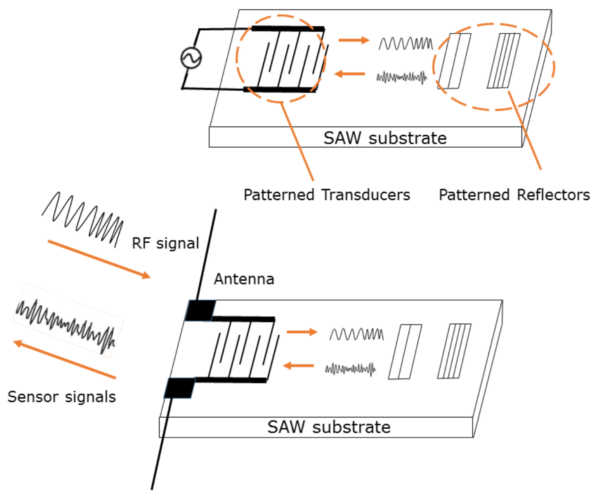

Figure 1: (a, top) The typical structure of a SAW device, based on an interdigitated transducer (IDT) and similarly structured reflectors patterned on top of the SAW crystal substrate. (b, bottom) A SAW device connected to an antenna: an RF signal is transmitted to SAW device wirelessly and ultimately the return signal is reflected back.

The transducer and reflector(s) consist of a simple inter-digitated pattern of conductors, as shown in Figure 1. The central frequency (f_0) at which the SAW device operates is controlled by the width and separation of the conductive patterning according to:

$$f_0 = Vr/4d$$

where Vr is acoustic wave velocity of the given crystal and substrate, d is the width of the patterned electrode traces.

SAW sensors and SAW RFID

A characteristic of SAW devices is that the operating environment can affect the propagation of the surface acoustic wave. For devices like filters, the SAW substrate must be carefully packaged to minimize these environmental effects. However for SAW sensors, this effect is used as the basis for sensing parameters such as pressure, humidity, temperature or the presence of certain chemicals [2]. Additional uses of SAW devices include tactile [10] & olfactory displays [3]. Note that some SAW sensors feature a second IDT to read out the modified wave instead of using reflectors to send it back to the first IDT.

SAW devices have also been used as the basis of passive radio frequency identification (RFID) tags [9]. In this configuration, each SAW RFID tag is made from a substrate that has a unique pattern of SAW reflectors. The SAW transceiver is connected directly to an RFID antenna as depicted in Figure 1(b). The RF signal is generated remotely by a specially designed RFID reader, transmitted wirelessly to the SAW device, where it is picked up by the antenna. The waveform passes along the surface of the SAW device and the unique combination of reflectors results in a reflected RF waveform that uniquely identifies the device. This waveform is reflected back out through the antenna and can be detected remotely by the RFID reader.

New methods for fabricating SAW devices

As noted earlier, SAW devices are typically fabricated in industrial settings using photolithography and clean room techniques. This allows manufacturers to fabricate transducers and reflectors with submicron resolution and have these devices operate in GHz frequency range, ideal for modern RF telecommunication circuits.

While this works well for the mass production of SAW filters, the cost and difficulty associated with photolithography makes it hard to prototype SAW devices. This means that customization of device operating frequency or experimentation with novel transducer patterns is prohibitively expensive.

However, new conductive printing technologies open up the possibility of fabricating custom SAW devices more easily. For example, researchers have recently looked at manufacturing low-cost SAW devices using aerosol jet printing (AJP) [8]. While such printers are potentially more accessible, the patterning resolution doesn't match that of photolithography, impacting maximum device operating frequency. For instance, Morales-Rodriguez et al. [7] printed SAW devices with a 20µm electrode finger size and a 20µm gap, resulting in operation at ~44MHz.

Initial SAW sensing explorations and results

To understand the operating principles of SAW technology, we have started characterizing different devices.

