Phase Velocity Control of Surface Acoustic Waves Based on Surface Shorting and Electrical Field Application using MEMS Switches

Jan H. Kuypers, Marek E. Schmidt, Shuji Tanaka, and Masayoshi Esashi
Department of Nanomechanics
Tohoku University
Sendai, Japan
jan@mems.mech.tohoku.ac.jp

***Abstract*—We have investigated controlling the phase velocity of a surface acoustic wave (SAW) by a microelectromechanical switch fabricated on a high coupling piezoelectric substrate. The principle is based on the interaction of the evanescent surface potential of the SAW with the conductive switch. In theory tuning of the velocity in the range given by v_0 and v_m, i.e. the velocity for a SAW on a free and metallized substrate, is possible. We have achieved up to 17.6 m/s (0.44 %) velocity tuning on 128°YX $LiNbO_3$. A maximum velocity sensitivity of $\Delta v/v$ of 15×10^{-3}/V and phase sensitivity of 700°/V was measured. This is five orders of magnitude larger than values obtained for electrical field tuning.**

Keywords-Surface Acoustic Waves, Velocity Tuning, Tunable SAW Device, Surface Shorting Effect, Electrical Field Tuning

I. Introduction

Tunable SAW devices are of great interest for acoustic phase shifters, active temperature compensation, novel sensors, and adaptive filters and oscillators. The sensitivity of a SAW towards mechanical and intrinsic effects as strain, stress, torque, pressure, mass loading, temperature etc. has been widely exploited [1][2]. Although high precision sensors have been demonstrated based on these effects, the actual velocity change is very small, in the tens to hundreds of ppm range. The sensitivity of a SAW for high coupling substrates towards changes in the electrical boundary conditions can be much larger and is in the range of 0.1~10 %. This effect has been applied to sensors [3][4], but moreover in combination with a semiconducting material to SAW amplifiers, phase shifters and power dividers [5][6][7][8].

This work is the first to investigate the most fundamental tuning principle of shorting the surface of a piezoelectric substrate by an actuated conductive sheet. The underlying theory of the interaction of a SAW with such a conductive sheet has been presented by Campbell and Jones [9] and by Auld [10]. The structure investigated in this work is illustrated in Figure 1, where a conductive MEMS switch is fabricated above the acoustic track of a two-port SAW device. The mechanically controlled shorting of the substrate surface is referred to as surface shorting effect throughout this paper.

This work was supported in part by the Strategic Information and Communications R&D Promotion Program (SCOPE) from the Ministry of General Affairs (062302002).

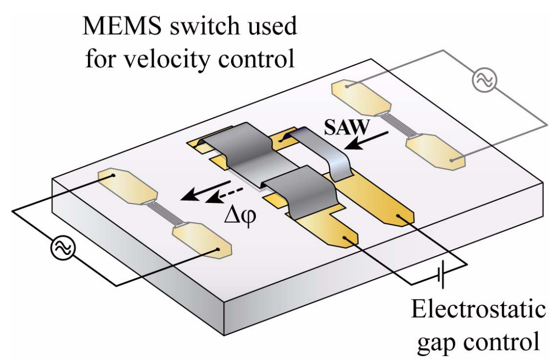

Figure 1. Investigated structure for velocity control of surface acoustic waves by means of an electromechanically actuated MEMS switch.

II. Operating Principle

The difference of the velocity of a SAW for a free v_0 and metallized surface v_m is related to the electromechanical coupling coefficient k^2 as [11]

$$k^2 \cong \frac{v_0^2 - v_m^2}{v_0^2} \approx \frac{2\Delta v}{v_0}. \tag{1}$$

For a high coupling substrate this refers to more energy of the SAW being stored in the electrical waves, and thus explains the higher sensitivity towards the electrical surface condition being free or shorted. The condition of a metallized surface corresponds to a conductive sheet being in contact with the substrate surface, and a velocity of the SAW of v_m, whereas for an infinite gap the velocity is v_0, as for a free surface. The cross-section of this piezoelectric half-space with the conductive sheet is shown in Figure 2 (a). The velocity as well as the distribution of the surface potential for different gap heights is numerically computed based on the work by Campbell and Jones [9], as shown in Figure 2 (b). Based on the perturbation approach by Auld [10], a closed form approximation for the velocity dependence is obtained.

