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TITLE:
Fabrication of Surface Acoustic Wave Devices on Lithium Niobate

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KEYWORDS:
acoustofluidics, surface acoustic waves, lithium niobate, interdigital transducers, lift-off, wet etching

SUMMARY:
Two fabrication techniques for producing interdigital transducers, lift-off and wet etching, are described. Interdigital transducers are widely used to generate surface acoustic waves on piezoelectric materials (e.g., lithium niobite). Both techniques are shown to produce useful 100 MHz-order surface acoustic wave devices.

ABSTRACT:
Manipulation of fluids and particles by acoustic actuation on a small scale has spurred rapid development of lab-on-a-chip applications. Megahertz-order surface acoustic wave (SAW) devices generate enormous accelerations of up to 10^8 m/s^2 on their surface. This is responsible for the effects that have come to define acoustofluidics: acoustic streaming and acoustic radiation forces. These effects have been used for particle, cell, and fluid handling at microscale and even nanoscale levels. In this paper we provide step-by-step descriptions of two major fabrication methods of SAW devices on lithium niobate: lift-off and wet etching. Representative results for the electrode pattern deposited on the substrate as well as the performance of SAW generated on the surface are provided in detail. Advice and troubleshooting for SAW production are covered as well. The aim is to provide the reader with a set of useful protocols for high frequency SAW device fabrication in future microfluidics applications.

INTRODUCTION:
Relying on the well-known inverse piezoelectric effect, where the atomic dipoles create strain corresponding to the application of an electric field, piezoelectric single crystal media such as lithium niobate $LiNbO_3$ (LN) and lithium tantalite $LiTaO_3$ (LT) can be used as electromechanical transducers to generate SAW for microscale applications[1-6]. SAW is capable of producing surface displacements of up to 1 nm at high frequency, making it possible for SAW-actuated acoustofluidics to overcome the obstacles of traditional ultrasonic methods: weak acceleration, relatively long wavelengths, and difficulty in device miniaturization. Thus, the investigation of

fluid and particle manipulation within small devices using SAW and related high frequency ultrasound has grown in recent years[7-10].

The fabrication of SAW-integrated microfluidic devices requires fabrication of the electrodes—the interdigital transducer (IDT)[11] on the piezoelectric substrate—to generate the SAW. These comb-shape fingers create compression and tension in the substrate when connected to an electric field. SAW is generated when this electric field is reversed at the resonance frequency of the SAW in the selected substrate. The fabrication process for SAW devices has been presented in many publications, either using lift-off ultraviolet photolithography alongside a metal sputter or a wet etching process[10]. For the lift-off technique[12-14], a sacrificial layer (photoresist) with an inverse pattern is created on a surface, so that when the target material (metal) is deposited on the whole wafer, it can bond to the substrate in the desired regions, followed by a lift-off step to remove the remaining photoresist. By contrast, in the wet etching process[15-18], the metal is first deposited on the wafer and then photoresist is added and patterned on the metal, serving to protect the desired region from later being etched away by a metal etchant.

In the most commonly used design, the straight IDT, the wavelength of the resonance frequency of the SAW device is defined by the periodicity of the finger pairs, where the finger width and the spacing between fingers are both $\lambda_{\mathrm{SAW}}/4$[19]. In order to balance the electric current transmission efficiency and the mass loading effect on the substrate, the thickness of the metal deposited on the piezoelectric material is optimized to be about 1% of the SAW wavelength[20]. Localized heating from Ohmic losses[21], potentially inducing premature finger failure, can occur if insufficient metal is deposited. On the other hand, an excessively thick metal film can cause a reduction in the resonance frequency of the IDT due to a mass loading effect and can possibly create unintentional acoustic cavities from the IDTs, isolating the acoustic waves they generate from the surrounding substrate. As a result, the photoresist and UV exposure parameters chosen vary in the lift-off technique, dependent principally upon the frequency but also the intended application of the device. Here, we describe in detail the lift-off process to produce a 100 MHz SAW-generating device on a double-sided polished 0.5 mm-thick 128° Y-rotated cut LN wafer, and the wet etching process to produce an identical device. Our approach enables one to consider these devices when investigating a variety of physical problems and biological micro- to nanoscale fluidics applications.

PROTOCOL:

1. SAW device fabrication via the lift-off method

1.1. Perform wafer solvent cleaning in a Class 100 clean room facility by immersing the 4 in. (101.6 mm) LN wafer into acetone, followed by isopropyl alcohol (IPA), and deionized water (DI water) in a sonication bath for 5 min each. Pick up the wafer and blow the surface dry with nitrogen (N_2) to remove the remaining DI water from the wafer.

CAUTION: Perform the acetone and IPA immersions in a fume hood. Avoid inhalation and skin contact with IPA. Avoid skin and eye contact with acetone. Do not swallow.

NOTE: Do not allow any fluid to evaporate upon the wafer. If there is any dust or contamination on the surface, start this step over.

1.2. Place the wafer onto a hotplate at 100 °C to prebake for 3 min.

NOTE: Because of the pyroelectric property of LN, it will generate static charges and associated stress within the wafer during heating and cooling. It is recommended to place the wafer onto a piece of aluminum (Al) foil after removing it from the hot plate to discharge any static charge from the wafer, thus preventing breakage.

1.3. Place the wafer onto a spin coater. Place negative photoresist onto the wafer using a dropper, covering about 75% of the wafer surface area. Program a speed of 500 rpm with an acceleration of 3,000 rpm/s for 5 s and then a speed of 3,500 rpm with an acceleration of 3,000 rpm/s for 40 s, creating ~1.3 µm thickness of the photoresist.

CAUTION: Perform spin coating in a fume hood. Inhalation of photoresist fumes can cause headaches. Avoid inhaling the photoresist.

NOTE: The thickness may vary depending on the condition of the photoresist and the spin coater, even using the same rpm. During spin coating, the photoresist may reach the edges of the wafer and spill over them, coating the back edges of the wafer underneath. This spillage must be removed using a swab doused with acetone. If it is not removed, it will cause the wafer to stick to the hotplate during the soft bake process, and the wafer will be difficult to pick up from the hotplate.

1.4. To soft bake, place the wafer onto a hotplate at 25 °C, ramp the temperature up to 150 °C, hold it at 150 °C for 1 min, turn off the hotplate, and let the wafer cool down to room temperature (RT).

NOTE: Due to the pyroelectric effect mentioned above, if the temperature of the LN wafer is suddenly changed, for example, by directly transferring the LN wafer onto the hotplate or Al foil at 150 °C, the abrupt temperature change will cause thermal shock within the wafer, likely shattering it. The presence of nonuniform metal on the surface, such as electrodes, significantly enhances the risk of wafer shattering due to differential stress. In applications where temperature excursions are necessary during fabrication or use, and the transparency of the LN is not important, consider using black LN (i.e., reduced LN), which is dark brown and translucent and has negligible pyroelectricity.

1.5. Transfer the wafer to the mask aligner for ultraviolet exposure. Expose the photoresist with an energy dose of 400 mJ/cm^2 at 375 nm to the wafer. The energy dose required may vary based on the mask design and the age and condition of the photoresist.

