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Thin Film Ferroelectrics for Guided Wave Devices

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Abstract. Thin film ferroelectrics are being developed for guided wave optical devices. Of particular interest is $BaTiO_3$ because of its high electro-optic coefficient. Epitaxial thin films have been deposited by metalorganic chemical vapor deposition that are suitable for electro-optic devices. Thin film electro-optic modulators have been fabricated and their optical properties characterized. Factors that determine the ultimate bandwidth of these devices are discussed.

Keywords: ferroelectrics, waveguide, optical properties

Introduction

There is considerable interest in ferroelectric thin films for opto-electronic integrated circuits (OEICs) [1]. Here they are being developed for fast electro-optic modulators, optical parametric amplifiers and when suitably doped as optical amplifiers. For electro-optic modulators, devices that operate at frequencies in excess of 40 GHz are currently desired. Furthermore, research on devices that operate at frequencies in excess of 100 GHz is now underway. Ferroelectrics are particularly well-suited for these applications because of their high electro-optic coefficients. Electro-optic coefficients r_{ij} for ferroelectrics of interest ranging from 33 pm/V for $LiNbO_3$ to 1640 pm/V for $BaTiO_3$. While $LiNbO_3$ is available as large single crystals suitable for small scale integration, $BaTiO_3$ is available only as crystals of less than one cm in diameter. Other ferroelectrics with high electro-optic coefficients are also of interest but are not available in crystal sizes suitable for integration. However these materials can be potentially deposited as epitaxial thin films on large area substrates. Thus there is a clear advantage to develop thin film ferroelectrics if OEICs are to be developed.

Several thin film deposition techniques are now being pursued for the preparation of epitaxial ferroelectric thin films for optical applications. These include molecular beam epitaxy [2], pulsed laser deposition [3] and metalorganic chemical vapor deposition (MOCVD) [4]. Thin film deposition of oxides has a number of advantages in that it can result in single crystalline materials that normally can not be made by bulk techniques because of their high melting points. Furthermore composite structures can be fabricated that can have enhanced optical, electro-optical and electronic properties. For example, thin film waveguide structures can be fabricated that have a high optical contrast, leading to excellent optical confinement [5].

Despite its promise ferroelectric thin films for optical applications are not well developed. This results from numerous requirements on material perfection for optical devices. For waveguide devices, the ferroelectric layer needs to be optically transparent with optical losses of less than one dB/cm desired. Optical scattering can lead to high losses. Scattering results from local changes in the refractive index such as surfaces, interfaces, ferroelectric domains and grain boundaries. It was previously observed that the as-deposited epitaxial films had a large surface roughness of the order of ten nanometers that leads to high loss films due to surface scattering [6]. The film roughening was attributed to the formation of islands as a result of a large lattice constant mismatch between the film and the substrate. The island formation subsequently resulted in columnar grain growth with a resultant rough surface. Nevertheless through improved deposition control, oxide layers with optical losses of one dB/cm have been obtained.

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In addition to optical loss, the non-linear optical properties of the ferroelectric films, while promising, have been lower than that of the bulk. This is a result, in part, of the complex domain structure of the films [7]. By suitable poling of the films, the electro-optic properties can be considerably improved, but still remain lower than that of the bulk material [8].

Using MOCVD, we have shown that low loss films can be deposited that have excellent electro-optic properties. From these films, electro-optic modulators have been fabricated that show considerable promise for high bandwidth electro-optical device applications [9]. In this paper we will provide an overview of ferroelectric thin films for electro-optic applications. Emphasis will be placed on both materials and devices to achieve multigigahertz operation.

Materials Issues

For optical waveguides, the epitaxial ferroelectrics must be deposited on substrates with a lower refractive index than the layer itself. Thus heteroepitaxial deposition is required, which leads to difficulties in obtaining low-loss films. For high bandwidth applications substrates with low microwave dielectric constants are also required. Furthermore for OEICs large area substrates are needed. It should be noted that the low refractive index requirement precludes the use of semiconductors as substrates for direct deposition of ferroelectrics, since their indices are higher than that of the oxides. There are several insulating oxides with refractive indices lower than ferroelectric oxides that make them attractive for waveguide applications, these include MgO, sapphire and spinel. The substrates usually have a large lattice constant mismatch of 1 to 5 per cent with the ferroelectric overlayer, leading to highly strained layers. The high strain can lead to lower crystalline perfection and non-linear optical properties. Thus there is an advantage to lattice matched substrates. Despite the lattice mismatch, epitaxial ferroelectric films several microns thick have been deposited on low index substrates where the mismatch is greater than 5 per cent. A fundamental question arises as to why epitaxy can be achieved under these conditions, whereas in the case of semiconductor heteroepitaxy, it is much less tolerant to lattice constant mismatch. While the issue remains open, prior work on $BaTiO_3$ heteroepitaxy indicates that the epitaxial films can readily relax by forming misfit dislocations [10]. The ability to potentially deposit on a wide range of substrates makes ferroelectrics especially attractive for integration.