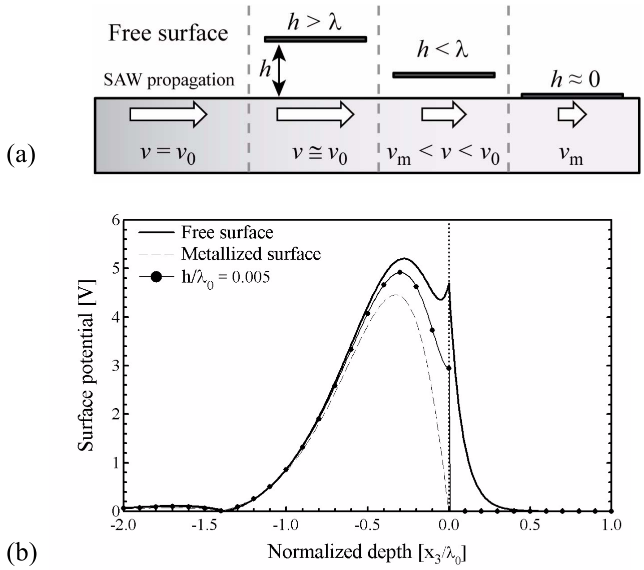

Figure 2. Piezoelectric half-space with a conductive sheet close to the substrate surface (a). Evanescent surface potential for 128°YX $LiNbO_3$ (b), for: a free surface, a conductive sheet touching the surface (metallized surface), and for a gap h of 0.005 λ_0.

For a gap height h between the substrate surface and the switch, the phase velocity of the SAW is given by

$$v(h) = v_0 - \Delta v \cdot \frac{1 - tanh(hk)}{1 + \varepsilon_\infty tanh(hk)}, \qquad (2)$$

where v_0 corresponds to the Rayleigh velocity for a free surface, $\Delta v = v_0 - v_m$ to the difference of free and metallized Rayleigh velocity, ε_∞ to the static relative permittivity of the substrate, and k to the propagation constant of the Rayleigh wave, respectively.

The comparison of the numerical result and the analytical expression is shown in Figure 3 revealing a slight discrepancy

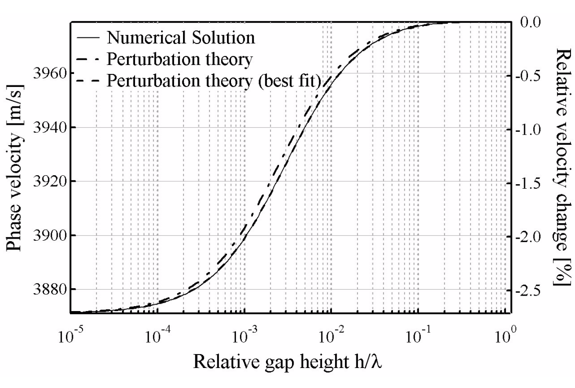

Figure 3. Velocity dependence of a SAW on 128°YX $LiNbO_3$ for a gap h between the substrate surface and the conductive sheet. The computation uses a numerical approach and a closed form expression based on perturbation theory.

of both solutions. This is referred to the perturbation approach assuming unchanged stress fields of the perturbed solution and an unchanged wave vector $k' = k$, which is incorrect for high coupling substrates. Nevertheless, a best fit value of the effective permittivity, i.e. for 128°YX $LiNbO_3$ $\varepsilon_\infty = 54.03$, leads to a close agreement of both results. Further we have $v_0 = 3979.3$ m/s and $v_m = 3870.7$ m/s. In theory this allows for velocity tuning of $\Delta v/v$ of up to 2.7 %.

