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High Performance Hybrid Silicon Evanescent Traveling Wave Electroabsorption Modulators

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In this paper, for the first time, a high performance hybrid silicon evanescent traveling wave electroabsorption modulator based on asymmetric intra-step-barrier coupled double strained quantum wells active layer is introduced which has double steps at III/V mesa structure. Through this active layer, hybrid silicon evanescent traveling wave electroabsorption modulator will be advantages such as very low insertion loss, zero chirp, high extinction ratio, and large Stark shift and better figures of merit as compared with multiquantum well and intra-step quantum well structures. Furthermore, traveling wave electroabsorption modulator with double steps III/V mesa structure results in a wider bandwidth as compared with one-step III/V mesa and mushroom structures. For the modulator with double steps III/V mesa structure with a 200 μm length, the 3 dB bandwidths are obtained as 132 and 52 GHz for 25 and 40 Ω characteristic impedances, respectively.

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1. Introduction

Silicon optoelectronic integrated devices are the next generation of electronic integrated circuits due to plenteous production, reduction in size and cost, improvement at performance and highly accurate CMOS technology [1]. Transparency of silicon at optical-fiber communication wavelengths of 1300 and 1550 nm has indicated low loss waveguide. Furthermore, highly confined optical modes are resulted due to the large index contrast of silicon waveguides with silicon dioxide cladding and, consequently, reduction of waveguide bend radii leading to dense photonic integration is obtained. This has led to progress in passive devices such as compact filters, optical buffers, photonic crystals, and wavelength multiplexer-demultiplexers [2]. The hybrid silicon evanescent platform, with the active III–V materials transplanted to the silicon-over-insulator (SOI) wafers seems the most promising approach to active silicon. The wafer-bonded structure forms a hybrid waveguide, where its optical mode lies both in silicon and III–V layers. This structure enables the use of III–V layers for active light manipulation such as gain, absorption, and electro-optical effect [3]. Several key components have been successfully demonstrated on the hybrid silicon evanescent platform, such as lasers [4], optical amplifiers [5], tunable filters [6] and photodetectors [7]. Furthermore, electroabsorption modulators and grating couplers for silicon platform are the key elements for the optical interconnects, especially for the inter-chip interconnects using the SOI wafer [8].

The choice of suitable material for active region of the hybrid silicon modulator is important due to trade off between driving voltage and extinction ratio. In previous papers, an asymmetric intra-step-barrier coupled double strained quantum wells (AICD-SQWs) structure has been proposed as the III/V material active layer of traveling wave electroabsorption modulators (TWEAMs) that has advantages such as very low insertion loss, zero chirp, large Stark shift, high extinction ratio, and higher figures of merit in comparison with the intra-step quantum well (IQW) structure [9–16].

Recently, we have investigated the modulation response of mushroom-type TWEAM with AICD-SQW active region using circuit model by considering interaction between microwave and optical fields in waveguide and compared with conventional ridge-type TWEAM [17].

In this paper, for the first time, a hybrid silicon evanescent TWEAM based on AICD-SQWs active layer is introduced which has double steps at III/V mesa structure in order to obtain larger bandwidth, very low insertion loss, and high extinction ratio. For this purpose, microwave properties and bandwidth of the proposed hybrid silicon evanescent TWEAM are calculated and compared with hybrid silicon modulators which have one step III/V mesa and mushroom-type structures.

2. Hybrid silicon evanescent TWEAM structure

A cross-section of the proposed hybrid silicon evanescent TWEAM is shown in Fig. 1, which consists of III–V epitaxial layers bonded to silicon waveguides fabricated on silicon on insulator wafer. The widths and thicknesses of steps have been chosen as 0.5 μm and modeling is performed for a wavelength of 1.55 μm. The optical modulator length is taken to be 200 μm.

