Comparison of Al_2O_3 and HfO_2 MOSCAP III-V/Si Power Splitters and (De-) Interleavers for DWDM Optical Links

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Abstract: We compare III-V/Si MZIs and (de-)interleavers using Al_2O_3- and HfO_2-based MOSCAP structures as phase tuners. HfO_2 twice as thick as Al_2O_3 exhibited lower $V_\pi L$. We demonstrate crosstalk improvement of ring-assisted (de-)interleavers with both structures.

1. Introduction

At Hewlett Packard Labs, we've proposed a novel dense wavelength division multiplexing (DWDM) architecture to drastically reduce chip power consumption (< 1.5 pJ/bit), while simultaneously increase transmission bandwidth (> 1 Tb/s) [1]. A heterogeneous III-V/Si platform has been developed to enable a complete DWDM transceiver-on-chip. This platform requires optical (de-)interleaving functionality for realizing high bandwidth DWDM systems with our heterogeneous optical frequency comb (OFC) sources [1], [2]. At the same time, tunable Mach-Zehnder interferometers (MZIs) are important fundamental building blocks that address the issue of tunable directional couplers which are important in yielding low channel crosstalk (XT) and symmetric (de-)interleaver passbands. Current state-of-the-art silicon photonic MZIs and (de-)interleavers use either power inefficient thermal [3]–[5] or current injection phase shifters to compensate for either waveguide phase errors, power splitting errors, or temperature drift. In this paper, we not only demonstrate the use of a heterogeneously integrated III-V/Si metal-oxide-semiconductor capacitor (MOSCAP) structure to efficiently tune the phase, but compare the performance of Al_2O3 vs. HfO_2 based structure. In this paper, we demonstrate use of both Al_2O_3 and HfO_2 based MOSCAP structures to realize (de-)interleavers, MZIs, and tunable directional couplers. A comparison between both Al_2O_3 and HfO_2 MOSCAP structure and performance will be presented.

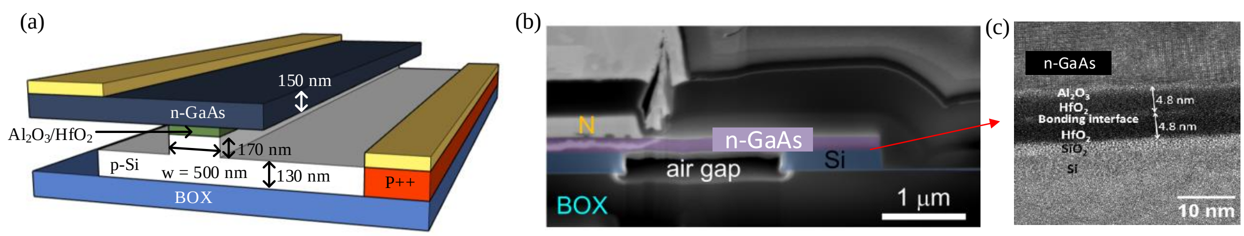

Fig. 1. (a) 3-D schematic of the heterogeneous III-V/Si MOSCAP tuner with either or both Al2O3/HfO2 dielectric, (b) SEM cross section of fabricated device, (c) TEM cross section of a HfO_2/Al_2O_3 MOSCAP bonding interface