The lowest velocity given by v_m is practically not achievable as this would require a perfect contact of the switch and the substrate. In reality the surface roughness of the substrate and moreover of the switch will lead to a residual gap. As the velocity shown in Figure 3 is related to the normalized gap h/λ, a residual gap is more severe at higher frequencies. At 2.45 GHz a residual gap of 8 nm still allows for 1 % velocity tuning, whereas at 500 MHz a gap of 39 nm is enough to achieve tuning of 1 %. In order to ensure that the initial velocity for the switch in the up-state is not affected within 0.01 % of v_0, an initial gap of 0.3 μm and 1.5 μm is sufficient for 2.45 GHz and 500 MHz, respectively. This means that the up-state of the MEMS switch can be chosen close to the substrate surface and that the tuning does not require a large displacement. Therefore, the structure lends itself to a low voltage operation of an electrostatic switch.

III. Fabrication

In order to characterize the velocity tuning for a controlled surface shorting, we fabricated two-port SAW devices with an electrostatic MEMS switch above the acoustic track, as illustrated in Figure 1. For the IDTs we chose single electrode transducers with a center frequency of 2.45 GHz and a split-finger IDT with passbands at 600 MHz and 1800 MHz to investigate the frequency dependence.

The device fabrication is similar to a standard SAW device with an additional low temperature surface micromachining process identical to the one used in [12]. First, alignment marks, IDT bondpads and switch electrodes are formed by the lift-off of 50 nm thick Cr and 400 nm thick Au. Next, the SAW device itself is fabricated using direct electron beam lithography and lift-off of 50 nm thick Al. In order to define a small initial gap height of the switch above the acoustic track, photoresist is used as the sacrificial layer. Furthermore, to prevent the pull-in and electrical shorting in the region of the actuation electrodes, another thicker sacrificial photoresist layer is patterned on top to form a larger initial gap. This approach consists of a simple consecutive two-mask process. The combination of the gap above the acoustic track and above the actuation electrodes of 0.5 μm/3.5 μm resulted in switching voltages of 2.6 V to 5 V. The switch is fabricated on this double layer of photoresist by depositing 1 μm thick Al by sputtering and patterning the Al by wet etching. The switch is finally released by an oxygen plasma process. The completed device is shown in Figure 4.

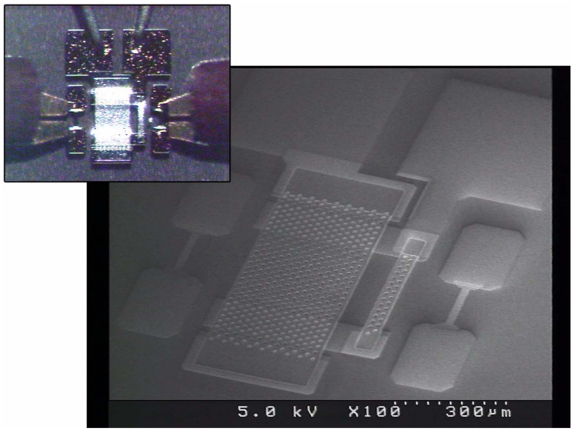

Figure 4. SEM image of the fabricated two-port SAW device used for the characterisation of the velocity tuning based on surface shorting. The inset shows the device during on-wafer level probing.

IV. EXPERIMENTAL

The velocity change induced by the gap height of the switch was evaluated from the induced phase shift $\Delta\varphi$ of S_{21}, given by

$$\Delta\varphi = 2\pi f\left(\frac{w}{v(h)} - \frac{w}{v_0}\right), \quad (3)$$

where w corresponds to the width of the switch, f to the frequency, h to the gap height, and v_0 refers to unperturbed SAW velocity and $v(h)$ to the sought-after velocity. The fabricated two-port device was measured using an ENA5071B network analyzer and wafer level probes. A probe-card was used for the DC voltage application to the switch. In order to relate the velocity change to the gap height of the switch, we installed a laser interferometer above the probe station and recorded the phase shift and switch position for a given DC voltage applied to the switch.

