Proposal and simulation of a low loss, highly efficient monolithic III-V/Si optical phase shifter

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***Abstract*—Carrier-depletion monolithic III-V/Si optical phase modulators are proposed and numerically investigated. Thanks to the larger carrier-induced refractive index change of the III-Vs compared to Si, the III-V/Si phase modulator is predicted to achieve 0.07-Vcm modulation efficiency at 16-dB/cm optical loss at 1310-nm wavelengths.**

I. Introduction

While Si Mach-Zehnder (MZ) modulators have been demonstrated with high-speed modulation and broad bandwidth, they still suffer from a relatively large device footprint of several mm, due to the insufficient electro-optic effect in Si [1, 2]. Heterogeneous III-V integration in conjunction with the Si photonics platform has been introduced not only for lasers but also modulators [3, 4] in order to address the mentioned problem, leveraging the greater carrier-induced change in refractive index in III-V materials compared to Si [5]. The demonstrated heterogeneous III-V/Si modulators are typically fabricated through die-to-wafer bonding with ultra-thin bonding layers (< 10 nm) and require metal contacts to the III-V material, to realize the desired III-V-insulator-Si capacitive phase-shifter structures. Such process steps are quite challenging and less CMOS compatible, which may result in lower manufacturability and scalability.

Integration of III-V on the Si platform through epitaxy has been investigated for the next-generation electronic and photonic devices in a CMOS pilot line [6]. Recently, optically pumped lasing has been demonstrated from monolithic III-V waveguides on Si [7]. Here, we propose the carrier-depletion monolithic III-V/Si optical phase modulator, leveraging the direct growth of III-V on Si and report its performance as predicted by TCAD simulations.

II. Carrier-induced change in refractive index and absorption coefficient of III-V materials

To simulate III-V/Si optical phase modulators based on carrier modulation, we first calculated the carrier-induced change in refractive index (n) and absorption coefficient (α) at 1.31 μm of III-V materials. The plasma dispersion effect, free-carrier absorption, bandfilling effect, bandgap shrinkage, and intervalence band absorption for III-V materials have been considered in this simulation. The plasma dispersion effect is expected to become significantly larger by introducing n-type III-V materials due to their light electron effective mass as shown in Fig. 1. In addition, the bandfilling effect helps to increase the carrier-induced change in n. Fig. 1(a) and (b) show the change in n and α as a function of electron concentration of InP, GaAs, and $In_{0.82}Ga_{0.18}As_{0.40}P_{0.60}$. Both n and α increase with an increase in electron concertation except n-InP for n less than 2×10^{17} cm^{-3}. The changes in n for the III-V materials are larger than that of Si, also for InP when the electron concertation is larger than $\sim 3 \times 10^{17}$ cm^{-3}. Among the III-V compounds, InGaAsP is the most promising for modulation efficiency as it has the largest the change in n larger than $\sim 3 \times 10^{17}$ cm^{-3}. Also, InP and GaAs show less absorption compared to Si due to their higher mobility, inversely proportional to free-carrier absorption. Hence, a lower phase-shifter loss is expected for GaAs/Si and InP/Si modulators compared to Si.

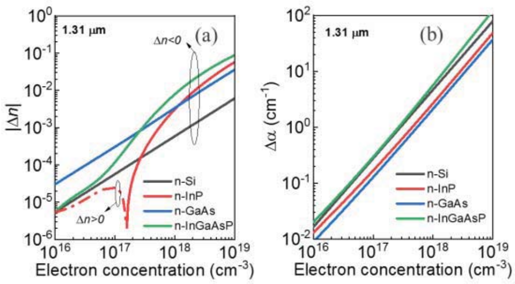

Fig. 1. Carrier-induced change in (a) refractive index and (b) absorption coefficient of n-type Si, InP, GaAs, and $In_{0.82}Ga_{0.18}As_{0.40}P_{0.60}$.

III. Carrier-Depletion Monolithic III-V/Si Optical Phase Modulator

Figure 2 shows the cross-section of the proposed monolithic III-V/Si optical phase modulator. The structure consists of a 220-nm-thick and a 450-nm-wide Si waveguide rib, and 60-nm-thick waveguide slab. The

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n-III-V can be grown on the (111) Si V-groove facet formed by TMAH etching [6]. It is located within the waveguide core, thus making a junction between n-III-V and p-Si. By operating this III-V/Si p-n junction in depletion, optical phase modulation can be realized. Finally, thanks to the direct contact between n-III-V and n-Si, no direct metal contact on III-V is required.