The conduction band profile of active region (AICD-SQW) is illustrated in Fig. 2. The asymmetric wells consisted of the same material to concentrate the heavy hole and electron wave functions in wide well at zero

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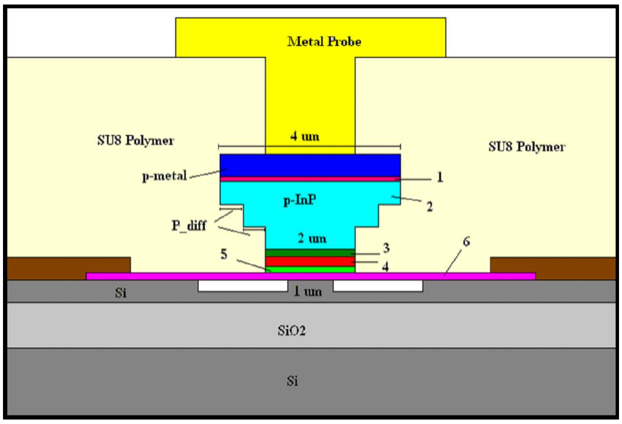

Fig. 1. Hybrid silicon evanescent TWEAM cross-section structure.

electrical field and decrease the insertion loss. For significant reduction of insertion loss, the wide well is placed over the tensile strained and the narrow band over the compressive strained so that the heavy hole and electron wave functions are separated from each other. The active region consists of eight periods of AICD-SQWs which was separated by $In_{0.52}Al_{0.48}As$ barriers with 10 nm thickness. Each period of AICD-SQW includes 4 nm thick $In_{0.53}Ga_{0.33}Al_{0.14}As$ intra step barrier (no strain), a 1.5 nm thick $In_{0.52}Al_{0.48}As$ as the narrow barrier, a 6.8 nm thick $In_{0.525}Ga_{0.475}As$ as the wide well (0.05% tensile strain) and a 3.5 nm thick $In_{0.68}Ga_{0.392}As$ (0.52% compressive strain) as the narrow well [10–17].

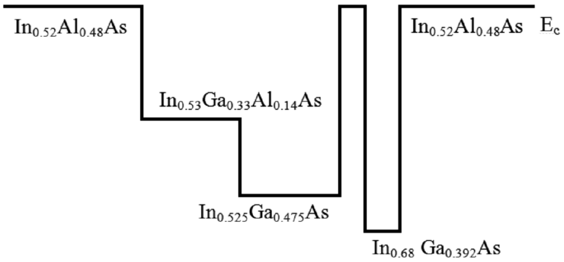

Fig. 2. Conductance band profile of AICD-SQW.

The III–V epitaxial structure is grown on an InP substrate. The details of the transferred epitaxial structure are shown in Table. TWEAMs are devices to modulate light waves corresponding to traveling electric fields along the electrode consisting of a transmission line. Because the absorption coefficient of TWEAMs is dependent on the electric voltage, the modulation of optical wave occurs by the absorption change due to modulated electric signals. Figure 3 shows the circuit model for a unit length of transmission line of TWEAM based on AICD-SQWs active layer [10–17].

The small signal frequency response for TWEAM can be obtained as follows [15]:

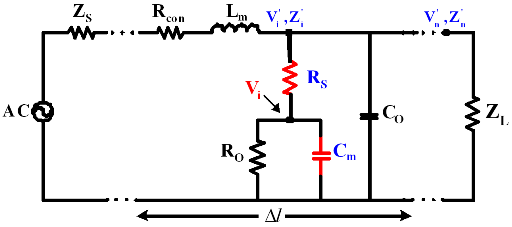

Fig. 3. Circuit model for a unit length of transmission line of the TWEAM based on AICD-SQWs active layer [15].

TABLE

III–V epitaxial layer structure.

Layer	Thickness	ε_r	σ [Ω^{-1} cm^{-1}]
1) InGaAs — p contact	0.1 μm	13.91	20
2) InP — p mesa	1.5 μm	12.5	1520
3) InGaAlAs — p SCH	0.15 μm	13.39	0
4) ACID-SQW — active layer	0.2164 μm	13.1414	0
5) InGaAlAs — n SCH	0.1 μm	13.39	32500
6) InP — N contact	0.1 μm	12.5	110400
Si	0.5 μm	11.9	0.1
SiO_2	1 μm	3.9	0
Si-substrate	10 μm	11.9	0.1

