Excitation of acoustic waves at the interface between lithium niobate and silicon plates

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***Abstract*—We discuss the fabrication and characterization of IAW resonators made by indirect bonding of lithium niobate onto silicon. In our fabrication process, IDTs are first patterned over the surface of a Y-cut lithium niobate wafer. A thin layer of SU-8™ photo-resist is then spun over the IDTs and lithium niobate to a final thickness below one micron. The SU-8™ covered lithium niobate wafer is then bonded to a silicon wafer using a wafer bonding machine. Measurements of resonators are presented and compared with theoretical computations based on our periodic finite element/boundary element code allows for explaining the actual operation of the device.**

I. Introduction

Interface acoustic waves (IAW) can propagate along the boundary between two perfectly bonded solids [1]. For a lossless IAW, all displacement fields are evanescent along the normal to the boundary inside both solids, but a variety of leaky IAW's also exist depending on the selected combination of materials. When at least one of the bonded solids is a piezoelectric, the IAW can in principle be excited by an inter-digital transducer (IDT) located at the interface [2]. However, the IDT has a finite and non vanishing thickness which must be properly taken into account in actual devices. This difficulty is probably the reason why most studies have remained theoretical and why few experiments have been reported in the past. One possibility previously discussed by our group is to bury the IDT inside one of the solids and achieve a subsequent direct bonding onto the other solid. Another possibility is to deposit a thick layer, for instance silicon oxide, atop an IDT patterned above a piezoelectric plate; but a thick enough layer must be deposited or otherwise Sezawa modes will be observed instead of interface waves [9].

We present here the fabrication and characterization of IAW resonators made by indirect bonding of lithium niobate onto silicon. In our fabrication process, IDT's are first patterned over the surface of a Y-cut lithium niobate wafer. A thin layer of SU-8 photoresist is spun over the IDT's and lithium niobate to a final thickness below one micron. The viscosity of the SU-8 layer is such that a uniform and flat deposition is achieved. The SU-8 covered lithium niobate wafer is then bonded to a silicon wafer into an EVG wafer bonding machine. During the bonding process, we heat the material stack at a temperature of 60°C and we apply a pressure of 10 kg.cm^2 to the whole contact surface. The SU-8 resist is insulated across the lithium niobate wafer to cross-link its molecules. The stack is subsequently cured and baked to enhance the acoustic properties of the interfacial resist. Measurements of resonators and delay lines operating up to 1.6 GHz are reported and compared to computation results, allowing us to identify the actual polarization of the interfacial acoustic modes and to estimate the viscoelastivity of the resist layer. The actual limits of IAW devices made by indirect bonding via a SU-8 layer are discussed.

II. IAW Device Fabrication

General wafer bonding technology can be divided in two main branches, direct bonding and intermediate layer bonding [4]. Currently, wafer bonding of piezoelectric substrates receives a certain interest [5]. However wafer surface waviness and roughness are critical issues in direct bonding. Hence a low temperature bonding method using photosensitive material as adhesive intermediate layer was developed that is based on chemical surface hydrophilization and SU-8™ resist. First, the aluminium (Al) inter-digital transducers (IDT) are realized on the lithium niobate wafer. A SU-8 layer is spun on the $LiNbO_3$ wafer. A silicon wafer with wet-etched vias then is bonded to the $LiNbO_3$ substrate. The possibility to combine in this case IAW devices with silicon microelectronics is a significant long run motivation. The fabrication and wafer bonding process are schematically summarized in Figure 1.

Once the resist developed, the metal layer is wet etched providing the usual IDT's grating pattern. The $LiNbO_3$ substrate then can be passivated using a SiO_2 layer. This silicon dioxide layer is assumed to protect the aluminum resonators during the harsh cleaning treatment before bonding, but this step can be well omitted because the SU-8™ also acts as an insulating layer.

Before any bonding operation, vias must be achieved in the silicon plate to access the electrodes and to probe the device. The starting substrate is a 0.25 mm thick 3 inch silicon wafer (100) covered with a uniform 1.4 µm thermal oxide layer. The SiO_2 layer then is etched locally thanks to a

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standard lithography process, creating an in-situ mask for potassium hydroxide (KOH) silicon anisotropic deep etch. Afterwards, A re-oxidation of the wafer is done to obtain a SiO_2 thickness of 0.4 µm.

