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Electro-Optic Characteristics Improvement of ZnMgTe/ZnTe Waveguide Devices

Wei-Che Sun[1], Fukino Kazami[1], Jing Wang[1], Taizo Nakasu[1], Shota Hattori[1], Takeru Kizu[1], Yuki Hashimoto[1], Masakazu Kobayashi[1,2] and Toshiaki Asahi[3]

[1] Waseda University, Department of Electrical Engineering,
3-4-1 Ookubo, Shinjuku-ku, Tokyo,169-8555, Japan
E-mail: sun@fuji.waseda.jp.
[2] Waseda University, The Kagami Memorial Laboratory for Materials Science and Technology
2-8-26, Nishiwaseda, Shinjuku-ku, Tokyo, 169-0051, Japan
[3] JX Nippon Mining & Metals Corp.
3453, Miyata-cho, Hitachi-shi, Ibaraki, 317-0055, Japan

Abstract

ZnMgTe/ZnTe waveguide Electro-Optic (EO) modulator growth by molecular beam epitaxy (MBE) showed a great potential for the practical application. For a low loss ZnMgTe/ZnTe waveguide, the Mg composition and the thickness of ZnMgTe cladding layer are critical factors. Various ZnMgTe/ZnTe waveguide structures were grown by MBE. A waveguide structure with Mg 20%, 0.6μm thick cladding layers exhibited higher performance than other waveguide structures having different cladding layers' parameters. The EO signal intensity was affected by the cladding layer thickness. It was related to the penetration depth at the ZnMgTe/ZnTe interface. At the same time, the lattice mismatch strain and associated defects have degraded the crystal quality of the device, and resulted in the poor EO property.

1. Introduction

Electro-Optic (EO) materials have been gotten much attention and utilized to develop practical novel devices. ZnTe is an attractive EO crystal with high EO coefficient (4.5pm/V). According to the linear EO effect equation,

$$\Gamma = \pi \cdot r_{41} \frac{L}{\lambda} \cdot \frac{V}{d} \cdot n^3 \qquad (1)$$

(Γ: phase shift, n: refraction index, r_{41}: EO constant, V: voltage bias, λ: light wavelength, d: device cavity thickness, L: device cavity length), EO crystals can generate phase shifts which depend on applied electrical fields (V/d). Thus, thin film EO devices can have better sensitivity at a given voltage than bulk devices.

ZnMgTe(Cladding)/ZnTe(Core)/ZnMgTe(Cladding) thin film waveguide has been fabricated and demonstrated a great potential to be a high performance EO modulator [1]. In order to achieve low propagation loss waveguide structures, high refractive index difference between the cladding and the core layer is needed. It can be achieved by adding Mg compositions (Mg x%) into ZnMgTe cladding layers. However, high Mg% would lead to the oxidation of the material itself along with the lattice mismatch enlargement between the cladding layer and the core layer. The lattice mismatch between zincblende ZnTe and MgTe is about 4.1% [2]. When ZnMgTe layer thickness has exceeded its calculated critical layers thickness (CCLT), the misfit dislocations would befall and degrade the crystal quality. It has been confirmed that low dislocation ZnMgTe/ZnTe waveguide structures could be grown at the condition that the ZnMgTe cladding layer thickness was within CCLT×20, and the in-plane lattice mismatch was under 0.2% [3]. A low dislocations waveguide with Mg 20%, 0.15μm cladding layers and 8μm core layer had been fabricated (the cladding layer thickness was corresponding to CCLT×20). It was revealed that the propagation loss in this device was relatively large (-14dB). It is probably because the cladding layer thickness was thinner than the penetration depth of the input light and the energy flow leakage associated with the evanescent wave couldn't be ignored.

The penetration depth ($d_{p1/e}$) was theoretically calculated [4]. In order to study the propagation loss in waveguide structures, two different kinds of structures were fabricated. One structure consisted with a thicker cladding layer while keeping the Mg%, and the other consisted with the higher Mg%. The cladding layer of these structures would exhibit large in-plane lattice mismatch, and the crystal quality deterioration should be also considered.

In this study, ZnMgTe/ZnTe waveguide devices were grown using molecular beam epitaxy (MBE), and the EO characteristics and crystallographic properties of the devices were compared.

2. Experiments

The calculated value of $d_{p1/e}$ was about 0.4μm for Mg 20%, and 0.3μm for Mg 40%, respectively. The cladding layer thickness was designed to be about 1.5 times of the penetration depth (0.60μm for the Mg 20% structure and 0.45μm for the Mg 40% structure). Cladding layer thicknesses of these structures were about 100 times and 200 times of CCLT, respectively. The waveguides were grown on (001) conductive P-doped ZnTe substrates. After the growth, gold stripes were vacuum evaporated on top of the waveguide (0.25mm wide). The cleaved edges without dielectric coating were used to form the cavity (about 1.3mm long).

