Efficient Simulation for Silicon-on-Insulator Waveguide Electro-Optic Devices

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Abstract—**This paper simulates the modulation efficiency and response time of free-carrier dispersion (FCD) effect on silicon-on-insulator (SOI) waveguide electro-optic (EO) devices using professional software called MEDICI. The dependence of free-carrier concentration on the applied voltage and device parameters and the corresponding response time are obtained, typically supporting a ~10^{19}cm^{-3} concentration variation and a 10-30ns response time at 1.5-2.0V voltage.**

Keywords: SOI waveguide; FCD; doping density; modulation efficiency of free carriers; response time of modulation process

I. INTRODUCTION

Demand for next-generation optical networks capable of high-capacity, high-speed and high-agility has been driving the research and development of new components and systems with highly integrated technologies [1], and as such silicon photonic integrated circuit (PIC) technology shows its exclusive merit in applications [2].

In silicon PIC systems, the essential technology for implementing high-speed active parts is a big challenge and a typical illustration is the electro-optic (EO) modulation of silicon-on-insulator (SOI) waveguide devices. The free-carrier dispersion (FCD) effect of the single-crystalline silicon material has been attracting research, but it also induces an extra optical absorption, leading to optical loss at the EO interaction area and intrinsic limitations in device performance [3,4]. The wide acceptability of SOI-PIC technology for the next-generation optical networks is also owing to its compatibility with the micro-electronic infrastructure [2].

II. ANALYSIS FOR FCD BASED EO MODULATION

A. Analysis for the FCD-based EO modulation

Unlike the traditional EO modulation of the LiNbO3 waveguide in which the refractive index of waveguide channel is modulated by an effective electric field, in the FCD based EO modulation the refractive index modulation is implemented by a concentration variation of free carriers in the waveguide followed by a negative effect - optical extra-absorption [2-4], which are defined at λ=1550nm

$$\Delta n = -[8.8\times10^{-22}\Delta N_e + 8.5\times10^{-18}(\Delta N_h)^{0.8}] \qquad (1)$$

$$\Delta\alpha = 8.5\times10^{-18}\Delta N_e + 6.0\times10^{-18}\Delta N_h \qquad (2)$$

Where Δn and $\Delta\alpha$ are respectively the changes of refractive index and absorption coefficient resulting from the concentration variations of free electrons and holes (ΔN_e and ΔN_h), respectively. As discussed below, apart from the electric field created in the waveguide, ΔN_e and ΔN_h are also dependent on some other parameters of devices such as the terminal structure, the background and contact doping densities of free carriers.

B. Device structure for EO modulation

As shown in Fig. 1, an electrical field is applied to a typical SOI rib waveguide by using a bi-terminal scheme of electrodes: the source and drain terminals.

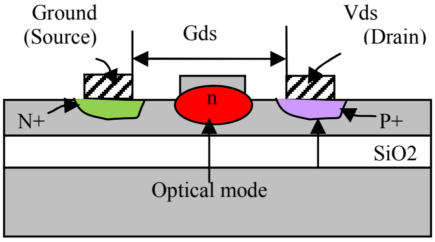

Figure 1. Cross-sectional view of FCD modulation scheme for SOI-waveguide

III. SIMULATION FOR MODULATION PROCESS

The outside applied voltage V_{ds} produces a new electric field distribution along x-direction E_x in EO modulation system shown in Fig. 1, and further forms a drive force to the free carriers (holes) transporting from the drain terminal. This transporting process forms two parts of free-carriers – holes: the original holes p and the generated excess holes δp [5]. For p, we have

$$E_x \approx (V_{ds}/G_{ds})\cdot\gamma \approx e\mu_p P/\sigma \qquad (3)$$

$$p \approx (\sigma/e\mu_p)\cdot(V_{ds}/G_{ds})\cdot\gamma \qquad (4)$$

γ is an attenuation factor of electric field along y-direction and less than 1.0 and μ_p is the mobility of free holes of silicon material. But, for δp, we have

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$$\delta p(x,t) \approx \frac{e^{-t/\tau_{p0}}}{(4\pi D_p t)^{1/2}} \exp\left[\frac{-(x-\mu_p E_x t)^2}{4D_p t}\right] \qquad (5)$$

Where D_p and τ_{p0} are the diffusion coefficient and the excess minority free-carrier hole lifetime. Notice from (4) and (5) that the increase of free carriers is a function of time and the above parameters. The total concentration of holes should be $p_t = p + \delta p$. Because E_x, γ and σ are the complicated functions of several parameters such as V_{ds}, G_{ds}, N^+ and P^+, the more accurate solution to the total concentration increase of free holes p_t should be simulated with a powerful software tool.