We started by using a custom-made SAW device with electrodes that are 5µm wide and separated by a 5µm gap. To achieve these dimensions we leveraged a traditional photolithography process where the lithium niobate crystal is entirely sputter-coated with aluminium, the required patterning is applied with contact lithography, and the excess aluminium is etched away. Figure 2 shows a photo of our lithium niobate wafer patterned with eight SAW devices. Each device uses the 'two IDT' architecture (i.e. no reflectors). The resulting SAW device has an expected central frequency of ~174 MHz, verified in Figure 3.

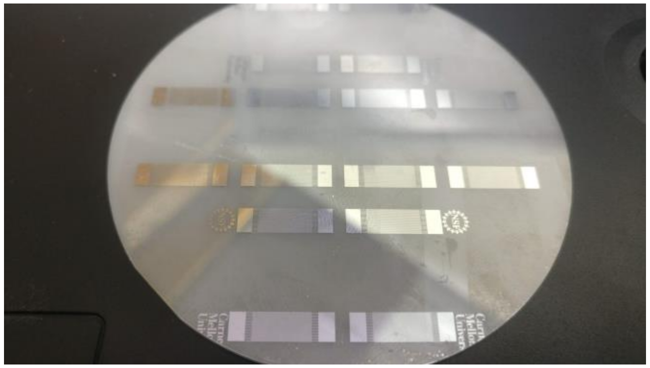

Figure 2: Our custom-made SAW devices on a lithium niobate wafer. We patterned 8 devices on a single wafer using traditional photolithography.

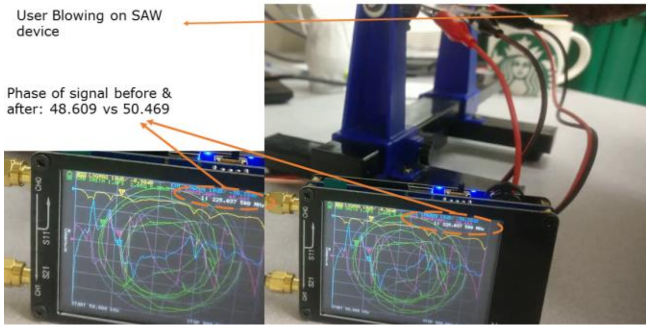

Figure 3: When a user blows on the SAW device our vector network analyser shows a distinct phase change of ~2°.

Our first evaluation of SAW sensing is the detection of blowing on the SAW device. We set up the SAW sensor

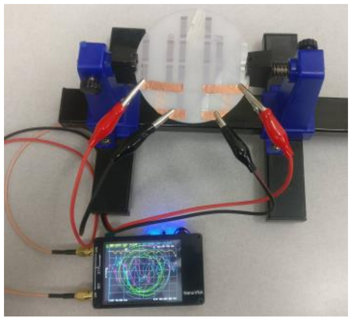

Figure 4: SAW IDTs are connected to input and output channels of a low cost vector network analyzer.

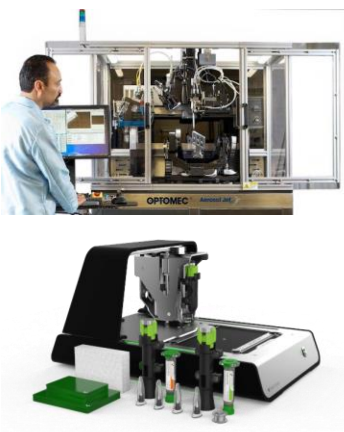

Figure 5: Non-clean room technologies for patterning SAW devices include (a, top) an Optomec aerosol jet printer and (b, bottom) a Voltera silver ink printer.

by coupling a pair of SAW IDTs to a vector network analyser (Figures 3 and 4). We monitored the phase changes in output signal channel. We noticed a distinct phase change of nearly 2° when a user was blowing over the surface, as seen in Figure 3. Before blowing the phase of the signal was at 48.6° and during blowing it was 50.5°. Subsequently the signal returned to 48.3°.

