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مدولاتورهای الکترواپتیک ترکیبی سیلیکون و لیتیم نایوبیت

زبیده دادخواه، ذاکرحسین فیروزه، و رضا صفیان

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چکیده- این مقاله روی مدولاتورهای لیتیم نایوبیت با روش ساخت آسان متمرکز شده‌است. از این رو، ما استفاده از یک موجبر سیلیکون غیر بلوری به جای موجبر سیلیکون بلوری را مورد بررسی قرار داده‌ایم. سپس، ابعاد موجبر ترکیبی سیلیکون غیر بلوری و لیتیم نایوبیت بهینه‌سازی شده‌است. درنتیجه، یک مدولاتور ماخ-زندر با پهنای باند بالا به کمک شبیه‌سازی‌هایCOMSOL و FDTD طراحی شده‌است.

کلید واژه- مدولاتورهای الکترواپتیک، لیتیم نایوبیت لایه نازک، ساختار ماخ-زندر، موجبرهای نوری،مدارهای مجتمع نوری.

Hybrid Silicon and Lithium Niobate Electro-Optic Modulators

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Abstract-This paper has been focused on lithium niobate (LN) modulators with simple fabrication process. For this aspect, we suggest the use of non-crystalline silicon (Si) (poly-Si or a-Si:H) instead of crystalline Si for a hybrid Si and LN optical waveguide. Then, dimensions of the hybrid non-crystalline Si and LNwaveguidewere optimized to obtain a high bandwidth Mach-Zehnder modulator using FDTD and COMSOL simulations.

Keywords:Electro-optic modulators, Thin-film lithium niobate, Mach-Zehnder structure, Optical waveguides, Photonic integrated circuits.

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1. Introduction

Mach-Zehnder (MZ) electro-optical modulator plays an important role in optical communication systems. This structure isused to analog and digital modulation. In addition, Lithium niobate (LN) is used for commercial electro-optic (EO) modulator thanks to its transparency at telecommunication wavelength and high EO coefficient (r_{33}=31pm/V). The EO modulation property ofLN is due to the Pockels effect (*i.e.*, linear EO modulation effect) [1]. Over the last decade, the thin-film LN (TFLN) on a low refractive index material such as Sio_2 or benzocyclobutene (BCB) has been fabricated using ion implantation and wafer bonding technologies [2]-[3]. Some common materials are used to fabricate hybrid LN waveguidesas the following: Silicon Nitride (SiN, Si_3N_4), Silicon (Si) and LN [2]-[4]-[5]. One of them, Si enables a high field confinement in an optical waveguide. For hybrid crystalline Si (c-Si) and LN waveguide, direct bonding of c-Si and LN wafers is a challenge. The deposition of non-crystalline Si on LN is a simple method to form the hybrid Si and LN waveguide. Unlike c-Si which is a transparent material at telecommunication wavelength, non-crystalline Si has some scattering and absorption loss [6]. In this work, we designed a hybrid non-crystalline Si and LN waveguide for a MZ traveling wave modulator. Also, we calculated V_{π}.L and EO response of the modulator.

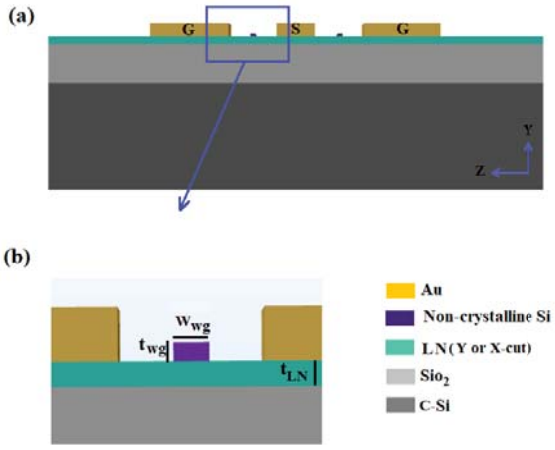

Fig. 1: (a) Cross section of MZ modulator. (b) hybrid non-crystalline Si and LN optical waveguide.