A. Simulation for the concentration of free carriers

For the device structure shown in Fig. 1, with a professional software tool – MEDICI, we simulate the relationship between ΔN_h and V_{ds} with respect to different gap values. In our simulations, two points should be noted: (i) in terms of basic physical principles of semiconductor devices in transport process of free carriers, the increase of free carriers with applied voltage V_{ds} should be the same for electrons and holes, which has also been validated by our simulation results and (ii) in terms of (1) ΔN_h is extremely dominant to contribute the refractive index modulation compared to ΔN_e. Thus, we only need to consider the increase of free holes in the applications of FCD-based EO modulation. For two gap values: 5 and 10μm, and two sets of the background doping and the contact doping densities underneath the two electrodes as DOPS1: $n = 1.0\times10^{15}/cm^3$ & $N^+(P^+) = 1.0\times10^{19}/cm^3$; and DOPS2: $n = 1.0\times10^{18}/cm^3$ & $N^+(P^+) = 3.0\times10^{21}/cm^3$, we obtain the relationship between ΔN_h and V_{ds} in the guided-mode as shown in Fig. 2.

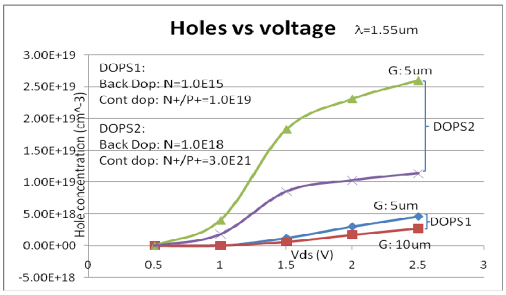

Figure 2. MEDICI simulation results of concentration of free carriers (holes) vs. drive voltage V_{ds} in the SOI-waveguide mode with respect to gap

Note that the general trend is a higher doping set produces higher ΔN_h under the same V_{ds} and G_{ds} values. For the low doping set (DOPS1), only when V_{ds} is greater than 1.0V, the free carrier concentration can start to increase and is strongly dependent on the gap between two terminals; but for the high doping set (DOPS2), ΔN_h quickly increases with V_{ds} and sensitively depends on G_{ds}.

B. Simulation for transport time of free carriers

In terms of the physical principle of semiconductor devices, the transport time of free carriers are also determined by several parameters of device structure and it directly determines the response speed of this modulation process. By taking the same values of parameters as for simulating the concentration of free carriers, we obtain the simulation results of the relationship between the concentration increase of free carriers and the response time in this process as shown in Fig. 3.

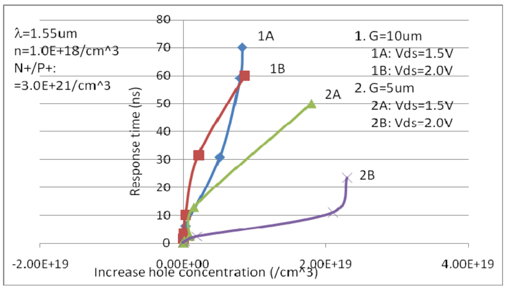

Figure 3. MEDICI simulation results of concentration of free carriers (holes) vs. response time in the SOI-waveguide mode with respect to gap and voltage

Note that both G_{ds} and V_{ds} value can have significant influences upon the response time of the modulation process of free carriers. For instance, the case of small G_{ds} (5um) only needs 10-30ns to reach a hole increase of $\sim 1.0\times10^{19}/cm^3$, but the case of big G_{ds} (10um) needs ~60ns to reach a hole increase of $\sim 5.0\times10^{18}/cm^3$.

IV. CONCLUSION

The efficient simulations for the concentration distribution of free carriers and response time in the FCD-based EO modulation show the performance of the SOI-waveguide EO devices with the FCD effect can be effectively optimized with this regime and reliable data obtained in simulations.

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