NOTE: The wave propagation direction induced by IDTs should be along the X-propagating

direction in order to effectively generate SAW. In other words, the fingers of the IDT should be perpendicular to the X-axis. Typical LN wafer manufacturers place the primary (larger) wafer flat (i.e., straight edge alongside of wafer) perpendicular to the X-axis, so the IDT fingers should be parallel to this flat. Some manufacturers introduce a second (smaller) wafer flat to help indicate the Y- and Z-axis directions, but this is unimportant for SAW generation. Manufacturers often request specifications for the surface finish of the wafer. If you require a transparent wafer, request double-sided optically polished wafers. However, keep in mind that LN is birefringent, so any object illuminated with standard laboratory light and seen through the material will produce not one but two images. Overcoming this problem is discussed later. Single-side polished LN is a better choice for SAW generation if you do not need to see through the wafer, because spurious acoustic waves are diffused by the rough back surface.

1.6. Place the wafer onto a hotplate at 100 °C for 3 min for a post-exposure bake. Then transfer it onto Al foil to cool down to RT.

1.6.1. The patterns should visible after the post-exposure bake. If not, consider stripping the photoresist and restarting the process over from step 1.1.

1.7. Develop the wafer by placing it in a beaker filled with pure RD6 developer for 15 s. Gently shake the beaker during development. Immerse the wafer into DI water for 1 min, then rinse the wafer under flowing DI water. Finally, dry with N_2 to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Develop the wafer in a fume hood. Avoid breathing in vapors or contacting the developer with eyes and skin.

NOTE: The photolithography is complete at this step. The protocol can be paused here.

1.8. Hard bake the wafer on a hotplate at 100 °C for 3 min. Then transfer it onto Al foil to cool down to RT.

NOTE: This step is to remove any moisture on the wafer, to prevent outgassing during sputtering, which could reduce the quality of the deposited metal film.

1.9. For electrode sputter deposition, place the wafer into a sputter deposition system. Vacuum the chamber to 5 x 10^{-6} mTorr. Use a 2.5 mTorr Argon flow, sputter Cr with a power of 200 W for 5 nm as an adhesion layer, followed by sputtering Al with a power of 300 W for 400 nm to form the conductive electrodes.

NOTE: Deposition time should be calculated from the expected thickness and the deposition rate. Titanium (Ti) can be used instead of chromium, though the removal process is more difficult, because Ti is tougher. Gold (Au) is also commonly deposited as electrodes. However, for higher frequency SAW devices, Al should be used instead to avoid the mass loading effects of the Au IDT fingers, which reduce the local SAW resonance frequency under the IDT, forming an acoustic

cavity from which the SAW can only escape with significant loss.

1.10. For the lift-off process, transfer the wafer into a beaker and immerse in acetone. Sonicate at medium intensity for 5 min. Rinse with DI water and dry the wafer with N_2.

CAUTION: Use acetone in a fume hood. Avoid inhalation and skin or eye contact with acetone. Do not swallow.

NOTE: The protocol can be paused here.

1.11. Use a dicing saw to dice the entire wafer into small pieces of chips as SAW devices for further applications. The process is complete. The protocol can be paused here.

NOTE: With some practice, a diamond-tipped wafer scribe (or even a glass cutter) can be used instead of a saw to dice the LN wafer, though due to the anisotropy of LN it is important to scribe and break the wafer first along scribe lines perpendicular to the X-axis, followed by those lines along the X-axis.

2. SAW device fabrication via the wet etching method

2.1. Perform wafer solvent cleaning in a Class 100 clean room facility by immersing the 4 in. (101.6 mm) LN wafer in acetone, followed by IPA, and DI water in a sonication bath for 5 min each. Pick up the wafer and dry the surface using N_2 to remove the remaining DI water from the wafer.

CAUTION: Use acetone and IPA in a fume hood. Avoid inhalation and skin contact with IPA. Avoid acetone contact with skin and eyes. Do not swallow.

2.2. Place the wafer onto a hotplate at 100 °C for thermal treatment for 3 min. Then transfer it onto Al foil to cool down to RT.

2.3. Place the wafer into a sputter deposition system. Vacuum the chamber to 5 x 10^{-6} mTorr. Use Argon flow at 2.5 mTorr, sputter Cr with a power of 200 W for 5 nm as an adhesion layer, followed by sputtering Au with a power of 300 W for 400 nm to form the conductive electrodes.

NOTE: The protocol can be paused here.

2.4. Place the wafer onto a spin coater. Place positive photoresist onto the wafer using a dropper, covering about 75% of the wafer surface area. Program a speed of 500 rpm with an acceleration of 3,000 rpm/s for 10 s and then a speed of 4,000 rpm with an acceleration of 3,000 rpm/s for 30 s, creating a ~1.2 µm thickness of the photoresist.

CAUTION: Perform spin coating in a fume hood. Inhalation of photoresist fumes can cause headaches.

2.5. To soft bake, place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil to cool down to RT.

2.6. Transfer the wafer to the mask aligner for ultraviolet exposure. Expose the photoresist with an energy dose of 150 mJ/cm^2 at 375 nm to the wafer. The energy dose required may vary based on the mask design and the age and condition of the photoresist.

2.7. Place the wafer into a beaker filled with pure AZ300MIF developer for 30 s. Gently shake the beaker during development. Immerse the wafer into DI water for 1 min, then rinse the wafer under flowing DI water. Finally, dry with N_2 to remove the remaining DI water. Never let any fluid evaporate on the wafer surface.

CAUTION: Avoid contacting AZ300MIF with skin or eyes. Do not swallow.

2.8. Immerse the wafer into a beaker filled with Au etchant for 90 s, gently shaking the beaker. After rinsing the wafer under flowing DI water, dry with N_2 to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Gold etchant can be hazardous for the eyes and skin, and causes respiratory irritation. This step requires more personal protective equipment (PPE), such as safety glasses, black neoprene gloves, apron, etc.

2.9. Immerse the wafer into a beaker filled with Cr etchant for 20 s, gently shaking the beaker. After rinsing the wafer under flowing DI water, dry with N_2 to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Chromium etchant can cause eye, skin, and respiratory irritation. This step also requires more PPE.

2.10. Clean the (sample) wafer, by putting it into acetone, followed by IPA, and DI water in a sonication bath for 5 min each. Pick up the wafer and dry with N_2 over the surface of the wafer to remove the remaining DI water from the wafer.

CAUTION: Use acetone in a fume hood. Avoid inhalation and skin contact acetone with skin and eyes. Do not swallow.

NOTE: This step is to remove undesired photoresist from the wafer. The protocol can be paused here.

2.11. Use a dicing saw to dice the entire wafer into chips as SAW devices for further use. The process is complete. The protocol can be paused here.

3. Experimental setup and testing

3.1. Observe the SAW device under an optical microscope in bright field mode.

NOTE: Scratches may be present upon the metal layers deposited on the LN. Generally, they will not cause a notable influence of the device performance as long as the scratches do not result in an open circuit.

3.2. For SAW actuation, attach absorbers at both ends along the propagation direction of the SAW device to prevent reflected acoustic waves from the edges.

3.3. Use a signal generator to apply a sinusoidal electric field to the IDT at its resonance frequency of ~100 MHz. An amplifier may be connected to amplify the signal.

3.4. Use an oscilloscope to measure the actual voltage, current, and power applied to the device. The amplitude and frequency response of the SAW generated by the device may be measured by a laser Doppler vibrometer (LDV). The SAW-actuated droplet motion may be recorded using a high-speed camera attached to the microscope.

REPRESENTATIVE RESULTS:

The IDT measured was designed to have a resonance frequency of 100 MHz, as the spacing between the fingers of the IDT and the widths of the fingers themselves were all 10 μm, making the wavelength 40 μm. **Figure 1B** is an image of the IDTs fabricated using the method described above.

