High Speed Electro-Optic Modulator with Comb Like p-i-n Diode

Aws Al-Saadi, Hans J. Eichler and Stefan Meister
Institut für Optik und Atomare Physik
TU Berlin
Berlin, Germany, aws@physik.tu-berlin.de

***Abstract*—We propose an electro-optic modulator with a comb like diode structure. By placing the doped regions into the minima of the standing wave inside the resonator, modulation bandwidth is increased with low additional losses.**

I. INTRODUCTION

Optical modulation represents one of the main required functionalities for optical interconnect solutions. Modulators based on silicon-on-insulator (SOI) show in recent years impressive progress in terms of demonstrated functionalities and compactness as well as low cost CMOS-technology compatibility. [1]

High performance electro-optic modulation in silicon has been demonstrated using Mach-Zehnder modulators [2]. These modulator devices have lengths in the millimeter range. For effective chip-scale integration, such electro-optic modulators are inappropriate.

More recently, electro-optic modulators based on ring resonators were demonstrated. The small modulators have ring diameters down to 12 µm and modulation frequencies of > 10 GHz [3]. If the size of the rings is further reduced to < 10 µm, the guided mode is leaking out of the ring waveguide. Therefore, reduction of the footprint of the modulator is limited. Another problem is the high temperature sensitivity of the ring resonators of 1.3 nm/K [4]. With a bandwidth of less than 0.1 nm the requirement on the temperature stability is extremely high.

The footprint of electro-optic modulators can be further reduced by using photonic crystal micro-resonators. Also the temperature sensitivity of such resonators is more than one order of magnitude smaller than for ring resonators [5]. But up to now, only 250 MHz modulation frequency was demonstrated [4]. Therefore, further investigations are required to increase the modulation bandwidth.

The most common method to achieve modulation in silicon devices is to utilize the plasma dispersion effect, in which the concentration of free carrier in silicon changes the real and imaginary parts of the refractive index [6]. In most cases p-i-n diode structures were formed around the waveguide to electrically control the injection/depletion of electrons and holes in/out the path of the propagating light. Commonly, to avoid excessive optical loss, the waveguides were positioned in the intrinsic region of the diode and the doped regions were positioned in such a way that the modal overlap was minimized. High doping concentration is used to provide strong electro-optic effect. But the modulation speed is limited in such injection based structures because of the slow recombination dynamics of minority carriers [2] and the wide width of the intrinsic region.

II. DEVICE STRUCTURE

The 1-D photonic crystal micro-cavity in Fabry-Perot structure [7] is built in a 450 nm × 220 nm rib waveguide on a 50 nm slab, which is passivated by SiO_2. The micro-cavity mirrors are formed by two pairs of holes with a lattice constant of 350 nm. To achieve a high Quality-factor, a 1-D photonic crystal micro-cavity with tapered holes [8] may used as resonator.

The p-i-n diode consists of comb like p- and n-doped regions, see Fig.1. The comb segments of 130 nm width are alternately positioned into the cavity where the standing light wave has minimum intensities. The period of p- (or n-) doped comb segments is assumed to be 590 nm, according to the optical wavelength in the waveguide λ_0/n_{eff}, where λ_0 is the free-space wavelength of 1550 nm and n_{eff} is the effective refractive index of 2.63. The p- and n-regions are assumed to be highly doped with concentrations of 10^{20} cm^{-3}.

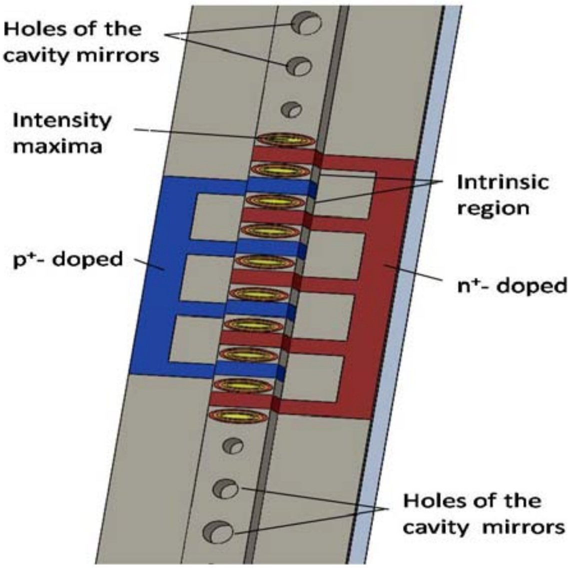

Fig 1. 1-D photonic crystal micro-cavity in Fabry-Perot structure with a comb like p-i-n diode structure. The comb segments are alternately positioned in the cavity, where the standing light wave has minimum intensities.

