Design of GaN based optical modulator with Mach-Zehnder interferometer structure

R.W. PURNAMANINGSIH, [a] N.R. POESPAWATI [a]
I. SARASWATI,[a,b] E. DOGHECHE[b]
[a]Departemen Teknik Elektro,
[a]Universitas Indonesia,[b]Institute of Electronics, Microelectronics and Nanotechnology,
Optoelectronics Group (IEMN CNRS UMR 8520)
[a]Kampus UI Depok, [b]Villeneuve d'Ascq
[a]INDONESIA, [b]FRANCE
retno.wigajatri@ui.ac.id

Abstract: - In this work we have designed a Mach Zehnder interferometer (MZI) for electro optic modulator at telecommunication wavelength using GaN on Sapphire. The knowledge of GaN sample optical properties were also investigated, resulting refractive index for the GaN layers were found to be nTE=2.279±0.001 and nTM = 2.316±0.001 and good temperatur stability. Optimization of the structure parameters and electrodes required for this structure was conducted accurately by theoretical tools using BPM methods. The results showed possibility to realize GaN based MZI for future optical modulator devices.

Key-Words: -GaN, Mach Zehnder interferometer, electro-optic, modulator

1 Introduction

Gallium Nitride (GaN) has attracted much attention among researcher because of its superior properties, such as wide-bandgap, high electron mobility and good thermal stability [1,2]. Moreover, nitride based devices are the most environmentally friendly among others compound semiconductors. Beside its prospective application in optics, such as in light emitting and detecting device [3-6]. GaN also has promising application in passive and active optical waveguide based devices such as directional coupler and electro-optic modulators used for high-speed optical communication systems and ultra-fast information processing applications [7,8]. GaN based optical modulator is believed could improve electro-optic modulator currently available because it has good transparency in telecommunication wavelength since the optical absorption edge is at 3.4eV, also it has good electro-optic coefficients, low optical losses, low dielectric constants and temperature stability [9,10]. GaN has a much smaller refractive index and potentially lower optical absorption compared to InP [11]. Previous study reported the index modulation Δn of the n-GaN active layer is 2×10^{-3}, indicates the suitability of such structure for high optical frequency modulation [12]. In this work we report the optical characterization of GaN on Sapphire and design of Mach Zehnder interferometer based optical modulator using GaN on Sapphire sample at telecommunication wavelength 1.55 µm.

2 Sample Characterizations

In order to design optical waveguide based devices, the knowledge of optical properties of the sample is required. The sample used in this work is composed of a GaN active layer grown on high temperature/low temperature AlN/GaN buffer layers. The 1st buffer layer is AlN of 300nm and the superlattice is AlN/GaN of 200nm, thinner than previous work [13]. Detailed optical characterizations of GaN structures were performed using the prism coupling technique of a rutile (TiO_2) prism in a Metricon M2010 setup, the heart of the system is given in Fig. 1. We measured refractive indices for four wavelengths, namely, 532, 633, 975 and 1550 nm with an accuracy of 10^{-3} as shown in Fig 2. We found that the refractive index of GaN decreases with wavelength and reaches to approximately nTE=2.279±0.001 and nTM= 2.316±0.001 in 1550 nm wavelength window. This measured refractive indices versus wavelength are in good agreement with previously reported values [13-15]. Because of its plane wave TM polarization refractive index values are more sensitive to layer quality.

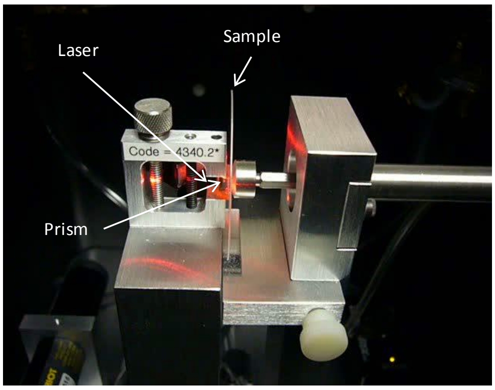

Fig. 1. Metricon M2010 prismcoupler used for GaN waveguide optical characterization