Applying a sinusoidal signal to the IDT near the designed resonance frequency allowed SAW to be generated and propagated across the surface of the piezoelectric material. The LDV measured the vibration via the Doppler effect on the surface, and through signal processing, information such as amplitude, velocity, acceleration, and phase could be acquired and displayed. We tested the frequency response under a frequency sweep from 90 – 105 MHz using an input power of 140 mW, a peak-to-peak voltage of 70 V, and peak-to-peak current of 720 mA. As **Figure 2A** indicates, the resonance frequency was 96.5844 MHz when measured, which is slightly lower than the design frequency of 100 MHz. This is attributable to the mass loading of the deposited metal for an amplitude of 19.444 pm. **Figure 2B** plots the vibration upon the substrate surface, showing the SAW propagating from the IDTs. The standing wave ratio (SWR) was 2.06, as calculated from the ratio of maximum amplitude to minimum amplitude. An SWR = 1 is produced for a pure traveling wave while SWR $= \infty$ for a pure standing wave, suggesting the value of SWR = 2.06 is a good traveling wave.

We also demonstrated the motion of a sessile droplet actuated by the SAW device using a single frequency signal input (80.6 mW) at its resonance (96.5844 MHz). A water droplet of 0.2 μL was pipetted on LN about 1 mm away from the IDT (see **Figure 3A**). When the SAW propagated and encountered the water droplet on the surface, it leaked into the liquid at the Rayleigh angle, which was determined by the ratio of sound speeds between sound in the water and SAW upon the substrate using

$$\theta_R = \sin^{-1}\left(\frac{v_{water}}{v_{LN}}\right) = \sin^{-1}\left(\frac{1498\ m/s}{3992\ m/s}\right) \approx 22°.$$

The jetting angle shown in **Figure 3B** confirmed the presence of SAW.

FIGURE AND TABLE LEGENDS:

Figure 1: Images of fabricated devices. (**A**) Gold-electrode IDTs with 7 mm aperture on an LN substrate for 100 MHz SAW generation and propagation. (**B**) The IDT fingers upon the LN substrate. Note the gratings on the left which served as reflectors to prevent spurious SAW back reflection from the chip edge. These gratings had similar design features to the IDT fingers but were not connected to each other in this version. Scale bar = 200 µm. The inset illustrates the details of the fingers at a greater magnification. Scale bar = 50 µm.

Figure 2: LDV measurement of the SAW device. (**A**) The frequency response (amplitude vs. frequency) from 90 MHz – 105 MHz, indicating the presence of a resonance at 96.5844 MHz with 19.444 pm amplitude. (**B**) A snapshot of the traveling wave generated by the IDT at the resonance frequency as it propagated across the LN substrate surface.

Figure 3: SAW-induced droplet jetting. (**A**) The experimental setup for SAW-induced sessile drop actuation on LN. Scale bar = 5 mm. (**B**) SAW propagated from left to right in the images at 80.6 mW power input, inducing the droplet jetting as shown. The angle was measured to be around the Rayleigh angle (22°). Scale bar = 1 mm.

Figure 4: Scheme for photoresist left on the substrate. (**A**) When positive photoresist was used, it was left in a trapezoidal shape with positively sloped edges after the development step. Metal deposited upon this structure will be difficult to remove. (**B**) When negative photoresist was used, however, this trapezoidal shape was inverted, with significant overhang that makes lift-off of the deposited metal easier later.

DISCUSSION:

Whichever method is chosen, it is possible to make SAW devices capable of generating good surface acoustic waves. Due to the deposition of metal when forming the IDTs, a small amount of additional mass is present upon the surface, reducing the SAW velocity in this region. Because the wavelength (λ_{SAW}) is determined by the IDT design, the resonance frequency is usually a little lower than the designed value due to the effect of the mass loading of the metal electrode upon the substrate. This is a key reason why lighter metals, such as aluminum, tend to be used in higher frequency applications, where this effect can be especially strong. Note that we focus on producing a SAW device that resonates at 100 MHz in this protocol. If a different resonance frequency is required, the thickness of the sputtered metal film needs to be recalculated (1% of λ_{SAW}). Also, the choice of photoresist needs to be adapted so that its thickness after spin coating is at least 2x that of the deposited metal. Further, the UV exposure and development times will need to be adjusted. It is generally possible to fabricate SAW devices that operate up to 700–800 MHz using these procedures with the appropriate equipment, although in order to make a

smooth pattern in microscale there are still some points that need to be considered.

Lift-off method

The first aspect to consider is the choice of photoresist. Typically, negative photoresists are used for lift-off fabrication even though they tend to be more difficult to work with than positive photoresists. Negative photoresists tend to be more difficult to strip off in the final step and can exhibit deswelling. The regions of the positive photoresist exposed to UV will be dissolved, leaving behind the unexposed regions. The boundaries between these regions form almost inevitably a trapezoidal cross-section with sloped edges, especially when underexposed, shown with exaggeration for clarity in **Figure 4A**. The metal sputtered on top of the photoresist in this shape will prevent the developing solvent from penetrating and dissolving the photoresist at the corners of the trapezoidal shape nearest the substrate, making it difficult to remove the metal in the lift-off step. On the other hand, **Figure 4B** is an example using a negative photoresist, where regions unexposed to UV are dissolved by the developer. The trapezoidal shape of the cross-section still tends to form on the substrate, but inverted with overhang, making the lift-off much easier. Apart from the lift-off problem when using a positive photoresist, the fingers will eventually be thinner and spaced slightly wider than designed due to the trapezoidal profile. Conversely, they will be wider and more narrowly spaced when using a negative photoresist.

Assuming the use of a negative photoresist, the UV exposure dose will also be crucial in the fabrication. Due to the different equipment and reagents used, the exposure time may still vary. If it is over-exposed (i.e., the exposed area is larger than wanted) the fingers will be narrower and the spacing wider than designed. Conversely, if it is underexposed, some of the photoresist may be left after development, in which case the metal in the desired area will peel off together with the thin layer of the remaining photoresist after lift-off. As mentioned above, some people use a single polished LN wafer, which is opalescent. The time/dose of UV exposure required for such wafers will increase, because the light will diffuse at the back.

Wet etching method

The key step for this method is to make sure that the photoresist is completely dissolved for the area of metal that needs to be etched away, otherwise the etchant will be blocked.

Because the process of the metal etching is isotropic, the etching not only occurs perpendicularly, but also across the metal layer. Thus, the metal left behind (i.e., the IDT fingers) will be narrower than expected. Negative photoresist is therefore a better choice for higher frequency devices in this technique to compensate for the undesired features.

Limitations

One of the advantages of the lift-off method over wet etching is that it achieves reproducibly defined structures that can always be easily washed away to restart the process if a problem is found. Both methods have a limit (e.g., isotropic etching). They can reliably reproduce structures with resolutions of about a few micrometers. According to our experience in our facilities, the practical limit is ~2–3 μm. If submicron features are required, other fabrication techniques may be called upon.