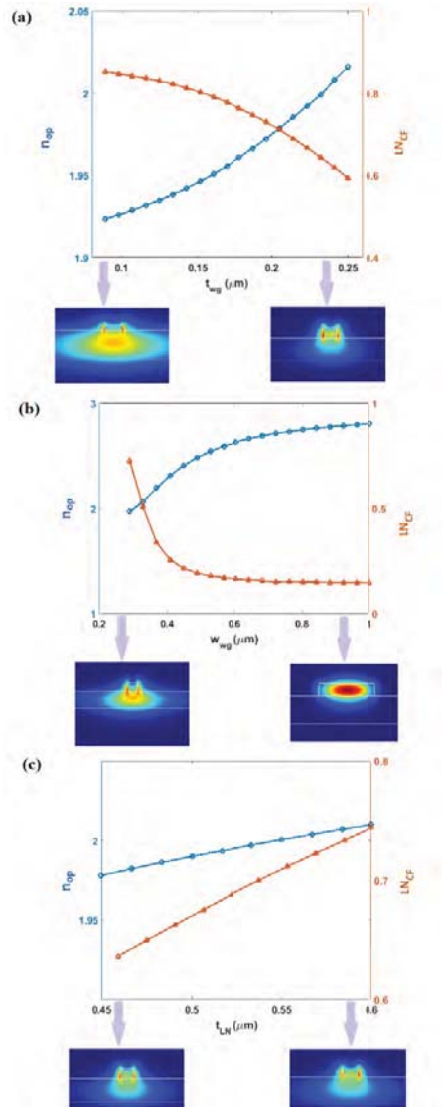

Fig 2: Effect of waveguide dimensions on LN_{CF}, optical mode area and n_{op}. (a) t_{wg} (b) w_{wg} (c) t_{LN}.

2. Design of Hybrid Si and LN Optical Waveguide

Schematic of the proposed MZ modulator based on the hybrid non-crystalline Si andLN is shown in Fig. 1. The optical waveguide in each arms of the MZ modulator is located between the signal and ground electrodes. The strong modulation achieves if the optical field in TFLN overlaps with the RF field between two electrodes. The geometrical parameters in Fig. 1bwas selected as

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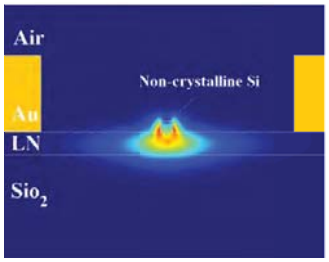

Fig. 3: Cross section of optical mode in hybrid non-crystalline Si and LN waveguide

design parameters ofthe hybrid waveguide. The impact of these parameters on optical effective refractive index (n_{op}), optical mode area and LN confinement factor (LN_{CF}) have been investigated for TE_0 mode at λ=1.55 µm [7]. As shown in Fig. 2a, by decreasing the waveguide thickness (t_{wg}), LN_{CF} and optical mode area are increased and n_{op} is reduced. In Fig. 2b, the optical mode is propagated in the LN layer by reducing waveguide width (w_{wg}). Therefore, LN_{CF} and optical mode area are improved. In addition, n_{op} is decreased. According to Fig. 3c, the thicker TFLN increases LN_{CF} and nop.