For the chosen two-port structure the passband ripple caused by the triple transit echo (TTE) is inevitable. Instead of removing the ripple with a time gating method, which is rather time consuming as it requires a large number of points of the frequency characteristic, we chose a single frequency on the lower shoulder of the passband. Although such a frequency suffers from an increased insertion loss, it effectively removes the problems of TTE and simplified the direct phase shift evaluation. The frequency used in the measurement is denoted in the graphs.

V. RESULTS

The results of the switch height and phase for a 220 µm wide switch are shown in Figure 5. The measured switch height is interpreted as follows: As the applied voltage increases the switch slowly moves downwards (1.) and snaps down (2.) due to the electrostatic forces exceeding the restoring force of the switch, which is often referred to as pull-in [13]. The larger gap height above the actuation electrodes prevents the pull-in and the electrical shorting of the switch. After pull-in the switch is in contact with the surface and does not move any further (3.). As the voltage is decreased (4.) the switch finally returns to the up-state at a negative voltage (6.). Decreasing the voltage even further causes a downwards movement of the switch (7.) and pull-in (8.). No movement of the switch is observed in (9.) and (10.). Finally, the switch returns to the up-state (12.). The hysteresis of the switch is characteristic for an electrostatic switch, however, it is generally symmetric to the origin at 0 V [13]. This asymmetry is believed to originate from the use of chemically reduced $LiNbO_3$ substrates and the internal bias observed for doped ferroelectrics [14].

The interpretation of the phase shown in Figure 5 (b) for 2320 MHz in terms of the measured displacement is as follows: Although the gap height decreases no phase shift is observed (1.). This is because the gap beneath the switch is larger than the 0.3 µm corresponding to a velocity change of 0.01 %, as discussed above. As the switch pulls-in a large phase shift of 40° is observed. This originates from the proposed surface shorting effect. Increasing the voltage even higher leads to a positive phase change, although the switch does not move (3.). This effect, observed also for negative voltages (9.) with an opposite sign, corresponds to the effect of electrical field tuning and is discussed later in more detail. As the voltage

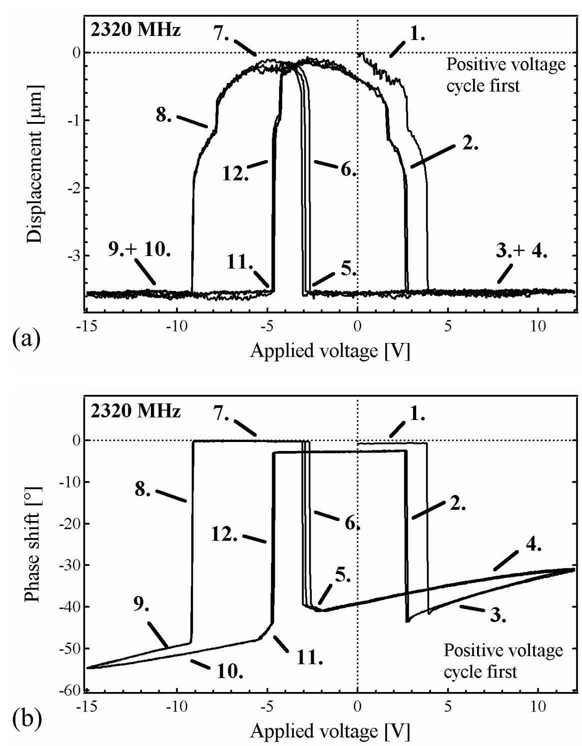

Figure 5. Results of the switch height (a) and related phase shift at 2320 MHz for a 220 µm wide switch (b).