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DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

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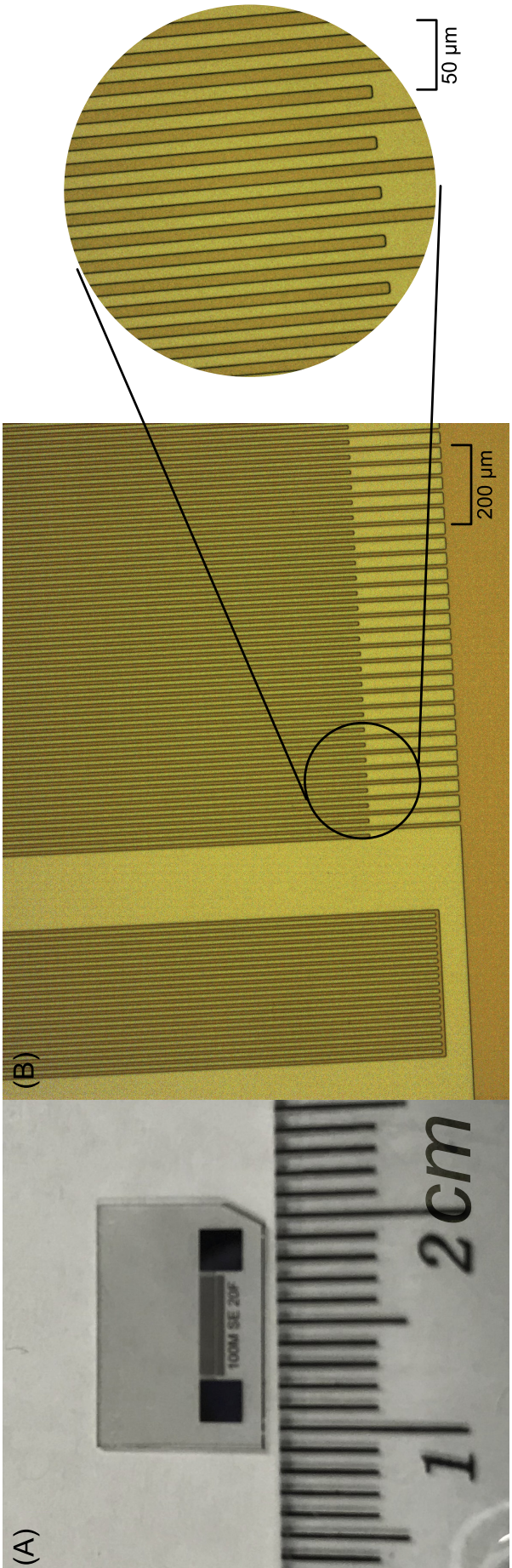
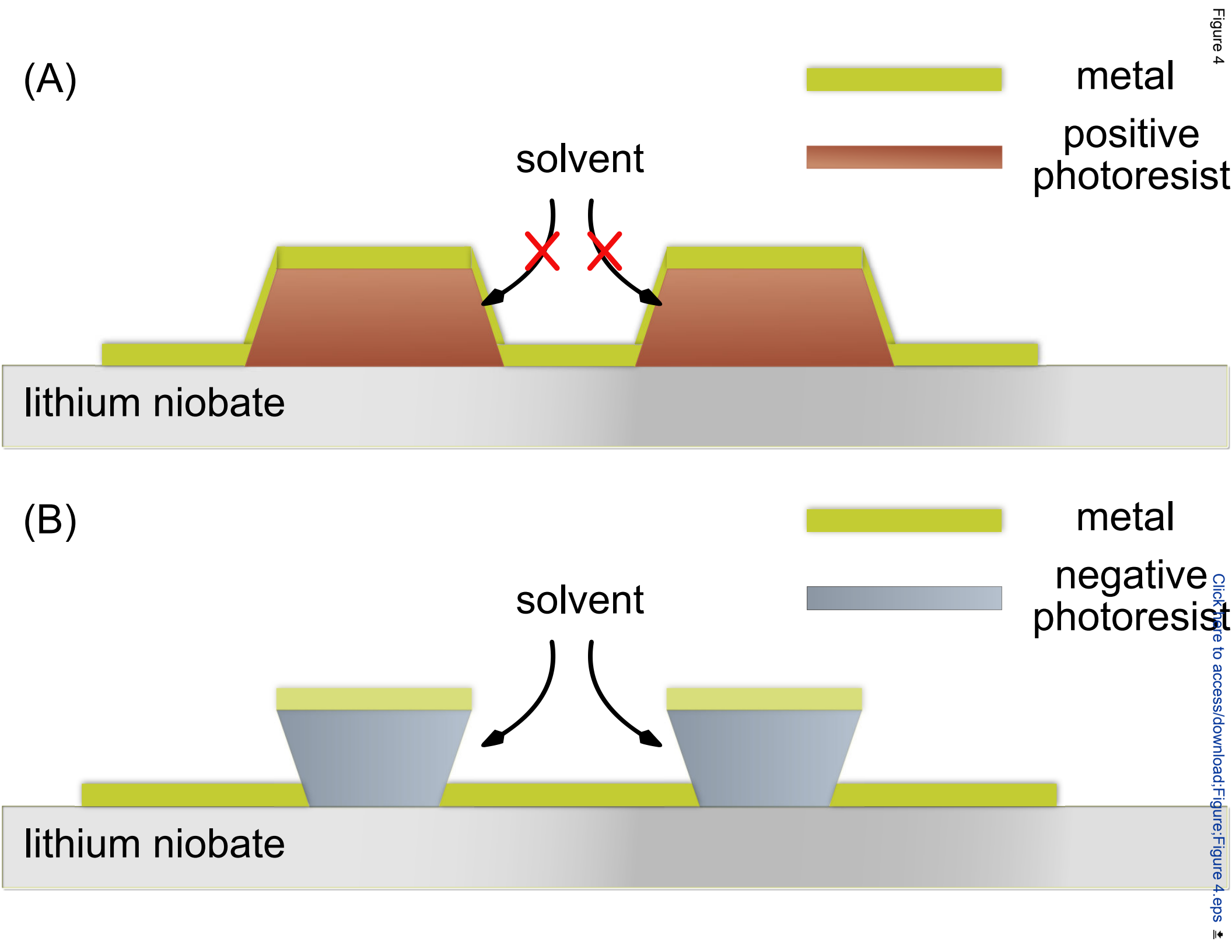


Figure 3



Name of Material/ Equipment	Company
Absorber	Dragon Skin, Smooth-On, Inc., Macungie, PA, USA
Amplifier	Mini-Circuits, Brooklyn, NY, USA
Camera	Nikon, Minato, Tokyo, Japan
Chromium etchant	Transene Company, INC, Danvers, MA, USA
Developer	Futurrex, NJ, USA
Developer	EMD Performance Materials Corp., Philidaphia, PA, USA
Dicing saw	Disco, Tokyo, Japan
Gold etchant	Transene Company, INC, Danvers, MA, USA
Hole driller	Dremel,Mount Prospect, Illinois
Inverted microscope	Amscope, Irvine, CA, USA
Laser Doppler vibrometer (LDV)	Polytec, Waldbronn, Germany
Lithium niobate substrate	PMOptics,Burlington, MA, USA
Mask aligner	Heidelberg Instruments, Heidelberg, Germany
Nano3 cleanroom facility	UCSD, La Jolla, CA, USA
Negative photoresist	Futurrex, NJ, USA
Oscilloscope	Keysight Technologies, Santa Rosa, CA, USA
Positive photoresist	
Signal generator	NF Corporation, Yokohama, Japan
Sputter deposition	Denton Vacuum, NJ, USA
Teflon wafer dipper	ShapeMaster, Ogden, IL, USA

Catalog Number	Comments/Description
Dragon Skin 10 MEDIUM	
ZHL–1–2W–S+	
D5300	
1020	
RD6	
AZ300MIF	
Disco Automatic Dicing Saw 3220	
Type TFA	
Model #4000	4000 High Performance Variable Speed Rotary
IN480TC-FL-MF603	
UHF-120	4” double-side polished 0.5 mm thick 128°Y-rotated cut lithium niobate
PWLN-431232	
MLA150	Fabrication process is performed in it.
NR9-1500PY	
InfiniiVision 2000 X-Series	
AZ1512	Denton Discovery 18 Sputter System
WF1967 multifunction generator	Wafer Dipper 4"
Denton 18	
SM4WD1	

Reviewer's comments are in black while our comments are in orange.