Ferroelectric Systems

The challenge for thin film waveguide fabrication is to identify suitable ferroelectric oxide materials that can be deposited on low index substrates. Table 1 lists a number of oxides we have deposited by MOCVD and their dielectric constants and electro-optic coefficients. Both perovskites and tungsten bronze structures have been deposited as epitaxial layers. For comparison bulk $LiNbO_3$properties are also included. For low power, high speed modulators a large electro-optic coefficient r_{ij} is desired. It can be seen that there are a number of ferroelectric oxides with an r_{ij} coefficient higher than $LiNbO_3$ even though it is the material currently used in high speed electro-optic modulators. This results from the availability of high quality $LiNbO_3$ bulk single crystals. Of particular importance is the voltage required for modulator operation denoted by the half-wave voltage V_π. The smaller the V_π parameter, the lower the drive voltage required for modulation. As can be seen from Table 1, there are a number of excellent candidates for low voltage, thin film modulators.

Another parameter of interest is the dielectric constant, this determines the microwave properties of the materials and particular microwave propagation. A low dielectric constant ε and a low microwave refractive index $\sqrt{\varepsilon}$ are needed for efficient and high speed modulation. Since the electro-optic coefficient scales with the $\sqrt{\varepsilon}$, the requirement of high r_{ij} and low ε are contradictory. Thus materials optimization is required. Alternatively waveguide structures need to be designed that minimize the microwave refractive index. By utilizing thin film structures some reduction in the index can be attained.

Table 1. Ferroelectric materials figures of merit.

	Dielectric constant	n^3r (pm/V)	V-π(V)*
$BaTiO_3$	2300	11300	0.14
$SrTiO_3$	300	–	
$(BaSr)TiO_3$	600	2460	0.63
$Sr_{0.75}Ba_{0.25}Nb_2O_6$	3400	16300	0.09
$KNbO_3$	55	715	2.1
$KNbTaO_3$	16000	1.9×10^6	7.9×10^{-4}
$LiNbO_3$	29	365	4.1

*Calculated for a 10 micron electrode spacing and $\lambda = 1550$ nm.

Thin Film Structures

For high bandwidth modulators low voltage operation and both phase and impedance matching are required. The importance of utilizing thin film waveguide structures can be understood by considering V_π and its dependence on $n^3 r_{ij}$ given by:

$$V_\pi = \lambda G / n^3 r_{ij} L \Gamma \tag{1}$$

where λ is the free space optical wavelength, n is the effective optical refractive index, Γ is the overlap integral, which is determined by the overlap of microwave and optical fields, L is the device length and G is the electrode spacing. As can be seen the voltage V_π required depends on electrode separation. The overlap factor Γ is highly efficient for thin film structures. The $V_\pi L$ product is a constant for a given material and electrode spacing. Calculated values of V_π are reported in Table 1, assuming an electrode spacing of 10 microns and overlap factor of one.

The bandwidth of a modulator depends on both the material and the device geometry. The velocity dispersion in the material affects the electro-optic modulation efficiency. The nominal phase modulation efficiency (reduction factor) η is given by [11].

$$\begin{aligned} \eta &= \sin u / u \\ u &= \pi f L (1/V_1 - 1/V_m) \end{aligned} \tag{2}$$

where f is the modulation frequency, L is the device length, and V_l and V_m are the velocities of the optical waves and microwaves in the ferroelectric, respectively. For a ferroelectric dispersion is large. Figure 1 plots the efficiency assuming different values of microwave index n_{mw} ranging from 2.5 to 5.5 using Eq. (2). As can be seen as the microwave index approaches the optical refractive index ($n = 2.1$), a higher frequency response results. Furthermore by decreasing the length the high frequency response increases. Short, high bandwidth devices can be potentially realized by using ferroelectrics with low V_π as shown in Fig. 2.

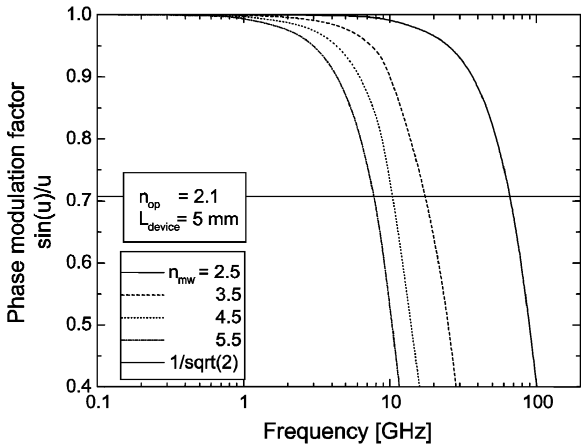

Fig. 1. Electro-optic response for different microwave indices.