2. Design, Fabrication and Measurement Results

For single-mode operation, the hybrid MOSCAP structure is defined by a width = 500 nm, height = 300 nm, and etch depth = 170 nm as shown in Fig. 1 (a). The wafer-bonded III-V consists of a 190 nm-thick n-GaAs doped at 3×10^{18} cm^{-3}. Fig. 2 (a) – (b) illustrates the calculated transverse electric (TE) effective index change (Δn_{TE00}) and associated free carrier absorption (FCA) optical losses for both n-GaAs/Al_2O_3/p-Si and n-GaAs/HfO_2/p-Si structures vs. forward bias for various dielectric thicknesses. A 5 nm-thick Al_2O_3 with a refractive index of n_{Al2O3} = 1.75, will yield calculated optical confinement factors of Γ_{Al2O3} = 1.154 % and $\Gamma_{III\text{-}V}$ = 28.27 % with an overall effective index of n_{eff} = 3.1144. A 5 nm-thick HfO_2 with a refractive index of n_{HfO2} = 1.88 has optical confinements of Γ_{HfO2} = 1.159 % and $\Gamma_{III\text{-}V}$ = 28.33 % with an overall effective index of n_{eff} = 3.1154. In forward bias, the MOSCAP structure operates in carrier accumulation mode for efficient phase change. Experimentally, we explored 2 different MOSCAP gate oxide designs with varying degrees of Si doping and a dielectric selection of Al_2O_3 and/or HfO_2. These designs are shown in Table 1. The bulk HfO_2 dielectric has a higher dielectric constant (k ~ 25) compared to Al_2O_3 (k ~ 9), therefore an HfO_2-based capacitor should have ~3× the capacitance for the same unit area. However, the measured thickness of HfO_2 in Design 2 is 10 nm with an additional 3 nm of Al_2O_3 which indicates the capacitance is only ~ 1.7× or less compared to Design 1.

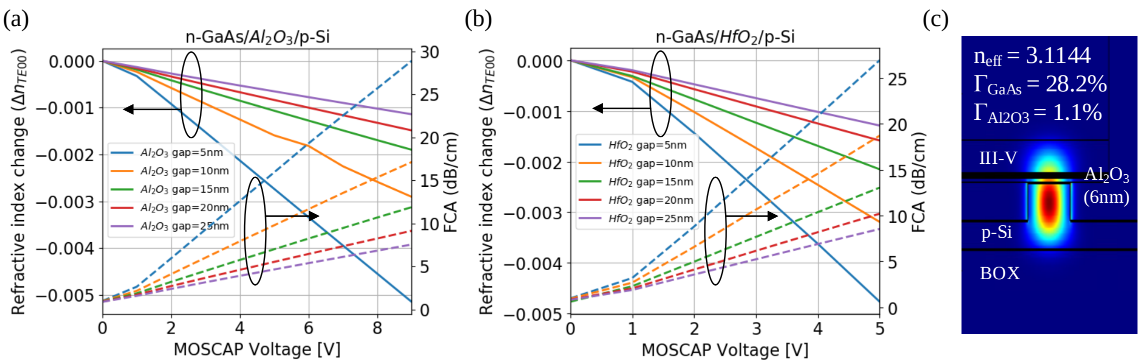

Fig. 2. (a) Simulated refractive index change and FCA losses for (a) n-GaAs/Al_2O_3/p-Si, and (b) n-GaAs/HfO_2/p-Si for gap thickness of 5, 10, 15, 20, and 25 nm. Layer doping: n-GaAs (3×10^{18} cm^{-2}), n-$Al_{0.20}Ga_{0.80}As$ (3×10^{18} cm^{-2}), Si (5×10^{16} cm^{-2}), (c) simulated mode profile for 6 nm thick Al_2O_3.

Table 1: Fabricated platform variations

Design name	Si doping (cm^{-3})	GaAs doping (cm^{-3})	Gate type	$V_\pi L$ (V-cm)
Design 1	4e16	3e18	Al_2O_3 (6 nm)	0.370
Design 2	5e17	3e18	HfO_2/Al_2O_3 (10/3 nm)	0.294

Initial phase tuning measurements were performed on a 350 µm-long p-Si/Al_2O_3(6 nm)/n-GaAs MOSCAP MZI structure and spectral responses indicated ~ 1.69 nm of tuning at a 2 V bias while maintaining an extinction ratio of ~ 24 dB as shown in Fig. 3 (a). The measured FSR = 17.9 nm and the calculated $V_\pi L$ = 0.370 V-cm which is 4× smaller than typical values seen in PN junction-based phase tuners. The observed leakage current appears to be smaller than the current meter limit of sub-nA, indicating negligible power consumption. The MOSCAP MZI is capable of achieving RC constant-limited 4 Gbps eye diagrams and an f_{3dB} ~ 1.5 GHz. We also measured a MZI with HfO_2 (10 nm)/Al_2O_3 (3 nm) dielectric as shown in Fig. 3 (b). The measured FSR = 19.0 nm with 2.26 nm of tuning at a 2V bias while maintaining an extinction ratio of ~ 30 dB. The $V_\pi L$ was slightly lower ($V_\pi L$ = 0.294 V-cm) than the Al_2O_3 counterpart even with double the dielectric thickness.