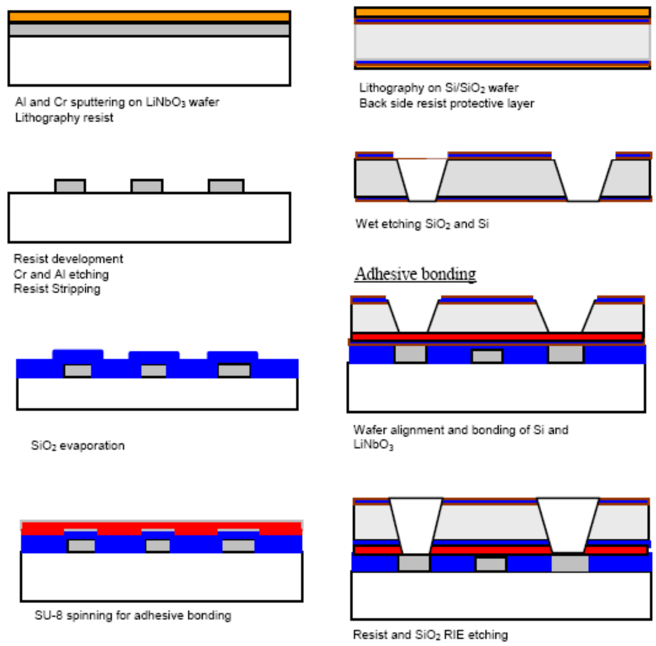


Figure 1. Flow chart for the adhesive wafer bonding process.

The starting substrate is a 0.5 mm thick 3-inch (YX) cut $LiNbO_3$ wafer. A 220 nm thick Chromium-Aluminum layer is sputtered on the polished side of the wafer. The photo-resist then is spun to form a 1.4 µm thin layer, on which prebake and hardbake are applied. The mask used for the photolithographic step has typical IDT patterns with a minimum finger size of 1 µm.

The wafers are cleaned to remove any kind of contaminants due to the process. Hydrophilic treatment on the Si/SiO_2 is achieved. The exact cleaning process is detailed in [6]. After that, Epon SU8-2001 is conventionally spun on the $LiNbO_3$ wafer to obtain 1 µm thick layer. A 30 min relaxation time on a flat support is respected to get an uniform coating on the wafer. The Si and $LiNbO_3$ wafers are aligned in an EVG 620 aligner. The pair is subsequently transferred to an EVG 501 bonder. The chamber of the wafer bonding machine is purged and evacuated to 10^{-3} mbar. The temperature rate in the heating process of the wafers is 1◦C/min from room temperature to 65◦C. Bonding occurred at 65◦C under a pressure of 500 N for 1 h. After bonding, the stacked wafers are annealed at 65 °C, for 1 hour in atmospheric N_2 ambient to enhance the bonding strength. The temperature then is decreased to room temperature with a 1◦C/min slope. Figure 12 displays the result obtained after the low temperature wafer bonding process.

Cross-sectional cuts are made with a dicing saw on the bonded device to analyze the bonding process, by imaging the bonded interface using scanning electron microscope (SEM). An example of a SEM picture is shown in Fig. 13, showing a very high quality bonding between the two wafers.

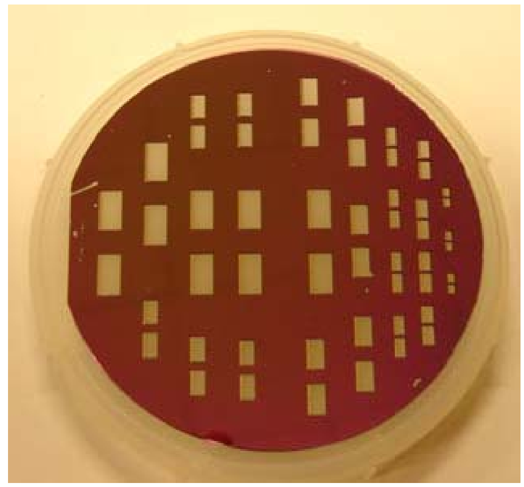


Figure 2. Picture of the 3-inches bonded wafers (LN/Si) from the silicon side

After the bonding process, SU-8™ and SiO_2 layers still remain inside the vias devised for electrical contact. SU-8™ hashing and SiO_2 etching are performed in a PLASSYS reactive ion etching reactor. The remaining resist is dry etched with a gas mixture composed of oxygen and C_2F_6. We chose to dry etch SiO_2 using CHF_3 and C_2F_6 reactive ion etching (RIE). A thin resist layer is deposited on the $LiNbO_3$ back side to reduce spurious bulk acoustic wave (BAW) reflections. The stack then is diced for measurement.

