Heating of Rayleigh Surface Acoustic Wave Devices in 128°YX $LiNbO_3$ and ST X Quartz Substrates

Shuangming Li, Jacob Desrosiers, Venkat R. Bhethanabotla
Department of Chemical & Biomedical Engineering
University of South Florida
Tampa, USA
bhethana@usf.edu

***Abstract*—Heating of surface acoustic wave (SAW) devices can be utilized for micro-heating and in microreactor applications, but is a disadvantage in biosensing. In this contribution, we fabricate SAW devices in 128° YX $LiNbO_3$ and ST X quartz substrates with same physical dimensions, having center frequencies approximately of 96 MHz and 78 MHz, respectively to study heating at several power levels. We demonstrate droplet heating is caused by acoustic wave streaming resulting from the coupling between fluid and solid. A 10 µm water droplet on a 128° YX $LiNbO_3$ device can be heated up by 3.3 °C with 15 dbm power level, whereas, the ST X quartz device is only heated up by 0.7 °C. Our work illustrates that the 128° YX $LiNbO_3$ substrate shows great potential for liquid heating applications. The ST quartz substrate is better suited for removal of non-specifically bound (NSB) proteins in biosensing applications, especially if shear horizontal SAWs propagating in the orthogonal direction are utilized for biosensing.**

Keywords—surface acoustic wave; Rayleigh wave; heating effect; piezocrystal

I. Introduction

Surface acoustic wave (SAW) devices have been extensively used in many areas such as electro-communication [1], sensing [2] and actuation [3]. Amongst various types of SAWs, Rayleigh wave, which has an elliptical displacement both parallel to the SAW propagation direction and normal to the surface, is a widely used acoustic wave for chemical sensing [4], droplet actuation [5], and particle separation [6]. The heating effect caused by acoustic wave streaming can be a favorable factor under certain circumstances. For example, some biological and chemical reactions for microfluidic analysis can only occur at a higher temperature than room temperature. Kulkarni et al. designed a new modality for chemical synthesis on a drop scale which employs the SAW device chip as the reactor and SAW streaming as the source of energy for heating [7]. However, under other circumstances, the heating effect can bring negative influences. Heating causes temperature change of the device, resulting in sensing and measurement, because of the device temperature coefficient [8]. Too high temperature can also cause the inactivation and denature of biomolecules such as DNAs and proteins, when using SAW devices for biodetection or particle separation applications.

Our previous experimental and numerical studies indicate that the acoustic streaming with appropriate energy can be used effectively to remove nonspecifically bound (NSB) proteins on the surface of biosensors [9-11]. A Rayleigh SAW platform can be used for NSB removal, while any modality, optical, electrochemical or SH-SAW can be used for sensing. NSB removal by acoustic streaming has been shown by us to be superior to traditional chemical removal in the above referenced papers. However, Rayleigh wave streaming can generate heat which leads to a drift of the SAW sensor's detection results [12]. This phenomenon could increase environment noise and reduce detection accuracy.

In this article, we fabricated SAW devices based on two different piezocrystals: 128° rotated Y-cut X-propagating $LiNbO_3$ and ST-cut X-propagating quartz. The heating effects of both materials were measured at known RF energy input levels suitable for NSB removal. Heating of the device with and without a droplet of water in the delay path were studied. Results indicate that SAW streaming can produce significant heating effects at these power levels, however, they are tolerable for biosensing applications in ST-X quartz devices.

II. Materials and Methods

A. Surface Acoustic Wave Devices

SAW devices used in this experiment were fabricated on 4-inch 0.5 mm thickness 128° YX $LiNbO_3$ and ST X quartz single-side polished wafers [13]. The input and output interdigital transducer (IDT) electrodes of each device consisted of 60 finger pairs with an electrode width of 10 µm and wavelength of 40 µm. E-beam evaporation was used to deposit 20 nm/100 nm Ti/Au adhesion and metal layers. The delay line is of 8 mm length and 2 mm width. The patterned wafers were diced into 20 mm×20 mm individual chips.