$$|P_{\mathrm{ac}}|^2 = \left|\sum_{i=1}^{n}\left(V_i \exp\left(j\frac{\omega}{c_0}n_{0\_\mathrm{eff}}(i-1)\Delta l\right)\Delta l\right)\right|^2, \quad (1)$$

where V_i is the modulating voltage in i section. The voltage on the transmission line is the superposition of forward and backward traveling voltage waves that arise from reflections at the source and the load terminal, respectively. Equation (1) can be developed analytically as follows [15]:

$$|P_{\mathrm{ac}}|^2 = \left|\frac{1}{\frac{R_s}{R_0}+1+\mathrm{j}\omega R_s C_m}\,\frac{V_0 Z_0/(Z_s+Z_0)}{1-\Gamma_{\mathrm{S}}\Gamma_{\mathrm{L}}\mathrm{e}^{-2\gamma_\mu L}}\right. \times \left[\frac{1-\mathrm{e}^{(-\gamma_\mu+\mathrm{j}\beta_0)L}}{\gamma_\mu-\mathrm{j}\beta_0} - \left.\frac{\Gamma_{\mathrm{L}}\mathrm{e}^{-2\gamma_\mu L}\left(1-\mathrm{e}^{(\gamma_\mu+\mathrm{j}\beta_0)L}\right)}{\gamma_\mu+\mathrm{j}\beta_0}\right]\right|^2, \quad (2)$$

where V_0 is the forward microwave voltage in the source transmission line, Z_0 is the characteristic impedance and γ_μ is the propagation constant of modulator transmission line. Γ_{S} and Γ_{L} are the modulator reflection coefficients at the source and load ports, respectively. ω is the microwave frequency, and $\gamma_\mu = \alpha_\mu + \mathrm{j}\beta_\mu$, where α_μ is the microwave loss and $\beta_\mu = \omega/v_\mu$ is the wave number associated with the microwave phase velocity v_μ and $\beta_0 = (\omega/c_0)n'_{0\_\mathrm{eff}}$ is the wave number associated with the optical phase velocity. The calculation of the small signal modulation response requires the knowledge of the optical index n_{0_eff} and the circuit model elements. The circuit elements can easily be extracted from the TWEAM transmission line microwave properties Z_0 (characteristic impedance) and γ_μ (propagation constant), which are obtained via full-wave calculations of the given geometry.

3. Results of calculations and discussion

The bandwidths of mushroom-type, one step and double steps hybrid TWEAM are compared to each other. The microwave characteristic of three structures such as characteristic impedance Z_C, propagation constant γ have been calculated by high frequency structure simulator (HFSS) [11].

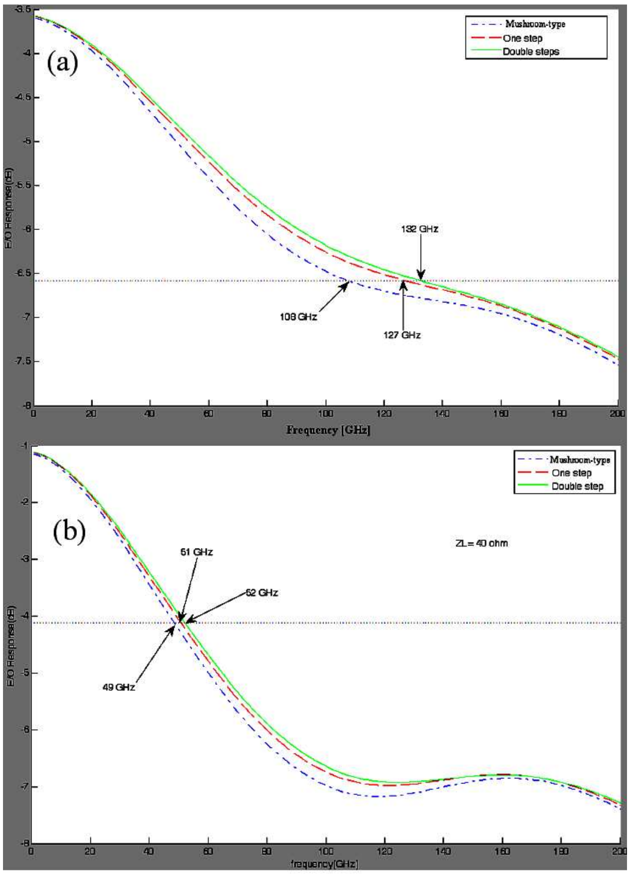

Fig. 4. E/O response of hybrid TWEAM with three structures for loads (a) 25 Ω, (b) 40 Ω.

