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Guided wave absorption and fluorescence in epitaxial Er:$BaTiO_3$ on MgO

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Abstract

We report on the observation of ~1.54 μm guided wave absorption and fluorescence in channel waveguides fabricated in erbium-doped thin-film epitaxial $BaTiO_3$. Luminescence transient measurements indicate that the relaxation of the excited Er ions is dominantly radiative.

Keywords: Er:$BaTiO_3$; Fluorescence; Luminescence

1. Introduction

The development of low-cost composite-substrate opto-electronic systems that can generate, guide, amplify, modulate and detect light would dramatically enhance the capabilities of long-distance communication systems, local-area-networks, and chip-to-chip optical interconnects. The integration of thin film ferroelectrics with silicon is one of several strategies toward the realization of this type of opto-electronic circuit. Proposed designs of hybrid opto-electronic devices, in such a composite host, typically incorporate a ferroelectric film, a low refractive index buffer layer, and a silicon substrate. At present, a fundamental issue in the development of this technology is identifying appropriate thin film ferroelectric and buffer layer materials. $BaTiO_3$ is a promising ferroelectric candidate due to its large electro-optic coefficients and high rare-earth solid solubility [1,2]. The use of MgO as a buffer layer provides a large film/buffer layer index difference, $\Delta n \approx 0.6$, which produces highly confining waveguides [3]. Highly confining waveguides allow large effective index changes to be made along the length of the waveguide. This enables a high degree of design flexibility and high packing densities for integrated optic elements [4]. A thin film ferroelectric and silicon composite substrate would provide the ability to guide, modulate, and detect light. To generate or amplify light, ferroelectrics are typically doped with rare earth ions, such as Er^{3+} [5,6]. However, relatively few reports have been made on the rare earth doping of thin film ferroelectrics [7–10]. We have recently demonstrated channel waveguides in epitaxial ferroelectric $BaTiO_3$ films on MgO and have also shown that $BaTiO_3$ layers can be readily doped with Er to concentrations on the order of 10^{21} cm^{-3} [3,7,8,11]. In this letter we report on the guided wave absorption and fluorescence characteristics of ~1.5 μm light in epitaxial Er:$BaTiO_3$ grown on single crystal MgO substrates to determine its suitability for integrated optic devices with gain.

2. Experimental details

Epitaxial Er:$BaTiO_3$ films on MgO were synthesized using low-pressure metalorganic chemical vapor deposition (MOCVD) that has been previously described [12]. Films were ~0.5 μm thick and epitaxial as determined by X-ray diffraction using phi angle scans. The *c*-axis of the Er:$BaTiO_3$ was aligned perpendicular to the plane of the substrate. Ridge waveguides were fabricated by photolithographically defining guides 2–6 μm wide and wet etching the films in a 1% HF in water solution for 60–80 s. Waveguide ridge heights of ~40 nm were measured using an Alpha Step profilometer. The samples were subsequently cleaved so that light could be end-fired into the waveguides. Light was end fired into the channel waveguides using input and output coupling lenses for absorption and fluorescence measurements. Absorption spectra were obtained by using two broad band light emitting diodes (LED) with central frequencies of ~1.465 μm (full width half maximum,

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FWHM ≈75nm) and ~1.55 μm (FWHM ≈75 nm). The waveguide absorption was determined by first coupling the broadband light emission of one of the LEDs into an undoped $BaTiO_3$ channel waveguide. The output from the waveguide was then coupled into a spectrometer, and the spectral character of the light measured. This process was then repeated for the doped waveguide. The relative heights of the two spectra were then scaled such that the fringes of the LED spectral output overlaid each other, i.e. the spectra were normalized at wavelengths where the Er absorption is presumed to be minimal. This process was repeated independently for each of the two LEDs used. The absorption spectra were then plotted by dividing the Er doped waveguide spectral transmission curve by the undoped waveguide spectral transmission curve, and subtracting the outcome from one. Finally, the spectral absorption curves from the two LEDs were combined to make one continuous curve.

