Fast and Efficient Light Intensity Modulation in SOI with Gate-All-Around Transistor Phase Modulator

P. Dainesi[1, 2], K. E. Moselund[2], L. Thévenaz[1] and A. M. Ionescu[2]
1: Nanophotonics and Metrology Laboratory, 2: Electronics Laboratory, Swiss Federal Institute of Technology, EPFL STI-IMM-LEG2, ELB 230, Station11, 1015 Lausanne, Switzerland. Paolo.Dainesi@epfl.ch

Abstract: We report fast modulation (> 30 GHz) in a SOI resonant cavity using integrated Bragg mirrors and a Gate-All-Around transistor as active element. Modulation depth > 90% can be obtained in 12.5 μm long devices.

OCIS codes: (130.0250) Optoelectronics; (230.4110) Modulators.

1. Introduction

Silicon-On-Insulator (SOI) photonics has unique capability for developing new classes of compact and attractive optoelectronic devices for telecommunications and/or on-chip optical clock/signal distribution. Recent results have proven the feasibility and given the rationale for scaling towards SOI submicron waveguides or nanowires (NWs) [1-4]. Using device architectures based on scaled NWs provides numerous advantages in terms of both optical performance and intrinsic electrical speed of state-of-the-art microelectronic devices. Moreover, a key strategic point is that electronics can be co-integrated in a unique multifunctional platform to offer the best performances in terms of optical transmission/modulation and electronic device progress.

In silicon NWs, single-mode IR light can propagate with losses below 1 dB/cm, provided that surface roughness is reduced using a smoothing process [1]. The extremely high index difference between Si and the surrounding media, typically SiO_2 and air, allows for very short bending radii and hence very compact devices [2]. Injection of free charges in Si NWs modulates the complex refractive index of the guiding medium [5] providing a mean for light phase modulation much faster than thermal solutions, though with a loss penalty limiting the modulator length. If charges injection is provided by a capacitive-based device, the modulation frequency can reach the GHz range, as shown recently [6]. Finally, interesting engineering solutions have also been proposed [3, 4] to overcome the serious light in/out-coupling loss due to mode mismatch with an external standard optical fiber.

Active resonant structures have been considered in the past on large rib waveguides with thermal actuation [7]. We propose *a new compact light intensity modulator based on a Fabry-Perot (FP) cavity in SOI NWs, capable of operation frequencies higher than 30 GHz.* The active element in the cavity is a Gate-All-Around (GAA) MOS transistor modulator [8]. State of-the-art CMOS electronics is evolving towards thin film fully depleted SOI and multi-gate architectures. In ultra-scaled (< 50 nm) GAA films, volume inversion can be obtained allowing improved mobility and transconductance, reduced short channel effect and near ideal subthreshold slope [9]. We have performed an in depth theoretical and numerical analysis of the intensity modulator and results are reported in this paper.

2. Device description and operation

The proposed device is shown in fig. 1. a). A silicon square NW on SOI (340 x 340 nm^2 cross section) is used as single-mode waveguiding medium.