is reduced (4.), hysteresis of the phase shift is observed, referred to here as remnant phase shift, which is believed to originate from surface charges. Before the switch returns to the upstate a small linear unloading region is observed (5.). The change to the up-state (7.) is related to a phase shift of close to 40° (6.). As the voltage is decreased initially no phase shift is observed (7.) although the gap height reduces. As the switch snaps down (8.) a large phase shift close to 50° is observed. For cycling the voltage further, without observing movement of the switch the phase decreases (9.), which again is related to electrical field tuning. Cycling the voltage back up again, leads to a remnant phase shift as observed earlier for a positive voltage. After unloading (11.) the switch returns to the up-state (12.). The phase difference observed for the initial phase (1.) and the phase after one cycle corresponds to the remnant phase shift observed between (9.) and (10.). In case of starting the voltage cycling with a negative voltage the difference corresponds to the remnant phase shift observed for (3.) to (4.), leading to a slightly larger offset.

A. SURFACE SHORTING EFFECT

The existence of the proposed surface shorting effect at 2320 MHz is confirmed based on the correlation of the large phase shift and the snap down of the switch. At pull-in a phase shift of 35° per 0.05 V is observed, as shown in Figure 6, leading to a sensitivity of 700°/V. This maximum sensitivity is characteristic for a structure with pull-in. The phase reduction of 35° relates to a velocity reduction of 3.01 m/s and a relative velocity change of 0.076 %. The relative fractional velocity change $\Delta v/v$ per volt is then 15.15×10^{-3}. This is 92,000 times larger than the electrical field tuning sensitivity reported by Joshi et al. [15], 46,000 times larger than the results by Budreau at al. [16], and 16,000 times larger than the most sensitive electrical field tuning device [17].

Nevertheless, we were unable to achieve the anticipated fractional velocity reduction of 1 %, i.e. velocity reduction of 39.8 m/s and corresponding phase shift for this 220 μm wide switch of 466° at 2320 MHz. The total velocity reduction observed in the region from 2.6 V to 2.7 V corresponds to a phase reduction of 41°, which relates to a velocity reduction of 3.53 m/s (0.089 %). Solving for the gap height using (2) leads to a residual gap height of 112 nm. The roughness of the switch, caused by the fabrication process of sputtering aluminum onto the sacrificial resist, could account for this residual gap and reduced sensitivity.

The phase shift result for a frequency of 520 MHz is shown in Figure 7. At this lower frequency the surface shorting effect leads to a phase shift of 46°, corresponding to a velocity reduction of 17.6 m/s, and relative velocity reduction of 0.44 %. This larger effect compared to the result at 2320 MHz is understood from the frequency dependence of the surface shorting effect, i.e. the evanescent surface potential extending further above the substrate. This is also seen from a small phase shift shown in Figure 7, just before the pull-in occurs, in comparison to the result shown in Figure 5. The measured velocity reduction of 17.6 m/s, based on (2) corresponds to a residual gap of 105 nm, which is in close agreement with the result obtained for 2320 MHz.

B. ELECTRICAL FIELD TUNING EFFECT

The sensitivity of surface acoustic waves towards an electrical field applied either normal to the substrate surface or in-plane with the substrate surface has been reported for metal electrodes directly deposited onto the substrate surface in [15][16][17]. The electrical field tuning for 128°YX $LiNbO_3$ was first reported by Joshi et al. [15], showing a linear relationship of the phase shift or fractional velocity versus the applied field, i.e. voltage. In this study after fabrication some of the switches were found to be in contact with the substrate surface, which was unintentional and is probably due to stress in the switches. For these switches we confirmed that no movement was observed when applying a voltage to the structure and that there was no electrical short. Such a structure was ideal to separate the electrical field tuning