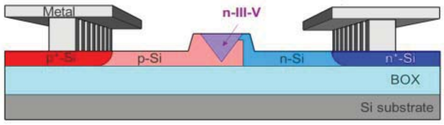

Fig. 2. Schematic of a monolithic III-V/Si optical phase shifter.

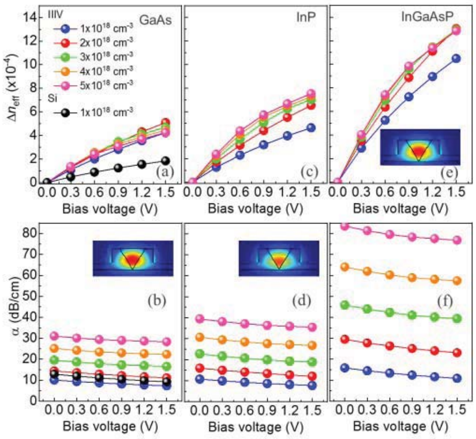

Fig. 3. Device simulation results of changes in effective refractive index (n_{eff}) and loss (α) as a function of reverse bias for (a), (b) GaAs, (c), (d) InP, and (e), (f) InGaAsP.

The carrier concentration as a function of the applied DC reverse-bias between the p^+ to n^+ contact regions is calculated by TCAD simulation. Ohmic contacts are assumed to the p^+ and n^+ regions (10^{20} cm^{-3} doping levels); the doping level of p-Si and n-Si regions are set to 1×10^{18} cm^{-3}; and doping levels of n-III-V region are varied from 1 to 5×10^{18} cm^{-3}. After calculating the carrier concentration, the TE optical mode at 1.31 μm was calculated as shown in inset of Fig. 3, considering the carrier-induced changes in n and α with the calculated carrier distribution, shown in Fig. 1. Then, the effective refractive index and loss at each bias were used for device performance analysis. Fig. 3 shows the Δn_{eff} and α as a function of applied reverse bias for GaAs, InP and InGaAsP. When reverse bias increases, the Δn_{eff} increases but α decreases due to carrier depletion. We also simulated a pure Si device for comparison which consists of an nSi region instead of n-III-V. In Fig. 3(a) and (b), the GaAs-Si device shows larger changes in n and smaller α compared to the pure Si device at the same doping level of 1×10^{18} cm^{-3} thanks to III-V material properties. As predicted in Fig.1, InGaAsP/Si shows the largest Δn_{eff} and α among the III-V materials being considered. InP/Si and GaAs/Si devices are in large order for Δn_{eff} and α. In terms of the doping level in n-III-V, the changes in n increase but saturate with increasing it, but α increases almost proportionally. Therefore, the modulation efficiency, $V_\pi L$, calculated by Δn_{eff} should be analyzed by considering α. Fig. 4 shows $V_\pi L$ as a function of α for III-V and Si devices with linear and log scales. The black-filled circles and white stars shows simulation and experimental results of the Si lateral diode device, respectively, showing good agreement and proper model calibration. The grey-filled circles show the Si device, replacing n-III-V with n-Si as mentioned above. This presents lower $V_\pi L$ compared to the Si lateral device due to larger junction area on V-groove. Finally, $V_\pi L$ as well as α are further improved by introducing n-III-V. As discussed, the InGaAsP/Si device shows the highest performance achieving ~ 0.07 Vcm and ~ 16 dB/cm and enabling an $\alpha V_\pi L$ product near 1-VdB line. The predicted optical absorption levels may be negatively affected by lower mobility values obtained in III-V directly grown on Si. Such impact is expected if threading dislocation densities in III-V would substantially exceed 10^8-$10^9$$cm^{-2}$.

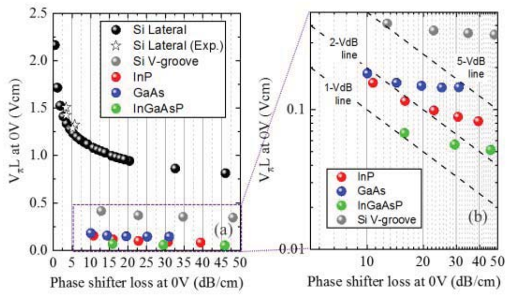

Fig. 4. $V_\pi L$ vs. phase shifter loss of (a) linear scale and (b) log scale for Si and III-V/Si optical modulators.

IV. Conclusion

Carrier-depletion monolithic III-V/Si optical phase modulators are proposed and numerically analyzed. Thanks to the larger carrier-induced refractive index change and smaller loss of the III-V materials compared to Si, the III-V/Si show an improved performance. The InGaAsP/Si phase modulator is predicted to achieve approximately 0.07 Vcm and 16 dB/cm, with $\alpha V_\pi L$ product near 1-V dB line.

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