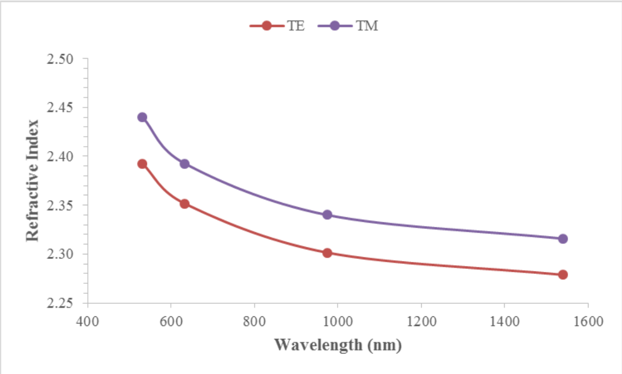

Fig. 2 Refractive index of GaN optical waveguide structure deposited on sapphire substrate for TE and TM polarization

The temperature dependence of the refractive index in both polarizations at λ= 1550 nm is plotted in Fig. 3. The results indicate that GaN possesses a relatively stable behavior with only 6.5×10^{-5} K^{-1} and 7.5×10^{-5} K^{-1} refractive index variations for temperatures from 300 to 375 K in TE and TM optical polarization respectively. This value is approximately on order of magnitude lower than that of InP which is about 3×10^{-4} ^0C[16].

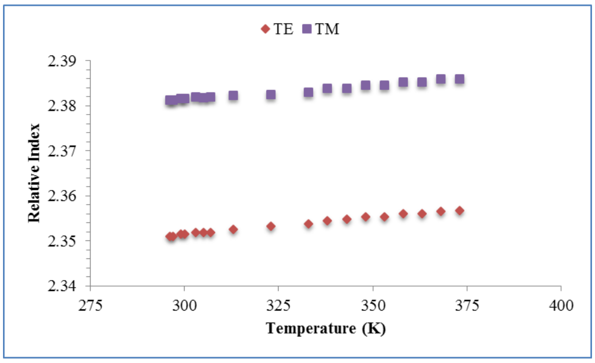

Fig. 3. Temperature dependence of the refractive index of GaN thin film for TE and TM polarization

3 Mach Zehnder Interferometer Based Optical Modulator Design

The optical modulator design were based on Mach Zehnder interferometer structure, consists of widely used large cross section rib waveguides and double Y junctions based on a reflected S-bends mathematic curve, for which excellent splitting ratio were demonstrated [17,18]. The functional form of S-bend is $\left(h/l\right)z-\left(h/2\pi\right)sin\left(\left(2\pi/l\right)z\right)$, where h is the height of the bend, l the length of the bend and z the propagation axis. The model was carried out using OptiBPM commercial software, the key design feature is to optimize the waveguide cross section and double Y junction configuration in order to minimize losses and achieve good optical field distribution. In order to obtain low loss 3 dB Y junction which divide and combine the light between the symmetric arms of the interferometer, we simulated the h/l ratio of the S-bend. In this design, the length of the interferometer arm was 3 mm. Using 3 D BPM we deduced the schematic structure of the optical modulator design with Mach Zehnder structure present in Fig. 4 and the cross sectional view was shown in Fig. 5 where n++ type GaN plays the role of bottom electrode. The calculated results show that the optimum parameter for the device are as follow: the width and thickness of input and output linear waveguides are 4 µm and support only single mode propagation. The investigated optical modulator was 10 mm long and not more than 0.05 mm wide. The 1.55 µm light as an input wave was coupled in through linear waveguide resulting relative power output of 0.71. The electrodes were deposited on one of the linear arm of waveguide and voltages were applied, the electric field will change the refractive index of waveguide material cause a phase shift on wave traverses.The induced phase shift is obtained as

$$\Delta\varphi = \pi\frac{rn^3LV}{\lambda d} \qquad (1)$$

in order to obtain the phase shift of π, the applied voltage V is given by :