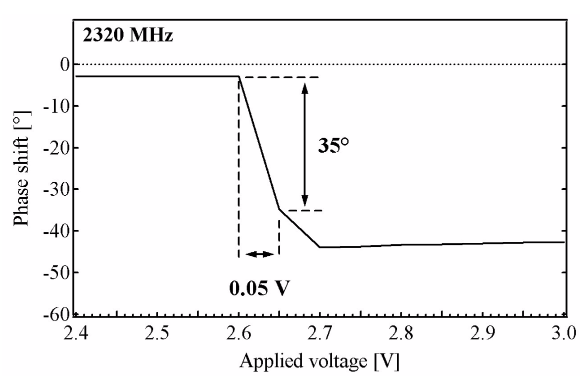

Figure 6. Close-up of the region of highest sensitivity of the phase-shift shown in Figure 5, related to the electrostatic pull-in of the switch.

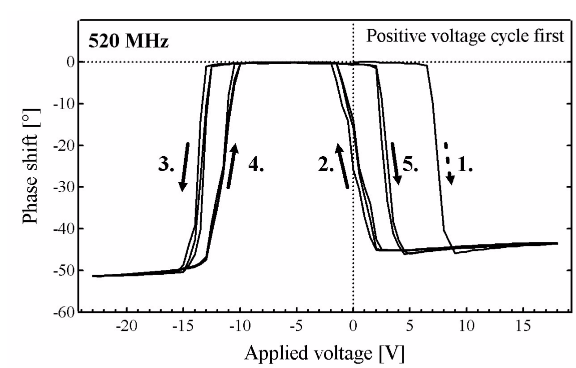

Figure 7. The phase shift for a 220 μm wide switch at 520 MHz occurs earlier in terms of the closing gap than at 2320 MHz due to the evanescent surface potential extending further above the substrate surface. This also leads to a larger velocity reduction for the same residual gap.

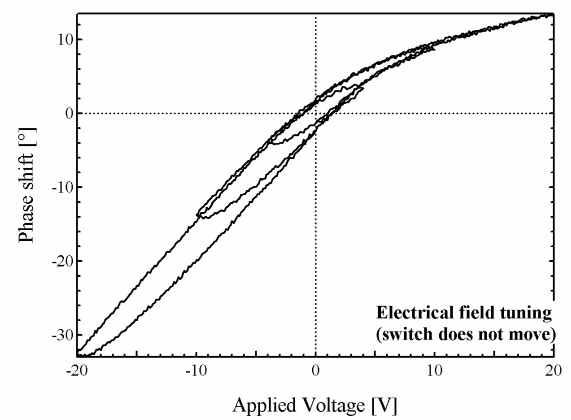

Figure 8. Result of the phase shift due to electrical field tuning for a 220 µm wide switch that was initially in the down-state and did not move for an applied voltage.

effect from the surface shorting effect. The result of such a switch initially in contact with the substrate surface is shown in Figure 8. For positive voltages a saturation of the induced phase shift is observed, which is highly non-linear, whereas for negative voltages a linear relationship is observed. These results reveal two fundamental differences compared to the results for the metal electrodes deposited directly onto the substrate [15]:

1. The phase shift is not linear for positive voltages, which is similar to the results observed for YZ $LiNbO_3$ [15]
2. Hysteresis of the phase shift is apparent.

We observed that the hysteresis strongly depended on the voltage sweep rate used for the characterisation. The results of three different rates is shown in Figure 9. The time dependence, which is also observed when applying a voltage step-function to the switch is believed to originate from surface charges and related charge adsorption and desorption phenomena due to the applied electrical field.