EO characteristics were measured by using continuous wave laser (45° linearly polarized to cladding/core layers interface). A lensed fiber was used to guide the light into the device and the propagated light was collected by a condenser lens. The propagation loss was measure using a light power meter. To observe the phase shift generated by the device, a 1/4 waveplate (QWP), a 1/2 waveplate (HWP) and a polarizer were placed after the condenser lens. The light was directed into a photo-diode (PD) and converted to the electrical current. The electrical current was then monitored using a 1MΩ impedance oscilloscope, and it was shown as voltage. The voltage bias used for this experiment was 10V pulse with the frequency of 300Hz. It was applied on the device between the top gold electrode and the bottom of the substrate (grounded). The EO characteristic was evaluated by measuring the output voltage difference (Vs) between 10V bias and 0V bias applied. The relationship between Vs and the measured phase shift (Γ_e) was described as follows:

$$\mathrm{Vs} \equiv \mathrm{V_{Signal}}(\mathrm{bias{:}\ 10V}) - \mathrm{V_{signal}}(\mathrm{bias{:}\ 0V}) = \mathrm{V_p} \sin\left(\frac{\Gamma_e + \frac{\pi}{2}}{2}\right)^2 - \frac{1}{2}\mathrm{V_p} \qquad (2)$$

where V_p was the voltage corresponding to propagated light without the voltage bias nor waveplates.

The X-ray diffraction reciprocal space mapping (RSM) was used to measure the in-plane lattice mismatch and evaluate the crystal quality of various waveguide structures.

3. Results and Discussions

Table 1 summarizes the propagation loss and the phase shift generated by the waveguide device. The propagation loss of $Zn_{0.8}Mg_{0.2}Te$ (0.60μm) and $Zn_{0.6}Mg_{0.4}Te$ (0.50μm) devices were -7dB and -10dB, respectively. Both data exhibited the improved propagation properties compared with the Mg 20% with high crystal quality cladding layers. Figure 1 shows the intensity modulation signal (upper) and applied voltage signal (downer) of the waveguide device structures. The output voltage difference (Vs) of Mg 20% (0.6μm) device was 220mW when 10V was applied. This output voltage difference (Vs) was much stronger than other devices, even though the cladding layer thickness is about 100 times of CCLT, and a large in-plane mismatch was observed. Based on Eq. (2), measured phase shifts (Γ_e) were about 8° for both devices. Since the phase shift was a function of the electric field, Mg % hasn't affected the amount of the phase shift. The obtained Γ_e was about 80% of theoretical values (Γ) calculated using the Eq. (1).

The Mg 20% structure with the 100 times of the CCLT thickness exhibited the larger signal intensity than the Mg 20% ZnMgTe structure with the 20 times of the CCLT cladding layer thickness. Based on this data, the penetration depth of the light is probably the controlling parameter for the device performance for the cladding layer thickness within 100 times of the CCLT range. However, higher Mg % (40%) with the thickness around 200 times of the CCLT has further extended the in-plane lattice mismatch (1.34%) , and raised the propagation loss due to the defects formed in the core layer.

These results indicate that the Mg% and corresponding CCLT are key factors for realizing high performance waveguide EO modulators. Further improvements are required to ameliorate the crystal quality and optimize layers' thickness to achieve high device performance.

Table 1 Experimental results of the waveguides

Mg%	cladding layer thickness	propagation loss	(Vs)output voltage difference	phase shift	In-plane lattice mismatch
20%	0.15μm	-14dB	54mV	9°	0.14%
20%	0.60μm	-7dB	220mV	8°	0.73%
40%	0.50μm	-10dB	120mV	10°	1.34%

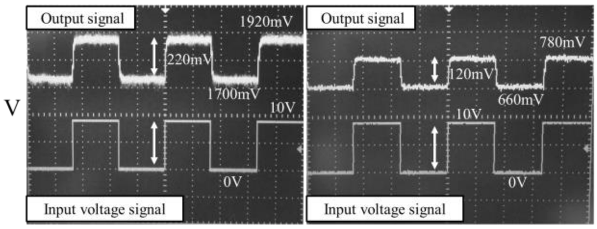

Fig.1 Output voltage modulation of EO waveguide devices (a) $Zn_{0.80}Mg_{0.20}Te$ (0.6μm) device (b) $Zn_{0.60}Mg_{0.40}Te$ (0.5μm) device

4. Conclusions

The ZnMgTe/ZnTe waveguides with high Mg% and thick cladding layer thickness were fabricated in order to reduce the propagation loss. The penetration depth ($d_{p1/e}$) of the light at the ZnMgTe/ZnTe interface was calculated to reduce the propagation loss in the waveguide. The calculated thickness was analyzed from the view point of the CCLT. For Mg 20% and Mg 40% devices, the $d_{p1/e}\times 1.5$ was around 0.6μm (CCLT×100) and 0.45μm (CCLTx200), respectively. Those structures were grown using MBE and the propagation loss and EO signal intensities were studied. Mg 20% structure with the cladding layer thickness of 0.6μm exhibited about 8 % of phase shift (220 mV of the signal shift) under the 10V of applied voltage.

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