

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.

1 **TITLE:**

2 Fabrication of Surface Acoustic Wave Devices on Lithium Niobate

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14 **KEYWORDS:**

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

18 **SUMMARY:**

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

24 **ABSTRACT:**

25 Manipulation of fluids and particles by acoustic actuation at small scales has spurred rapid
26 development of lab-on-a-chip applications. Megahertz-order surface acoustic wave (SAW)
27 devices generate tremendous acceleration on their surface, up to 10^8 m/s², in turn responsible
28 for many of the observed effects that have come to define acoustofluidics: acoustic streaming
29 and acoustic radiation forces. These effects have been used for particle, cell, and fluid handling
30 at the microscale, and even at the nanoscale. In this paper we explicitly demonstrate two major
31 fabrication methods of SAW devices on lithium niobate: the details of lift-off and wet etching
32 techniques are described step by step. Representative results for the electrode pattern
33 deposited on the substrate and also the performance of SAW generated on the surface are
34 provided in detail. Fabrication tricks and troubleshooting are covered as well. The aim is to
35 provide the reader with a set of useful protocols for high frequency SAW device fabrication in
36 future microfluidics applications.

38 **INTRODUCTION:**

39 Relying on the well-known inverse piezoelectric effect, where the atomic dipoles create strain
40 corresponding to the application of an electric field, piezoelectric single crystal media such as
41 lithium niobate (LN) LiNbO₃ and lithium tantalite (LT) LiTaO₃ can be used as electromechanical
42 transducers to generate SAW for microscale applications.¹⁻⁶ SAW is capable of producing
43 surface displacements of up to 1 nm at high frequency, making it possible for SAW actuated
44 acoustofluidics to overcome the obstacles of traditional ultrasonic methods: weak acceleration,

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

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

90 In the most commonly used design, the straight IDT, the wavelength of the resonance
91 frequency of this SAW device is defined by the periodicity of the finger pairs, where the finger
92 width and the spacing between fingers are both $\lambda_{\text{SAW}}/4$.¹⁹ In order to balance the electric
93 current transmission efficiency and the mass loading effect on the substrate, the thickness of
94 the metal deposited on the piezoelectric material is optimized to be about 1% of the SAW
95 wavelength.²⁰ Localized heating from Ohmic losses,²¹ potentially inducing premature finger
96 failure, can occur if insufficient metal is deposited. A excessively thick metal film can cause a
97 reduction in the resonance frequency of IDT due to a mass loading effect, and can possibly
98 create unintentional acoustic cavities from the IDTs, isolating the acoustic waves they generate
99 from the surrounding substrate. As a result, the photoresist and UV exposure parameters
100 chosen vary in the lift-off technique, dependent principally upon the frequency but also the
101 intended application for the device. Here, we describe in detail the lift-off process to fabricate a
102 100 MHz SAW-generating device on a double-sided polished 0.5 mm-thick 128° Y-rotated cut
103 LN wafer, and the wet etching process to fabricate a 100 MHz device of identical design. Our
104 approach enables one to consider these devices in investigation of a variety of physical
105 problems and biological micro to nano-scale fluidics applications.

107 PROTOCOL:

108 1. SAW Device Fabrication via Lift-Off Method

110 1.1. Wafer solvent cleaning: In a Class 100 clean room facility, immerse the 4” (101.6 mm) LN
111 wafer into acetone, followed by isopropyl alcohol (IPA), and deionized water (DI water) in a
112 sonication bath for 5 min, respectively. Pick up the wafer and use dry nitrogen (N₂) gas flow
113 over the surface of the wafer to remove the remaining DI water from the wafer.

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

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

148
149 Note: Do not allow any fluid to evaporate upon the wafer; if there is any dust or contamination
150 on the surface, start this step over.

151
152 1.2. Pre-bake: Place the wafer onto a hotplate at 100 °C for 3 min.

153
154 NOTE: Because of the pyroelectric property of LN, it will generate static charges and associated
155 stress within the wafer during heating and cooling. It is recommended to place the wafer onto a
156 piece of aluminum (Al) foil after removing it from the hot plate to discharge any static charge
157 from the wafer, thus preventing breakage.

158
159 1.3. **Spin coating**: Place the wafer onto a spin coater. Place negative photoresist (NR9-1500PY)
160 onto the wafer using a dropper, covering about 75% of the wafer surface area. Program a speed
161 of 500 rpm with acceleration of 3000 rpm/sec for 5 sec and then a speed of 3500 rpm with
162 acceleration of 3000 rpm/sec for 40 sec, giving a thickness of the photoresist of around 1.3 µm.