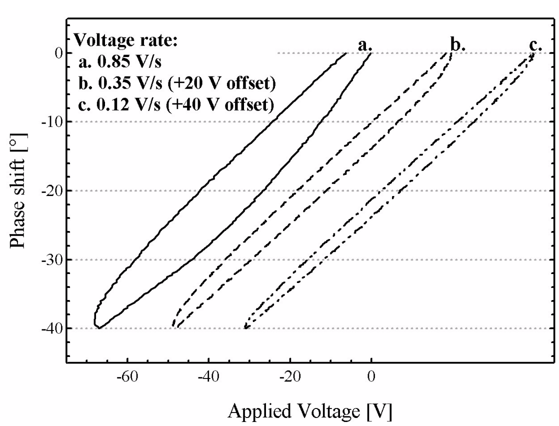

Figure 9. Results emphasizing the time dependence of the electrical field tuning for negative voltages applied to the switch.

It is interesting to note that the electrical field tuning sensitivity also depends on the gap height. This is understood from comparing the phase shift achieved for –8 V of Figure 8 to the result of Figure 5. However, finite element simulation of the normal electrical field strength for the structure shows only a difference of factor 2.6, whether the switch is in the up-state or down-state, taking into account buckling of the switch causing an initial gap of 5 µm. Based on this result we expect a slight phase shift due to the electrical field in (7.) of Figure 5, which is in fact not observed. Adsorbed surface charge is believed to reduce the electrical tuning for the switch in the up-state. We have measured electrical field tuning sensitivities in the range of 0.89 to 1.9 °/V and sensitivities of the phase velocity $\Delta v/v$ per volt of $19.3{\sim}41\times10^{-6}$/V. Joshi et al. [15] defines a sensitivity coefficient γ, as

$$\frac{\Delta v}{v} = \frac{\Delta\varphi}{\varphi} = \gamma E , \qquad (4)$$

where E corresponds to the electrical field and the delay line is taken to be non-dispersive. From FEM simulation the maximum normal field component for the switch in contact with the substrate surface was computed as 6 kV/m for one volt applied to the switch. For our result this leads to values for γ in the range of 3.21×10^{-9} m/V to 6.86×10^{-9} m/V, which is 40~84 times larger than the results given in [15] and 23~49 times larger than the results of [16] for the same substrate, except that the switches were fabricated directly on the substrate surface, without the air gap. As mentioned earlier these results of [15][16] are linear in respect to the applied voltage and do not show hysteresis effects.

VI. Discussion and Applications

Electrical field tuning effects can be prevented by electrically isolating the region of the switch above the acoustic track intended for the actual shorting and the electrode region used for actuation and voltage application. An alternative is to use a guard-electrode beside the actuation electrode close to the acoustic track at the same potential as the switch to prevent electrical fields in the acoustic track region. Another possibility to prevent electric field effects is to apply alternative actuation principles instead of electrostatic actuation.

The measured velocity reduction due to surface shorting is smaller than anticipated, which is to be improved by modifying the fabrication process. However, the effect has demonstrated tuning of 0.44 % and a large sensitivity in terms of a phase shift. The presented effect is promising for the application to acoustic phase shifters [12], programmable SAW ID tags, tunable resonators and filters using an electromechanical control. Further applications include displacement sensors for nano-metric sensing and pressure sensing, using the area of a conductive sheet in contact with the substrate surface as a measure. For such a pure mechanically induced shorting charge effects as well as hysteresis effects are prevented.

VII. Conclusion

We have demonstrated tuning of the phase velocity of a SAW based on shorting the substrate surface using a MEMS switch. Velocity reduction as large as 17.6 m/s was obtained for devices operating at 520 MHz on 128°YX $LiNbO_3$, relating to a relative velocity change of 0.44 %. The measured sensitivities of the relative fractional velocity change $\Delta v/v$ per volt of 15.15×10^{-3} and phase shift of 700°/V are shown to be five orders of magnitude larger than the most sensitive electrical field tuning device. The sensitivity of the SAW towards the normal electrical field created in the substrate area beneath the switch was found to be at least one order of magnitude larger than reported results for the electrode deposited directly on the substrate surface. Furthermore, the air gap of the presented structure and surface charge phenomena lead to a time dependence and hysteresis of the phase shift with respect to an applied voltage. For this electric-field-induced phase shift, the velocity reduction is only linear for negative voltages applied to the switch.

