Dielectric properties of PZT thin films measured in-plane for nanophotonic electro-optic applications

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Recently, electro-optic modulation at high-speed with low optical loss is demonstrated using lead zirconate titanate (PZT) thin films on silicon nitride. Here, co-planar electrode structures are used on top of the ferroelectric thin film. Further optimization of the electro-optic modulators in terms of speed and efficiency requires accurate analysis of the dielectric properties of the ferroelectric thin film, measured in-plane. In this paper we will discuss the in-plane dielectric properties, such as dielectric constant, capacitance and leakage current, of preferentially oriented PZT thin films using interdigitated transducer electrodes (IDTs) combined with finite element simulations of the device structure.

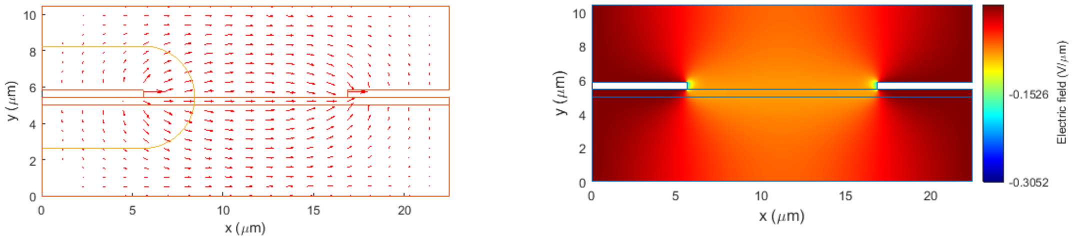
Introduction

In modern telecommunication networks, the demand for data transmission at high rates is increasing [1]. The modulation of optical signals using silicon-photonics is promising due its compatibility with CMOS fabrication technologies [2]. Recently, high-speed low-loss electro-optic modulators on silicon nitride using a lead zirconate titanate (PZT) thin film have been demonstrated [3]. Since most electro-optic modulators make use of co-planar electrode structures, in-plane measurements of the ferroelectric PZT thin film's dielectric properties are required to further optimize the devices.

Different in-plane dielectric measurements are performed using a preferentially oriented PZT thin film obtained by a sol-gel (spincoating) deposition method using a lanthanide-based seed layer [4]. Interdigitated transducer electrodes (IDTs) are fabricated on top of the PZT thin film by optical lithography techniques. At first, the in-plane dielectric constant of the film is obtained by combining a finite element method simulation and capacitance measurements. The result of this simulation is compared to existing mathematical descriptions, such as the parallel-plate model, Gevorgian and Igreja model [5]. Additionally, polarization loops are measured in-plane by a Sawyer-Tower circuit. Values for the remnant and saturation polarization are obtained together with a value of the dielectric constant of the material, which is compared to the simulation result. Furthermore, IV-measurements are performed to determine the leakage current.

Simulation of the capacitance and dielectric constant relation

The relation between the in-plane dielectric constant and capacitance of an IDT-PZT-glass structure is obtained from a finite element method (FEM) simulation using MATLAB and low frequency capacitance C(f) measurements. Due to the periodicity of the IDT structure, it is possible to simulate only one period, consisting of one-half positive and one-half negative electrode, as shown in figure 1a. The periodicity is implemented by applying Neumann boundary conditions to the left and right edge of the simulation domain. In the first step, the PDE solver is used to solve the Laplace equation $\boldsymbol{\nabla . \epsilon \nabla V = 0}$ in the different materials. Once the electric potential is known, the electric field can be calculated by $\boldsymbol{E} = -\boldsymbol{\nabla V}$. In the next step, the charge is determined by calculating the Gauss integral along a smooth curve around one electrode (yellow line in figure 1a). Finally, once the charge per unit length at one electrode is known, the capacitance per unit length can be obtained using c = q/V (in F/m). Multiplying c with 2N-1, where N is the number of finger pairs, and the aperture of the IDT (overlap length of the electrode fingers) gives the capacitance (in F) of the total structure.



(a) (b)

Figure 1: Simulation result of the electric field of the structure. The PZT layer is a 440 nm thin layer just below the electrodes, which are modeled as perfect electric conductors. (a) Flowline representation of electric field lines in simulated structure, the yellow line indicates the smooth curve along which the Gauss integral was calculated. (b) Electric field distribution (absolute value) in the device.

