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SURFACE ACOUSTIC WAVE FERROELECTRIC PHONONIC CRYSTAL TUNABLE BY ELECTRIC FIELD

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Theoretical investigation results of the periodic domain structures induced by an electric field in barium strontium titanate $(Ba_xSr_{1-x})TiO_3$ ferroelectric thin film are presented. A novel type of tunable phononic crystal based on an electric field-induced piezoelectric effect in a thin ferroelectric film is proposed. Surface acoustic wave propagation equations for the substrate under electric field-induced periodic domains are derived. Finite element simulation revealed the possibility of applying the ferroelectric phononic crystal as an electrically tunable surface acoustic wave filter.

Keywords: tunable phononic crystal, induced piezoeffect, surface acoustic wave (SAW), periodic domains, ferroelectric film.

1. Introduction

Periodic domain structures in piezoelectric and ferroelectric materials have attracted much interest from researchers. There are various acousto-optics and laser devices based on periodic domains [1]. Periodic domain structures are mainly created in strong piezoelectrics, such as iron-doped (Fe_{2+} and Fe_{3+}) lithium niobate and lithium tantalate. A direct electric field (E $\sim 10^7$ V/m) applied to piezoelectric crystals leads to sufficiently stable periodic domain formation. The periodic domain's polarization is in alignment with the electric field's orientation [2].

Tunable SAW filters based on phononic crystals with periodic domains have been reported previously [3]. Major disadvantages of these phononic crystals are the laser-induced tunability and the required use of a high voltage source. In this paper we propose a novel type of surface acoustic wave phononic crystal based on an electric field-induced piezoelectric effect in the ferroelectric [4–7]. Tuning of the proposed phononic crystal is achieved by applying voltage ranging from 1 to 5 V.

2. Theory

The proposed tunable phononic crystal is shown schematically in Fig 1. The phononic crystal consists of a substrate with a deposited ferroelectric film and a series of interdigital transducers (IDT) atop the ferroelectric film. Phononic crystals have a SAW delay line design. Input and Output IDTs must excite and receive the SAW in a wide band, therefore their topology must be like chirped IDTs with a linear variation of the finger pitch. The conventional topologies of Input IDT and Output IDT are depicted in Fig. 1 for simplicity. Alternative electric signal are applied to the Input IDT and excite the surface acoustic wave. The output signal is received from Output IDT. DC control voltage is applied to the IDT located between the Input IDT and Output IDT, namely the Bias IDT. The bias IDT has a conventional topology.

The ferroelectric film thickness is approximately 0.5 to 1 μm. Due to such values of the film thickness, we can obtain a high electric field in ferroelectric film in areas according to Bias IDT location. So, if the applied bias is 1 V and the ferroelectric film thickness is 0.5 μm, we obtain an electric field value of $2{\cdot}10^6$ V/m.

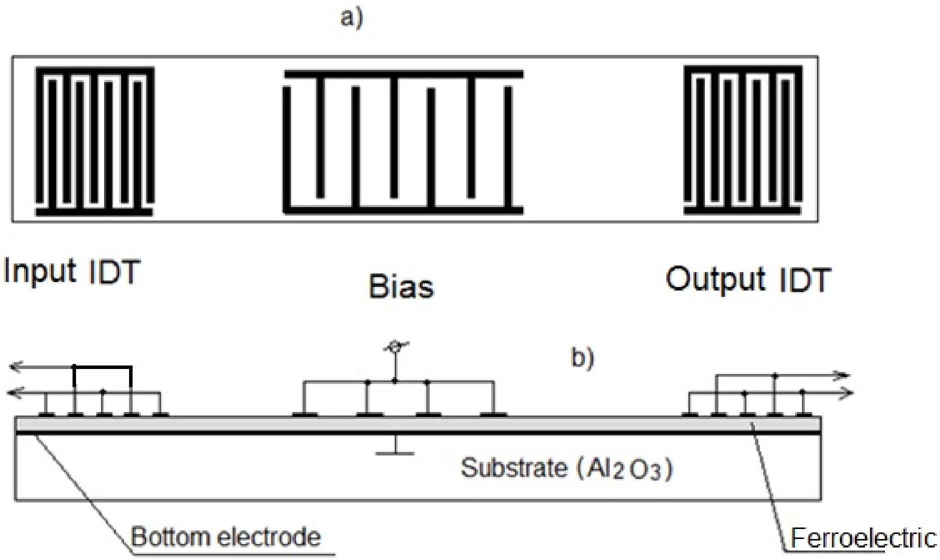

FIG. 1. Electric field tunable phononic crystal. a) Top view. b) Side view

The ferroelectric in the paraelectric phase is well known to have no spontaneous polarization. A DC electric field applied to a ferroelectric in the paraelectric phase causes piezoelectric phenomena in the film. This effect is used in tunable bulk acoustic wave resonators [4–5]. The applied DC electric field exerts an influence on the elastic and piezoelectric moduli of the ferroelectric film. The relations between the electric field and material properties were obtained in [6]:

$$\tilde{h}_{ijm}\left(E_i\right) = h_{ijm} - 2G_{ijmn}\varepsilon_0\varepsilon_{ij}\left(E_i\right)E_i, \tag{1}$$

$$\tilde{C}_{ijmn}\left(E_i\right) = C_{ijmn} + M_{ijklmn}\left(\varepsilon_0\varepsilon_{ij}\left(E_i\right)E_i\right)^2, \tag{2}$$

where h_{ijm} — piezoelectric tensor in absence of electric field (caused by defects in film), G_{ijmn} — electrostriction tensor, E_i — electric field components ($i = 1, 2, 3$), C_{ijmn} — stiffness tensor, M_{ijklmn} — nonlinear electrostriction tensor, $\varepsilon_0 \approx 8{,}8542{\cdot}10^{-12}$ F/m, ε_{ij} — permittivity tensor.

When an electric voltage is applied to the Bias IDT, piezoelectric domains are formed under the electrodes with piezoelectric module $\tilde{h}$ and stiffness module $\tilde{C}$. Between the biasing electrodes, where the electric field is zero, piezoelectric domains are formed with piezoelectric module h and stiffness module C. Thereby, we have a material with periodic piezoelectric and elastic properties along the substrate length. The domain period is defined by the Biasing IDT period. Consequently, SAW propagate on the ferroelectric film and interact with the periodic domains. Frequency band gaps occur due to the periodic domains in such structures. Varying the Bias IDT period or the applied voltage's magnitude allows the possibility of tuning the phononic crystal band gap. This can be implemented for a tunable SAW filter based on this phononic crystal.

Let's consider the equations which describe acoustic wave propagation in anisotropic piezoelectric media [7]:

$$\begin{cases} C_{ijmn}\frac{\partial^2 U_m}{\partial x_j \partial x_n} + e_{mij}\frac{\partial^2 \phi}{\partial x_j \partial x_m} = \rho\frac{\partial^2 U_i}{\partial^2 t}, \\ e_{ijm}\frac{\partial^2 U_j}{\partial x_i \partial x_m} - \varepsilon_{ij}\frac{\partial^2 \phi}{\partial x_i \partial x_j} = 0, \end{cases} \quad (3)$$

where U — mechanical displacement, ρ — ferroelectric material mass density, ϕ — electric potential, e — piezoelectric tensor which coupled with the tensor h accordingly with [5]:

$$e_{ijm} = \varepsilon_0(\varepsilon_{ij} - 1)h_{ijm}. \quad (4)$$

Substituting (1) and (2) into (3), taking into account (4) and that the electric field is a function of the spatial coordinates, we obtain the system of equations which describe elastic wave propagation in a phononic crystal:

$$\begin{cases} \left(C_{ijmn} + M_{ijklmn}\left(\varepsilon_0\varepsilon_{ij}\left(E_i\left(x,y,z\right)\right)E_i\left(x,y,z\right)\right)^2\right)\frac{\partial^2 U_m}{\partial x_j \partial x_n} + \\ +\varepsilon_0(\varepsilon_{ij} - 1)\left(h_{mij} - 2G_{ijmn}\varepsilon_0\varepsilon_{ij}\left(E_i\left(x,y,z\right)\right)E_i\left(x,y,z\right)\right)\frac{\partial^2 \phi}{\partial x_j \partial x_m} = \rho\frac{\partial^2 U_i}{\partial^2 t}, \\ \varepsilon_0(\varepsilon_{ij} - 1)\left(h_{ijm} - 2G_{ijmn}\varepsilon_0\varepsilon_{ij}\left(E_i\left(x,y,z\right)\right)E_i\left(x,y,z\right)\right)\frac{\partial^2 U_j}{\partial x_i \partial x_m} - \varepsilon_{ij}\frac{\partial^2 \phi}{\partial x_i \partial x_j} = 0. \end{cases} \quad (5)$$

2.1. Numerical simulation results

We have performed 2D numerical simulations using COMSOL software.

The problem was divided into two steps. In the first step, an electric field distribution has been found by solving the electrostatic problem. In the second step, the piezoelectric problem was solved using the electric field distribution stored in the previous step. The material constants for $BaTiO_3$ were taken from [4–6].

Input IDT excited the SAW from 490 to 520 MHz bandwidth. The bias IDT has a center frequency of 500 MHz, which is defined by *fc = V/(2p)*, where V and p are SAW velocity in the structure and the IDT period respectively. The bias IDT electrode's width is chosen as $p/2$. The period p is equal to the SAW wavelength. Thus, $p/2$ satisfies the Bragg condition and *fc* is the forbidden frequency. The number of electrodes in the Bias IDT is 40.

COMSOL simulation results of the electric field distribution are depicted in Fig. 2. We can see from Fig. 2 that there are edge effects on the electrodes and electric field distribution is not homogenous. These effects can be taken into account due to numerical simulation only.