Please do note that the grammar and usage in the manuscript has been thoroughly reworked; the details of these changes are provided at the end of this rebuttal.

We are aware some of the notes in the protocol are exceedingly long. Unfortunately, these statements are important to the user of the protocol, representing subtle and hard-won fabrication facts that will help them avoid problems.

Reviewer #1:

Manuscript Summary:
Two fabrication techniques, lift-off and wet etching, are described to produce interdigital electrode transducers upon a piezoelectric substrate, lithium niobate, widely used to generate surface acoustic waves now finding broad utility in micro to nanoscale fluidics. The as-produced electrodes are shown to efficiently induce megahertz order Rayleigh surface acoustic waves.

Major Concerns:

The manuscript explains two methods of fabricating IDT on piezoelectric substrate. The fabrication methods were explained briefly in several previous publications. I don't see any novelty in the current work.

Though the IDT fabrication process has been briefly explained in numerous publications from our and many other groups, the main benefit of this contribution is for those unfamiliar with the process. After having had many researchers contact us asking how to make these devices, with several researchers having visited our group in the past year alone just to learn how to make a SAW device, we believe there is a need to communicate a comprehensive protocol. We are not aware of any detailed video and written protocol describing the process, and in that sense we believe the work is novel, though we certainly agree with the reviewer that this is neither new science nor new engineering. We believe the details of the process are especially valuable, as perhaps nearly all researchers are unaware of black LN, the issue of birefringence when observing objects through LN, the importance of surface finish, and many other aspects we have sought to explain in this contribution.

However, this is the first manuscript details only the fabrication methods of IDT for applications related to acoustophoresis. The authors need to discuss the two methods in details before the manuscript is considered for publication. A missing part in the manuscript is the bonding of PDMS element to the piezoelectric substrate. Some publications suggest adding a very thin layer of PDMS on the substrate before the PDMS element is attached. Others are attaching the substrate and the PDMS element without adding the layer using O2-plasma. Modifying the protocol to cover the full fabrication method is essential.

Unlike the SAW IDT fabrication process, curiously, the PDMS bonding and surface processing protocols have been widely published in the literature, with Whitesides' group responsible for a majority of the publications on this topic. Notably, Friend and Yeo, Biomicrofluidics 2010 026502

is dedicated to this particular topic and may be beneficial to the reviewer. Further, because PDMS is really a terrible choice for acoustofluidics due to its extraordinary large acoustic loss, other choices are available in the literature such as thin film epoxy bonding in Langelier, et al., LoC 2012, 2970-2976, which is cited in our manuscript, and another forthcoming JoVE publication on direct LN-LN bonding for nanofluidics devices (#60648). That written, we certainly agree that PDMS is ubiquitous.

The problem with including other fabrication aspects is the format peculiar to JoVE does not permit lengthy elaboration on multiple fabrication topics. It is for this reason we have chosen to focus upon IDT fabrication via two closely related methods.

Other comments include :
- 52- (normal photolithography) if this is a protocol then it's better to be specific.

“normal or” is deleted.

- Paragraphs from line 48 to 72 have no references.

Eleven additional citations have been added.

- 66- (The metal thickness should be 1% of the SAW wave length) needs more explanation.

It is re-explained with more detail.

- 69- The protocol is performed experimentally for only one frequency (100 MHz), more experiments with different parameters will make the protocol more beneficial.

It is true that only one frequency is described in the protocol. Changing the frequency will not affect many of the steps (or order) in fabricating the device. Only minor modifications will be necessary, and the risk is that the protocol will become convoluted and confusing as a consequence. Imagine stating something like “ one would use AZ4562 for IDT structures with dimensions greater than 35 μm, but AZ1518 for 20–35 μm, AZ1512 for 15–25 μm, and AZ1505 for 10–20 μm”...and so on repeated for each photoresist and developer step. We chose to instead provide a concise protocol that would work as an introduction into the technique that could be readily adapted.

That written, a few sentences have been added explaining some of the basic design rules in the first paragraph of “Discussion” section as follows:

“Note that we focus upon producing a SAW device that resonates at 100 MHz in this protocol. If a different resonance frequency is required, the thickness of the sputtered metal film needs to be recalculated (1% of λ_{SAW}). Also, the choice of photoresist needs to be adapted so that its thickness after spin-coating is at least twice that of the deposited metal. Further, the UV exposure and development times will need to be adjusted. It is generally possible to fabricate SAW devices that operate up to 700–800 MHz using these procedures with the appropriate

equipment, although in order to make a smooth pattern in microscale there are still some points worth discussing."

- The authors have not included any references that support the protocol being introduced. After line 47, there is no references for any information, equation, chemicals specifications … etc.

11 more citations have been added.

- 184- usually this should be baking (or thermal treatment) instead of hard baking. The photoresist doesn't exist yet to call the step hard baking.

Changed to "Thermal treatment".

- 216- this caution should be applied for all chemical used not only at this step. Similar comments should be added for all other chemicals.

Agreed. Multiple "Cautions" are added to the protocol.

- While etching, I'm not sure the time is the only factor to decide if whether the sample etched properly or not. Observing the deposited material etched physically is more effective specially at micro and nano scale. Other factors might affect the etching process are temperature, etchant concentration, and newness.

Yes, higher temperature and concentration will reduce the time of etching. But the etching time is about 1-2 min at room temperature, which is still fairly short and easy to control. Shorter times introduce their own problems, mainly in the heterogeneity of etch across the wafer.

- 266- which software is used.

The equipment model and company name have been added to address this point, thank you.

- 271- more explanation about (mass loading effect) will be helpful.

Thank you. We have added more information to better explain the effect as follows:

"As the wavelength (λ_{SAW}) is determined by the IDT design, the resonance frequency is usually a little lower than the designed value due to the effect of the mass loading of the metal electrode upon the substrate. This is a key reason why lighter metals, such as aluminum, tend to be used in higher frequency applications where this effect can be especially strong."

- 287- 0.7mm has a typo, it should be 6 to 7 mm. (according to ref. 10)

Changed to 7 mm.

- 311- travelling and standing can be generated. (it is better to write Surface Acoustic Waves)

Modified to “surface acoustic waves”.

- A comparison between the two methods is going to be very beneficial.

A comparison of the two methods has been added to the “limitation” section.

TITLE:

Fabrication of Surface Acoustic Wave Devices on Lithium Niobate

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KEYWORDS:

Acoustofluidics, Surface Acoustic Waves, Lithium Niobate, Interdigital Transducers, Lift-Off, Wet Etching

SUMMARY:

Two fabrication technique, lift-off and wet etching, are described in producing interdigital transducers, which are widely used to generate surface acoustic waves on piezoelectric materials, e.g., lithium niobate. Both techniques are shown to produce useful 100 megahertz-order surface acoustic wave devices.