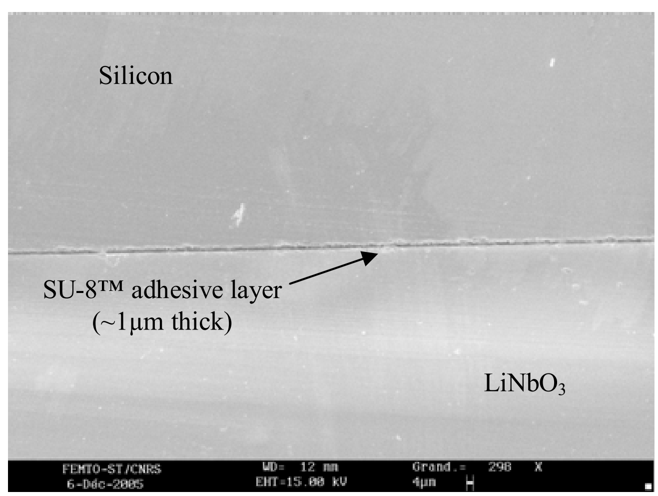


Figure 3. SEM picture of the stack after sawing. It shows the Lithium Niobate wafer, the adhesion interface and the Silicon substrate.

III. MEASUREMENTS

The devices first have been characterized under RF probes connected to a network analyzer Rohde & Schwarz ZVCE. The wavelength of the tested devices has been set to 5µm, 3.3 µm and 2.8 µm respectively, yielding a minimum strip width of 0.7 µm near the very limit of our mask aligner. Most devices have been successfully tested but also have been found to suffer from parasitic elements limiting the measurement quality. Figure 4 shows the typical IDT pattern implemented for our experiments and fig.5 shows a device ready to be tested, i.e. SU-8 bonding has been achieved and the contact pads have been wired.

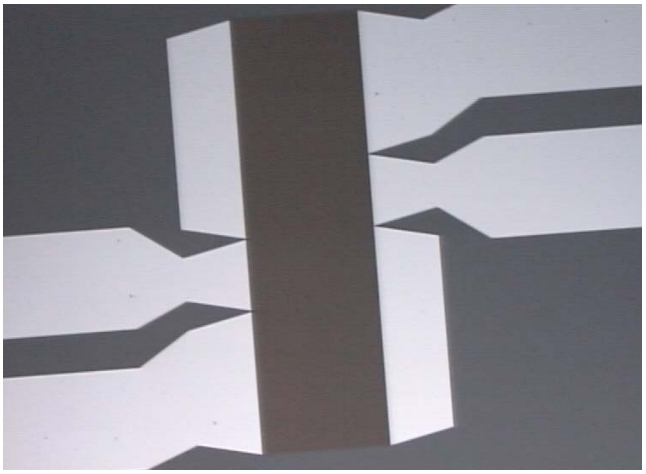


Figure 4. Typical IDT pattern implemented for the IAW test devices

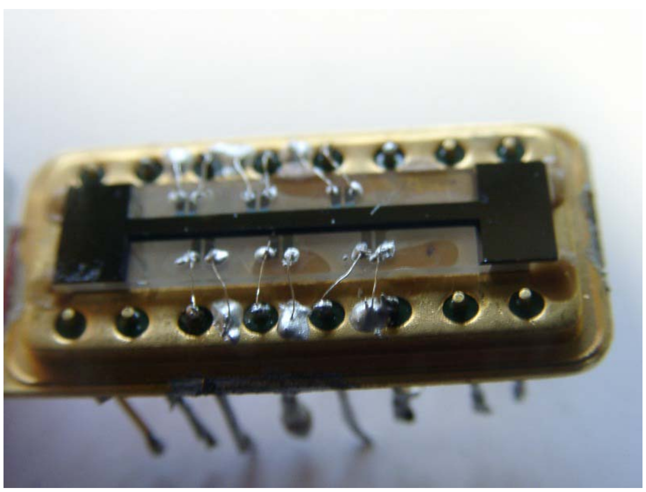


Figure 5. Final device ready for electrical tests

Figure 6 displays the experimental admittance of the tested devices. It shows the existence of three modes, the two modes at 1.4 and 1.6 GHz corresponding to phase velocities near 3600 $m.s^{-1}$ and 4600 $m.s^{-1}$. One should keep in mind that the operation condition are quite far from the expected concept for which the guiding only is due to the inetrface, not to an extra material at the interface.