In addition to using this technique to determine the waveguide absorption we also compared the transmission throughput of a laser at $\lambda = 1.465$ μm, at maximum power, to that of a very low power light source at a wavelength of 1535 nm in the Er:$BaTiO_3$ waveguides. Waveguide throughputs were determined by dividing the measured system throughput with the waveguide sample in the beam line, by the system throughput without the waveguide sample. We found that the two techniques presented above gave similar results to within ~1 dB/cm of each other. We note that there is Er absorption in the waveguides at $\lambda \approx 1465$ nm, however, at this pump wavelength and power density (waveguide area ~3 μm^2 with ~3 mW coupled into the waveguide) the propagation loss due to Er absorption should be less than 1 dB/cm. Fluorescence and Er relaxation lifetime measurements were made by exciting the Er ions with a diode laser pump at 980 nm. The waveguide output was spectrally resolved using a monochromator with a ~2.0 nm resolution.

3. Results

The propagation losses of a 5 μm wide channel waveguide were measured in a film annealed for 1 h at 700°C in flowing O_2 and mechanically planarized to have a root mean square surface roughness of 2 nm. The as-grown film had a surface roughness of ~10 nm rms. Annealing of the films was performed to increase the waveguide throughput. The amount of throughput improvement was dependent on the doping level in the films. In general, the more highly doped films showed more dramatic improvements in waveguide throughput. Propagation losses as low as ~6 dB/cm for the quasi-TM polarization and ~10 dB/cm for the quasi-TE polarization have been measured for channel waveguides in a 300 nm thick Er doped film. However for this film the propagation losses were found to be ~10 and 20 dB/cm for coupled TE and TM polarized light, respectively. This is to be compared to propagation losses as low as ~4 ± 2 dB/cm in undoped waveguides with a SiO_2 buffer layer [3]. We note that all of the above measurements were made in channel waveguides. The differences in the propagation losses mentioned above presumably result from waveguide structure (i.e. surface and waveguide side-wall roughness) and film microstructure irregularities. This is also a cause of the difference in the propagation loss of the quasi-TE and quasi-TM polarization for the various films.

To help determine the potential of this material as a guided wave gain medium we measured the absorption in an 8.2 mm long by 5 μm wide channel waveguide. Fig. 1 shows the measured resonant absorption in the waveguide. The absorption spectrum shows a number of interesting characteristics. The Er absorption spectrum is nearly as broad as that found in Er doped glass (~30 nm) and the waveguide has a peak absorption of ~−7 to −8 dB/cm at ~1535 nm. There are, however, two extra absorption peaks in the spectrum that can not be attributed to Er alone. The absorption peak at ~1440 nm is attributed to an O–H bond resonance and is coincident with the second harmonic of the bond stretch mode. O–H ions have been previously observed in epitaxial films presumably resulting from the metal-organic precursors [13]. The absorption peak at ~1600 nm is, as yet, unidentified. The guided wave Er fluorescence spectrum is also nearly as broad as that found in Er doped glass and did not show any remarkable features except for the characteristic Er luminescence (Fig. 2).

To investigate the Er radiative efficiency non-guided 1.535 μm photoluminescence (PL) decay transients were measured in our films at both room temperature and at ~20 K. The room temperature fluorescence decay showed a non-exponential decay with $\tau_{meas} \approx 6.2$ ms, where τ_{meas} is the measured time needed for the Er luminescence to be reduced to $1/e$ of its initial value (Fig. 3). The room temperature fluorescence decay has both a slow relaxation component and a fast relaxation component in the transient. This indicates that there is some fluorescence quenching in the

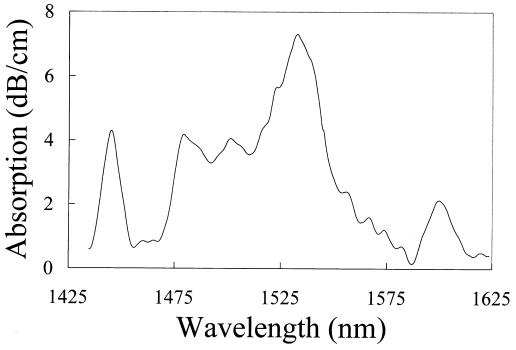

Fig. 1. Resonant absorption in a 8.2 mm long 5 μm wide Er:$BaTiO_3$ channel waveguide after an oxygen anneal at 700°C. (monochromator resolution ~2 nm).