This simulation is performed for a 440 nm PZT structure using IDTs with a spatial wavelength λ_0 of 50 and 45 μm consisting of 20 finger pairs and an aperture of $36\lambda_0$. Figure 1 shows the results of the electric field simulation for 45 μm IDTs. Due to the high dielectric constant of the PZT layer, the electric field is quasi-parallel to the PZT layer and almost constant in-between the electrodes. Only near the edges of the electrodes (see figure 1b) there is a stronger electric field. C(f) measurements of different IDTs with sizes of 50 and 45 μm are performed to obtain the dielectric constant. The measured capacitance at 10 kHz is 25 pF and 25.5 pF for the 50 and 45 μm IDTs, respectively. Comparing this to the simulated relation between the dielectric constant and capacitance gives an in-plane dielectric constant of about 1000.

For obtaining the hysteresis curve we need the relation between the geometrical and material parameters and the charge [6]. This can be obtained by interpolating the results of a limited set of simulations or by using approximate analytical models. Multiple analytical descriptions exist for the relation between the capacitance and dielectric constant, taking the electric field lines into account [5], [7], [8]. The simplest description is the parallel-plate electrode (PPE) model which extends the electrodes through the ferroelectric thin film. The capacitance per unit finger length is then given by $\boldsymbol{c} = \frac{\boldsymbol{\epsilon_0 \epsilon_r t_f}}{\boldsymbol{a}}$, where t_f is the film thickness and a the distance between the electrodes. This model is similar to the out-of-plane structure where the capacitance is given by $\boldsymbol{C} = \frac{\boldsymbol{\epsilon_0 \epsilon_r A}}{\boldsymbol{t_f}}$ and A is the electrode area. More extended descriptions are given by the Gevorgian and Igreja model, which also take the stray fields at the end of the fingers and first and last finger into account. It is assumed that the PZT thin film is homogeneous and isotropic, and the presence of the dielectric anisotropy and domain walls is negligible [8]. If the electrode width and gap are much larger than the ferroelectric film thickness, the capacitance per unit length for both models is given by [5] $\boldsymbol{c} = \frac{\boldsymbol{\epsilon_0 \epsilon_r t_f}}{\boldsymbol{a + \Delta a}}$, where for the Gevorgian capacitance model $\boldsymbol{\Delta a} = \frac{4\ln(2\sqrt{2})t_f}{\pi}$ (full calculation given by Nigon et al. [8]) and for the Igreja model $\boldsymbol{\Delta a} = \frac{4\ln(2)t_f}{\pi}$ (full calculation given by Nguyen et al. [5]).

The PPE, Gevorgian and Igreja models can be compared to the results of the FEM simulation for the capacitance and dielectric constant relation for 45 μm IDTs and 440 nm PZT on glass, as shown in figure 2. For these relatively large structures, the PPE model gives the best estimation of the capacitance-dielectric constant relation. This was also discussed by Chidambram [7] where they showed that the error using the PPE model decreases for larger gaps and thinner films. So, it is safe to assume the PPE model will be sufficient to calculate the P-E loop for the in-plane hysteresis measurements.

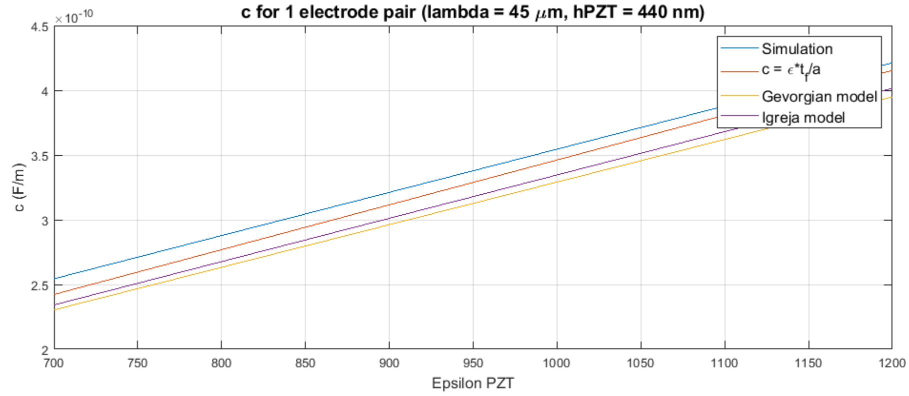


Figure 2: Comparison of the simulated capacitance-dielectric constant relation with the different mathematical descriptions.