163
164 CAUTION: Perform spin coating in a fume hood. Inhalation of photoresist fumes can cause
165 headaches.

166
167 NOTE: The thickness may vary depending on the condition of the photoresist and the spin
168 coater, even with the same rpm. After spin coating, the photoresist may be spun to the edge
169 and over it to coat the back side edge of the wafer during spin coating. This must be removed
170 by using a swab doused with acetone. If present, it will stick the wafer to the hotplate during
171 the soft bake process, and the wafer will be difficult to pick up from the hotplate.

172
173 1.4. **Soft bake**: Place the wafer onto a hotplate at 25 °C, ramp the temperature up to 150 °C,
174 hold it at 150 °C for 1 min, turn off the hotplate and let the wafer cool down to room
175 temperature.

176
177 CAUTION: Avoid breathing in the photoresist. Inhalation of photoresist can cause headache.

178
179 NOTE: Due to the pyroelectric effect mentioned above, if the temperature of the LN wafer is
180 suddenly changed, for example by directly transferring the LN wafer onto the hotplate or Al foil
181 at 150 °C, the sudden temperature change will cause thermal shock within the wafer, likely
182 shattering it. The presence of nonuniform metal on the surface, such as electrodes, significantly
183 enhances the risk of wafer shattering due to differential stress. In applications where
184 temperature excursions are necessary during fabrication or use, and the transparency of the LN
185 is not important, consider using so-called “black” LN or more accurately reduced LN, which is a
186 dark brown translucent color but more importantly has negligible pyroelectricity.

187
188 1.5. **Ultraviolet exposure**: Transfer the wafer to the mask aligner (MLA150). Expose the
189 photoresist with an energy dose of 400 mJ/cm² at 375 nm to the wafer. The energy dose
190 required may vary based on the mask design and the age and condition of the photoresist.

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

235
236 1.6. **Post-exposure bake:** Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it
237 onto Al foil to cool down to room temperature.

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238
239 NOTE: The patterns should be able to be seen after the post-exposure bake. If not, consider
240 stripping the photoresist and restarting the process from step 1.1 above.

241
242 1.7. **Develop:** Place the wafer into a beaker filled with pure RD6 developer for 15 sec. Gently
243 shake the beaker during development. Immerse the wafer into DI water for 1 min, then rinse
244 the wafer under DI water flow. Finally, use dry N₂ flow to remove the remaining DI water from
245 the wafer. Never let any fluid evaporate on the wafer surface.

246
247 CAUTION: Develop the wafer in a fume hood. Avoid breathing vapors or developer contact with
248 eyes and skin.

249
250 NOTE: The photolithography is complete at this step. The protocol can be paused here.

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251
252 1.8. Hard bake: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil
253 to cool down to room temperature.

254
255 Note: This step is to remove any moisture on the wafer, preventing outgassing during
256 sputtering that could reduce the quality of the deposited metal film.

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257
258 1.9. **Electrode sputter deposition:** Place the wafer into a sputter deposition system. Vacuum
259 the chamber to 5×10^{-6} mTorr. Use argon flow at 2.5 mTorr, sputter Cr with a power of 200 W
260 for 5 nm as an adhesion layer, followed by sputtering Al with a power of 300 W for 400 nm to
261 form the conductive electrodes.

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262
263 NOTE: Deposition time should be calculated from the expected thickness and the deposition
264 rate. Titanium (Ti) can be used instead of chromium, though the process is more difficult as Ti is

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

273
274 1.10. **Lift-off process:** Transfer the wafer into a beaker and immerse into acetone. Sonicate at
275 medium intensity for 5 min. Rinse with DI water and dry the wafer with dry N₂ flow.

276
277 CAUTION: Use acetone in a fume hood. Avoid inhalation and skin or eye contact with acetone.
278 Do not swallow.

279
280 1.11. Dicing process: Use a dicing saw to dice the entire wafer into small pieces of chips as SAW
281 devices for further applications.

282
283 NOTE: The fabrication is complete. The protocol can be paused here.