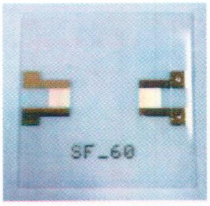

Fig. 1. Image of fabricated SAW device.

This work was financially supported by the National Science Foundation grant number IIP-1640668, which is gratefully acknowledged.

978-1-5090-1012-7/17/$31.00 ©2017 IEEE

B. Measurement System

The measurement setup is shown in Fig. 2. The signal generator (Rohde & Schwarz) was set at the center frequency of the SAW device which was previously measured by the Network Analyzer (Agilent 8753ES). The generated alternating current RF signal was amplified by the RF amplifier (Mini-Circuits) which has a 35 dB gain in the 0.5 MHz – 1000 MHz range. An RF splitter (Mini-Circuits, 0.5~600 MHz) was used to divide the RF power into two channels and load the signal on the two ports of the SAW device. The device temperature was measured by an infrared camera (FLIR T420).

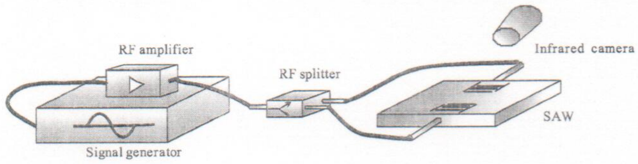

Fig. 2. Schematic diagram of the measurement system.

III. RESULTS AND DISCUSSION

A. Characterization of SAW Devices

The electrical properties of the SAW devices were measured using a network analyzer. The 128° YX $LiNbO_3$ and ST X quartz devices have center frequencies of approximately 96 MHz and 78 MHz, respectively. Insertion loss (IL) at the center frequency indicates the acoustic wave power consumption, which is one of the sources of the heating effect. Fig. 3 shows the S_{21} parameters. It is illustrated that the 128° YX $LiNbO_3$ SAW device has lower insertion loss than ST X quartz, which is due to its high electromechanical coupling coefficient (K^2) [14].

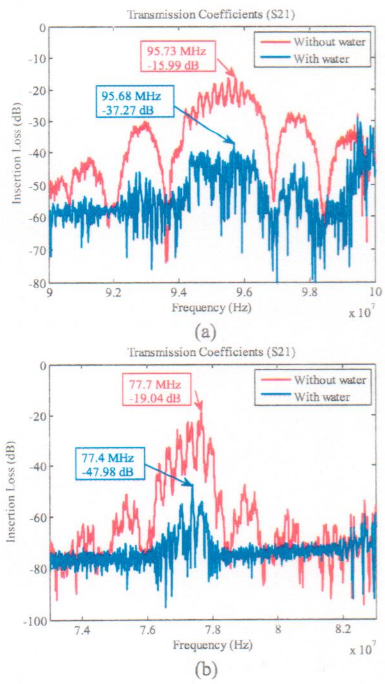

Fig. 3. Frequency characteristic of (a) 128° YX $LiNbO_3$ and (b) ST X quartz SAW device with and without water droplet on the surface.

A deionized water droplet of 10 μL volume was deposited in the delay path of the SAW device, forming an approximately 2 mm diameter water hemisphere. A large drop in insertion loss is seen, a result of the large damping of the Rayleigh wave.

B. Heating without Water Droplet

An infrared camera was used to measure the surface temperature of the SAW devices. The average temperatures on the delay path were recorded. Table I shows the average temperature increase at various RF power levels at the device center frequencies. Heating is significant only for power levels larger than 10 dbm. The ST X quartz device has a slightly higher temperature increase compared to the 128° YX $LiNbO_3$ device.

The principal reason for heating without liquid loading on the surface is the acoustic waves converting to heat from anelastic effects in the substrate. Since the measured S_{21} value (insertion loss) is larger for ST X quartz, the temperature rise is also correspondingly larger, as expected.