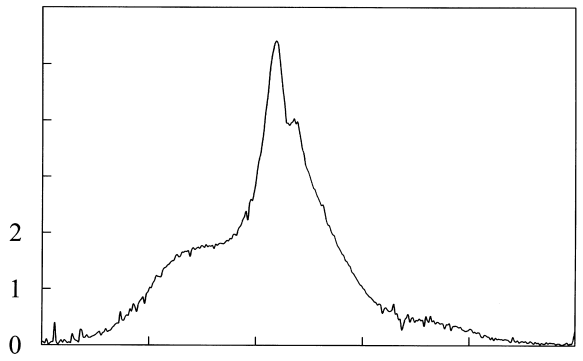

Fig. 2. Guided wave fluorescence from a 3.6 mm long 5 μm wide Er:$BaTiO_3$ channel waveguide.

film at room temperature. In contrast, the low temperature fluorescence decay showed a purely single exponential decay with a relaxation lifetime of ~8.2 ms. At low temperatures the fast decay component is not seen. This indicates that the relaxation mechanism that produces the fast component of the PL transient is most likely phonon assisted since the process abates at low temperatures. The efficiency of the Er de-excitation can be estimated by assuming that the low temperature transient represents the purely radiative relaxation constant, τ_{rad}. The PL transient indicates that the room temperature radiative efficiency was ~76%, by using the equation, efficiency = τ_{meas}/τ_{rad} [14].

4. Conclusions

In conclusion, guided wave absorption and fluorescence measurements were presented from epitaxial Er:$BaTiO_3$ films grown on MgO. The guided wave Er fluorescence had a FWHM similar to that from Er doped glass (~30 nm) with a peak emission at ~1534 nm. However, the guided wave absorption spectrum showed an absorption peak at ~1440 nm that was attributed to the second harmonic of an O–H bond resonance. PL decay transient measurements indicate that the Er luminescence has an efficiency of 76%. The Er relaxation is dominantly radiative, however, some competing Er relaxation mechanisms are present in the Er:$BaTiO_3$ film. We are presently optimizing growth parameters and post-growth annealing processes to minimize the O–H content in the films. Efforts are also under way to perform gain measurements with these films using a 1480 nm pump laser. Once the competing non-radiative processes and propagation losses are minimized, and the Er dopant concentration is optimized, active electro-optic low-threshold devices with gain should be realizable.

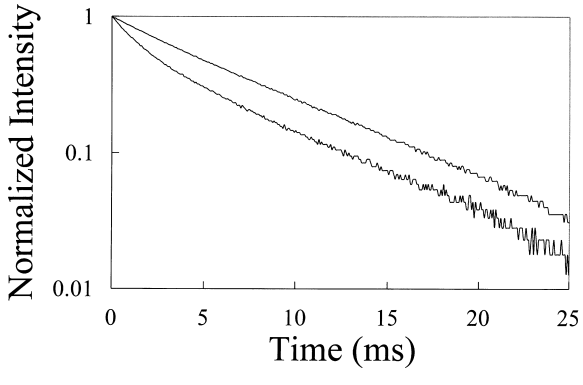

Fig. 3. Photoluminescence decay transients from an Er:$BaTiO_3$ film. The upper curve is the low temperature (~20 K) fluorescence transient and shows a ~8.2 ms single exponential decay. The lower curve shows the room temperature fluorescence transient to have a non-single exponential radiative decay with a 1/*e* relaxation time constant of ~6.2 ms.

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