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Surface acoustic wave trapping in a periodic array of mechanical resonators

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The existence of two families of surface acoustic modes trapped by steep ridges on a piezoelectric substrate, shear horizontal and vertically polarized surface modes, is demonstrated experimentally using high aspect ratio interdigital transducers fabricated on lithium niobate. The experimental variation of the resonance frequencies of the various surface modes is obtained experimentally, and up to an order of magnitude slowing of surface waves is observed, with the phase velocity dropping from 4000 down to 450 m/s. It is argued that the observed resonances are surface modes trapped by the ridge electrodes. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2338523]

The influence on the propagation of elastic or acoustic waves of micro-or nanostructures present on an otherwise planar surface is a problem of both fundamental and practical importance.[1,2] This problem has a strong connection with phononic crystals,[3,4] which are periodic arrangements of two or more materials giving rise to strong modifications of the acoustic band structure leading to such effects as complete band gaps or negative refraction.[5] The fact that surface defects modify the physical properties of the crystal surface can in turn serve as a tool for the characterization of surface inhomogeneities. In particular, the periodically corrugated surface of an isotropic substrate supports a family of localized shear horizontal modes, which do not appear in the case of a substrate with a flat surface.[6] The propagation of surface acoustic waves (SAW's) across a grating or a periodic array of ridges deposited on a substrate is of great current interest. Such a system is a model for randomly rough surfaces that can be studied exactly. It can also be viewed as a one-dimensional phononic crystal supporting surface modes. In the case of piezoelectric materials, this is a step towards phononic devices constructed directly on the surface and providing direct means for electrical excitation and detection of surface waves. In the system such as investigated here, the conversion of surface acoustic waves into bulk waves is strongly inhibited by the slowing of surface modes and the results could well be useful in the design of filters for surface acoustic waves and more generally of periodic transducers on piezoelectric materials. Let us also remark that the periodic array of ridges or dots on a surface is complementary to the periodic array of holes etched in a substrate.[7,8]

Surface acoustic wave transduction by the use of interdigital transducers[9] (IDT's) is a well-known and widespread technique. An IDT forms a one-dimensional array of metal electrodes on a surface, devised in view of the electrical transduction in piezoelectric materials. However, usual IDT's make use of electrodes with limited heights, so that surface mode properties do not differ appreciably from those of a free or a fully metalized surface. We proposed in Ref. 10 a theoretical analysis of the transduction of SAW under a metallic array of electrodes with a large aspect ratio on a piezoelectric substrate, whereby allowing the electrode height to become larger than one wavelength. We were prompted in this direction by former works that were restricted to shear horizontal (SH) waves propagating on a periodically corrugated surface[6] (see also the references cited in Ref. 10). In contrast to these works, our purpose was to consider waves of a general polarization associated with the surface of a piezoelectric substrate—hence with a general anisotropy—supporting a periodic array of ridges. In addition, the consideration of the possibility of using the array of ridges as an IDT opened the way for their experimental study by simple electrical measurements. We considered in our numerical simulations a number of standard cuts of piezoelectric substrates, including lithium niobate, lithium tantalate, and quartz. The number and dispersion of the surface waves are highly dependent upon the height of the aluminum electrodes, while their polarization is strongly dependent on the crystalline symmetry of the substrate. As the electrode height is gradually increased, SH surface waves start to appear in a fashion very similar to the isotropic substrate case. However, at the same time, we observed the appearance of vertically polarized (VP) surface waves, i.e., with their polarization mostly in the sagittal plane, thus combining shear vertical and longitudinal displacements. Both SH and VP surface waves undergo a strong decrease in their phase velocity as the electrode height increases.

In this letter, we report on the experimental observation of the multimode character of SAW propagation under periodic arrays of electrodes, in direct support of the analysis of Ref. 10. We also obtain experimentally the explicit dependence of the SAW velocities as a function of the electrode height.

Figure 1 shows a close-up view of one of the high aspect ratio interdigital transducers used in this study. IDT's were fabricated based on the lithography *galvanoformung abformung* ultraviolet (UV) technique[11] as follows. The surface of a Y+128-cut lithium niobate wafer was first metalized with a thin copper film needed for the electroplating step. A thick photoresist AZ9260 (35 μm) was subsequently deposited and used to achieve a negative mold of the final metallic IDT's using standard UV lithography. Nickel IDT's were then grown by electroplating from a nickel sulfamate bath. Stripping of the resist was eventually followed by argon ion etching to remove the copper seed layer. A total of 63 IDT's