ABSTRACT:

Manipulation of fluids and particles by acoustic actuation at small scales has spurred rapid development of lab-on-a-chip applications. Megahertz-order surface acoustic wave (SAW) devices generate tremendous acceleration on their surface, up to 10^8 m/s^2, in turn responsible for many of the observed effects that have come to define acoustofluidics: acoustic streaming and acoustic radiation forces. These effects have been used for particle, cell, and fluid handling at the microscale, and even at the nanoscale. In this paper we explicitly demonstrate two major fabrication methods of SAW devices on lithium niobate: the details of lift-off and wet etching techniques are described step by step. Representative results for the electrode pattern deposited on the substrate and also the performance of SAW generated on the surface are provided in detail. Fabrication tricks and troubleshooting are covered as well. The aim is to provide the reader with a set of useful protocols for high frequency SAW device fabrication in future microfluidics applications.

INTRODUCTION:

Relying on the well-known inverse piezoelectric effect, where the atomic dipoles create strain corresponding to the application of an electric field, piezoelectric single crystal media such as lithium niobate (LN) $LiNbO_3$ and lithium tantalite (LT) $LiTaO_3$ can be used as electromechanical transducers to generate SAW for microscale applications.[1-6] SAW is capable of producing surface displacements of up to 1 nm at high frequency, making it possible for SAW actuated acoustofluidics to overcome the obstacles of traditional ultrasonic methods: weak acceleration,

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relatively long wavelengths and difficulty in device miniaturization. Research to manipulate fluids and particles within small devices using SAW and related high frequency ultrasound has prospered in recent years as a consequence.[7-10]

The fabrication of SAW-integrated microfluidic devices requires fabrication of the electrodes—the *interdigital transducer* (IDT)[11] on the piezoelectric substrate—to facilitate generating the SAW. The comb-shape fingers create compression and tension in the substrate when connected to an electric field; SAW is generated when this electric field is reversed at the resonance frequency of the SAW in the selected substrate. The fabrication process for SAW devices has been presented in many publications, whether using lift-off ultraviolet photolithography alongside a metal sputter or a wet etching process.[10] For the lift-off technique,[12-14] a sacrificial layer (photoresist) with an inverse pattern is created on the surface, so that when the target material (metal) is deposited on the whole wafer, it can bond to the substrate in desired regions, followed by a "lift off" step to remove the remaining photoresist. By contrast, in the wet etching process,[15-18] the metal is first deposited on the wafer and photoresist is deposited and patterned on the metal, serving to protect the desired region from later being etched away by a metal etchant.

In the most commonly used design, the straight IDT, the wavelength of the resonance frequency of this SAW device is defined by the periodicity of the finger pairs, where the finger width and the spacing between fingers are both $\lambda_{\mathrm{SAW}}/4$.[19] In order to balance the electric current transmission efficiency and the mass loading effect on the substrate, the thickness of the metal deposited on the piezoelectric material is optimized to be about 1% of the SAW wavelength.[20] Localized heating from Ohmic losses,[21] potentially inducing premature finger failure, can occur if insufficient metal is deposited. A excessively thick metal film can cause a reduction in the resonance frequency of IDT due to a mass loading effect, and can possibly create unintentional acoustic cavities from the IDTs, isolating the acoustic waves they generate from the surrounding substrate. As a result, the photoresist and UV exposure parameters chosen vary in the lift-off technique, dependent principally upon the frequency but also the intended application for the device. Here, we describe in detail the lift-off process to fabricate a 100 MHz SAW-generating device on a double-sided polished 0.5 mm-thick 128° Y-rotated cut LN wafer, and the wet etching process to fabricate a 100 MHz device of identical design. Our approach enables one to consider these devices in investigation of a variety of physical problems and biological micro to nano-scale fluidics applications.

PROTOCOL:

1. SAW Device Fabrication via Lift-Off Method

1.1. Wafer solvent cleaning: In a Class 100 clean room facility, immerse the 4" (101.6 mm) LN wafer into acetone, followed by isopropyl alcohol (IPA), and deionized water (DI water) in a sonication bath for 5 min, respectively. Pick up the wafer and use dry nitrogen (N_2) gas flow over the surface of the wafer to remove the remaining DI water from the wafer.

CAUTION: Perform acetone and IPA immersion in a fume hood. Avoid inhalation and skin

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contact with IPA. Avoid skin and eye contact with acetone. Do not swallow.

Note: Do not allow any fluid to evaporate upon the wafer; if there is any dust or contamination on the surface, start this step over.

1.2. Pre-bake: Place the wafer onto a hotplate at 100 °C for 3 min.

NOTE: Because of the pyroelectric property of LN, it will generate static charges and associated stress within the wafer during heating and cooling. It is recommended to place the wafer onto a piece of aluminum (Al) foil after removing it from the hot plate to discharge any static charge from the wafer, thus preventing breakage.

1.3. Spin coating: Place the wafer onto a spin coater. Place negative photoresist (NR9-1500PY) onto the wafer using a dropper, covering about 75% of the wafer surface area. Program a speed of 500 rpm with acceleration of 3000 rpm/sec for 5 sec and then a speed of 3500 rpm with acceleration of 3000 rpm/sec for 40 sec, giving a thickness of the photoresist of around 1.3 µm.

CAUTION: Perform spin coating in a fume hood. Inhalation of photoresist fumes can cause headaches.

NOTE: The thickness may vary depending on the condition of the photoresist and the spin coater, even with the same rpm. After spin coating, the photoresist may be spun to the edge and over it to coat the *back* side edge of the wafer during spin coating. This must be removed by using a swab doused with acetone. If present, it will stick the wafer to the hotplate during the soft bake process, and the wafer will be difficult to pick up from the hotplate.

1.4. Soft bake: Place the wafer onto a hotplate at 25 °C, ramp the temperature up to 150 °C, hold it at 150 °C for 1 min, turn off the hotplate and let the wafer cool down to room temperature.

CAUTION: Avoid breathing in the photoresist. Inhalation of photoresist can cause headache.

NOTE: Due to the *pyroelectric* effect mentioned above, if the temperature of the LN wafer is suddenly changed, for example by directly transferring the LN wafer onto the hotplate or Al foil at 150 °C, the sudden temperature change will cause thermal shock within the wafer, likely shattering it. The presence of nonuniform metal on the surface, such as electrodes, significantly enhances the risk of wafer shattering due to differential stress. In applications where temperature excursions are necessary during fabrication or use, and the transparency of the LN is not important, consider using so-called "black" LN or more accurately *reduced* LN, which is a dark brown translucent color but more importantly has negligible pyroelectricity.

1.5. Ultraviolet exposure: Transfer the wafer to the mask aligner (MLA150). Expose the photoresist with an energy dose of 400 mJ/cm^2 at 375 nm to the wafer. The energy dose required may vary based on the mask design and the age and condition of the photoresist.

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NOTE: The wave propagation direction induced by IDTs should be along the X-propagating direction in order to effectively generate SAW. In other words, this implies the "fingers" of the IDT should be perpendicular to the X-axis direction. Typical LN wafer manufacturers place the primary (larger) wafer flat (straight edge alongside of wafer) perpendicular to the X-axis, so your IDT fingers should be parallel to this flat. Some manufacturers introduce a second (smaller) wafer flat to help indicate the Y and Z-axis directions, but this detail is unimportant for SAW generation. Manufacturers often request specifications for the surface finish of the wafer; if you require the ability to see through the wafer, request double-side optically polished wafers, though keep in mind that LN is birefringent, so any object illuminated with standard laboratory light and seen through the material will produce not one but two images. Overcoming this problem is discussed later. Single-side polished LN is a better choice for SAW generation if you do not need to see through the wafer, as spurious acoustic waves are diffused by the rough back surface.