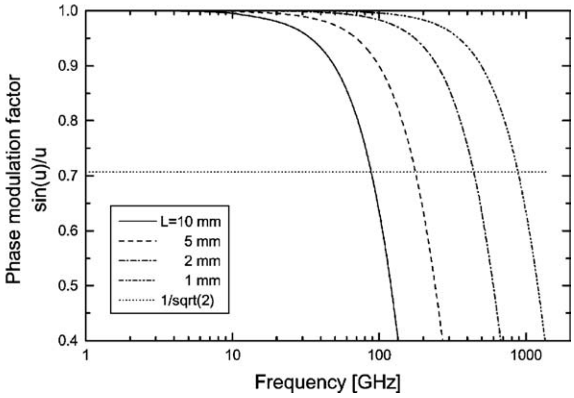

Fig. 2. Electro-optic response for different modulator lengths.

Device Realization

Thin film electro-optic modulators have been fabricated from $BaTiO_3$ on MgO substrates [12]. $BaTiO_3$ was chosen because of its large electro-optic coefficient in the bulk. Epitaxial films were deposited on single crystal MgO using MOCVD. Films were typically 0.5–0.7 microns, thick. To minimize light scattering films were planarized by chemically-mechanically polishing to less than a 1 nm rms surface roughness. An eight micron wide waveguide was defined photolithographically. Ridge waveguides were fabricated by wet chemical etching in a 5 per cent diluted HF solution. An effective ridge height of 10 nm was formed. Co-planar electrodes, consisting of a 270 nm, thick gold film was deposited by e-beam evaporation on the patterned photoresist. The electrodes were patterned using a lift-off technique. Electrodes, 80 microns wide, were formed. The gap between the electrodes is 14 microns wide.

The electro-optic response at 1550 nm of this thin film modulator was previously reported in Ref. [12]. Figure 3 shows the broadband, small signal analysis for a 4 mm device. Optical signal modulation is observed out to 20 GHz. While the response is promising

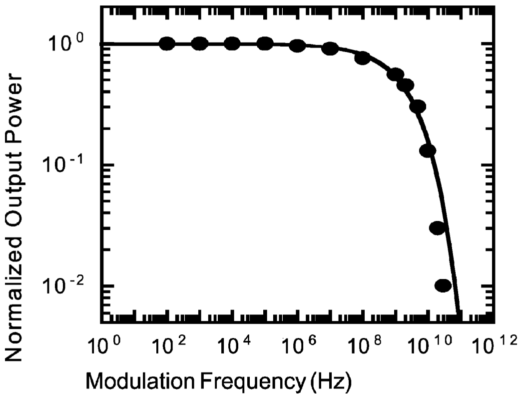

Fig. 3. Measured electro-optic response for a thin film modulator after Ref. [12].

the bandwidth is well below theoretical predictions. The observed roll-off is tentatively attributed to the RC time constant of the structure [14]. Improvements in the electrode structure to decrease the RC time constant and increase the bandwidth are currently under study. Furthermore improvements in the thin film electro-optic r_{ij} coefficient are needed so that shorter devices can be used.

The question of course arises as to what ultimately limits the bandwidth of the thin film devices. Presumably phase velocity mismatch as shown in Fig. 1 will limit the ultimate bandwidth. To improve the bandwidth, thin film structures are being developed that have lower dielectric constants at microwave frequencies. This is achieved by using thin ferroelectric overlayers on low dielectric constant substrates. Initial dielectric measurements of the $BaTiO_3$/MgO composite structure has a lower dielectric constant than the $BaTiO_3$ layer itself [13]. Furthermore improved device performance should result using low dielectric constant buffer layers to further lower velocity mismatch.

Advanced Structures

In addition to the rib waveguide modulator structure, strip-loaded optical waveguides are being investigated. In this case a low index cladding layer is deposited on top of the ferroelectric layer. Cladding layers such as silicon nitride and silicon dioxide can be used. This has the advantage that reactive ion etching can be used to define the waveguide structures. The dry etch chemistry for silicon nitride and silicon dioxide are well developed unlike that of ferroelectrics. Standard silicon processing techniques can be used. For example we have previously demonstrated strip waveguides of silicon nitride on ferroelectric films of $KNbO_3$ [15]. Second harmonic generation was observed upon pumping the waveguide with 1.06 micron laser excitation. We have also recently fabricated this type of structure using $BaTiO_3$ as the ferroelectric layer [16]. Optical loss measurements for the waveguides have shown that losses of less than 0.9 dB/cm can be achieved.

Acknowledgments

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