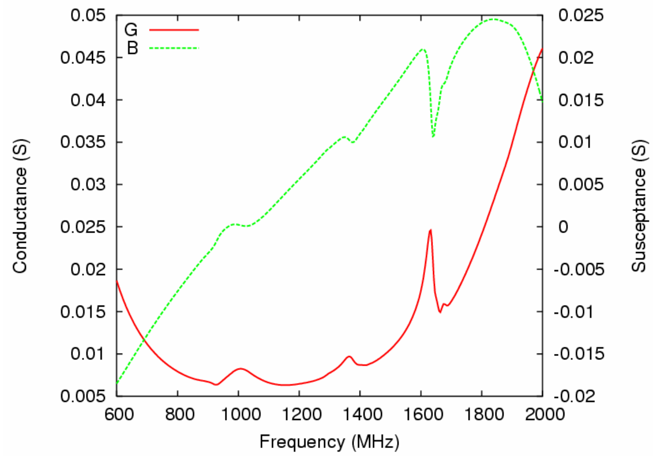


Figure 6. Experimental admittance of a 1.6 GHz IAW device, pointing out three main comtributions.

IV. Analysis

We have computed the harmonic admittance considering the actual adhesive layer thickness and IDT parameters using our periodic FEA/BEM code [7] and compared it to the experimental results. The implemented mesh is plot in fig.7, giving the definition of the computation conditions.

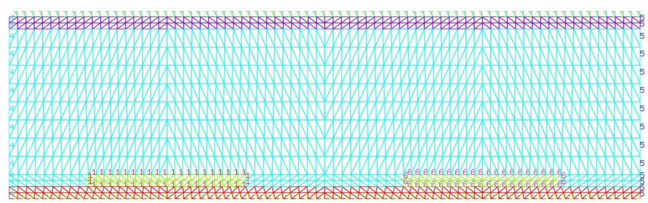


Figure 7. Implemented mesh for the simulation of interface wave excitation and guiding using a periodic FEA/BEM computation code. The boundary numbers correspond to the applied boundary conditions, i.e. unit voltage excitation applied on boundary #1 , periodicity conditions applied to boundaries #4 and #5, radiation in silicon applied to boundary #3 and radiation in lithium niobate applied to boundary #2.

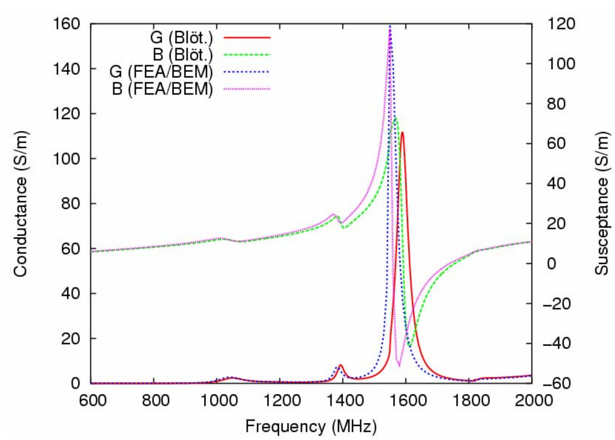
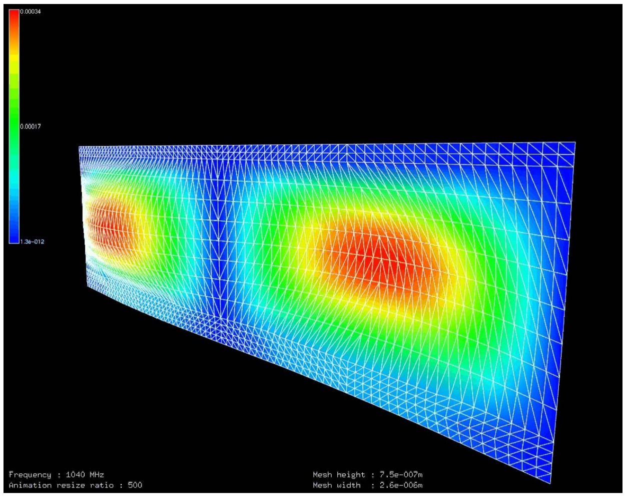
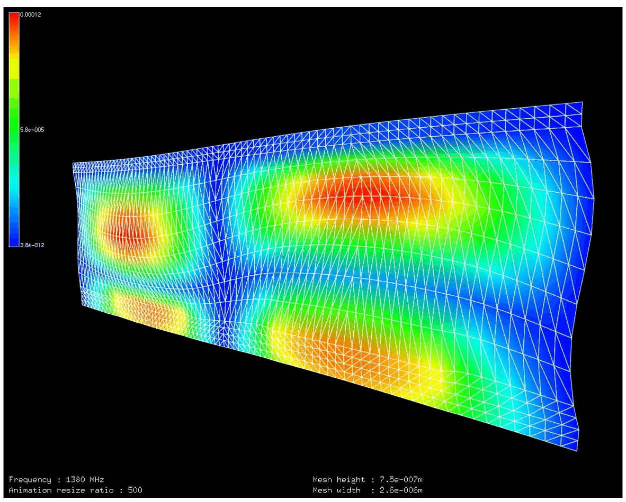