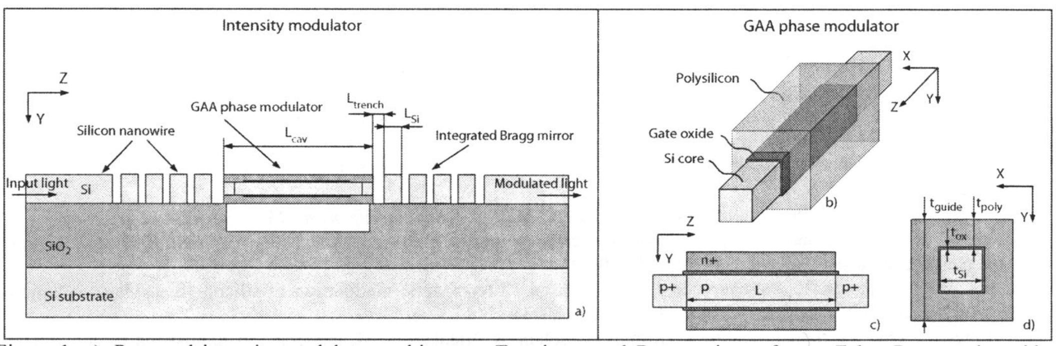

Figure 1. a). Proposed intensity modulator architecture. Two integrated Bragg mirrors form a Fabry-Perot cavity with a GAA phase modulator as active element in the cavity. b) 3D view of the GAA phase modulator c) Longitudinal cross section showing doping configuration. d) Transversal cross section.

By etching air trenches along the waveguide, a periodic pattern with lengths L_{trench} and L_{Si} can be obtained forming an integrated Bragg mirror for $L_{trench} + n_{eff}L_{Si} = \lambda/2$, where n_{eff} is the effective index of the fundamental mode in the Si NW and λ its wavelength ($\lambda = 1.55\mu m$). A GAA transistor phase modulator is inserted between two Bragg mirrors to form an active FP cavity.

A detailed description of the GAA phase modulator is shown in fig. 1. b). A crystalline Si core is wrapped in a SiO_2 gate oxide and in a conductive Poly-Si to form a MOSFET transistor with gate completely wrapping the conductive channel. Connecting both $p+$ regions to ground and giving a bias voltage V_g on the $n+$ region (fig. 1.c), the structure is in a capacitive configuration resulting in very low power consumption and negligible parasitic heating effects. We have considered and analyzed two possible doping case figures: (i) a higher doping case, with p region at $NA = 10^{18}$ cm^{-3} and $n+$ region at $ND = 10^{19}$ cm^{-3}, and (ii) a lower doping case, with p region at $NA = 10^{17}$ cm^{-3}, and $n+$ at $ND = 10^{18}$ cm^{-3}; for both cases $p+$ regions are at $NA = 10^{19}$ cm^{-3}. We have considered square GAAs with fixed cross section ($t_{guide}^2 = 340 \times 340$ nm^2) (fig. 1.d) equal to the guiding NW to maximize mode matching between the guiding section and the modulating one. We have analyzed different possible Si-core thicknesses ranging for $t_{Si} = 20$ to 250 nm. The oxide thickness is $t_{ox} = 10$ nm.

3. Optical and electronic numerical analysis

At thermal equilibrium and for $V_g = 0V$, the GAA Si core is in depletion regime; applying a gate voltage it can be driven to flatband ($V_g \sim -0.9V$) and to accumulation ($V_g < -0.9V$) regimes. 2D and 3D free carrier concentrations, in capacitive configuration, have been simulated (fig. 2) with software ISE. Accumulated charges on the border of the gate oxide are clearly visible for both doping case figures. Close to the core corners, we have clearly seen that injected carriers can be one order of magnitude higher than on the gate oxide border (inset in fig. 2), due to the corner effect, as predicted in [10]. Simulations of capacitive operation show also negligible thermal effects.

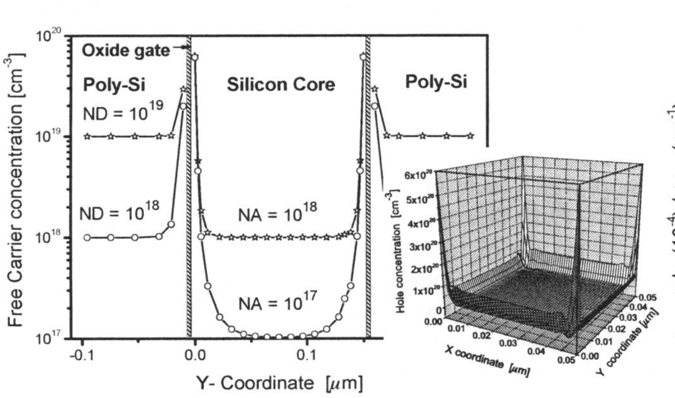

Figure 2. Free carrier concentration in the nanowire center for the two doping cases ($V_g = -6V$, p+ contacts grounded). Inset: 3D simulation for $t_{Si} = 100$ nm and $V_g = -6V$ showing the corner effect (higher doping case).

