# Design of lumped electrodes for silicon Mach-Zehnder Interferometer switches

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## Abstract

The emergence of intra-chip optical interconnects on a silicon photonics platform is gradually expected to overwhelm copper based-interconnects. As a result, significant research efforts have been made to realize low drive voltage, low power and fast switching devices featuring high throughput bandwidth. This work deals with the design of lumped-electrodes for silicon Mach-Zehnder Interferometer (MZI) switches with active performance based on carrier-depletion. Carrier depletion has been largely used for implementing silicon modulators [1] however no switches based on carrier depletion have been demonstrated so far despite the perspective of achieving faster switching times and lower power consumption with respect to carrier injection.

Figure 1(a) shows the MZI switch with lumped-electrodes. The active region design has been designed relying on a shallow etched waveguide configuration. Figure 1(b) depicts the cross-section of the active region with electrodes. The chosen semiconductor structure is a vertical PN junction, which on one hand achieves larger effective index change than horizontal PN junctions and on the other hand is more tolerant to potential mask alignment errors since its formation is dictated by the implantation energy rather than the resolution of the optical lithography. Additionally, the combination of a slightly lower modal confinement and wider PN junction leads to a higher interaction between the propagating light and charge carriers.

The active (doped) region has been optimized with ATHENA and ATLAS, respectively process and device simulation software from SILVACO. The fractional change in effective index will depend on holes/electrons density ratio. According to Soref's equations [2], holes are more efficient than electrons in changing the refractive index for carrier concentrations up to $10^{19}$ $cm^{-3}$, and absorb less light than electrons. As a result, our PN junction has been designed in such a way that the high intensity region of the optical mode interacts mostly with holes. Static and transient performance of the optimized vertical PN junction has also been analysed. The obtained figures of merit are much lower (<0.55 V.cm from 1 to 10V) than typical values obtained from horizontal PN junction schemes (from 2 to 4 V.cm). The phase shifter insertion loss is 1.55 dB/mm when no bias is applied. For increasing voltages, the losses decrease because the charge carriers are removed from the waveguiding region. The intrinsic rise and fall times (90 % of the maximum effective index change) derived from the transient analysis are both around 30 ps thus confirming the ultra-fast response of the switch.

Lumped-electrodes have been designed taking into account the proposed active region. Electrodes are based on a symmetrical coplanar microwave strip. The main parameters to be optimized are the ground and signal electrodes width (W), the gap between both contacts (G) and the length of the electrode (L). The optimization should be carried out to avoid that electrodes restrict the switching time and power consumption. The optimum gap depends on the drive voltage and the propagation losses. A small electrode gap is required to increase the switching efficiency and so minimizing the required drive voltage. However, the gap should be sufficiently wide to avoid the interaction of the optical mode with the metallic contacts which would drastically increase propagation losses. In the proposed switch, an optimum gap of ~3.5µm has been designed. The optimum length has been designed based on a trade-off between the drive voltage and the insertion losses and switching time. A longer length will decrease the required drive voltage at expenses of increasing the insertion losses and reducing the bandwidth. An optimum electrode length of around 1mm has been chosen to keep the drive voltage below 4V and the insertion losses below 1.5dB. The switching time will be limited by the electrical bandwidth of the lumped-electrode.

The bandwidth in lumped-electrodes is usually limited by the electrode capacitance, C, and load resistance, R. The electrode capacitance depends basically on the W/G ratio [3]. Several simulations were carried out taking into account the silicon substrate in order to obtain the capacitance per unit length as a function of the W/G ratio. Figure 2(a) shows the obtained results. The corresponding bandwidth-length product is also shown taking into account R= 50Ω. As expected, a small W/G ratio results on a higher electrical bandwidth. Therefore, the electrode width, W, can be reduced to increase

the bandwidth. However, the width must also be sufficiently wide to ensure that the static electric resistance does not become a limiting factor in the achievable bandwidth [4]. The static electric resistance will be inversely proportional to the electrode width and the electrode thickness. The maximum electrode thickness depends partly on the fabrication process and in our case values around 1µm are expected to be achieved. Therefore, an optimum electrode width of ~20µm has been designed. Such a value will give rise to W/G~5.7 which ensures a bandwidth-length product above 1GHz·cm. Hence, the bandwidth will be around 10GHz for the designed electrode length (L=1mm) that will allow switching times below 35ps and therefore will not limit the ultra-fast time response achieved thanks to the carrier-depletion effect. Finally, a higher bandwidth could also be achieved by using a parallel resistance of 50 Ω to allow broadband matching to the impedance of the driving source. However, it is also important to notice that in that case it would be needed twice the drive voltage thus penalizing the power consumption of the switch.

## References

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## Acknowledgments

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## Figures

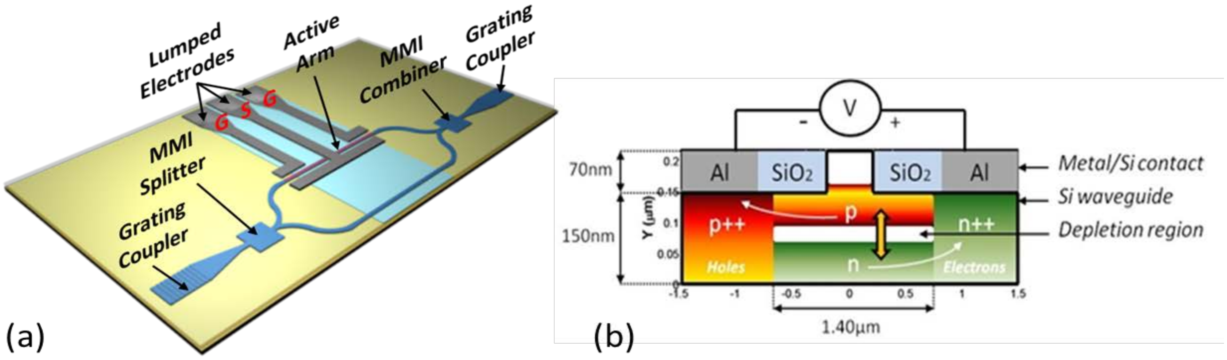

Figure 1: Schematic of (a) the MZI switch with lumped-electrodes and (b) cross-section of the active region with electrodes.

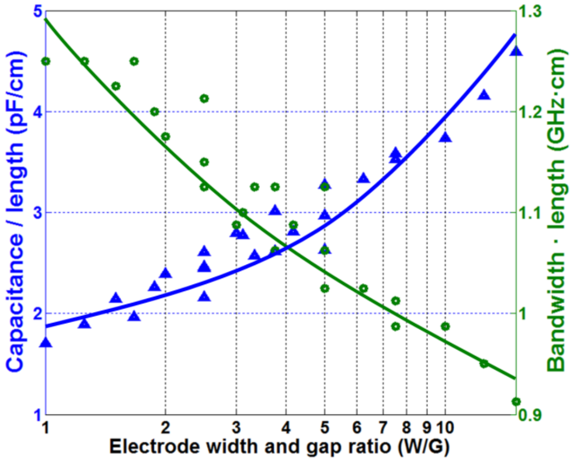

Figure 2: Capacitance and corresponding bandwidth-length product as a function of the W/G ratio.