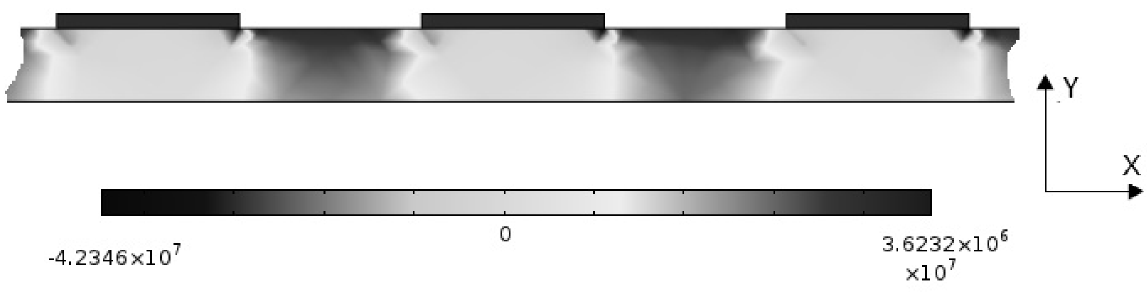

Fig. 2. Electric field (Y component) distribution in phononic crystal. Bias 5 Volts

The phononic crystal transmission coefficient as a function of frequency is shown in Fig. 3. The phononic crystal stopband is approximately 7 MHz. Dispersion curves and the

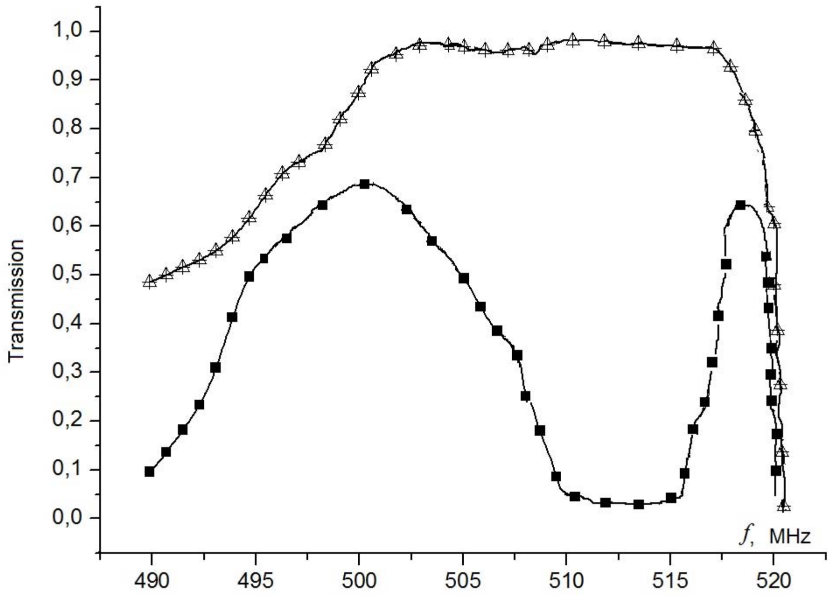

FIG. 3. SAW transmission versus frequency in phononic crystal.

— Electric field off (Bias 0 V)

—Electric field on (Bias 5 V)

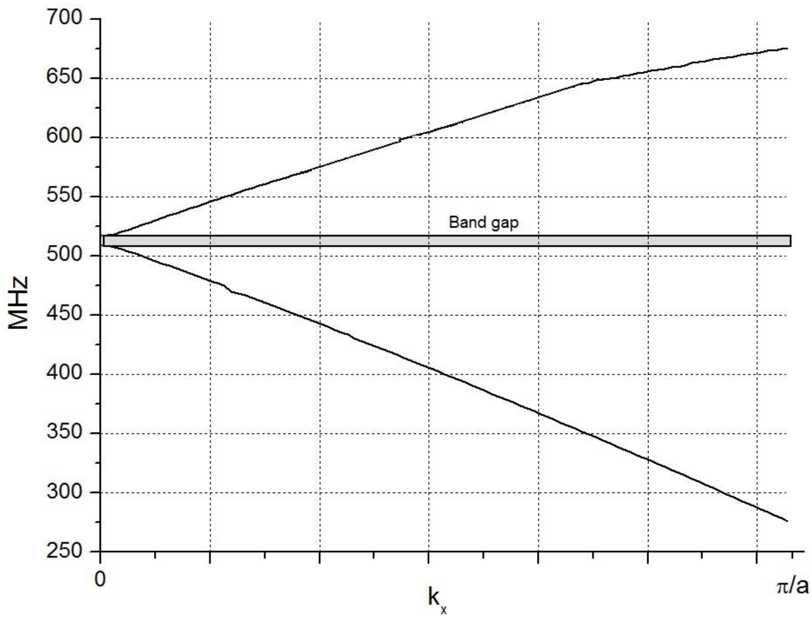

FIG. 4. Dispersion curves for SAW

band gap for two SAW modes at the first Brillouin zone are depicted in Fig. 4. Bulk acoustic wave modes are not taken into account.

3. Conclusion

Finite-element modeling in COMSOL software revealed the presence of a phononic band gap for surface acoustic waves in a structure consisting of electrically-induced periodic ferroelectric domains. This effect can be used in tunable surface acoustic wave filters. The influence of electric field and the number of electrodes on the band gap will be investigated further.

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