

A Mach-Zehnder interferometric switch within the POLarization based Integration Scheme (POLIS)

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We present an electro-optical switch operating on TM polarized light in POLIS. All relevant electro-optical effects, including bandgap shrinkage, bandfilling, intra-band and inter-valence band absorption are modeled, properly accounting for the magnitude of these effects at various doping levels. Based on the results of the model switches were realized on POLIS material, and by optimizing the doping profile a decrease in switching voltage from 4.6 V to 2.8 V was obtained. A good agreement between the model and measurements was found. The switches have 3 mm long phase shifters and show low crosstalk values of -17 dB.

Introduction

In enabling fast, low-cost and reliable optical communication, optical integrated circuits will play a vital role. In these circuits a variety of optical components is needed, including passive structures like waveguides and couplers and active structures such as light sources and detectors. The integration of these different devices puts different requirements on the material used, and to meet these requirements an additional processing step (e.g. regrowth) is needed. In the POLarization Based Integration Scheme (POLIS) this issue is overcome by having a material that can offer both passive and active properties, depending on the polarization of the light. In this scheme, TE polarized light is used for active components (absorbing) and TM polarized light for passive components (transparent) [1]. The material responsible for this behavior contains one or more compressively strained quantum wells, resulting in different bandgaps for TE and TM due to band splitting. The change between active and passive behavior can be achieved with polarization converters [2], defined during device processing.

One of the key components in optical integrated circuits is the electro-optical switch. By applying an electric field, it is capable of changing the path followed by a confined light wave. Its main applications are the generation of optical data by modulation of a continuous optical signal and the routing of signals in an optical network. Various designs are possible, but a Mach-Zehnder interferometer (MZI) based switch has the advantages of operating under reverse bias and of using multi-mode interference (MMI) couplers, which are fabrication tolerant. The electro-optical switch presented here fits into the POLIS scheme and operates on TM polarized light. Because the polarization state of the light in a POLIS circuit is always defined, the polarization dependence that limits other designs, does not play a role here.

Principle of operation

The MZI based switch features 2 MMI's and two branches connecting these (figure 1). In applying a phase shift to the light in one of the two branches, we can arrive at

constructive or destructive interference at either of the two output ports. In our case, the phase shift is generated by applying a reverse bias over the p-n junction that is formed by the doping profile of the POLIS material. The applied field results in both field-induced and carrier related refractive index change mechanisms. The latter are due to the removal of carriers under the influence of the reverse bias.

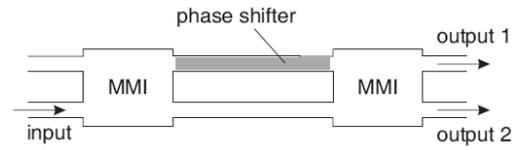


Figure 1: MZI based electro-optical switch

Model

The only field-induced mechanism that has to be considered is the Kerr or quadratic electro-optic effect. As we are operating on TM polarized light, the Pockels (linear electro-optic) effect does not contribute to a change in refractive index for the field and crystal orientations used. The quantum confined Stark effect only plays a role in quantum wells and is neglected here because of the small optical overlap with the thin quantum well (less than 0.5%).

The magnitude of the Kerr effect has a quadratic dependence on the applied field strength. It is modeled according to the model in reference [3], where the relevant coefficients for our material have been determined by fitting to experimental data.

Two carrier induced effects usually simultaneously referred to as the plasma effect are intra-band absorption and inter-valence band absorption. The first describes the transition of a carrier to a higher energy level in the same band, whereas the second describes the transition of a hole from one valence band to another. In modeling the refractive index change due to the plasma effect, other works only consider the intra-band absorption. In this work, we extended the model by applying the Kramers-Kronig transform to experimentally fitted data of the inter-valence band absorption from reference [4].