$$V_\pi = \frac{d}{L}\frac{\lambda}{rn^3} \qquad (2)$$

Where L is the length of waveguide linear arm, d is the distance between electrodes, r is the electro-optic coefficient tensor, n is the refractive index of medium [19]. In this simulation, electric field was applied to GaN using tensor $r_{33} = 8.94\ pm/V$ and $r_{13} = 3.09\frac{pm}{V}$ [20] in order to obtain vertical and horizontal electro-optic coefficient. The equation above (Eq. 1) shows that the phase shift is proportional to the ratio of l/d and V. In this design the electric field were applied through 1 µm thickness and 3 mm long of Au electrode deposited at the top and bottom for one of the interferometer arm. This thickness was chosen from technological process concern. This electric field allows phase modulation of the optical signal traveling through it.

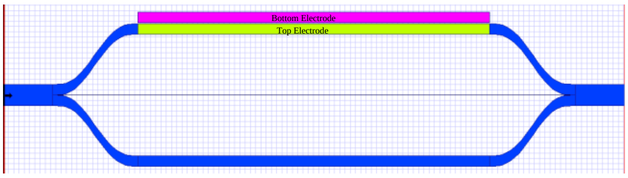

Fig. 4 Schematic of Mach Zehnder optical modulator with single mode profile

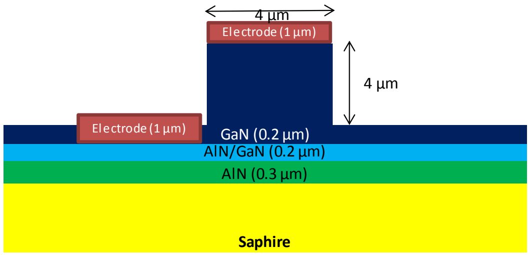

Fig.5 Cross sectional view of the proposed modulator

The depositions of Au ($n_{Au} = 0.56$) electrodes increase the power losses 0.43 % due to dielectric values of gold.These power losses obtained by comparing MZI output power before and after Au electrodes depositions. Without applied electric field, constructive interference was achieved at the output of modulator as shown in Fig. 6. The relative optical power distribution of this optimum device is shown in Fig. 7.

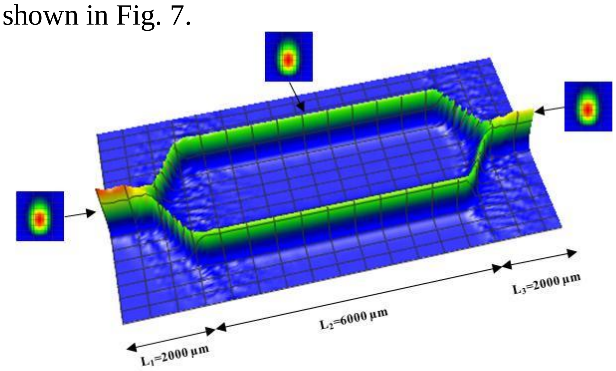

Fig. 6 The optical field distribution without applied voltage

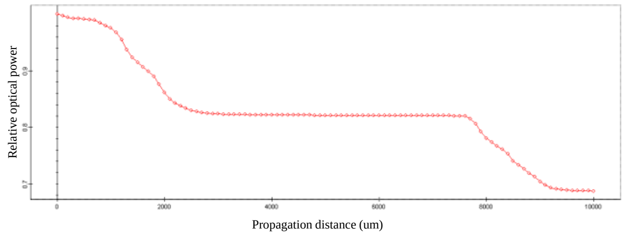

Fig. 7 The relative optical intensity variation without applied voltage.

Although GaN also display piezoelectricity [21], these properties were ignored in the simulation. By changing the applied voltage from 0 up to 40 V and monitoring the output power, the simulated results showed that the driving voltage V_π of the device are 33 Volt (Fig. 8). At this voltage the optical field distribution and relative output power distribution are shown in Fig. 9 and 10 respectively. This means that the optical signal propagating through the two arms of the interferometer destructively interfere with each other with phase difference of π. These results were consistent with the theoretical calculation if we assume there were no electrode losses and the piezoelectric field can be ignored. This value is still much larger compared to the available modulators with V_π at around 6 – 10 Volt.

