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Proton-exchanged (PE) regions in $LiNbO_3$ create an invisible inhomogeneity that can be used as surface acoustic wave (SAW) reflectors similar to metallized overlays, implanted layers, or grooves. We report the detection of coherently reflected SAW, from a dispersive array of proton-exchanged dot rows, by utilizing a sensitive interferometric heterodyne laser probe. © *1995 American Institute of Physics.*

Grooves and metal strips/dots have been used extensively in the realization of reflection based surface acoustic wave (SAW) devices[1] such as resonators, reflective array compressors (RAC),[2] reflective dot arrays (RDA),[3] and recently in low-loss filters. While devices utilizing metal reflectors may be cheaper to fabricate and require less sophisticated process technology than grooved devices, precise metal thickness control over large device areas and performance degradation due to aging of the metal layer/metal-substrate adhesion are some obvious drawbacks. Attempts have been made to explore other varieties of reflectors such as introducing inhomogeneity in the material properties by implantation.[4] However, implantation is an expensive technology. An implementation that is simple and cheap, requiring inexpensive fabrication technology while producing reproducible/reliable devices, would be attractive to explore.

The underlying principle of SAW reflection lies in creating an impedance discontinuity in the propagation path of surface acoustic waves. In materials such as $LiNbO_3$ and $LiTaO_3$, which are extensively used in SAW devices, discontinuity in the material property can be realized by proton exchange (PE)[5,6] for the purpose of SAW scattering. For this reason, the possibility of using the PE process for forming reflector regions in SAW devices was considered promising. It may be mentioned that proton exchange in $LiNbO_3$ and $LiTaO_3$ is an established technology in the field of integrated optical devices ever since the first demonstration by Jackel and co-workers[7] and Canali *et al.*[8] Whereas change of refractive index is the parameter of prime interest in optical waveguides, change in elastic and piezoelectric properties is of interest in SAW.

Proton exchange is a low temperature process carried out in the range 150–280 °C.[5–8] It is generally achieved using benzoic acid or a mixture of benzoic acid and lithium benzoate as the source, but pyrophosphoric acid has also been used for this purpose. We have used "dilute melts" (0.25–2 mol %) of lithium benzoate in benzoic for the purpose of PE in *Y*-cut *Z*-propagating $LiNbO_3$, the commonly used substrate for RAC/RDA dispersive delay lines. Biebl and Russer[5] have, in a recent article on the study of elastic properties of PE $LiNbO_3$, summarized its known properties.

The schematic layout of the dispersive SAW RDA used in the present investigation[9] is shown in Fig. 1. The 9 finger pair IDT, with 2.5 mm aperture and 35 μm finger width/gap, generates SAW synchronously at 24.8 MHz. The 126 dot rows (angled at 46.82° to the z axis) comprising the dispersive reflective array were placed according to a linear FM law with the spacing between neighboring dot rows in the array varying from 133 μm (nearest to IDT) to 139 μm (center dot row) to 145 μm (farthest from IDT). The dot dimensions also varied from 23.5 μm (nearest to IDT) to 24.6 μm (center dot row) to 25.6 μm (farthest from IDT). The center-to-center distance between first and last dot rows was 17.35 mm.

The 2-in. diam *Y-Z* $LiNbO_3$ wafers were cleaned, metallized, and only the dot arrays first defined using a dark field mask and positive photoresist. At this stage the wafer had, apart from the alignment marks provided deliberately, holes in the Cr/Au layer corresponding to the dot positions. The wafer was then subjected to proton exchange at 240 °C in benzoic acid diluted by 1 mol % lithium benzoate for about 40 h. For this purpose the wafer and powdery mixture were placed in a tightly sealed quartz ampoule and then put in an oven at the determined temperature. At the end of the exchange period, the wafer was allowed to cool down to room temperature and the benzoic acid crystallized on the cooled samples was removed by dissolving in dimethyl formamide followed by ultrasonic cleaning in propanol/acetone. At the end of this stage, the PE reflector dots of the RDA DDL had