284
285 NOTE: Instead of a saw, a diamond-tipped wafer scribe (or even a glass cutter) can be used to
286 dice the LN wafer with some practice, though due to the anisotropy of LN it is important to
287 scribe and break the wafer *first* along scribe lines *perpendicular to the X-axis*, followed by those
288 lines along the X-axis.

290 2. SAW Device Fabrication via Wet Etching Method

291
292 2.1. Wafer solvent cleaning: In a Class 100 clean room facility, immerse the 4" (101.6 mm) LN
293 wafer into acetone, followed by IPA, and deionized DI water in a sonication bath for 5 min,
294 respectively. Pick up the wafer and use dry N₂ gas flow over the surface of the wafer to remove
295 the remaining DI water from the wafer.

296
297 CAUTION: Use acetone and IPA in a fume hood. Avoid inhalation and skin contact with IPA.
298 Avoid acetone contact with skin and eyes. Do not swallow.

299
300 Note: Do not allow any fluid to evaporate upon the wafer; if there is any dust or contamination
301 on the surface, start this step over.

302
303 2.2. Thermal treatment: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it
304 onto Al foil to cool down to room temperature.

305
306 2.3. **Electrode sputter deposition:** Place the wafer into a sputter deposition system. Vacuum
307 the chamber to 5×10^{-6} mTorr. Use argon flow at 2.5 mTorr, sputter Cr with a power of 200 W
308 for 5 nm as an adhesion layer, followed by sputtering Au with a power of 300 W for 400 nm to
309 form the conductive electrodes.

310
311 NOTE: The protocol can be paused here.

312
313 2.4. **Spin coating:** Place the wafer onto a spin coater. Place positive photoresist (AZ1512) onto

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318 the wafer using a dropper, covering about 75% of the wafer surface area. Program a speed of
319 500 rpm with acceleration of 3000 rpm/sec for 10 sec and then a speed of 4000 rpm with
320 acceleration of 3000 rpm/sec for 30 sec, giving a thickness of the photoresist at around 1.2 µm.

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

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

331 2.5. Soft bake: Place the wafer onto a hotplate at 100 °C for 3 min. Then transfer it onto Al foil
332 to cool down to room temperature.

334 2.6. Ultraviolet exposure: Transfer the wafer to the mask aligner (MLA150). Expose the
335 photoresist with an energy dose of 150 mJ/cm² at 375 nm to the wafer. The energy dose
336 required may vary based on the mask design and the age and condition of the photoresist.

338 2.7. Develop: Place the wafer into a beaker filled with pure AZ300MIF developer for 30 sec.
339 Gently shake the beaker during development. Immerse the wafer into DI water for 1 min, then
340 rinse the wafer under DI water flow. Finally, use dry N₂ flow to remove the remaining DI water
341 from the wafer. Never let any fluid evaporate on the wafer surface.

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

345 2.8. Au etching: Immerse the wafer into a beaker filled with Au etchant for 90 sec, gently
346 shaking the beaker. After rinsing the wafer under DI water flow, use dry N₂ flow to remove the
347 remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

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

353 2.9. Cr etching: Immerse the wafer into a beaker filled with Cr etchant for 20 sec, gently
354 shaking the beaker. After rinsing the wafer under DI water flow, use dry N₂ flow to remove the
355 remaining DI water from the wafer. Never let any fluid evaporate on the wafer surface.

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

360 2.10. Sample cleaning: Put the wafer into acetone, followed by IPA, and DI water in a sonication
361 bath for 5 min, respectively. Pick up the wafer and use dry N₂ gas flow over the surface of the

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385 wafer to remove the remaining DI water from the wafer.

386
387 CAUTION: Use acetone in a fume hood. Avoid inhalation and skin contact acetone with skin and
388 eyes. Do not swallow.

389
390 NOTE: This step is to remove undesired photoresist from the wafer.

391
392 2.11. Dicing process: Use a dicing saw to dice the entire wafer into chips as SAW devices for
393 further use.

394
395 NOTE: The fabrication is completed. The protocol can be paused here.

396 Experimental Setup and Testing

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

398
399
400 NOTE: Scratches may be present upon the metal layers deposited on the LN. Generally, they
401 will not cause a notable influence of the device performance, as long as the scratches do not
402 result in an open circuit.

