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Periodically poled transduction structures built on thinned single crystal Lithium Niobate layers bonded onto Silicon

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The demand for highly coupled high quality acoustic wave devices has generated a strong innovative activity, yielding the investigation of new excitation principles and waveguide structures. In a recent work, we have investigated the interest of periodically poled transducers (PPTs) on single crystal $LiNbO_3$ Z-cut plates. The PPT simply consists of a periodically poled ferroelectric layer metallized on its two faces for acoutoelectric excitation. In this work, we have fabricated PPTs on single crystal $LiNbO_3$ Z-cut thinned layers reported on Silicon to develop a new kind of waveguide. Their fabrication is based on a home-made wafer bonding technique based on a metal-metal adhesion, the lithium niobate being lapped and polished in order to obtain a layer exhibiting a few tenth micrometer thick. The corresponding devices have been successfully fabricated and tested in the frequency range 100-600 MHz. The comparison between experimental measurements and theoretical analysis (using a combination of finite and boundary element analysis) shows that the modes are well controlled and that different kind of wave polarization may be excited.

Introduction

The demand for highly coupled high quality acoustic wave devices has generated a strong innovative activity, yielding the investigation of new excitation principles and waveguide structures. In a recent work, we have investigated the interest of periodically poled transducers (PPTs) on single crystal $LiNbO_3$ Z-cut plates [1]. The PPT simply consists of two electrically conductive medias deposited on each side of a periodically poled ferroelectric layer. The first experiments have been performed on optical grade 500 µm thick 3" wafers. The fabrication of PPTs then allowed the excitation of symmetrical Lamb modes with operating frequencies twice higher than the one obtained by using standard inter-digital transducers. It also has been demonstrated that such transducers can be built on thin epitaxial ferroelectric films deposited on $SrTiO_3$. It has been successfully implemented and tested for the excitation of elliptically polarized waves at frequencies ranging from a few tenth MHz up to 3 GHz [2].

In this work, we propose to fabricate PPTs on single crystal $LiNbO_3$ Z-cut layers bounded atop Silicon to develop RF passive devices compatible with silicon-based technologies. The fabrication of PPTs exhibiting poling periods of 10, 20 and 40 µm (corresponding to 5, 10 and 20 µm line-width respectively) has been successfully achieved. Several millimeter long periodically poled gratings of respectively 3960, 1980 and 990 periods have been manufactured and tested. These transducers are then bonded on a (100) 3" silicon wafer using a wafer bonding technique developed in our group based on a metal-metal adhesion. Finally the lithium niobate is lapped and polished in order to obtain a layer exhibiting a few tenth micrometer thick.

The resulting devices have been metallized and tested using our radio-frequency tip-probing machine together with a spectrum analyzer, yielding devices operating in the frequency range 100-500 MHz. These devices exhibit multi-mode responses because the thickness of the $LiNbO_3$ layers (between 50 and 30 µm) still is too large to reach a single mode regime. We also have used our finite element/boundary element code to simulate the implemented devices and a particular effort has been paid to extract the propagation and excitation parameters of the corresponding modes. We have tried to compute dispersion curves of our devices in order to derivate mixed-matrix parameters allowing for an objective estimation of the PPT capabilities. This point is discussed as a conclusion of the present work.

Fabrication of Periodically Poled Transducers

The Periodically Poled Transducer is fundamentally based on a periodically poled piezoelectric medium. Each side of this medium is metallized in order to obtain a capacitive dipole in which elastic waves can be excited thanks to phase construction. Such a periodically poled structure can be advantageously achieved on ferroelectric materials like PZT [2, 3] because of the rather small value of its coercive electric field (the absolute value of the electric field above which the spontaneous polarization can be inverted) or $LiNbO_3$.

As previously presented [1-3], we have performed our experiments on a dedicated poling bench which can control the poling of thick (500 µm) optical quality Z-cut $LiNbO_3$ plates. It mainly consists of a high voltage amplifier used to submit the wafer to an electric field strong enough to invert the negative poling of the material. The coercive electric field of the lithium niobate is 21kV/mm, consequently, the voltage needed to invert the domains is approximately 11kV. The domains to be poled are defined thanks to a photo-resist pattern on top of a plate surface. We have used a set of masks with poling periods (which correspond to acoustic wavelengths) equal to 10, 20 and 40 µm (corresponding to 5, 10 and 20 µm line-width respectively). The plate is held in a PMMA mounting by means of two O-ring joints which create two cavities fullfilled by a satured lithium chloride solution used as a liquid electrode (as it is shown in the scheme of fig.1).