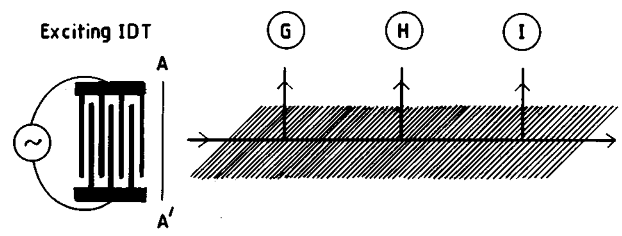

FIG. 1. Schematic layout of the investigated downchirp SAW reflective dot dispersive array consisting of an exciting interdigital transducer and chirped array of proton-exchanged dot rows as reflectors. A laser probe is used for characterizing the SAW reflection properties of this array by probing at the various regions shown—*AA*′, *G*, *H*, and *I*.

been defined. Subsequently, the IDTs were defined by using the alignment marks provided and the device was then bonded and packaged. To suppress SAW reflections from the edges of the crystals, RTV absorber is applied on all sides of the device.

One of the crucial design parameters is the depth of discontinuity. We had recently reported two techniques for proton-exchange depth determination from laser induced pyroelectric voltage measurements[10,11] utilizing an automated nondestructive characterization system for pyroelectric materials.[12] In devising a strategy to measure the PE depth, use has been made of the fact that $LiNbO_3$ is not only piezoelectric but also pyroelectric. In fact, proton exchange renders $LiNbO_3$ practically nonpiezoelectric,[13] creating a nonpiezoelectric over piezoelectric multilayer structure. This also has a corresponding effect on the pyroelectric properties of the exchanged materials, which is then measured. The PE layer depth was thus measured to be 3.2 μm.

Since SAW are mechanical waves propagating at the substrate surface, apart from the electrical characterization in time and frequency domain, the device performance can be gauged by measuring the displacement of the SAW at different frequencies and at various regions. For this purpose, a variety of highly sensitive methods has been developed, most of which are optical. One such laser probe is the off-centered compact asymmetrical heterodyne probe,[14,15] with 10^{-4} Å/$\sqrt{\text{Hz}}$ sensitivity in the range 200 kHz to 45 MHz, and has been used in the present investigations.

The nature of the reflective array decides the dispersive performance, the input IDT generally being broadband. This is commensurate to the geometry of conventional RAC/RDA. The number of dot rows is decided on the basis that neighboring rows are spaced a wavelength λ (or its multiples for row withdrawn geometry) apart, in order to have coherent reflections. This adjacent row spacing changes from the beginning of the rows to the end, such that one end has maximum coherent reflection at the highest FM chirp frequency, and the other end at the lowest chirp frequency, depending on the nature of the chirp.

Referring to Fig. 1, SAW generated by the input IDT are reflected through 90° by a reflective array in their path. Therefore, a laser probe scan in the region AA' will give a profile of the initially launched SAW and at points G, H, and I will give the SAW amplitude of the once-reflected wave. The important point to note is that due to the chirped nature of the reflective arrays, the frequency response spectrum at these points will be different.

In the present case the arrays are designed for a *downchirp*, i.e., frequency decreasing with time. Therefore, G should have dominant coherent reflections at a higher frequency as compared to that at H and I, H dominant reflections at the center frequency and I at the lower edge of the chirp bandwidth. In the row withdrawn device design under consideration,[9] the design specifications of the reflective array that were laser probed are as follows: center frequency f_0=24.7 MHz, and chirp bandwidth Δf=2.16 MHz in a time dispersion ΔT=5 μs.

Figure 2 gives the laser probe measured frequency response of the SAW launched by the input IDT (region near the center of AA'). In the expected $(\sin x/x)$ response, characteristic of an unapodized IDT, the first nulls fall near 22.25 and 27.75 MHz, in excellent agreement with the predicted $2f_0/N$ (=5.5 MHz) bandwidth. Also, it may be noticed that the peak displacement of the SAW at the center frequency corresponds to about 1.75 Å for an applied voltage of 22 V (measured in 1 MΩ oscilloscope input) to the IDT!