403
404 2. SAW actuation: Attach absorbers at both ends along the propagation direction of the SAW
405 device to prevent reflected acoustic waves from the edges. Use a signal generator to apply a
406 sinusoidal electric field to the IDT at its resonance frequency around 100 MHz. An amplifier may
407 be connected to amplify the signal. Use an oscilloscope to measure the actual voltage, current,
408 and power applied to the device. The amplitude and frequency response of the SAW generated
409 by the device may be measured by a laser Doppler vibrometer (LDV, UHF-120, Polytec,
410 Waldbronn, Germany). The SAW-actuated droplet motion may be recorded using a high-speed
411 camera attached to the microscope.

412 REPRESENTATIVE RESULTS:

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

417
418
419 Applying an sinusoidal signal to the IDT near the designed resonance frequency allows SAW to
420 be generated to propagate across the surface of the piezoelectric material. The LDV measures
421 the vibration via the Doppler effect on the surface, and through signal processing, information
422 such as amplitude, velocity, acceleration, and phase can be acquired and displayed. We
423 illustrate the frequency response under a frequency sweep from 90 to 105 MHz using an input
424 power of 140 mW, a peak-to-peak voltage of 70 V, and peak-to-peak current of 720 mA. As
425 Figure 2(A) indicates, the resonance frequency is measured to be 96.5844 MHz, slightly lower
426 than the design frequency of 100 MHz, attributable to the mass loading of the deposited metal,
427 for an amplitude of 19.444 pm. Figure 2(B) plots the vibration upon the substrate surface,
428 showing a SAW to be propagating from the IDTs. The standing wave ratio (SWR) is calculated to

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Deleted: of around 100 MHz. An amplifier should...ay be connected to amplify the signal. Use an oscilloscope to measure the actual voltage, current, and power applied onto the device. The amplitude and frequency response of of the SAW are...enerated by the device may be measured by a laser Doppler vibrometer (LDV); the ... UHF-120, Polytec, Waldbronn, Germany). The SAW-actuated droplet motion ... [4]

Deleted: at of 100 MHz, as the finger width and the spacing between them...he fingers of the IDT and the widths of the fingers themselves are all 10 μm , producing amaking the wavelength of ...0 μm . Figure 1(B) shows...s an IDT image of the IDTs fabricated using this... [5]

Deleted: Using...plying an oscillating electrical...inusoidal signal matched ...o the resonant...DT near the designed resonance frequency of the IDT,...llows SAW can...o 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 using the software.. We illustrate the frequency response under a frequency sweep from 90 to 105 MHz, with...using an input power of 140 mW, a peak-to-peak voltage of 70 V, ...nd a peak-to-peak current of 720 mA. As Figure 2(A) indicates, the amplitude of the SAW is 19.444 pm at a ...esonance frequency of ...s measured to be 96.5844 MHz. The slight reduction in ... slightly lower than the design frequency from theof 100 MHz design is attributed... attributable to the mass mass loading of the deposited metal IDT electrodes... for an amplitude of 19.444 pm. Figure 2(B) illustrates...lots -the LDV-measured ...ibration of...pon the SAW on the...ubstrate surface, shown ... [6]

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.

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

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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Deleted: A gold...old-electrode IDT...DTs with 0.... mm aperture on an LN substrate for 100 MHz SAW generation and propagation. (B) The IDT fingers of...pon the IDTs... [10]

Moved down [1]: Scale bar: 200 μm.

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Deleted: of the SAW device from 90 MHz to 105 MHz includes its... 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 input level of 1 V from the LDV. (B) The SAW present upon...esonance frequency as it propagates across the LN substrate as it propagates from the IDT. The phase has been determined by scanning the LDV head to measure in multiple locations, with the phase referenced against the input electrical signals [12]

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Deleted: SAW devices fabricated from either method are capable of generating useful traveling waves on the surface, and these methods underpin more complex processes to produce other designs. The resonance frequency is usually a little lower than the designed value, due to the mass loading effect of the metal deposited on top. However, there are [16]

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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... [18]

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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.

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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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ACKNOWLEDGMENTS:

The authors are grateful to the University of California and the NANO3 facility at UC San Diego for provision of funds and facilities in support of this work. This work was performed in part at the San Diego Nanotechnology Infrastructure (SDNI) of UCSD, a member of the National Nanotechnology Coordinated Infrastructure, which is supported by the National Science Foundation (Grant ECCS-1542148). The work presented here was generously supported by a research grant from the W.M. Keck Foundation. The authors are also grateful for the support of this work by the Office of Naval Research (via Grant 12368098).

DISCLOSURES:

The authors have nothing to disclose.

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