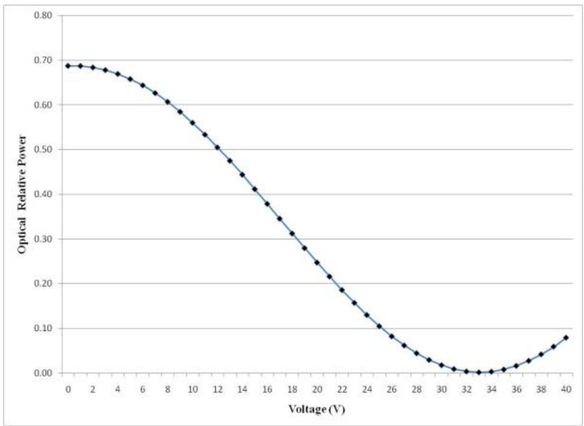

Fig. 8 The relation between output optical power and applied voltage

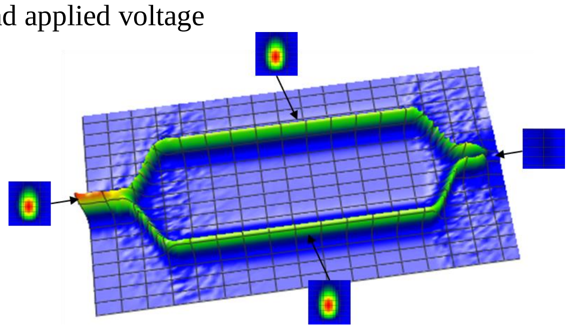

Fig. 9 The optical field distribution with applied voltage of V_π

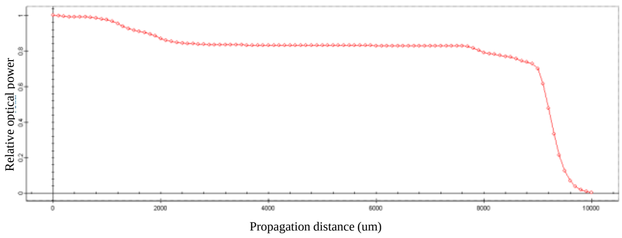

Fig. 10 The relative optical power variation with applied voltage of V_π

It was shown that when applied voltage is V_π the output of the modulator was completely zero. The possibility of fabrication the Mach Zehnder interferometer for optical communication has been duscussed

4 Conclusion

In conclusion, the design of a Mach Zehnder interferometer based electrooptic modulator using GaN on Sapphire sample was demonstrated for a telecomunication wavelength 1.55 µm. Optical characteristics of the sample required for this simulation have also been investigated. Based on three dimensional simulation using Opti BPM, the Mach Zehnder interferometer based electrooptic modulator was analyzed. The propagation and distribution of infrared wavelength, 1.55 µm field were simulated precisely. We have demonstrated the relationship between the applied voltage and output power and obtained optimum parameter of the device. The modelling results shows the possiblity of GaN based optical modulator with Mach-Zehnder interferometers for future optoelectronic applications.

Acknowledgments
This work was supported by IJR Grant Research from DGHE Indonesia and France Embassy.

References:

[1] S.J. Pearton, F. Ren, A.P. Zhang, K.P. Lee, Fabrication and performance of GaN electronic devices, Material Science and Engineering, R30, (2000), 55-212
[2] D. Pavlidis, Recent advances in III-V nitride electronic devices, IEDM **04**, (2004), 795-798 .
[3] P.C. Chang, C.L.Yu, S.J. Chang, Y.J. Liu and S.L. Wu, Low-Noise and High-Detectivity GaN UV Photodiodes With a Low-Temperature AlN Cap Layer," IEEE Sensor Journal **07**, (2002), pp.1289-1292
[4] J. Ariajay, B. Maung, T.S. Lang, C.H. Choy and S.J. Chua, High Brightness GaN LED with Engineered Sapphire Substrate, 9th Electronic Packaging Technology Conference, (2007), pp. 343-346
[5] Y. Wang, Y. Zou, X. Ma, N. Yu, D. Deng, K. M. Lau, Progress on the GaN-based LEDs and LDs, International Conference on Optoelectronics and Microelectronics (ICEM), (2012), pp. 105-110
[6] I. Akasaki, GaN-Based p-n Junction Blue-Light-Emitting Devices, Proc. Of the IEEE 101**(**10), (2013), pp. 2200-2210
[7] Y. Zang, L. McKnight, E. Engin, I. M. Watson, M.J. Cryan et al., GaN directional couplers for integrated quantum photonics, Appl Phys. Lett 99, (2011), pp. 161119 -1-3
[8] N. Kheirodin, L. Nevou, H. Machadani, P. Crozat, L. Vivien, M. Tchemycheva, A. Lupu, F. H. Julien, G. Pozzovivo, S. Golka, G. Strasser, F. Guillot and E. Monroy, Electro optical Modulator at Telecommunication 20 **(**9), (2008), pp. 724-726.
[9] R. Hui, Y. Wan, J. Li, S. Jin J. Lin and H. Jiang, III-Nitride Based Planar Lightwave Circuits for Long Wavelength Optical Communications, IEEE Journal of Quantum Electronics 41(01), (2005) pp. 100-109
[10] R. Hui, S. Taherion, Y. Wan, J. Li, S.X. Jin et al, GaN-based waveguide devices for long-wavelength optical communications, Appl. Phys. Lett. 82(09), (2003) pp. 1326-1328
[11] M. K. Smith and C.V Dam, PHASAR-BasedWDM-Devices: Principles,Design and Applications IEEE J. Sel. Top. Quantum Electron 2, (1996), pp. 236
[12] A. Stolz, L. Considine, E. Dogeche, D. Pavlidis, D. Decoster, Prospective for a Galium Nitride-based Optical Waveguide Modulator Structure, IEICE Transaction on Electronic, (2012), E95-C **8.**
[13] A. Stolz, E. Cho, E. Dogeche, Y. Androusi, D.Troadec, D. Decoster, Optical waveguide loss minimized into gallium nitride based structures grown by metalorganic vapor phase epitaxy, Applied Physics Letters 98, (2011), 161903
[14] A. Chowdhury, H. Ng. M. Bhardwaj, and N. Weimann, Second-harmonic generation in periodically poled GaN, Appl. Phys. Lett. 83,(2003), pp. 1077.
[15] S. Pezzagna, J. Bault, M. Leroux, J. Massies, and M. De Micheli, Refractive indices and

elasto-optic coefficients of GaN studied by optical waveguiding, J. Appl. Phys. 103, (2008), pp. 123112

[16] M. Bertoloti, V. Bodanov, A. Ferrari, A. Jascow, N. Nazorova, A. Pikhtin, and L. Shirone, Temperature dependence of refractive index in semiconductor, J. Opt. Soc. Amer. B., vol. 7,(1990), pp. 918-922

[17] G.A. Bogert and Y.C Chen, Low loss Y branch power dividers, Electron Lett. 25, (1989), pp. 1712-1714

[18] M. Zegaoui, D. Decoster, J. Harari, V. Magnin, X.Wallart and J. Chazelas, A new low crosstalk InP digital optical switch based on carrier-induced effects for 1.55 µm application, IEEE Photonics Technology Letters 21, (2009), pp 456-548

[19] J. Yariv and P.Yeh, *Photonic – Optical Electronics in Modern Communications*, 6th ed., Oxford University Press, New York (2007).

[20] P. Chen, S. P. Li, X. G. Tu, Y. H. Zuo, L. Zhao, S. W. Chen, J. C. Li, W. Lin, H. Y. Chen, D. Y. Liu, J. Y. Kang, Y. D. Yu, J. Z. Yu and Q. M. Wang, Pockels effect in GaN/AlxGa1-xN superlattice with different quantum structures, *Proc. SPIE* 6984, (2008), 69841G1-4

[21] E.T. Yu XS Dang, P.M, Asbeck, S.S Lau and G.J. Sullivan, Spontaneous and piezoelectric polarization effect in III-V nitide heterostructure, J.Vac. Sci. Tech. B17, (1999), pp.