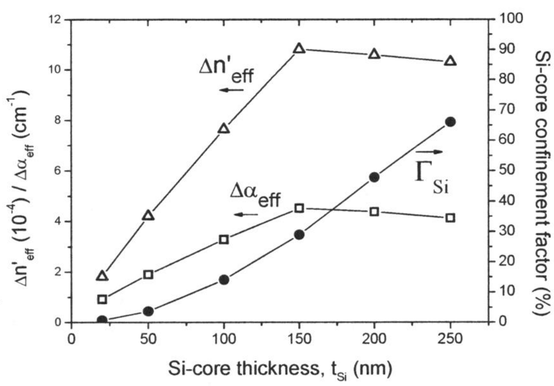

Figure 3. Effective index difference and absorption for different core thicknesses with applied bias $V_g = -6V$. The confinement factor in the Silicon core Γ_{Si} is also presented.

BPM simulations of the GAA phase modulator show that for a thin gate oxide the whole GAA is a single mode waveguide in which the fundamental mode matches very well ($\eta > 99.7\%$) the one in the NW region. The confinement factor in the GAA as well as in the Si NW is $\Gamma \sim 83\%$. On the other hand the confinement factor in the Si core of the GAA (Γ_{Si}) varies depending on the core thickness t_{Si}; results are reported in fig .3. Since injected carriers distribution vary very rapidly in the Si core where the propagating modal field amplitude varies also depending on the Si core thickness, to correctly determine the refractive index difference due to injected carriers in the Si core, we have first calculated the index difference distribution $\Delta n(x,y)$ [5], and then, with a first order perturbation approach, an effective index difference Δn_{eff} depending on the overlap between $\Delta n(x,y)$ and the propagating field. Writing $\Delta n_{eff} = \Delta n'_{eff} + i(\lambda/4\pi)\cdot\Delta\alpha_{eff}$, it is possible to find the phase shift and the attenuation in the GAA due to injected carriers. Results (fig. 3) show that index differences as high as 10^{-3} can be obtained for cores thickness $t_{Si} \geq 150$ nm with about 4.5 dB/cm additional losses. Assuming that the Poly-Si has the same refractive index dependence on doping concentration as silicon, losses in the GAA will be dominated by doping concentration, and, consequently, for the higher doping case only GAAs with the largest possible Si cores have acceptable overall losses; for example for $t_{Si} = 250$ nm the losses in the GAA are $\alpha_{cav} \sim 93$ dB/cm. On the other hand for the lower doping case, smaller Si cores can be used with fewer losses ($\alpha_{cav} \sim 30$ dB/cm for $t_{Si} = 150$ nm).

Simulations of transient times have also been performed for both the two doping case figures, in order to determine the maximum charge injection frequency in the GAA modulator. Results for a modulator length of $L_{cav} = 1$ μm, with applied gate pulse $V_g = -6V$, are shown in fig. 4. It is clear that both configurations are suitable for high frequency modulation, though for higher doping GAAs the maximum operation frequency is double than that of the lower doping case increasing from about 38 to 80 GHz. Since carrier diffusion from the $p+$ region limits the operation speed, longer GAAs will work at rather lower frequency. Simulations for $L_{cav} = 5$ μm, show operation frequency of about 3 GHz. It is then preferable to repeat $p+$ contacts each micron in length to keep very high frequency operation.