TABLE I. TEMPERATURE INCREASE OF SAW DEVICES WITHOUT WATER DROPLET

Power (dbm)		-5	0	5	10	15
Temperature Increase (°C)	128° YX $LiNbO_3$	0	0.1	0.1	0.2	0.4
	ST X quartz	0.2	0.3	0.4	0.8	1.0

C. Heating with a Water Droplet in the Delay Path

To analyze the influence of liquid, heating of a water droplet was measured with a 10 μL deionize water on the surface of SAW device. Table II shows the average temperature increase with the water droplet. It is seen that the droplet temperature rises with increasing RF power.

TABLE II. TEMPERATURE INCREASE OF WATER DROPLET ON SAW DEVICES

Power (dbm)		-5	0	5	10	15
Temperature Increase (°C)	128° YX $LiNbO_3$	0.3	0.4	0.6	1.4	3.3
	ST X quartz	0.1	0.1	0.1	0.4	0.7

These results indicate that the main heating source when used in biosensing applications is from viscous dissipation and not from anelastic effects in the piezoelectric solid. Due to acoustic streaming, the Rayleigh waves are converted to leaky-SAWs and are partially radiated into the liquid as longitudinal waves [12, 15]. This fluid-solid coupling phenomenon leads to the agitation of the liquid, and heating from the associated viscous dissipation. The acoustic streamings induced fluid velocities are responsible for the various forces that cause NSB protein removal in biosensor applications.

It is seen that 128° YX $LiNbO_3$ device can heat the water droplet rapidly from an initial temperature (24.9 °C) up to 28.5 °C at 15 dbm RF power, as shown in Fig 4. However, the ST X quartz device does not have heat as much (0.7 °C) which could be due to its low electromechanical coupling coefficient (0.15 %). We also observed that although having a larger insertion loss (-47.98 dB), the droplet temperature rise is lower than that of the device without water droplet, because of the large heat capacity of water [4.2 kJ/(kg·K)] compared to that of crystalline quartz [0.8 kJ/(kg·K)].

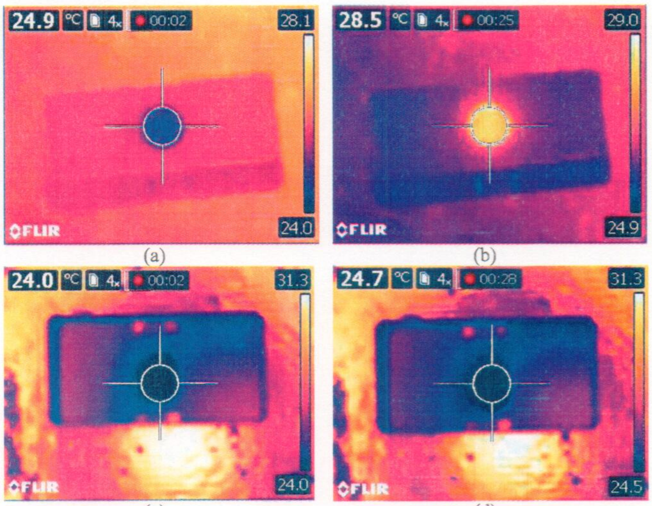

Fig. 4. Infrared images of SAW devices with water droplet on the surface: (a) 128° YX $LiNbO_3$ before RF on; (b) 128° YX $LiNbO_3$ at 15 dbm RF; (c) ST X quartz before RF on; (d) ST X quartz at 15 dbm.

IV. CONCLUSION

In this paper, we experimentally analyzed the heating effect of SAW devices in 128° YX $LiNbO_3$ and ST X quartz. The SAW devices were fabricated and tested with and without a water droplet in their delay paths. The thermal measurements demonstrate that the heating of droplet is principally generated from fluid-solid coupling resulting from acoustic wave streaming. The ST X quartz SAW device heats up less compared to the 128° YX $LiNbO_3$ device. Our results suggest that 128° YX $LiNbO_3$ substrate can be used for droplet heating or for microreactor applications, with much higher temperatures realized at higher power levels. The ST X quartz substratre is better suited for NSB protein removal in biosensing applications.