In this structure, the p-i-n diode are oriented longtudinal to the waveguide and the inrinsic zones are centered at the maximum intensities of the standing wave in the resonator.

III. Device Modeling

First, LaserMOD tool from Rsoft Inc. [9] was used to calculte the electron and hole dynamics in the diode cross section. Numerical solutions of Poisson's equation and charge continuity equations for electrons and holes used to simulate p-i-n semiconductor device built around Si waveguide.

Further, beam propagation method (BPM) was used to calculate the mode and field profile. The induced real refractive index and optical absorption coefficient variations (Δn and $\Delta\alpha$, respectively) produced by free-carrier dispersion at a wavelength of 1.55 µm were calculated by LaserMOD tool using numerical values of [6]. The real and imaginary refractive indeces induced by applying reverse and forward voltages was calculated in the waveguide cross section.

In a second step, 3-D finite difference time domain method (FDTD) in Fullwave tool from Rsoft Inc. was used to calculate the optical output spectrum of the resonator. For specific values of hole and electron concentrations in the p-, i-, and n-region, the values for real and imaginary refractive indices, determined above, were used to calculate the influence of carrier density on light propagation in both modulators on- and off-states.

IV. Results And Discussion

To prove the modulator concept, the calculated performance of the proposed structure is compared to “conventional” injection based p-i-n structures with homogeneous diode. For comparison of the different p-i-n diode structures, the change in effective refractive index is hold constant at $\Delta n_{eff} = 0.004$ by adjusting the on/off voltages. In previously demonstrated injection based p-i-n structures [2,4], with an intrinsic width of about 1.2 µm the 10-to-90 switch-on time (forward bias) is about 1.6 ns. By applying pre-emphasis technique the rise time can be strongly reduced as shown in [2]. If then a reverse bias is applied (e.g. -1 V), the 10-to-90 switch-off time is as low as 0.3 ns, as shown in Fig. 2a.

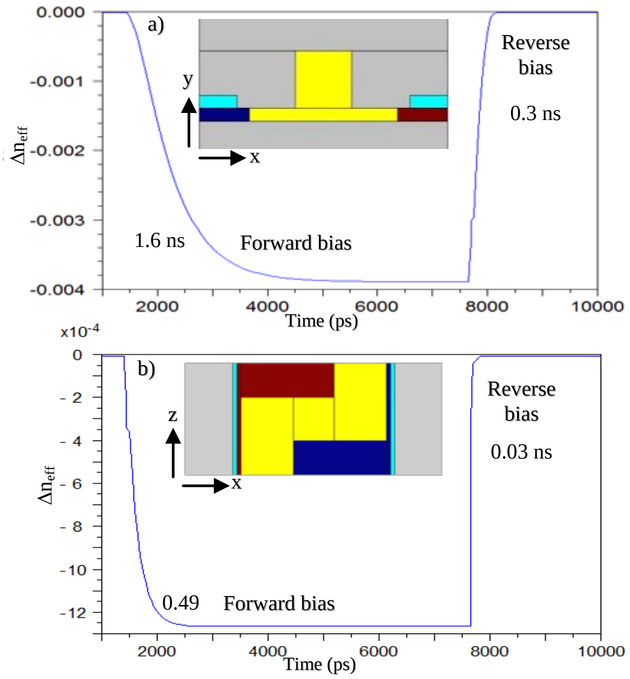

Fig 2. Calculated switching transient for a) homogeneous [4,6] and b) proposed comb diode.

A x, z-cross section of one segment of the comb diode is used to calculate the carrier dynamics of the proposed structure. Those 2-D simulations give proper values for the switching times of the diode as well as for the change of real and imaginary refractive index in silicon. But the real change of the effective refractive index in the resonator has to be determined by the on-/off-shift of the transmission peak using 3-D simulation with FullWAVE tool.

In the proposed comb diode structure, the intrinsic width between p- and n-doped comb segments is 165 nm. The reduced intrinsic width leads to a decreased 10-to-90 switch-on time of 0.49 ns and to a 10-to-90 switch-off time of 0.03 ns by applying a reverse bias of -1 V, see Fig. 2b.

For simulations of the modulator on/off transmission spectra, 1-D photonic crystal micro-cavities with a quality factor of 600 are chosen. The maximum transmission of the modulator with comb diode is 0.61 in the off state. That is only slightly lower than the maximum transmission of 0.67 for the modulator with homogeneous diode with 1.2 µm intrinsic gap.

We conclude that the modulator with the proposed comb like diode structure provide 3-times reduces switch-on and 10-times reduces switch-off time compared to an injection based modulator with homogenious p-i-n diode and has low additional losses of about 0.4 dB.

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