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Performance Benchmarking of InGaAsP, $Si_{0.8}Ge_{0.2}$ and Si-based Photonics Homojunction and Heterojunction PN modulators

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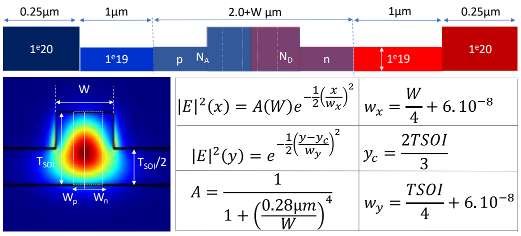
***Abstract* - Using an analytical model, we benchmark the performance of Si, SiGe and InGaAsP homo- and heterojunction based optical modulators, in terms of OMA and energy per bit. Strengths and weaknesses of each devices are discussed.**

1. Introduction

Silicon Photonics has received a growing interest due to its low cost, allowing this technology to enter the datacenters. Nevertheless, Silicon has several weaknesses, such as a low optical generation efficiency, but also the lack of efficient optical modulators. Recently, the use of heterogeneous integration of III-V or Si-Ge-based materials has been proposed to improve the optical performance of Si-based photonics, by integrating light sources [1] or efficient hybrid III-V/Si MOS modulators [2]. In this work, we propose to benchmark the performance of PN-junction modulators at λ=1310nm, based on various material configuration. Besides Si, we selected InGaAsP (λ_{gap}=1.19µm) and $Si_{0.8}Ge_{0.2}$ for their much improved free-carrier dispersion effect properties (for electron and holes respectively), and consider the following combinations: n-Si/p-Si, p-Si/n-InGaAsP, p-SiGe/n-Si, n-InGaAsP/p-InGaAsP. We use the Optical Modulation Amplitude (at the output of the modulator) as a figure of merit (FoM) rather than VπLπ or αVπLπ products since OMA is generally used as a system specification for direct detection, and for the next 400G-PAM-4. For this, we first introduce an analytical opto-electrical modeling of the PN modulators. Next, we use this model to calculate the optimal devices designs for maximizing the OMA. Finally, we compare the modulators in terms of OMA-energy-per-bit trade-off.

2. Analytical Model

The performance evaluation of PN junction-based optical modulators is usually done by using FDTD solvers and Poisson solvers for optical mode and carrier distribution calculation respectively [3]. To reduce the computation time, we modeled both optical mode and carrier concentration



$\lvert E\rvert^2(x) = A(W)e^{-\frac{1}{2}\left(\frac{x}{w_x}\right)^2}$	$w_x = \frac{W}{4} + 6.10^{-8}$
$\lvert E\rvert^2(y) = e^{-\frac{1}{2}\left(\frac{y-y_c}{w_y}\right)^2}$	$y_c = \frac{2TSOI}{3}$
$A = \frac{1}{1+\left(\frac{0.28\mu m}{W}\right)^4}$	$w_y = \frac{TSOI}{4} + 6.10^{-8}$

Fig.1: Modeled structure and optical mode analytical approximation

analytically. Considering a rib waveguide with a thickness T_{SOI}, a slab thickness $T_{SOI}/2$, and a width W, the optical mode is approximated by a 2D Gaussian profile, which expression are given in fig.1. The depletion widths are also analytically calculated assuming an abrupt junction or heterojunction. The charge-induced effective index variation is given by:

$$\Delta n_{eff} = \frac{\iint \Delta n(x,y)|E(x,y)|^2}{\iint |E(x,y)|^2} = \Delta n(x,y)\frac{\int_0^{TSOI}|E(y)|^2 \int_{Wdep(0)}^{Wdep(V)}|E(x)|^2}{\iint |E(x,y)|^2} \quad (1)$$

Therefore, the analytical calculation can be reduced to the

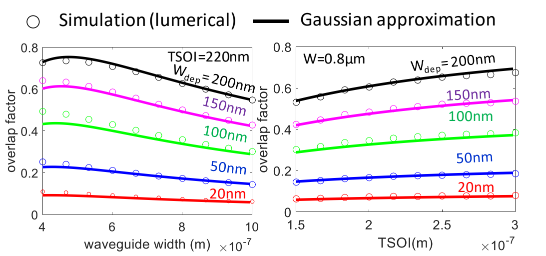


Fig. 2: overlap integral between depletion zone and optical mode: comparison between analytical and numerical calculations.