With a FDTD algorithm we have simulated integrated Bragg mirrors in Si NW. The result is that, due to the high numerical aperture caused by the large index difference between Si and air, the etched air trenches need to be as short as possible to minimize scattering losses, and as a consequence, a larger number of periods will be necessary to have high reflectivity. We have simulated 10 and 13 periods with L_{trench} = 30 nm and L_{Si}= 330 nm and found reflectivity of 88% and 98.5% respectively with scattering losses of about α_{scat} = 0.3%. With those values we have calculated FP transmission curves for both doping case figures (corresponding to $\alpha_{cav} \sim 30$ and 100 dB/cm), and results are shown in fig. 5. In the OFF state the transmission is mainly determined by the Bragg mirror scattering loss and by the cavity length. Short cavity lengths are required to reduce total losses, increase the cavity finesse and be capable to exploit high frequency operations.

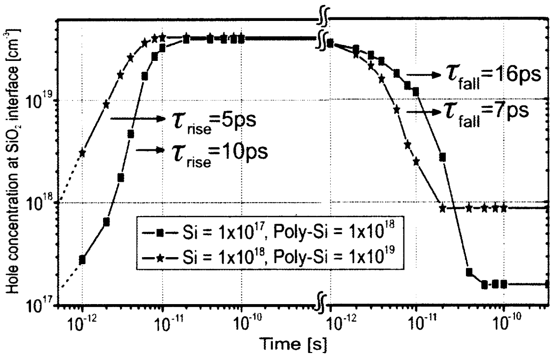

Figure 4. Transient simulated on a 1 μm long GAA for the two doping case figures. Both show comparable efficiencies but the higher doping case is almost two times faster.

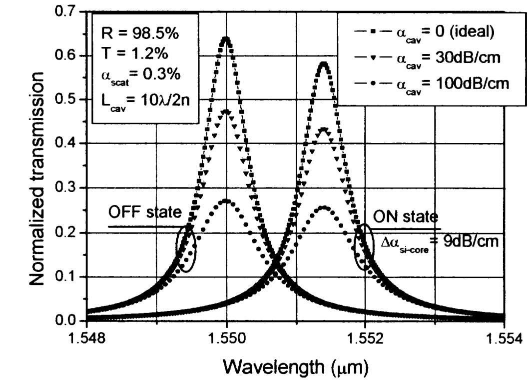

Figure 5. Simulation of OFF/ON intensity modulation for a 13 periods Bragg mirror and a cavity length of L_{cav} = 3.5 μm. Two different cavity losses are compared to the ideal case.

In fig. 5 results are shown for the 13 periods Bragg mirror with a cavity length of L_{cav} = 3.53 μm (corresponding to 10 half wavelengths). In this case the free spectral range is $FSR \sim$ 19.53 THz and the finesse is larger than 250 for the worst case. To simulate the ON state a $\Delta n = 2\cdot 10^{-3}$ is added in the cavity together with the corresponding added losses $\Delta\alpha$ = 9 dB/cm. Results show that with modest additional loss, modulation depths of about 85% for the worst case and 91% for the best one can be achieved. The total device length from first mirror input to second mirror output is about 12.3 μm. Better results in term of total device losses can be obtained using the 10 periods Bragg mirror. In this case we have seen that the total device loss can be reduced of about 1.5 dB but to obtain the same modulation depth a cavity at least 8 times longer is needed, which is either slower, or requires a more delicate arrangement of multiple $p+$ contacts. In this last case for L_{cav} = 28.2 μm (corresponding to 80 half wavelengths), the total device length is about 34.8 μm.

4. Conclusion

We have proposed and validated by numerical analysis very compact and high frequency light intensity modulators in SOI technology based on an a Fabry-Perot cavity with a Gate-All-Around MOS transistor as active element, in capacitive mode. Simulations show that a modulation depth of 85% at frequency up to 80 GHZ can be obtained in a 12.5 μm long device with 6 dB insertion losses, or, alternatively, modulation depth of 91% at frequency up to 38 GHz can be obtained in a 35 μm long device with 1.5 dB total insertion losses.

5. References

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