ACKNOWLEDGMENT

The authors thank NREC at the University of South Florida for providing cleanroom and metrology facilities.

REFERENCES

[1] C. W. Ruppel, R. Dill, A. Fischerauer *et al.*, "SAW devices for consumer communication applications," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control,* vol. 40, no. 5, pp. 438-452, 1993.

[2] K. Länge, B. E. Rapp, and M. Rapp, "Surface acoustic wave biosensors: a review," *Analytical and bioanalytical chemistry,* vol. 391, no. 5, pp. 1509-1519, 2008.

[3] S. Thalhammer, and A. Wixforth, "Surface acoustic wave actuated Lab-on-Chip system for single cell analysis," *J Biosens Bioelectron,* vol. 4, no. 13, pp. 2, 2013.

[4] H. Wohltjen, "Mechanism of operation and design considerations for surface acoustic wave device vapour sensors," *Sensors and Actuators,* vol. 5, no. 4, pp. 307-325, 1984.

[5] Z. Guttenberg, H. Müller, H. Habermüller *et al.*, "Planar chip device for PCR and hybridization with surface acoustic wave pump," *Lab on a Chip,* vol. 5, no. 3, pp. 308-317, 2005.

[6] J. Shi, H. Huang, Z. Stratton *et al.*, "Continuous particle separation in a microfluidic channel via standing surface acoustic waves (SSAW)," *Lab on a Chip,* vol. 9, no. 23, pp. 3354-3359, 2009.

[7] K. Kulkarni, J. Friend, L. Yeo *et al.*, "Surface acoustic waves as an energy source for drop scale synthetic chemistry," *Lab on a Chip,* vol. 9, no. 6, pp. 754-755, 2009.

[8] K. Hashimoto, and T. Nakamoto, "Stabilization of SAW atomizer for a wearable olfactory display," in Ultrasonics Symposium (IUS), 2015 IEEE, pp. 1-4.

[9] K. J. Suthar, S. K. R. S. Sankaranarayanan, M. Richardson *et al.*, "Comparison of Newtonian and non-Newtonian fluid dynamics on removal efficiency of non-specifically bound proteins in SAW biosensors," in Ultrasonics Symposium (IUS), 2013 IEEE, pp. 1347-1350.

[10] S. Cular, D. W. Branch, V. R. Bhethanabotla *et al.*, "Removal of nonspecifically bound proteins on microarrays using surface acoustic waves," *IEEE Sensors journal,* vol. 8, no. 3, pp. 314-320, 2008.

[11] S. K. R. S. Sankaranarayanan, R. Singh, and V. R. Bhethanabotla, "Acoustic streaming induced elimination of nonspecifically bound proteins from a surface acoustic wave biosensor: Mechanism prediction using fluid-structure interaction models," *Journal of Applied Physics,* vol. 108, no. 10, pp. 104507, 2010.

[12] K. J. Suthar, S. K. R. S. Sankaranarayanan, M. Richardson *et al.*, "Liquid heating can cause denaturation of sensing layer in SAW biosensors," in In SENSORS, 2013 IEEE, pp. 1-4.

[13] S. Li, Y. Wan, Y. Su *et al.*, "Gold nanoparticle-based low limit of detection Love wave biosensor for carcinoembryonic antigens," *Biosensors and Bioelectronics,* vol. 95, pp. 48-54, 2017.

[14] K. Yamanouchi, and H. Furuyashiki, "Low-loss SAW filter using internal reflection types of new single-phase unidirectional transducer," in Ultrasonics SymposiumI, 1984 IEEE, pp. 68-71.

[15] A.-L. Zhang, Y.-Q. Wei, and Q.-J. Han, " A microreactor with surface acoustic wave micro-heating system," *Ferroelectrics,* vol. 432, no. 1, pp. 22-31, 2012.