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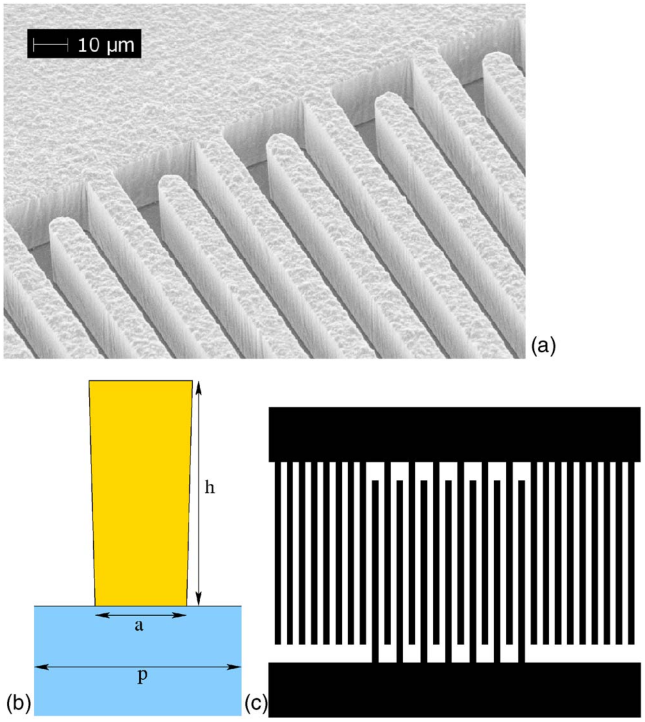

FIG. 1. (Color online) (a) Scanning electron microscope image of a high-aspect-ratio surface acoustic wave transducer on Y+128-cut lithium niobate. The 6 μm wide, 30 μm high, electrodes are grown by nickel electroplating over a piezoelectric Y+128 lithium niobate substrate. (b) Cross section of one mechanical period of the surface wave transducers with a definition of the principal lengths. The metallization ratio a/p equals 0.5. (c) Schematic representation of the synchronous transducer mask; a central interdigital transducer is surrounded by two Bragg mirrors.

were fabricated with pitches of 12, 16, or 20 μm. Because the current has a nonuniform distribution on the surface of the wafer, the electroplated nickel thickness was found to vary from IDT to IDT, depending both on the position on the wafer and on the pitch. Electrode heights ranging from 22 to 32 μm were obtained. This translates into a distribution of the parameter $h/(2p)$ covering 0.55–1.25. It is worth noting that twice the pitch, $2p$, is a measure of the wavelength at resonance, because of the alternating electrical excitation used.

The SAW IDT's were characterized electrically using radio-frequency probes and a network analyzer (Rohde & Schwarz model ZVCE). Figure 2 shows an example of the measurement of the electrical reflection (S_{11} parameter) of one of the IDT's, with $h/(2p)\approx 1$. A series of six frequency resonances is identified in the figure. Each of these resonances is the signature of the existence of a propagating surface mode, the phase velocity of which is given by the condition $v=2f_r p$, where f_r is the resonance frequency. The slowest surface mode has a phase velocity of 600 m s^{-1}, which is considerably slower than the SAW velocity for thin electrodes, approximately 4000 m/s. Resonances labeled SHn are caused by mostly shear horizontally polarized surface modes, while resonances labeled VPn are caused by mostly vertically polarized surface modes. SH surface modes have smaller piezoelectric coupling than VP surface modes and thus create smaller dips in the reflection curve.

The theory of Ref. 10 indicates that for a given electrode shape, the phase velocity at resonance, $v=2f_r p$, is uniquely related to the parameter $h/(2p)$. In order to check this property, all IDT's were probed and the observed resonances monitored as a function of the parameter $h/(2p)$, as displayed in Fig. 3. It can be clearly seen that the experimental points distribute along seven different modal lines in this diagram, in close agreement with theory. Two limiting horizontal lines have been added to the diagram. These lines correspond to the slowest SH and VP bulk acoustic waves in the substrate, limiting the radiation region for surface modes. Above the SH bulk line, all generally polarized surface modes are leaky in principle, because they couple to radiation modes of the substrate. Purely VP surface modes are possibly leaky between the SH and the VP bulk lines, but certainly above the latter.

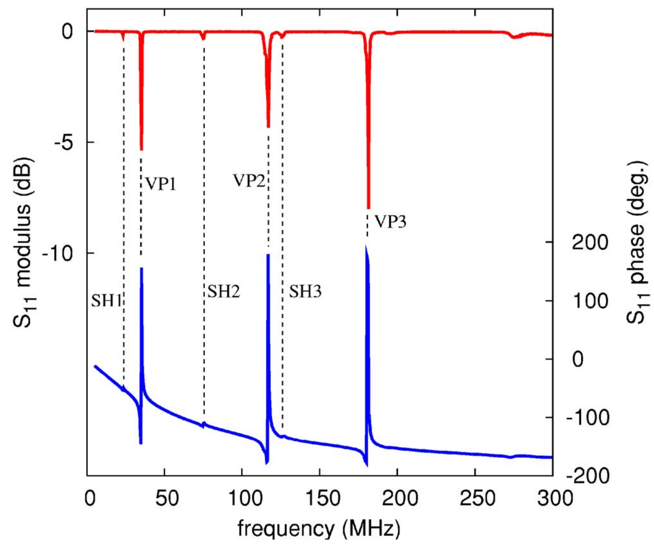

FIG. 2. (Color online) Measurement of the electrical reflection (S_{11}) of one high aspect ratio surface acoustic wave transducer. The array pitch is $p=12$ μm and the electrode height is $h=24.2$ μm $(h/(2p)\approx 1)$.