Figure 3 not only demonstrates the coherent reflections taking place from a proton-exchanged reflective dot array,

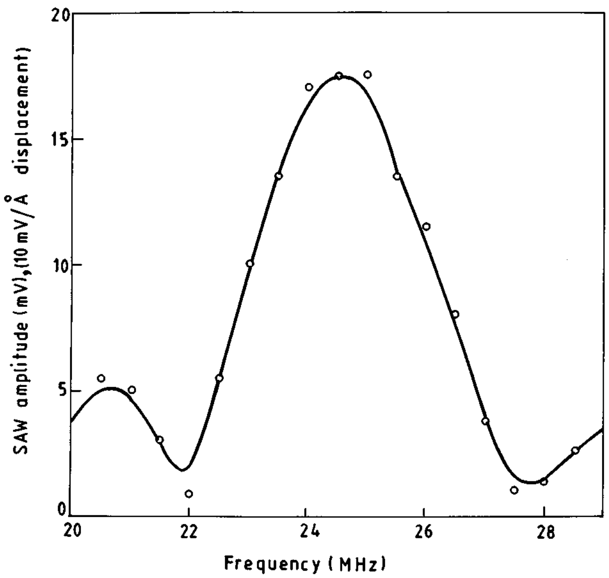

FIG. 2. Laser probe measured frequency response of the SAW launched by the input IDT (region near the center of AA' in Fig. 1) exhibiting the characteristic $(\sin x/x)$ shape. The peak displacement of the SAW at the center frequency corresponds to about 1.75 Å for an applied voltage of 22 V.

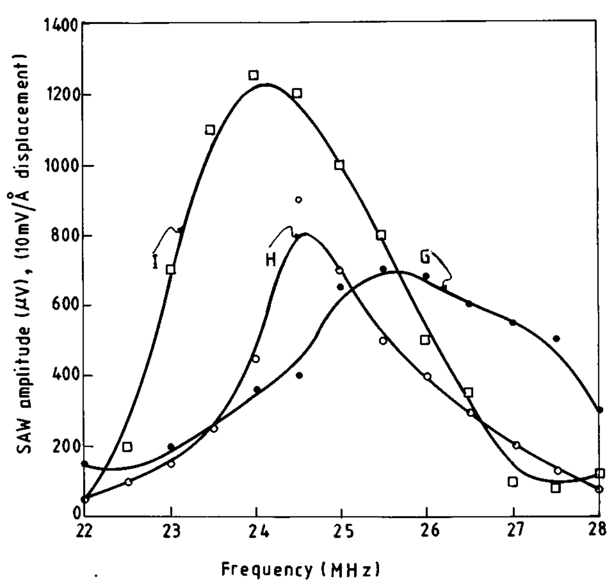

FIG. 3. Demonstration of the SAW reflections taking place from the proton-exchanged reflective dot array. At point G closest to the IDT (Fig. 1), the reflections peak at around 25.5 MHz. At H in the center of the array, the peak occurs at the center frequency in the region of I; at the farthest end, the maximum reflections occur at around 23.5 MHz. This is as expected in a downchirp array.

but also establishes its chirped nature. Shown are the laser probe measured frequency response profiles of the SAW reflected from various regions of the PE dot reflective array. In region *G* closest to the IDT, the reflections peak at around 25.5 MHz. At *H* in the center of the array, the peak occurs at the center frequency, and in the region of *I* at the farthest end, the maximum reflections occur at around 23.5 MHz. This is exactly as expected in a downchirp array. Quantitatively also, this measured band of peak reflections closely meets the design chirp bandwidth of 2.16 MHz.

To the best knowledge of the authors, this is the first reported illustration of SAW reflections from PE $LiNbO_3$. It may be noted that the shape of the frequency response plots at *G*, *H*, and *I* is due to the cumulative scattering of dots/dot rows near that point,[3,16] combined with the frequency response to the launching IDT itself, and as observed by the 25 μm laser probe spot. Williamson and Smith[2] has used a similar logic to visualize the change with distance, along a reflecting array of grooves in an RAC, of the frequency at which peak reflections occur. He has utilized an electrostatic probe for this purpose.[17]

A difference in peak reflection amplitudes at points *G* and *I* is probably due to fabricational defects and/or is related to the frequency dependance of reflections, $r = C(h/\lambda)$,[2,3,16] where h is the thickness/depth of discontinuity and λ the wavelength of incident/reflected SAW. In the present case, $(h/\lambda) \simeq 2.3 \times 10^{-2}$ and the number of dots in a row varies from 59 in the end row near *G* to 71 in the other end row at *I*. The SAW reflection amplitudes, in practical devices at frequencies $\geqslant$60 MHz, would be larger for similar PE depths, leading to improved insertion loss values.

To conclude, surface acoustic waves coherently reflected from a dispersive array of proton-exchanged dot rows have been observed by utilizing a sensitive interferrometric heterodyne laser probe. It opens up the possibility of realizing reflection-based SAW filters such as RDA, RAC, and resonators using PE reflectors.

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