The two last effects that were considered are bandgap shrinkage and bandfilling. These effects both describe a change of the absorption around the band edge of the material due to Coulomb interaction of carriers (bandgap shrinkage) and the occupation of available energy states (bandfilling). For the bandgap shrinkage, we adopt an analytically obtained model valid at $T = 300$ K for all doping levels [5]. The bandfilling is modeled according to the model given in reference [6]. To accommodate for experimental results indicating that the absorption doesn't increase at energies more than 0.2 eV above the bandgap, we add a quickly decaying exponential to limit the magnitude of these effects at high photon energies.

The absorption around the bandgap is described using a square-root law [6], fitted to experimental data from reference [7]. The dependence of the magnitude of the Urbach

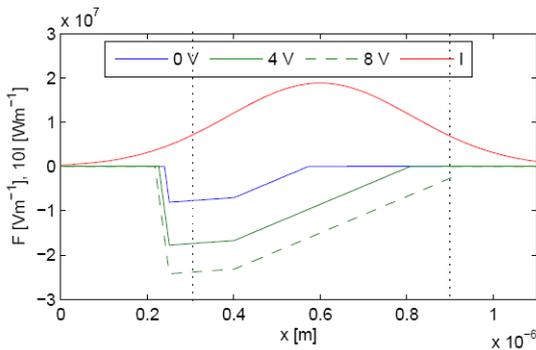


Figure 2: Field distributions of a POLIS wafer

tail on the doping level is accounted for by assuming a Gaussian distribution of the absorption strength.

With the distribution of the electric field and all refractive index change mechanisms modeled, the effective change in refractive index that the light experiences was determined by calculating the overlap of the local optical intensity with the local refractive index change due to the electric field (figure 2).

Layer stack design

The original layer stack design (figure 3, A) has the strained quantum well in the middle of an undoped waveguide. The simulations based on the model described above showed that a slight intentional n-type doping of the waveguide would be advantageous for the switching efficiency. However, the series resistance of the layer stack would increase in this case, due to a reduced mobility of holes in this region. Therefore a second wafer (B) was grown with a displaced quantum well (towards the p-contact) and a slightly n-type doped waveguide below the quantum well.

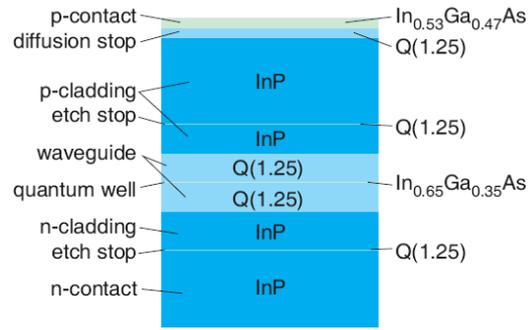
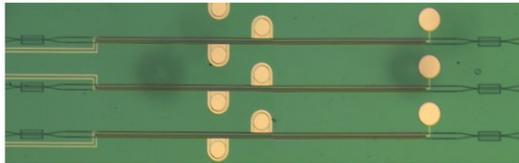


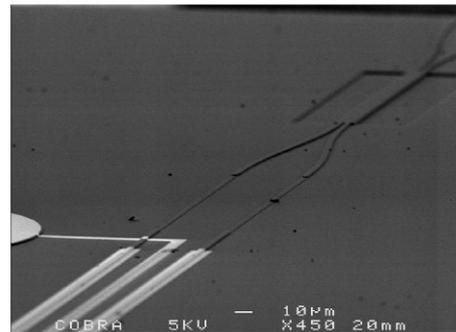
Figure 3: POLIS layer stack design for wafer A

Realization

A series of switches with 3 mm phase shifters was realized on both wafers. The processing consisted of 6 lithography steps. The complete realization was done with established in-house techniques. The various regions defined during processing are: shallow waveguides, thin cladding waveguides for electrical isolation of two phase shifter branches, deeply etched MMI's, contact pads, p-contacts on top of the phase shifters and n-contacts. In figure 4 microscope and SEM pictures are given of the realized switches.