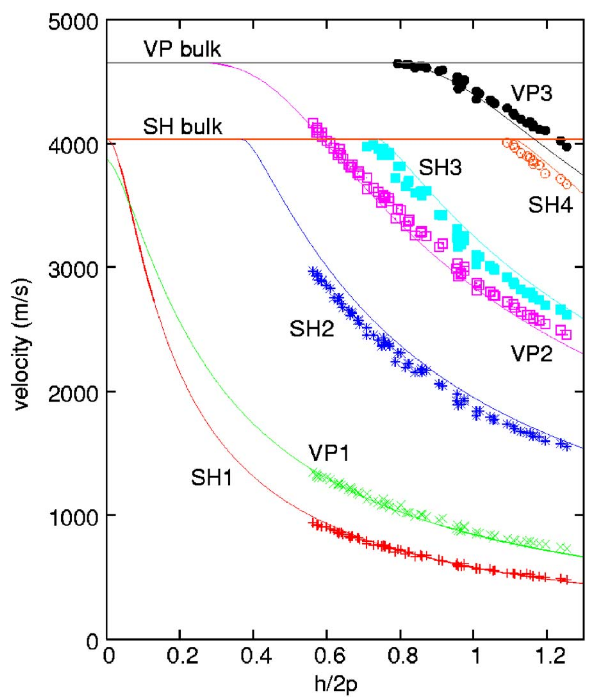

FIG. 3. (Color online) Dependence of phase velocities at resonance with the aspect ratio of the electrodes. Experimental values are represented by points while theoretical values are represented by lines.

The measurements were compared to the theory of Ref. 10, which in addition to the electrical response gives access to the wave polarization inside the substrate. The mechanical contribution of the electrodes is treated by a finite element method whereas the substrate behavior is represented by its full piezoelectric Green's function, both approaches being coupled in a boundary integral formulation that is well suited to two-dimensional elasticity. The cross section of the electrodes is meshed using second degree interpolating triangles ($L2$ finite elements). The nickel electrodes are modeled as isotropic, with a mass density of $8600\ \mathrm{kg\ m^{-3}}$, Young's modulus of 200 GPa, and a Poisson coefficient of 0.31. The value for Young's modulus was obtained from experiment with our electroplating apparatus.[12] The actual shape of the electrodes used for the finite element mesh was estimated from scanning electron microscope images. The theory predicts the existence of modes guided by the surface, their number increasing with the electrode aspect ratio. These surface modes are of two types. The first type is quasi-SH surface modes for which, in opposition to isotropic materials, the polarization state is not purely shear horizontal but also contains some displacement in the sagittal plane. The second type of modes, quasi-VP, exists only on anisotropic materials. Again, although the polarization of quasi-VP surface modes is mostly in the sagittal plane, some shear horizontal displacement is always present. The first VP branch (noted VP1 in Fig. 3) is that of the usual Rayleigh SAW. This surface mode exists even with a vanishing electrode thickness, which is not the case of subsequent VP modes. The first SH branch (noted SH1 in Fig. 3) also exists for a vanishing electrode thickness, although its electromechanical coupling coefficient is vanishingly small at this point. The slowest surface mode observed in this study has a phase velocity of $450\ \mathrm{m\ s^{-1}}$ (branch SH1).

We attribute the apparent slowing of surface modes to the storage of part of the elastic energy of the waves inside the electrodes. Propagation along the surface can then be viewed as the coherent oscillation of mechanical resonators (the electrodes) coupled by acoustic waves in the substrate. In this picture, each branch, SHn or VPn, would be associated with a particular modal vibration of a single electrode. Further numerical simulations and optical observations of the electrode deformations are in progress to fully support this explanation.

Higly compact IDT designs are achievable thanks to the strong reduction in phase velocity under an array of thick ridges. For a given operating frequency, dimensions can be reduced by an order of magnitude with respect to shallow IDT's. As another possible application of slow surface waves trapped by a thick array of ridges, let us remark that velocities lower than that of water ($1480\ \mathrm{m\ s^{-1}}$, typically) are obtained. In principle, it is then possible to generate guided acoustic waves at the interface between the piezoelectric substrate, supporting the array of thick electrodes coated with a dielectric overlay, and water.[13] This would be an alternative to plate mode devices, supporting, for instance, Lamb waves, without requiring the fabrication of thin membranes.

As a summary, we tested experimentally the existence of two families of surface acoustic modes trapped by high aspect ratio ridges on a piezoelectric substrate, shear horizontal and vertically polarized surface modes. In that purpose, we fabricated interdigital transducers on the Y+128-cut lithium niobate using electroplating of nickel. The slightly pyramidal electrodes are up to five times higher than wide. The experimental variation of the resonance frequencies of the various surface modes was obtained experimentally. Up to a tenfold slowing of surface waves is observed, with the phase velocity dropping from 4000 down to 450 m/s. The comparison a theory based on a coupled finite element boundary element method is excellent.

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