3. Impact of Non-Crystalline Si on Optical Loss of Hybrid Optical Waveguide

C-Si is a transparent material in a wide range of wavelength. In previous works, the Si on isolator (SOI) wafer has been used to fabricate hybrid LN and c-Si waveguide [3]-[4]-[8]. The optical loss of such waveguideis less than 1 dB/cm [3]-[4]. Beside, non-crystalline Si can be deposited on a wide variety of substrates. Amorphous Si (a-Si) is a non-crystalline form of Si that suffers from optical loss due to Si dangling bond defects [6]. Hybrid a-Si and LN waveguide with high optical loss 44 dB/cm has been reported [9]. The intrinsic optical loss can be reduced in a-Si material using hydrogen passivation of dangling bond defects. Hydrogenated a-Si (a-Si:H) film deposited from SiH_4 [10]. Optical loss 3 dB/cm has been acquired for ahybrid a-Si:H and LNwaveguide [11]. Optical loss of such waveguide is a function of deposition parameters and annealing condition. Moreover, polysilicon (poly-Si) is a polycrystalline form of Si. Optical loss of poly-Si is due to polycrystallization [6]. Recent works have shown that the optical loss of the poly-Si waveguide can be lower than 10 dB/cm [12]-[13]. According to above, a-Si:H can be suggested for hybrid Si and LN optical waveguide

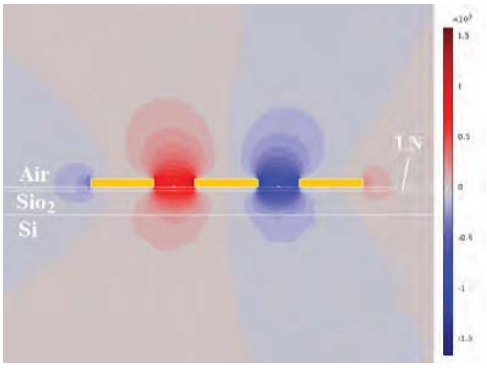

Fig. 4: Cross section of RF mode in MZ structure

due to its low optical loss. Also, poly-Si can be selected because it is easy to process. In the following, we specifiedthe geometrical parameters ofthe hybrid waveguide. To mitigate the material absorption loss, the optical power in the non-crystalline waveguide should be decreased and optical power in TFLN should be increased. To do so, w_{wg} is selected 250 nm, t_{LN} and t_{wg} are selected as 220 and 450 nm, respectively. In this case n_{op} is 1.90 and LN_{CF} is 0.67. the optical mode of the hybridwaveguide is shown in Fig. 3.

4. Electro-Optic Response of the Modulator

To calculate frequency response of the modulator, V_π.L should be calculated. L is the active length of the modulator. Also, V_π is the voltage required for inducing a phase shift of π between two arms of the MZ modulator. Strong overlap between RF and optical mode has a significant effect on V_π.L. Cross section of RFmodeshown in Fig. 4. After V_π.L calculation, the active length of the modulator has been chosen. Then, the electro-optical response of the modulator was calculated. According to frequency response of the modulator from [1], RF refractive index (n_{RF}), RF loss, characteristics impedance (Z_0), n_{op} and L affect on electro-optic response of the modulator. Frequency sweep of n_{RF}, RF loss and Z_0 are plotted using FDTD simulations. We calculated V_π.L 2.6 V.cm at 60 GHz from [7] using COMSOL. These result are obtained in the electrode thickness=1.5 µm, the distance between center and outer electrode=5 µm, the center electrode width=8 µm, the outer electrode width=15 µm and the sio_2 thickness=3 µm. Finally, the electro-optic response of the

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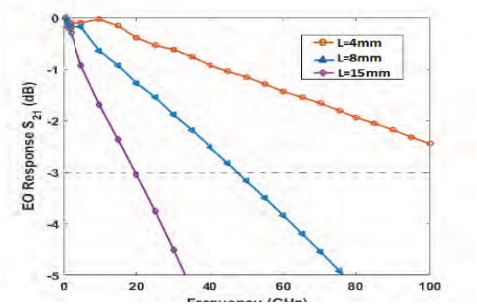

Fig. 5: Electro-optic response of the modulator.

modulator has been plotted in Fig. 5 for L=4,8,15mm.