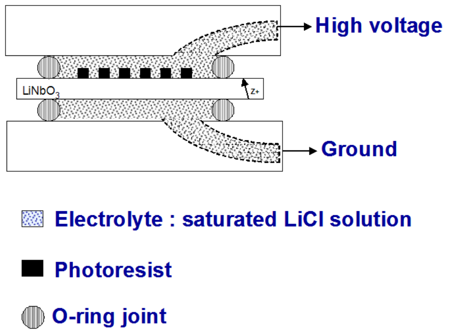


Fig.1 Device used to invert the domain

The high poling voltage is applied to the plate following the sequence reported in ref [1]. This sequence is designed to favor the domain nucleation, to stabilize the inverted domains (i.e. to avoid back-switching of the domains) and to avoid electrical breakdowns. The poling process is monitored thanks to the measurement of the electric current crossing the wafer during the sequence. The signature of a successful domain inversion corresponds to a voltage dropping while a current discharge occurs simultaneously. The poling can be easily controlled by a simple optical post-observation, as it generates a contrast between at the edge of the poled domains (see fig. 2).

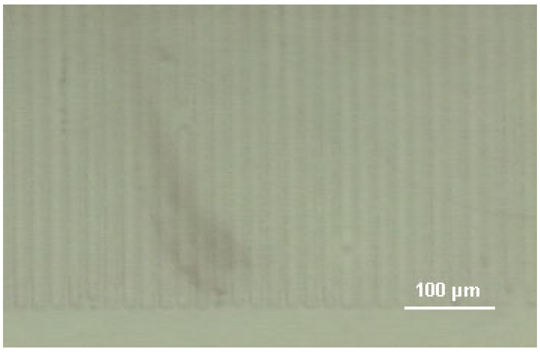
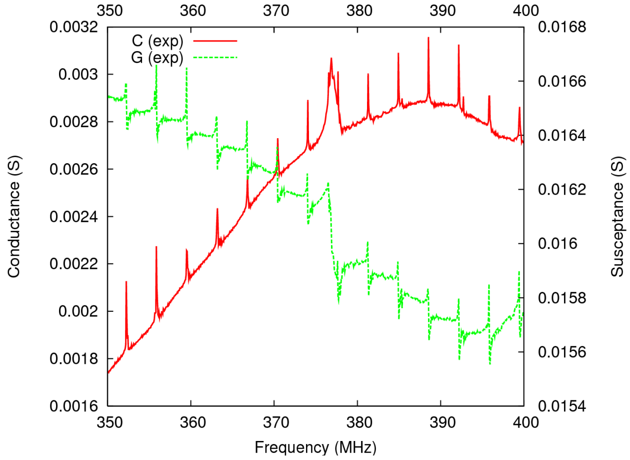


Fig.2 Optical verification of the poling efficiency, case of a 20 µm period device, evidence of contrast changes between Z^+ (native polarization) and Z^- (switched polarization) domains. The evidence of contrast modification in the vicinity of the poled domain walls at the poled strip edge (the whole plate is Z+ oriented, the poled strips are Z^- oriented) may be due to diffusion effects.

Experimental Results

All the devices have been found to operate and allowed for electrical measurements. However, significant contributions of longitudinal bulk waves are superimposed on the device responses, indicating that for most of the transducers, the poling was partially achieved and/or a perfect 50% volume ration between + and – domains was not obtained troughout the transducer length.



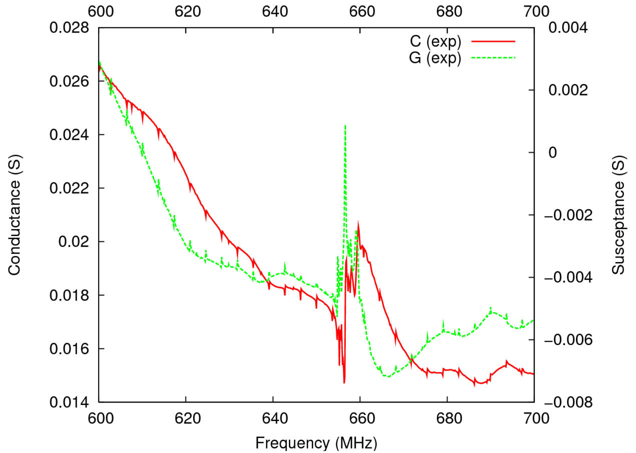


Fig.3a Experimental admittance of 10 µm period PPT (elliptic polarization wave at 375 MHz)

Fig.3b Experimental admittance of 10 µm period PPT (longitudinal polarization wave at 660 MHz)