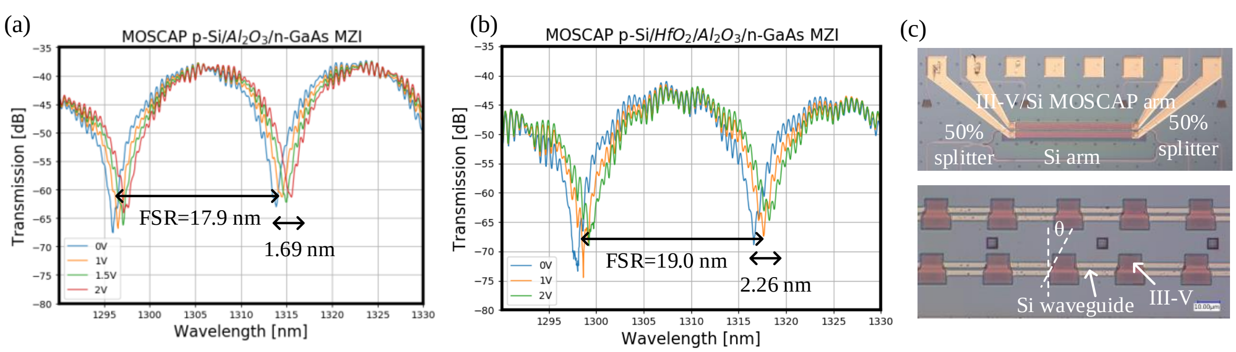

Fig. 3. Optical response vs. voltage for MOSCAP MZI with dielectric (a) Al_2O_3 (6nm), and (b) HfO_2/Al_2O_3 (10/3nm). (c) Image of MOSCAP MZI and angled GaAs/Si interface loss test structures.

We compared the measured refractive index change for both dielectrics with the calculated values as shown in Fig. 4. For the case of Al_2O_3, the measurements point to either an effective thickness of 15 nm or higher $n_{Al2O3} > 1.75$. Similarly, for HfO_2, measurements indicate either larger effective thickness of the HfO_2/Al_2O_3 stack or the respective refractive indices. We are currently investigating this. Angled GaAs/Si interface losses were evaluated by cutback loss structures as shown in Fig. 3 (c). The interface losses for angles of θ = 0 °, 45 °, and 72 ° were measured to be 1.08, 0.69, and 0.29 dB/facet respectively and match up with simulated values quite well. Measurements were taken on 65 GHz 1-ring assisted AMZIs (1-RAMZI) for different MOSCAP dielectrics as indicated by Design 1 and Design 2 in Table 1. However, fabrication non-uniformity and directional coupler variation due to etch differences between two wafers play a significant role in determining (de-)interleaver passband XT and symmetry.

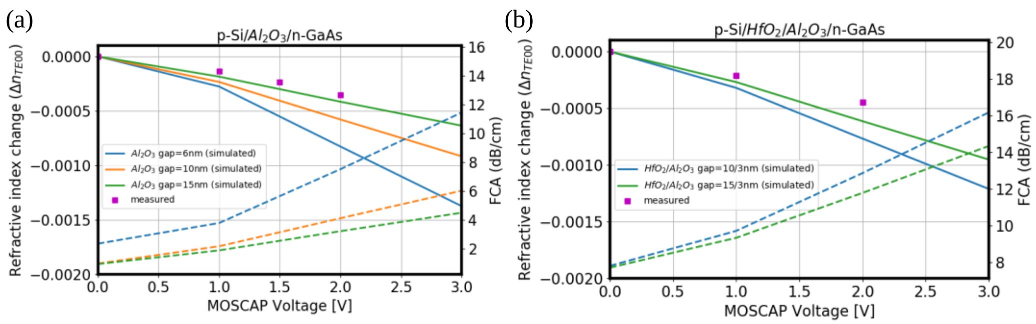

Fig. 4. Comparison of experimental and calculated refractive index change of MOSCAP MZI with dielectric (a) Al_2O_3 (6nm), and (b) HfO_2/Al_2O_3 (10/3nm).

