ECIO 2016
18TH EUROPEAN CONFERENCE ON INTEGRATED OPTICS 2016
18–20 MAY | WARSAW | POLAND

Transparent Conducting Oxide Electro-Optic Modulators: a Comprehensive Study based on the Drift-Diffusion Semiconductor Model

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SOI-based field-effect electro-optic (EO) modulators comprising a transparent conducting oxide (indium tin oxide, ITO) are rigorously studied in the near-infrared (NIR) under a multiphysics modelling framework. The performance of two representative silicon photonics platforms (Si-rib and Si-slot) is evaluated, Fig. 1(a)-(b). The proposed modulators attain very satisfactory extinction ratio (ER), resulting in μm-length configurations of negligible insertion loss (IL), accompanied by ultra-high bandwidth.

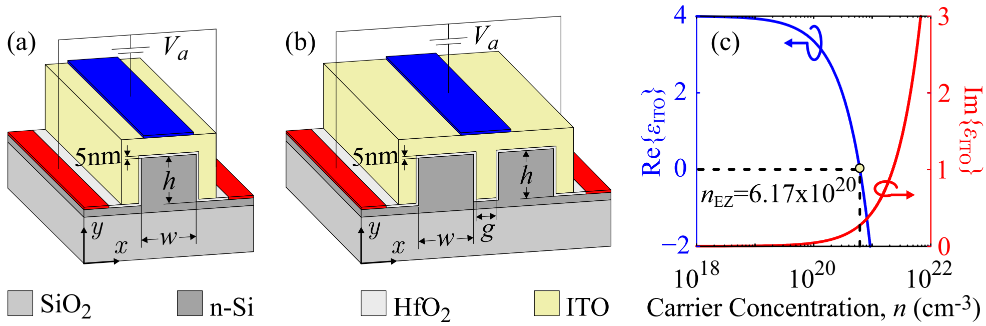

Fig. 5. (a) Si-rib and (b) Si-slot EO modulators ($w \times h = 220 \times 220$ nm, $g = 20$ nm). (c) ITO NIR permittivity ($\lambda = 1.55$ μm) as a function of carrier concentration n. The espilon zero carrier concentration (n_{EZ}) is 6.17×10^{20}cm^{-3}.

Introduction: In EO modulation applications, electrically induced changes in the effective refractive index (n_{eff}) of the guided mode are exploited for realising the necessary binary logic states. In this work, we consider changes in the losses of the optical wave, as represented by Im{n_{eff}}, in order to identify states of low and high IL (ON and OFF state, respectively) [1]. The EO functionality is achieved by incorporating an ITO layer, whose electrical [2] and optical properties can be controlled by electrical biasing. Specifically, by forming a capacitor-like n-doped silicon (n-Si)/hafnium oxide (HfO_2)/ITO junction, we exploit the response of ITO free electrons to the RF electric field developed in the insulating HfO_2 layer. When positive biasing is applied, an excess of electrons is built up at the HfO_2/ITO interface (accumulation layer), whereas a deficit of electrons occurs under moderately negative biasing (depletion layer). This perturbation in ITO carrier concentration successively leads to a change in its infrared permittivity (ε_{ITO}), allowing for nearly zero permittivity values, Fig. 1(c). An epsilon-near-zero (ENZ) region combined with a properly polarised optical mode results in increased IL (OFF state), since the electric field is greatly enhanced in the narrow (a few nm) and lossy ENZ region. On the other hand, at dielectric values of ε_{ITO}, the mode is less confined, having a typical photonic mode spatial distribution, and is nearly lossless (ON state). Thus, the desired logic states can be realised by electrically modulating the spatial distribution of carrier concentration n in order to toggle $\varepsilon_{\mathrm{ITO}}$ between the low loss dielectric and ENZ regime.

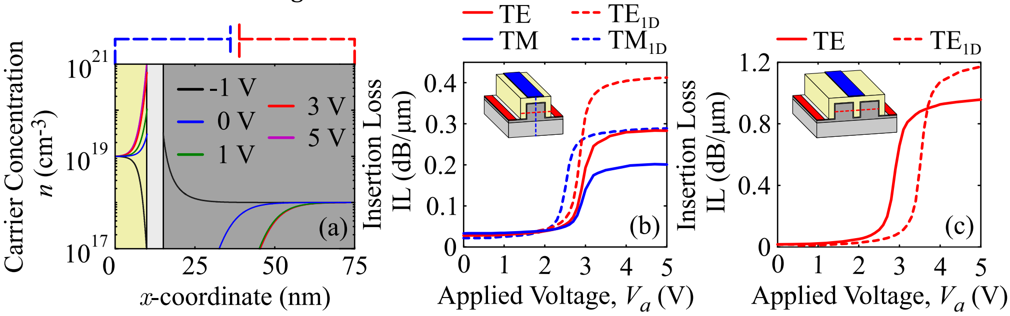

Fig. 6. (a) Spatial distribution of n along an ITO /HfO₂/ n-Si junction for five biasing values. (b) ILs for the TE/TM mode of the Si-rib modulator and (c) for the slot mode in the Si-slot design as functions of biasing. The dashed curves originate from 1D equivalent models, extracted from vertical and horizontal cuts as denoted with dashed lines in the insets.

Methods: A rigorous approach for modelling the semiconductor electrical behaviour is adopted, admitting the drift-diffusion model for carrier action combined with Fermi-Dirac statistics for carrier concentration [3]. The calculated carrier concentration is translated to a NIR permittivity profile by utilizing a Drude model for $\varepsilon_{\mathrm{ITO}}$, while the changes in the Si refractive index are indeed negligible. Finally, the carrier dependent infrared permittivity is supplied to Maxwell's equations for conducting a cross-sectional modal analysis of the structures. Thus, the RF manipulation of the carrier concentration is eventually reflected onto the n_{eff} of the guided mode in the NIR. The studies were conducted using the COMSOL Multiphysics® software platform.

Results: The spatial distribution of carrier concentration along the ITO/HfO_2/n-Si junction is presented in Fig. 2(a) for positive and negative biasing. The epsilon zero carrier concentration in ITO, $n_{\mathrm{EZ}} = 6.17 \times 10^{20}\mathrm{cm}^{-3}$, is achieved for $V_a > 3$ V. Indeed, the ILs of both Si-rib and Si-slot configurations exhibit a sharp increase for biasing values greater than 3 V, as shown in Fig. 2(b)-(c). In the case of Si-rib waveguide, both TE and TM modes are examined. By toggling between 0-4 V, the Si-rib platform yields an $\mathrm{ER} = \mathrm{IL}_{\mathrm{OFF}}/\mathrm{IL}_{\mathrm{ON}} = 0.3\ (0.2)\ \mathrm{dB/\mu m}$ with an $\mathrm{IL}_{\mathrm{ON}} = 0.03\ (0.03)\ \mathrm{dB/\mu m}$ for the TE (TM) mode. The Si-slot waveguide, which supports a highly confined TE mode in the slot, is proven superior, achieving an $\mathrm{ER} \approx 1\ \mathrm{dB/\mu m}$ with $\mathrm{IL}_{\mathrm{ON}} = 0.02\ \mathrm{dB/\mu m}$. Thus, a 10 dB Si-slot modulator would require a 10 μm length resulting in 0.2 dB of IL. The dashed curves in Fig. 2(b)-(c) are rudimentary estimates of the modulators performance, originating from equivalent one-dimensional (1D) archetypes and, thus, indicating the upper performance limit. The bandwidth of the proposed structures is anticipated to exceed 100 GHz, while the necessary energy per bit is in the sub-pJ order.

References

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