1.6. Post-exposure bake: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil to cool down to room temperature.

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NOTE: The patterns should be able to be seen after the post-exposure bake. If not, consider stripping the photoresist and restarting the process from step 1.1 above.

1.7. Develop: Place the wafer into a beaker filled with pure RD6 developer for 15 sec. Gently shake the beaker during development. Immerse the wafer into DI water for 1 min, then rinse the wafer under DI water flow. Finally, use dry N_2 flow to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Develop the wafer in a fume hood. Avoid breathing vapors or developer contact with eyes and skin.

NOTE: The photolithography is complete at this step. The protocol can be paused here.

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1.8. Hard bake: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil to cool down to room temperature.

Note: This step is to remove any moisture on the wafer, preventing outgassing during sputtering that could reduce the quality of the deposited metal film.

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1.9. Electrode sputter deposition: Place the wafer into a sputter deposition system. Vacuum the chamber to 5×10^{-6} mTorr. Use argon flow at 2.5 mTorr, sputter Cr with a power of 200 W for 5 nm as an adhesion layer, followed by sputtering Al with a power of 300 W for 400 nm to form the conductive electrodes.

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NOTE: Deposition time should be calculated from the expected thickness and the deposition rate. Titanium (Ti) can be used instead of chromium, though the process is more difficult as Ti is

tougher. For higher frequency SAW devices, Al should replace Au to avoid the mass loading effects of the Au IDT fingers which reduce the local SAW resonance frequency under the IDT, forming an acoustic cavity from which the SAW can only escape with significant loss.

1.10. Lift-off process: Transfer the wafer into a beaker and immerse into acetone. Sonicate at medium intensity for 5 min. Rinse with DI water and dry the wafer with dry N_2 flow.

CAUTION: Use acetone in a fume hood. Avoid inhalation and skin or eye contact with acetone. Do not swallow.

1.11. Dicing process: Use a dicing saw to dice the entire wafer into small pieces of chips as SAW devices for further applications.

NOTE: The fabrication is complete. The protocol can be paused here.

NOTE: Instead of a saw, a diamond-tipped wafer scribe (or even a glass cutter) can be used to dice the LN wafer with some practice, though due to the anisotropy of LN it is important to scribe and break the wafer *first* along scribe lines *perpendicular to the X-axis*, followed by those lines along the X-axis.

2. SAW Device Fabrication via Wet Etching Method

2.1. Wafer solvent cleaning: In a Class 100 clean room facility, immerse the 4" (101.6 mm) LN wafer into acetone, followed by IPA, and deionized DI water in a sonication bath for 5 min, respectively. Pick up the wafer and use dry N2 gas flow over the surface of the wafer to remove the remaining DI water from the wafer.

CAUTION: Use acetone and IPA in a fume hood. Avoid inhalation and skin contact with IPA. Avoid acetone contact with skin and eyes. Do not swallow.

Note: Do not allow any fluid to evaporate upon the wafer; if there is any dust or contamination on the surface, start this step over.

2.2. Thermal treatment: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil to cool down to room temperature.

2.3. Electrode sputter deposition: Place the wafer into a sputter deposition system. Vacuum the chamber to 5×10^{-6} mTorr. Use argon flow at 2.5 mTorr, sputter Cr with a power of 200 W for 5 nm as an adhesion layer, followed by sputtering Au with a power of 300 W for 400 nm to form the conductive electrodes.

NOTE: The protocol can be paused here.

2.4. Spin coating: Place the wafer onto a spin coater. Place positive photoresist (AZ1512) onto

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the wafer using a dropper, covering about 75% of the wafer surface area. Program a speed of 500 rpm with acceleration of 3000 rpm/sec for 10 sec and then a speed of 4000 rpm with acceleration of 3000 rpm/sec for 30 sec, giving a thickness of the photoresist at around 1.2 µm.

CAUTION: Perform spin coating in a fume hood. Inhalation of photoresist fumes can cause headaches.

NOTE: The thickness may vary depending on the condition of the photoresist and the model of spin coater used, even at the same rpm. After spin coating, the photoresist may be spun to the edge and over it to coat the *back* side edge of the wafer. This must be removed by using a swab doused with acetone. If present, it will stick the wafer to the hotplate during the soft bake process, and the wafer will be difficult to pick up from the hotplate.

2.5. Soft bake: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil to cool down to room temperature.

2.6. Ultraviolet exposure: Transfer the wafer to the mask aligner (MLA150). Expose the photoresist with an energy dose of 150 mJ/cm^2 at 375 nm to the wafer. The energy dose required may vary based on the mask design and the age and condition of the photoresist.

2.7. Develop: Place the wafer into a beaker filled with pure AZ300MIF developer for 30 sec. Gently shake the beaker during development. Immerse the wafer into DI water for 1 min, then rinse the wafer under DI water flow. Finally, use dry N_2 flow to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Avoid AZ300MIF contact with skin or eyes. Do not swallow.

2.8. Au etching: Immerse the wafer into a beaker filled with Au etchant for 90 sec, gently shaking the beaker. After rinsing the wafer under DI water flow, use dry N_2 flow to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Gold etchant can be hazardous for the eyes and skin, and causes respiratory irritation. This step requires higher level personal protective equipment (PPE), such as safety glasses, black neoprene gloves, apron, etc.

2.9. Cr etching: Immerse the wafer into a beaker filled with Cr etchant for 20 sec, gently shaking the beaker. After rinsing the wafer under DI water flow, use dry N_2 flow to remove the remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

CAUTION: Chromium etchant can cause eye, skin and respiratory irritation. This step also requires higher level PPE.

2.10. Sample cleaning: Put the wafer into acetone, followed by IPA, and DI water in a sonication bath for 5 min, respectively. Pick up the wafer and use dry N2 gas flow over the surface of the

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wafer to remove the remaining DI water from the wafer.

CAUTION: Use acetone in a fume hood. Avoid inhalation and skin contact acetone with skin and eyes. Do not swallow.

NOTE: This step is to remove undesired photoresist from the wafer.

2.11. Dicing process: Use a dicing saw to dice the entire wafer into chips as SAW devices for further use.

NOTE: The fabrication is completed. The protocol can be paused here.

Experimental Setup and Testing

1. Observation: Observe the SAW device under an optical microscope in bright field mode.

NOTE: Scratches may be present upon the metal layers deposited on the LN. Generally, they will not cause a notable influence of the device performance, as long as the scratches do not result in an open circuit.

2. SAW actuation: Attach absorbers at both ends along the propagation direction of the SAW device to prevent reflected acoustic waves from the edges. Use a signal generator to apply a sinusoidal electric field to the IDT at its resonance frequency around 100 MHz. An amplifier may be connected to amplify the signal. Use an oscilloscope to measure the actual voltage, current, and power applied to the device. The amplitude and frequency response of the SAW generated by the device may be measured by a laser Doppler vibrometer (LDV, UHF-120, Polytec, Waldbronn, Germany). The SAW-actuated droplet motion may be recorded using a high-speed camera attached to the microscope.