5. Conclusion

In this paper, we offered a hybrid non-crystalline Si and LN modulator. Unlike c-Si, non-crystalline Si can be deposited on crystalline material such as LN. But, non-crystlline Si has absorption loss due to the nature of material. By engineering the hybrid optical waveguide geometry andfabrication technology, the optical loss is reduced. Therefore, we designed a high bandwidth modulatorusinga hybrid Si and LN optical waveguide.

References

[1] G. Ghione, Semiconductor devices for high-speed optoelectronics, Cambridge University Press, 2009, ch. 6.

[2] A. Rao, A. Patil, P. Rabiei, A. Honardoost, R. DeSalvo, A. Paolella and S. Fathpour, “High-performance and linear thin-film lithium niobate Mach–Zehnder modulators on silicon up to 50 GHz,” Optics letters, vol. 41, no. 24, pp. 5700-5703, 2016.

[3] M. He, M. Xu, Y. Ren, J. Jian, Z. Ruan, Y. Xu, S. Gao, S. Sun, X. Wen, L. Zhou, L. Liu, C. Guo, H. Chen, S. Yu, L. Liu and X. Cai, “High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s− 1 and beyond,” Nature Photonics, vol. 13, no. 5, pp. 359-364, 2019.

[4] P. O. Weigel, J. Zhao, K. Fang, H. Al-Rubaye, D. Trotter, D. Hood, J. Mudrick, C. Dallo, A. T. Pomerene, A. L. Starbuck, C. T. DeRose, A. L. Lentine, G. Rebeiz and S. Mookherjea, “Bonded thin film lithium niobate modulator on a silicon photonics platform exceeding 100 GHz 3-dB electrical modulation bandwidth,” Optics express, vol.26, no. 18, pp. 23728-23739, 2018.

[5] C. Wang, M. Zhang, X. Chen, M. Bertrand, P. Winzer and M. Lončar, “Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages,” Nature, vol. 562, no. 7725, pp. 101-104, 2018.

[6] L. Liao, “Low loss polysilicon waveguides for silicon photonics,” PhD diss, Massachusetts Institute of Technology, 1997.

[7] P. O. Weigel, “High-Speed Hybrid Silicon-Lithium Niobate Electro-Optic Modulators & Related Technologies,” PhD diss, UC San Diego, 2018.

[8] R. Safian, M. Teng, L. Zhuang and S. Chakravarty, “Foundry-compatible thin film lithium niobate modulator with RF electrodes buried inside the silicon oxide layer of the SOI wafer,” Optics Express, vol. 28, no. 18, pp. 25843-25857, 2020.

[9] Y. Wang, Z. Chen, L. Cai, Y. Jiang, H. Zhu and H. Hu, “Amorphous silicon-lithium niobate thin film strip-loaded waveguides,” Optical Materials Express, vol. 7, no. 11, pp. 4018-4028, 2017.

[10] R. Takei, “Amorphous Silicon Photonics,” Crystalline and Non-crystalline Solids , p. 21, 2016.

[11] L. Cao, A. Aboketaf, Z. Wang and S. Preble, “Hybrid amorphous silicon (a-Si: H)–$LiNbO_3$ electro-optic modulator,” Optics Communications, vol. 330, pp. 40-44, 2014.

[12] Y. Franz, A. F. Runge, S. Z. Oo, G. Jimenez-Martinez, N. Healy, A. Khokhar, A. Tarazona, H. M. Chong, S. Mailis and A. C. Peacock, “Laser crystallized low-loss polycrystalline silicon waveguides,” Optics Express, vol. 27, no. 4, pp. 4462-4470, 2019.

[13] A. H. Atabaki, S. Moazeni, F. Pavanello, H. Gevorgyan, J. Notaros, L. Alloatti, M. T. Wade, C. Sun, S. A. Kruger, H. Meng, K. Al Qubaisi, I. Wang, B. Zhang, A. Khilo, C. V. Baiocco, M. A. Popović, V. M. Stojanović and r. J. ram, “Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip,” Nature, vol. 556, no. 7701, pp. 349-354, 2018.

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