(a)



(b)

Figure 4: Microscope (a) and SEM (b) pictures of the realized switches

Characterization

The characterization was performed by coupling light from an EDFA (after passing through a bandwidth filter) into one input port of a switch on the chip and collecting the light from both output ports. A chopper together with a lock-in amplifier is used to reduce noise levels and probes were used to apply a bias to the phase shifter. A typical switching curve for sample A is given in figure 5.

We fitted this measurement data to the description of an MZI with one perturbed branch, relating it directly to a number for the

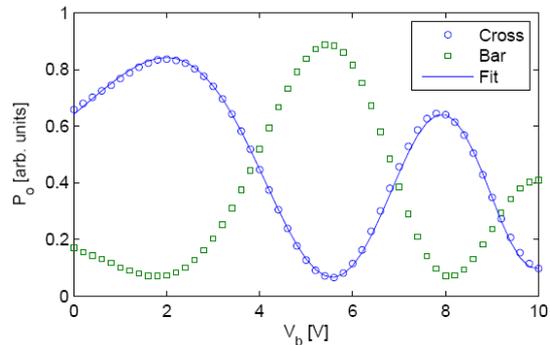


Figure 5: Typical switching curve for a switch realized on wafer A

imposed refractive index change at various bias voltages. The refractive index change obtained in this way is given in figure 6, with the simulation results for both samples.

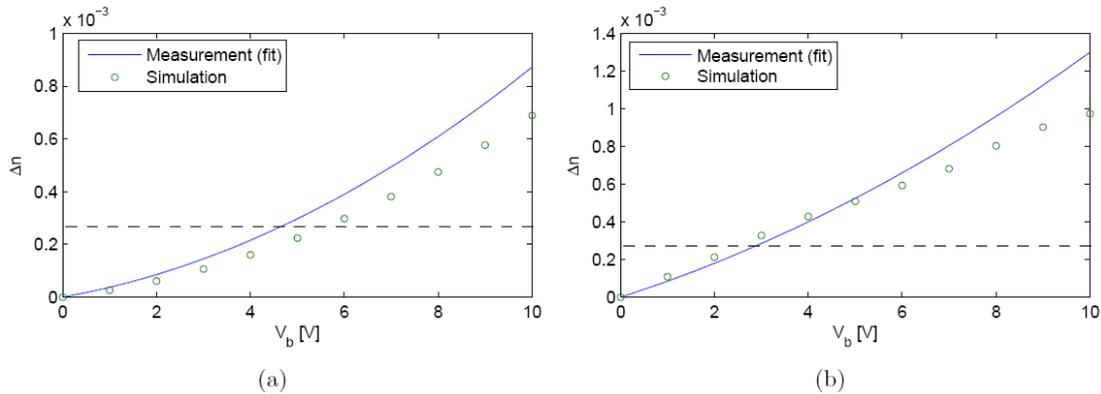


Figure 6: Refractive index change from fitting and simulation for sample A (a) and B (b)

Discussion

The simulation and measurements are seen to give a good agreement, but the total effect is underestimated by the simulations at higher reverse biases. This is most likely due to a slight deviation in the strength of the Kerr effect for our material.

The switching voltage is determined to be 4.6 V and 2.8 V for sample A and B respectively, corresponding to a switching efficiency of 13.0 °/Vmm and 21.4 °/Vmm. The adjusted doping profile of sample B is seen to give a large improvement on the switching efficiency. Unfortunately, displacing the quantum well is seen to give additional losses. The losses of the switch are high, most likely due to diffusion of the p-type dopant (silicon) towards the waveguide region.

Obtained crosstalk values are -11.8 dB and -17.2 dB at 1550 nm, for sample A and B respectively; the difference in these values is attributed to a small fabrication error during the processing of sample A.

Conclusion

Mach-Zehnder switches with 3 mm phase shifters, showing a switching voltage as low as 2.8 V and a crosstalk value of -17 dB have been demonstrated on POLIS material. All relevant refractive index change mechanisms were modeled to arrive at an improved design for the layer stack. A good agreement between simulations and measurements was found.

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