REPRESENTATIVE RESULTS:

The IDT to be measured is designed to have a resonance frequency of 100 MHz, as the spacing between the fingers of the IDT and the widths of the fingers themselves are all 10 µm, making the wavelength 40 µm. Figure 1(B) is an image of the IDTs fabricated using the method described above.

Applying an sinusoidal signal to the IDT near the designed resonance frequency allows SAW to be generated to propagate across the surface of the piezoelectric material. The LDV measures the vibration via the Doppler effect on the surface, and through signal processing, information such as amplitude, velocity, acceleration, and phase can be acquired and displayed. We illustrate the frequency response under a frequency sweep from 90 to 105 MHz using an input power of 140 mW, a peak-to-peak voltage of 70 V, and peak-to-peak current of 720 mA. As Figure 2(A) indicates, the resonance frequency is measured to be 96.5844 MHz, slightly lower than the design frequency of 100 MHz, attributable to the mass loading of the deposited metal, for an amplitude of 19.444 pm. Figure 2(B) plots the vibration upon the substrate surface, showing a SAW to be propagating from the IDTs. The standing wave ratio (SWR) is calculated to

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be 2.06 from the ratio of maximum amplitude to minimum amplitude. A SWR = 1 is produced for a pure traveling wave while SWR = ∞ for a pure standing wave, suggesting the value of SWR = 2.06 is a good traveling wave.

We also demonstrate the motion of a sessile droplet actuated by the SAW device while using a single frequency signal input (80.6 mW) at its resonance (96.5844 MHz). A water droplet of 0.2 µL is pipetted on LN about 1 mm away from the IDT (*see* Figure 3(A)). When SAW propagates and encounters the droplet (water) on the surface, it "leaks" into the liquid at the Rayleigh angle, itself determined by the ratio of sound speeds between sound in the water and SAW upon the substrate,

$$\theta_R = \sin^{-1}\left(\frac{v_{water}}{v_{LN}}\right) = \sin^{-1}\left(\frac{1498\ m/s}{3992\ m/s}\right) \approx 22°.$$

The jetting angle shown in Figure 3(B) confirms the presence of SAW.

FIGURE AND TABLE LEGENDS:

Figure 1: Images of fabricated devices. (A) Gold-electrode IDTs with 7 mm aperture on an LN substrate for 100 MHz SAW generation and propagation. (B) The IDT fingers upon the LN substrate; note the gratings on the left which serve as reflectors to prevent spurious SAW back reflection from the chip edge. These gratings have similar design features to the IDT fingers but are not connected to each other in this version. Scale bar: 200 µm. The inset illustrates the details of the fingers at greater magnification. Scale bar: 50 µm.

Figure 2: LDV measurement of the SAW device. (A) The frequency response (amplitude vs frequency) from 90 MHz to 105 MHz, indicating the presence of a resonance at 96.5844 MHz with 19.444 pm amplitude. (B) A snapshot of the traveling wave generated by the IDT at the resonance frequency as it propagates across the LN substrate surface.

Figure 3: SAW-induced droplet jetting. (A) The experimental setup for SAW-induced sessile drop actuation on LN. Scale bar: 5 mm. (B) SAW is propagating from the left to right in the images at 80.6 mW power input, inducing the droplet jetting as shown. The angle is measured to be around the Rayleigh angle (22°). Scale bar: 1 mm.

Figure 4: Scheme for photoresist left on the substrate. (A) When positive photoresist is used, it is left in a trapezoidal shape with positively sloped edges after the development step. Metal deposited upon this structure will be difficult to remove. (B) When negative photoresist is used, however, this trapezoidal shape is inverted, with significant overhang that makes lift-off of the deposited metal easier in a later step.

DISCUSSION:

Whichever method is chosen, it is possible to make SAW devices capable of generating good surface acoustic waves. Due to the deposition of metal in forming the IDTs, a small amount of additional mass is present upon the surface, reducing the SAW velocity in this region. As the wavelength (λ_{SAW}) is determined by the IDT design, the resonance frequency is usually a little lower than the designed value due to the effect of the mass loading of the metal electrode

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upon the substrate. This is a key reason why lighter metals, such as aluminum, tend to be used in higher frequency applications where this effect can be especially strong. Note that we focus upon producing a SAW device that resonates at 100 MHz in this protocol. If a different resonance frequency is required, the thickness of the sputtered metal film needs to be recalculated (1% of λ_{SAW}). Also, the choice of photoresist needs to be adapted so that its thickness after spin-coating is at least twice that of the deposited metal. Further, the UV exposure and development times will need to be adjusted. It is generally possible to fabricate SAW devices that operate up to 700–800 MHz using these procedures with the appropriate equipment, although in order to make a smooth pattern in microscale there are still some points worth discussing.

1. Lift-off Method

The first aspect to consider is the choice of photoresist. Typically, negative photoresists are used for lift-off fabrication, though they tend to be more difficult to work with than positive photoresists, as they tend to be more difficult to strip off in the final step and can exhibit deswelling. The regions of the positive photoresist exposed to UV will be dissolved, leaving behind the unexposed regions. The boundaries between these regions form almost inevitably form a trapezoidal cross-section with sloped edges, especially when underexposed, shown with exaggeration for clarity in Figure 4(A). The metal sputtered atop the photoresist in this shape will prevent the developing solvent from penetrating and dissolving the photoresist at the corners of the trapezoidal shape nearest the substrate, making it difficult to remove the metal in the lift-off step. On the other hand, Figure 4(B) is an example when using a negative photoresist, where regions unexposed to UV are dissolved by the developer. The trapezoidal shape of the cross section still tends to form on the substrate, but inverted with overhang, making the lift-off much easier. Apart from the lift-off problem when using a positive photoresist, the fingers will eventually be thinner and spaced slightly wider than designed due to the trapezoidal profile. Conversely, they will be wider and more narrowly spaced when using a negative photoresist.

Assuming the use of a negative photoresist, the UV exposure dose will also be crucial in the fabrication. Due to the different equipment and reagent used, the exposure time may still vary. If it is over-exposed, meaning the exposed area is larger than wanted, which will cause the fingers to be narrower and the spacing wider than designed. Oppositely, if it is under-exposed, there is possibly some of the photoresist left after development, in which case the metal in the desired area will peel off together with the thin layer of the remaining photoresist after lift-off. Sometimes people tend to use a single polished LN wafer, as mentioned above, which is opalescent. The time/dose of UV exposure required for such wafers will be increased, since the light will be diffused at the back.

2. Wet Etching Method

The key step for this method is that make sure that the photoresist is completely dissolved for the area of metal that needs to be etched away, otherwise the etchant will be blocked.

As the process of the metal etching is isotropic, suggesting the etching not only occurs

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When using negative photoresist, the UV

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perpendicularly, but also across the metal layer, the metal left behind—in this case as IDT fingers—will be narrower than expected. Negative photoresist is therefore a better choice in this technique so as to compensate for the undesired feature loss.

3. Limitations

One of the advantages of the lift-off method over wet etching is that it achieves reproducibly defined structures that can always be easily washed away to restart the process if a problem is found. Both methods have a limit (e.g. isotropic etching) in the resolution of the structures they can reliably reproduce at about a few micrometers. According to our experience in our facilities, the practical limit is around 2-3 µm. If sub-micron features are required, other fabrication techniques may be called upon.

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DISCLOSURES:

The authors have nothing to disclose.

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