Figure 4 shows the electro/optic response of hybrid TWEAM for three structures of double steps, one step and mushroom-type at Z_L (a) 25 Ω, (b) 40 Ω. The Z_C of TW is lower than 25 Ω. This leads to large microwave reflections at modulator input and output. By increasing the load, the bandwidth is decreased for a reason of mismatching of impedance. The 3 dB bandwidths which were obtained for mushroom-type, one step and double steps by 25 Ω load are 108, 127, 132 GHz and by 40 Ω are 49, 51, 52 GHz, respectively.

4. Conclusions

To increase the bandwidth and decrease of insertion loss, the hybrid silicon TWEAM was presented with AICD-SQWs active region and double steps p-InP layer. The active region has advantages such as very low insertion loss, zero chirp, large extinction ratio, and large Stark shift as compared with IQW. TWEAM with double steps III/V mesa structure results in a wider bandwidth, better microwave properties as compared with one step III/V mesa and mushroom structures. For the modulator with double steps III/V mesa structure with a 200 μm length, the 3 dB bandwidths are obtained as 132 and 52 GHz for 25 and 40 Ω characteristic impedances, respectively.

References

[1] H.W. Chen, Y.H. Kuo, J.E. Bowers, *IEEE Photon. Technol. Lett.* **20**, 1920 (2008).

[2] H. Park, A.W. Fang, D. Liang, Y.-H. Kuo, H.-H. Chang, B.R. Koch, H.W. Chen, M.N. Sysak, R. Jones, J.E. Bowers, *Adv. Opt. Technol.* 2008, Article ID 682978, 17 pages, doi:10.1155/2008/682978 (2008).

[3] L.P. Hou Li, W. Wang, H.L. Zhu, *Optoelec. Lett.* **1**, 83 (2005).

[4] D. Liang, M. Fiorentino, T. Okumura, H.-H. Chang, D.T. Spencer, Y.-H. Kuo, A.W. Fang, D. Dai, R.G. Beausoleil, J.E. Bowers, *Opt. Expr.* **17**, 20355 (2009).

[5] H. Park, A.W. Fang, O. Cohen, R. Jones, M.J. Paniccia, J.E. Bowers, *IEEE Photon. Technol. Lett.* **19**, 230 (2007).

[6] H.W. Chen, A.W. Fang, J. Bovington, J.D. Peters, J.E. Bowers, in: *Proc. Int. Topical Meeting on Microwave Photonics, MWP'09*, Valencia 2009, p. 1.

[7] H. Park, A.W. Fang, R. Jones, O. Cohen, O. Raday, M.N. Sysak, M.J. Paniccia, J.E. Bowers, *Opt. Expr.* **15**, 6044 (2007).

[8] Y. Kuo, H.W. Chen, J.E. Bowers, *Opt. Expr.* **16**, 9936 (2008).

[9] K. Abedi, V. Ahmadi, E. Darabi, M.K. Moravvej-Farshi, M.H. Sheikhi, *Solid State Electron.* **53**, 312 (2008).

[10] K. Abedi, *Eur. Phys. J. Appl. Phys.* **56**, 10403 (2011).

[11] K. Abedi, *Opt. Quantum Electron.* **44**, 55 (2012).

[12] K. Abedi, *J. Semicond.* **33**, 064001 (2012).

[13] K. Abedi, *Optoelectron. Lett.* **8**, 176 (2012).

[14] K. Abedi, *Int. J. Eng. Sci. Technol.* **3**, 6684 (2011).

[15] K. Abedi, *Int. J. Adv. Eng. Technol.* **1**, 388 (2011).

[16] K. Abedi, *Canad. J. Electric. Electron. Eng.* **2**, 209 (2011).

[17] K. Abedi, V. Ahmadi, M.K. Moravvej-Farshi, *Opt. Quant. Electron.* **41**, 719 (2009).