References

[1] D. S. Ballantine, R. M. White, S. J. Martin, A. J. Ricco, E. T. Zellers, G. C. Frye, H. Wohltjen, "Acoustic Wave Sensors", Academic Press, Inc., 1997.

[2] G. Fischerauer, "Surface Acoustic Wave Devices", W. Gopel, J. Hesse, J. N. Zemel, H. Meixner, R. Jones (Eds.), Sensors: A Comprehensive Survey, vol. 8., Weinheim: VCH, 1995.

[3] T. Nomura, T. Yasuda, S. Furukawa, "Humidity Sensor using Surface Acoustic Waves Propagating along Polymer/LiNbO3 Structures", Proc. IEEE Ultrason. Symp. 1993, pp. 417-420.

[4] T. Nomura, K. Oofuchi, T. Yasuda, S. Furukawa, "SAW Humidity Sensor Using Dielectric Hygroscopic Polymer Film", Proc. IEEE Ultrason. Symp. 1994, pp. 503-506.

[5] G. S. Kino, "Acoustoelectric Interactions in Acoustic-Surface-Wave Devices", Proc. IEEE, 1976, pp. 724-748.

[6] J. D. Crowley, J. F. Weller, T. G. Giallorenzi, "Acoustoelectrically Controlled SAW Power Divider", Proc. IEEE Ultrason. Symp. 1977, pp. 633-636.

[7] S. Urabe, "Voltage Controlled Monolithic SAW Phase Shifter and Its Application to Frequency Variable Oscillator", IEEE Trans. Son. Ultrason., su-29, no. 5, 1982, pp. 255-261.

[8] M. Rotter, W. Ruile, A. Wixforth, J. P. Kotthaus, "Voltage Controlled SAW Velocity in GaAs/LiNbO3-Hybrids", IEEE Trans. Ultrason., Ferroelect., Freq. Contr., vol. 46, no. 1, 1999, pp. 120-125.

[9] J. J. Campbell, W. R. Jones, "A Method for Estimating Optimal Crystal Cuts and Propagation Directions for Surface Waves", IEEE Trans. Sonics Ultrason., vol. su-15, no. 4, 1968, pp. 209-217.

[10] B. A. Auld, "Acoustic Fields and Waves in Solids", vol. 2, 2nd ed.

[11] K. Hashimoto, "Surface Acoustic Wave Devices in Telecommunications", Springer, 2000, ISBN 3-540-67232-X.

[12] J. Kuypers, M. Schmidt, S. Tanaka and M. Esashi, "Monolithic Phase Shifter based on Mechanically Tunable SAW Delay Line", Proc. Transducers 2007, pp. 161-164.

[13] J. R. Gilbert, G. K. Ananthasuresh, S. D. Senturia, "3D Modeling of Contact Problems and Hysteresis in Coupled Electromechanics", Proc. IEEE MEMS 1996, pp. 127-132.

[14] H. Neumann, G. Arlt, "The Deformation of Hysteresis Curves by an Internal Bias in Ferroelectric Ceramics", Proc. IEEE Ultrason. Symp. 1987, pp. 671-674.

[15] S. G. Joshi and B. B. Dasgupta, "Electronically Variable Surface Acoustic Wave Time Delay using a Biasing Electric Field", Proc. IEEE Ultrason. Symp. 1981, pp. 319-323.

[16] A. J. Budreau, P. H. Carr, J. H. Silva, "New Configuration for Electronically Variable SAW Delay Line", Proc. IEEE Ultrason. Symp. 1982, pp. 399-400.

[17] A. J. Budreau, G. J. Scalzi, P. H. Carr, H. L. Bertoni, "Electrostatically Variable SAW Delay Lines-Theory and Experiment", IEEE Trans. on Sonics Ultrason., vol. su-31, no. 6, 1984, pp. 646-651.