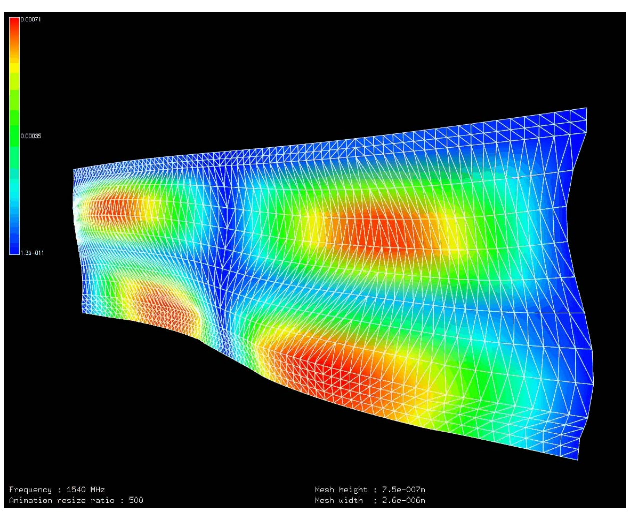
Figure 8. Theoretical harmonic admittance of the 1.6 GHz IAW device, three contributions are predicted in good agreement with experiments.



(a)



(b)



(c)

Figure 9. Deformed mesh of the three IAW device contribution
(a) 1 GHz (b) 1.4 GHz (c) 1.6 GHZ.

The theoretical analysis allows for predicting three modes as found experimentally, at frequencies very close to those pointed out in fig.6. It is conseque ntly liable to plot the deformed mesh in order to identify the corresponding wave polarisation. Figure 9 a, b and c show that the first contribution near 1GHz mainly is shear polarized, whereas the second exhibit an elliptical motion comparable to the one of a Rayleigh wave. The main contribution is mainly shear polarized as expevcted, but with a full sinus displacement distribution along the SU-8 thickness.

V. Conclusion

Interface waves have been successfully fabricated and their electrical response has been measured, the devices operating in GHz range. A low temperature wafer hetero-bonding process of Lithium Niobate onto Silicon has been developed in that matter, exploiting a thin spin-coated SU-8™ film as an adhesive layer. It is the first experimental demonstration of interface acoustic wave devices made with indirect wafer bonding technique and operating at frequencies larger than 1 GHz. A theoretical analysis of the operation of IAW has been proposed to describe the characteristics of a wave guide composed of Silicon and Lithium Niobate bonded together thanks to an adhesive layer, accounting for the presence of the excitation/detection electrode grating. Three modes are guided at the interface, the first ehibiting pure shear polarisation, the second being close to the free-surface Rayleigh wave and the third exhibiting a quasi-shear polarisation. It is found that the presence of an adhesive layer between the $LiNbO_3$ wafer and the Silicon wafer leads to improved guiding, increased losses on the IAW modes compared to the case of a mineral guiding interface layer, but allows for the excitation of a highly coupled shear mode (K_s^2>10%).

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