Although we have started our exploration using a sputter-coated electrode pattern, we would like to move to a more accessible patterning process, like those shown in Figure 5. However, AJP printers are also expensive (~US$200k) so we would like to use low-cost direct ink writing (DIW) printers like the Voltera V-One [11] (~US$4k).

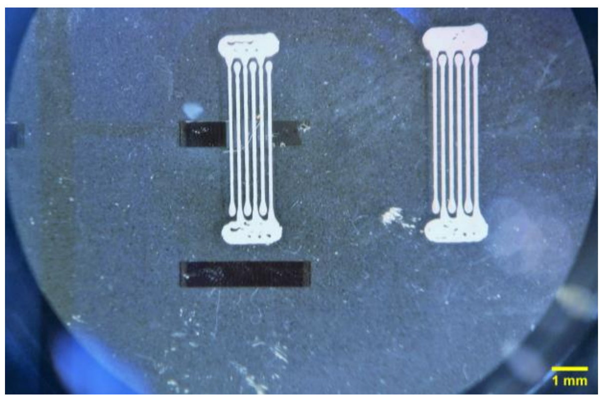

Figure 6: A Voltera DIW printed SAW device. The traces that make up the IDTs are 100μm wide.

To this end, we have also started to test-print SAW devices with a Voltera DIW printer. DIW tends to result in lower resolution than AJP, so we don't expect to achieve 44MHz operation as previously reported [7]. However, we do hope to support ~10MHz operation. Our first results are shown in Figure 6. As can be seen, the printed electrodes are 100μm wide and the gap is 100μm. A key thing to note also is that ends of the electrodes bulged out due to droplet size in the ink printing. In the future, we intend to improve on the printing technique to create uniform rectangular electrodes.

Future directions

Going forward, we hope to combine our explorations in SAW 'blow' sensing (using a traditionally patterned substrate) with our evaluation of DIW-printed SAW patterns. Since the low-cost DIW-printed devices should lend themselves to operation in the MHz range, we also hope to combine them with a suitable antenna to support entirely passive, wireless sensing. We believe that recent advances in the sophistication of software defined radios (SDRs) will enable us to build the wireless reader necessary to receive and decode the reflected RF signal. In particular, we hope to leverage low cost SDR solutions such as the RTL-SDR and HackRF one.

If the above integration steps are successful, we envision a range of sensing possibilities, including:

- Vibration sensing: A small mass suspended on a SAW substrate will interact with the surface acoustic wave. Any external vibration of the mass will perturb the acoustic wave. This could ultimately be used for passive detection of wide variety of gestures such as knocking, tapping, and perhaps even activity sensing.

- Liquid presence detection and identification: Various liquids on the surface of the SAW substrates are known to change the phase of the acoustic wave [4]. This can be used to detect and/or monitor liquid levels and types, perhaps distinguishing between types of liquids like orange juice, coffee, milk, etc.
- Temperature sensing: Changes in temperature cause the substrate to expand or contract which then influences its frequency response.
- Humidity detection: If the substrate is coated with thin chemical film it can attract water vapor to the surface of the substrate. This influences the wave velocity and again alters the SAW device's frequency response.

Conclusion

In this paper we introduced SAW devices: how they operate, what they can be used for and how they are made. We then reported on our initial experiments with SAW technology, in particular demonstrating the possibility of new types of SAW sensing and a new approach to 'printing' custom SAW devices that we believe has the potential to lower the barrier for prototyping and ultimately low volume production.

We believe that SAW devices, in combination with low-cost software defined radio solutions, have the potential to enable a new class of cheap, simple and self-powered wireless sensing that will unlock new interactive experiences and applications. We hope that by sharing our ideas and this early work we can solicit input and feedback from the research community that accelerates our future research and ultimately the practical application of wireless SAW sensors that support sustainable interaction.

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