calculation of $Ov(W_{dep}) = \frac{\int_0^{TSOI}|E(y)|^2 \int_0^{Wdep}|E(x)|^2}{\iint |E(x,y)|^2}$. Since the mode intensity is approximated by a Gaussian function, the integral mainly consist in evaluating the error function erf(x). Fig.2 is showing the comparison of the analytical integration of Ov(W) using the Gaussian approximation with the exact solution using the actual mode profile calculated into Lumerical's Mode solver, for various values of W_{dep}, T_{SOI} and W. Finally, Since the refractive index (λ=1310nm) of InGaAsP (3.41), SiGe (3.5) and Si (3.45) are very close, we make the approximation that this model stands in the case of InGaAsP homojunction and Si/InGaAsP and Si/SiGe hetero-junctions. The variation of the optical index with charge (doping) in known from [2], [4], [5]. Finally, the effective index and loss variation are obtained from:

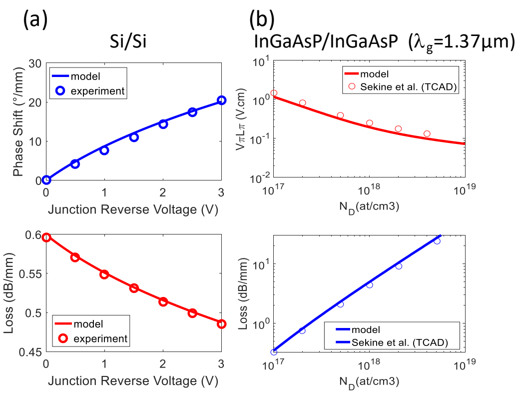


Fig. 3 (a) phase-shift and loss vs V: model vs Si-experiments (b) InGaAsP (λ_{gap}=1.37µm) PN modulator VπLπ vs doping: model vs TCAD from [7]

$$\Delta n_{eff} = \Delta n(N_D)\times\left(Ov(W_{n,Vdd}) - Ov(W_{n,0})\right) + \Delta n(N_A)\times\left(Ov(W_{p,Vdd}) - Ov(W_{p,0})\right) \text{ and } \Delta\alpha = \Delta n(N_D)\times\left(Ov(W/2) -\right.$$

$Ov(W_{n,Vdd})\big) + \Delta n(N_A) \times \big(Ov(W/2) - Ov(W_{p,Vdd})\big) + fixed\_loss$, where fixed_loss is accounting for propagation losses other than related to doping. Fig 3 is showing the excellent agreement between our model and Silicon PN-modulator experimental data from [6] and InGaAsP full-numerical calculation from [7]. This model can also be used for an horizontal PN-junction.

3. Optimal Design

In this study, we concentrate on materials and doping variations, while keeping the same T_{SOI}=220nm and W=0.4µm for all structures. The dynamic OMA at the TX side of a 400G-PAM4 (4x53Gbauds PAM-4) system can be easily calculated from the modulator phase shift and optical loss. Assuming a 0dBm input power, we have [8]

$$OMA_{dyn,max} = \left|\sin\left(\frac{2}{9}atan(\beta)\right)\right| \frac{e^{-\frac{2}{3\beta}atan(\beta)}}{\sqrt{1+r^2}} \quad (2)$$

with $\beta = \Delta\varphi/\Delta\alpha$, ($\Delta\varphi = 2\pi\Delta n_{eff}/\lambda$), and $r = f_0/f_c$, f_0 = 26.5GHz and f_c the cut-off frequency of the modulator. This last one is calculated from the access resistance (fig. 1) and the capacitance if the modulator. Note that specific mobility models are used for the different materials. As a result, the dynOMA FoM takes into account both static and