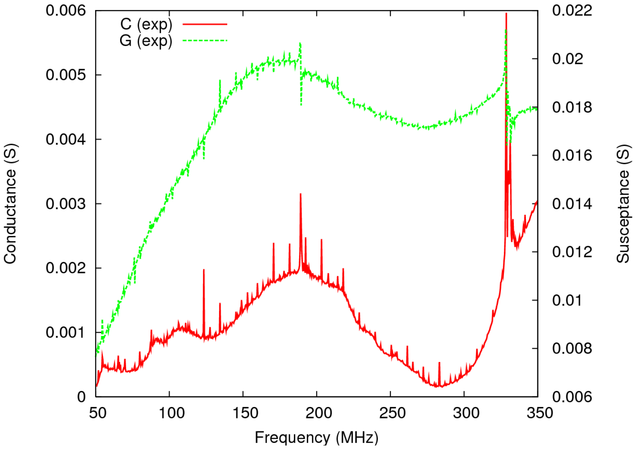


Fig.4 Experimental admittance of a 20 µm period PPT (elliptically polarized wave at 190 MHz and in-plane longitudinal wave at 335 MHz)

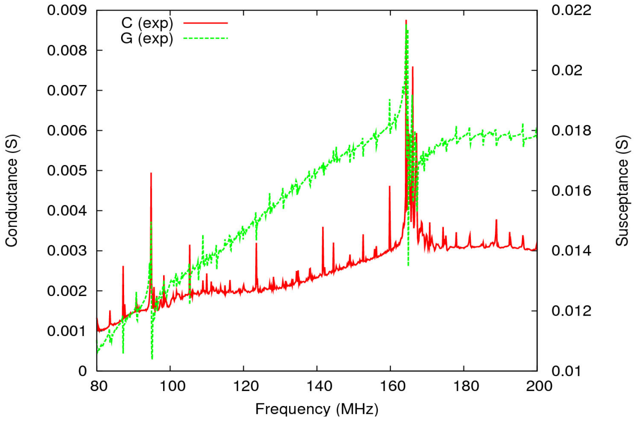


Fig.5 Experimental admittance of a 40 µm period PPT (elliptically polarized wave at 95 MHz and in-plane longitudinal wave at 170 MHz)

Figure 3a, 3b, 4 and 5 show strong contributions related to elliptically polarized and in-plane longitudinal waves respectively are pointed out at 95, 190, 375 MHz and 170, 335 and 660 MHz respectively, yielding wave velocities respectively equal to 3750 and 6600 m.s^{-1}, as theoretically expected [1]. We have shown in a previous work that our transducer actually is capable to efficiently excite high velocity in-plane longitudinal waves [4], these measurements demonstrate that these kind of wave is eventually better coupled and provides more admittance contributions than the elliptical one. This can be related to the coupling strength of longitudinal wave excited by an orthogonal electric field represented by the piezoelectric coefficient e_{21} (which equals the initial value of e_{33} after tensorial rotation)

Bonding and Lapping

The last two steps of our experiments consist in bonding the periodically poled wafer onto a silicon wafer and lapping the lithium niobate down to some tenth microns. In that purpose, the lithium niobate wafer is bonded on a (100) 3" silicon wafer using a wafer bonding technique developed in our group based on a metal-metal adhesion at room temperature promoted by a high pressure applied to the material stack (fig.6). The lithium niobate wafer then is lapped and polished in order to obtain a layer thinner than 50 microns. Finally, a metal coating of the $LiNbO_3$ top surface is achieved in order to measure the admittance of each device by means of a Suss Microtech tip-prober coupled to a RF spectrum analyzer. The process flow chart is reported in fig.7, showing the different implemented coatings and the technological sequence.

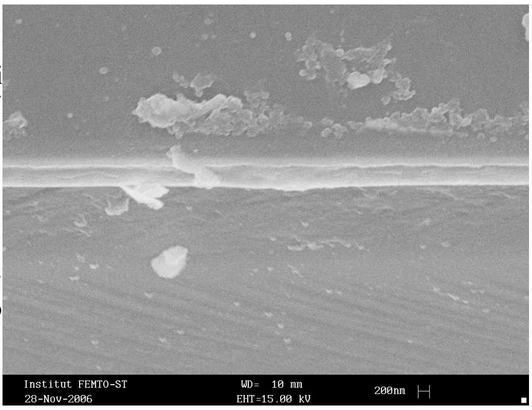


Fig.6 Bonding of a lithium niobate wafer (bottom of the photograph) with a silicon wafer (top) thanks to a gold layer

Figures 8 and 9 present the comparison between the experimentally measured responses of the implemented devices and the theoretical harmonic admittances obtained with our periodic finite element code. The $LiNbO_3$ layer thickness has been measured for both devices, allowing for accurate computations based on realistic parameters. Measurements have been achieved successfully for the 40 and 20 µm period devices. Since the implemented single-port test devices are quite long and almost behave as single port resonators, the comparison between measurement and harmonic admittance results [] makes sense.