Hysteresis measurements

To measure the hysteresis loop a modified Sawyer-Tower circuit is used, consisting of a triangular AC voltage source and a known capacitor (C_0) in series with the IDT-PZT-glass sample (device under test, DUT). An oscilloscope is used to measure the input voltage (V_{in}) and voltage across the known capacitor(V_0). Knowing the voltage across the DUT ($V_{in} - V_0$) and the thickness of the capacitor gives us the electric field in the sample. The electric displacement field can be calculated by assuming the instantaneous charge stored by the DUT and C_0 are equal and knowing the area of the electrodes: $\boldsymbol{D(t)} = \frac{C_0}{A_{DUT}}\boldsymbol{V_0(t)}$. Since the IDT electrode can be seen as multiple PPE's in parallel (as shown in the previous section), the thickness of the capacitor is equal to the gap between the electrodes and the area $\boldsymbol{A_{DUT} = t_f W(2N - 1)}$, where W is the aperture length of a single IDT electrode and N the number of electrode finger pairs. Additionally, IV measurements show that the leakage current is negligible (< 100 pA) and any leakage resistance contributions of the ferroelectric sample may be neglected.

Different hysteresis measurements are performed using varying IDT sizes and layer thicknesses, C_0 values, amplitudes and frequencies of the AC signal. Figure 3 shows the obtained D-E and P-E loop measured using 50 μm IDTs and a 440 nm thick PZT layer. The frequency and amplitude of the triangular AC signal are 1 kHz and 175 V, respectively. The size of the capacitor in series is 2 nF, which is about 100 times larger than the capacitance value of the PZT device. At first the D-E loop was calculated (red curve in figure 3). Next a line was fitted to the linear curve at large electric fields to obtain the dielectric constant. The obtained value of the dielectric constant is 1055, which is in agreement with the results of the capacitance and dielectric constant simulation. The polarization P(t) is than obtained from $\boldsymbol{D(t)} = \boldsymbol{\epsilon_0 \epsilon_r E(t)} + \boldsymbol{P(t)}$, and the P-E loop can be plotted (blue curve in figure 3). The obtained remanent polarization is about 0.18 C/m^2 and spontaneous polarization is about 0.21 C/m^2, where the small difference between these values indicates the squareness of the loop. The coercive field is about 4 V/μm.

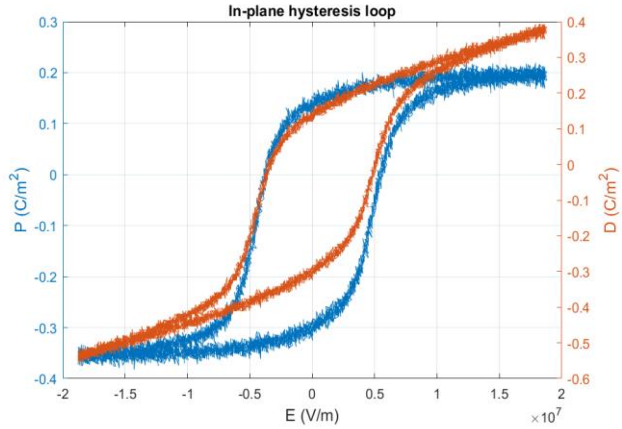


Figure 3: P-E and D-E hysteresis loops measured in-plane using 50 μm IDTs on a 440 nm thick PZT layer.

Conclusion

We have shown that in-plane dielectric characterization is possible using IDT electrodes. The dielectric constant obtained from FEM simulation and capacitance measurements is in agreement with the value obtained from hysteresis measurements and is about 1000. Furthermore, hysteresis measurements show the possibility to pole the ferroelectric PZT film in-plane which is important to improve the efficiency of the electro-optic modulators.

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