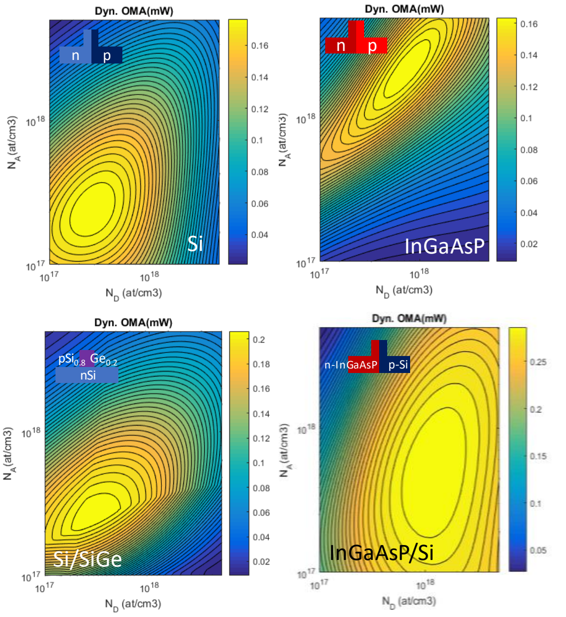


Fig.5: surface-response of dyn.OMA vs N_A/N_D doping for various configurations, at V=-3V.

dynamic behavior of the modulator which are depending on materials and doping values. For each device, the doping is chosen to maximize dynOMA (fig. 5)

4. Benchmark Results and Discussion

Optimal doping value and resulting optical and electrical device parameters are summarized in Tab.1. Note that in the case of a PAM-4 signal, the total modulator length maximizing the dynOMA is given by $L_{opt}=\frac{2}{3\Delta\varphi}atan(\beta)$. From eq(2), device with a higher β factor will result into better OMA. Replacing the p-Si by p-SiGe is increasing β, thanks to the reduced hole effective mass, leading to improved hole-induced refractive index (n) change. Despite its better electron-induced n change, InGaAsP homo-junction modulator does not lead to a better dynOMA. This is due to the poor mobility of p-InGaAsP layers, that is limiting the dynOMA at doping values in the range of 10^{17}~$3x10^{17}$ at/cm^3 due to a high access resistance that is increasing r-factor in eq.2. Therefore, a higher doping (2.2x10^{18} at/cm^3) is needed to reduce the r-factor, but is leading to a higher optical loss, limiting the β value. Nevertheless, the optimal length of this device is much shorter than in the Si/Si case, leading to a lower total capacitance. One possible solution to overcome

TSOI=220nm W=0.4µm	Doping (at/cm³)	β	L_{opt} (mm)	f_c (GHz)	C (fF/mm)	dynOMA (mW)
n-Si/p-Si	NA=2.4e17 ND=2.8e17	2.5	2.7	53	180	0.18
n-Si/p-SiGe	NA=2.8e17 ND=2.9e17	5.4	1.3	39	341	0.20
n-InGaAsP/n-InGaAsP	NA= 2.2e18 ND = 7.7e17	3.2	0.2	36	377	0.167
n-InGaAsP/p-Si	NA=2.5e17 ND=1.1e18	13.2	0.5	67	204	0.3

Table 1: device parameters from analytical calculations (V=-3V).

the p-InGaAsP access resistance issue, would be to fabricate a Si/InGaAsP hybrid heterojunction modulator. This way, both electrical properties and optical properties are optimized, leading to a much improved dynOMA level, and a short length. Fig 6a is showing the overall trade-off between OMA and energy-per-bit given by ¼.C.V². If InGaAsP/Si hybrid modulator would be the best trade off, two main issues arises. First, the process integration is complex and necessitate InGaAsP-on-Si growth with a defect-free junction. Next,

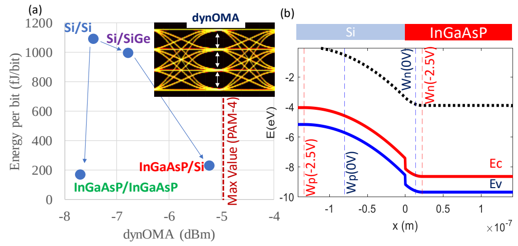


Fig. 6: (a) OMA vs Energy/bit benchmarking (b) band-diagram of the InGaAsP/Si heterojunction

Si/InGaAsP results into a type-II heterojunction. When a reverse bias is applied, this may lead to a high band-to-band-tunneling current (Fig.6b). Si/SiGe is a good compromise between improvement and complexity. InGaAsP homojunction would allow a 5X reduction in energy per bit, but is not improving the dynOMA.

5. Conclusion

We benchmarked several possible PN-junction and hetero-junction modulators and analyzed their pro and cons. Si/SiGe is a good short term candidate for data-center application, while InGaAsP could help in reducing the power consumption.

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