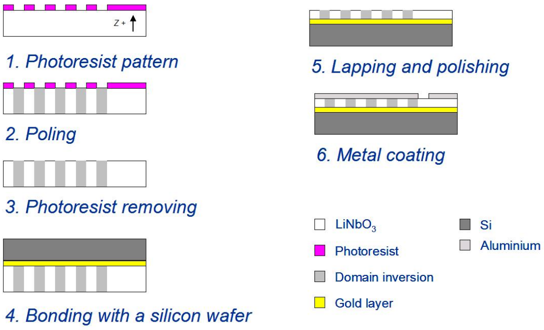


Fig.7 Flowchart which summarizes the different steps of fabrication of the device

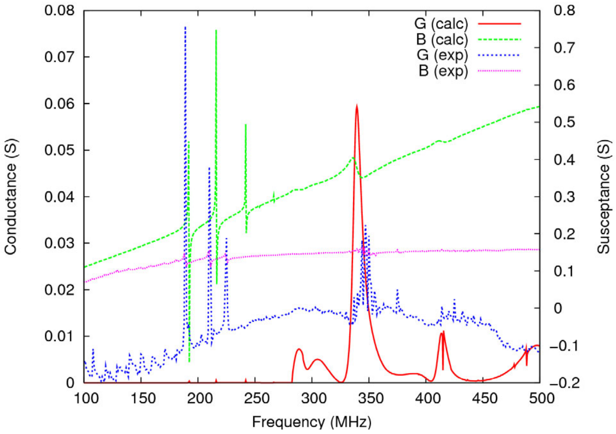


Fig.8 Theory/experiment comparison for the 20 µm period PPT on Silicon ($LiNbO_3$ thickness = 26 µm)

These plots point out the good agreement between both results even if the modes are slightly shifted from theory to experiment and that unwanted parasitic effects are visible. This discrepancy is certainly due to the gold layer not accounted for in our simulations. However, we find again the two main contributions corresponding to an elliptical mode propagating at a phase velocity close to 3800 m.s^{-1} and the longitudinal mode (at 6600 m.s^{-1}) for both cases. As theoretically predicted, only the modes exhibiting phase velocity smaller than the SSBW phase velocity in Silicon (5800 m.s^{-1}) are guided. This explain the leaky contribution of the in-plane longitudinal mode which mainly radiates into the bulk. We can also note that the first mode is almost insensitive to the $LiNbO_3$ thickness, as theoretically predicted. Moreover, these experiments show the robustness of our devices to lapping and polishing steps. This proves the feasibility of $LiNbO_3$-based PPT/Silicon devices.

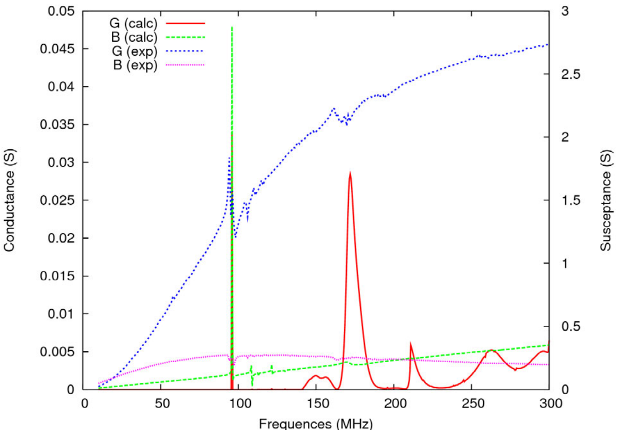


Fig.9 Theory/experiment comparison for the 40 µm period PPT on Silicon ($LiNbO_3$ thickness = 50 µm)

Conclusion

We have demonstrated the feasibility of acoustic wave-guides using periodically poled transducer on $LiNbO_3$ Z-cut bonded on silicon wafer. The devices have been found to operate according to the theoretical predictions, allowing for a reliable analysis of their operation. We have tried to derivate dispersion curves of the corresponding devices, but it turns out that only half of the curve could be efficiently fit. Nevertheless, this helps identifying the fact that the resonance of the fundamental mode generally occurs at the end of the stop-band. More work will be achieved to better describe the mode properties in future developments.

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