Due to this, it is difficult to make a fair comparison of Design 1 and Design 2, however, we searched for devices on the two wafers that yielded similar XT values before phase error correction. In any case, Fig. 5 (a) – (b) shows the measured optical response for a 1-RAMZI with Al_2O_3 (6 nm). The measured bar and cross channel exhibit XT ~ -7.3 dB and – 10.7 dB respectively before phase correction. A bias of – 2 V on the delay length (V_{delay}) results in improving the cross channel XT from -7.3 dB to -16.4 dB and the bar channel XT from -10.7 dB to -26.6 dB. At V_{delay} = -2 V, approximately 5.0 nA was drawn resulting in a total tuning power consumption of 10.0 nW, x orders of magnitude lower than typical thermal tuners. Fig. 5 (c) – (d) shows results of a 1-RAMZI with HfO_2/Al_2O_3 (10/3 nm). By applying a – 2.1 V bias on the V_{ring1}, the cross and bar channel XT improved from -13.8 dB to -16.4 dB and -6.8 dB to -13.7 dB respectively. At V_{ring1} = - 2.1 V, approximately 24.0 nA was drawn resulting in a total tuning power consumption of 50.4 nW. Note, the passbands are far from flat-top compared to theoretical designs. This is attributed to waveguide loss, whereas increased channel XT indicates non-ideal power coupling. In the future, this will be remedied with robust 50% MMI power couplers and improved fabrication to reduce waveguide losses.

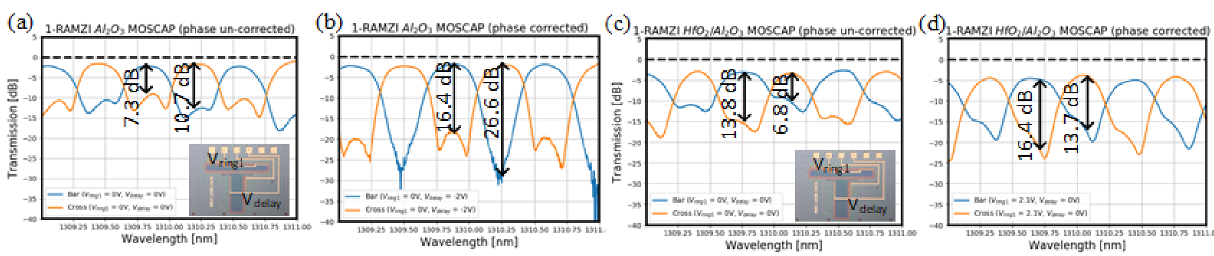

Fig. 5. Measured response of Al_2O_3 (6nm) 1-RAMZI (de-)interleaver with (a) un-corrected errors, and (b) corrected errors with V_{ring1} = 0 V, V_{delay} = - 2 V yield power consumption of 10.0 nW. Measured response of HfO_2/Al_2O_3 (10/3nm) 1-RAMZI (de-)interleaver with (a) un-corrected errors, and (b) corrected errors with V_{ring1} = - 2.1 V, V_{delay} = 0 V.

3. Conclusion

The work presented here, demonstrates for the first time, a comparison between III-V/Si MOSCAP MZIs and 65 GHz 1-RAMZI (de-)interleavers based on high-k dielectric Al_2O_3 and HfO_2. A 6 nm thick Al_2O_3 and 10/3 nm thick HfO_2/Al_2O_3 MOSCAP structure resulted in $V_\pi L$ values of 0.370 V-cm and 0.294 V-cm respectively. Even though the HfO_2/Al_2O_3 structure is twice as thick, the $V_\pi L$ is still lower indicating the potential of using HfO_2 MOSCAP as efficient phase tuners. 1-RAMZI (de-)interleavers were measured for both dielectrics and resulted in significant channel XT improvement down to -26.6 dB with tuning powers of only 10.0 nW. These wafer-bonded MOSCAP structure allows for ultra-low-power phase tuning compared to thermal counterparts.

3. References

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