Comparative performance evaluation of transparent conducting oxides with moderate mobility for all-optical switching in silicon

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All-optical switching is an appealing approach for signal processing, optical communications or sensing systems. In this paper, we compare the performance of aluminium doped zinc oxide (AZO) and indium tin oxide (ITO) as epsilon-near-zero materials in thin-film configuration integrated in a hybrid silicon photonic waveguide. Our results reveal the best operational parameters for enabling compact, ultrafast and energy-efficient operation.
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INTRODUCTION

Nonlinear optical effects enable a wide variety of photonic applications in the fields of telecommunications and information technology [1]. These effects can be utilized to control all-optically the amplitude, phase and frequency of light. Furthermore, with the arrival of new computational demands such as artificial intelligence, all-optical signal processing may become a key technology to enable the next generation of computation and communication devices. However, such technologies are fundamentally limited by the weak optical nonlinearity exhibited by most CMOS compatible materials [2]. This leads to high power consumption and long propagation lengths, making the integration of compact and efficient nanophotonic devices a challenging task. In view of these considerations, recent studies have demonstrated that epsilon-near-zero (ENZ) materials can be leveraged to perform large ultrafast modulations of their complex refractive indices, enabling highly efficient all-optical switching in ultra-compact devices[3]. An interesting subset of ENZ materials are low-loss ENZ materials, also known as near-zero index (NZI) materials, in which the real index is less than unity. Such materials allow an enhancement of nonlinear processes due to strong light confinement effects, especially in hybrid silicon photonic waveguide architectures[3]. In this regard, transparent conductive oxides (TCOs) can be considered CMOS compatible NZI materials that operate in the near infrared (NIR), thereby offering great potential for integrated photonic applications. Indeed, when TCOs permittivity becomes close to zero the materials induces an extraordinary enhancement of local electric field[4] and extreme optical nonlinear effects [3], [5], [6]. In 2016 Alam et al. showed that indium tin oxide (ITO) exhibits unity order nonlinear response linked to its ENZ resonance upon optical pumping. This effect was understood as a consequence of the change in effective mass due to the non-parabolic electron dispersion [7]. Similar nonlinear response has been observed in other TCOs such as doped zinc oxides [8] and cadmium oxide (CdO) [9]. To date, all-optical switching with CdO hybrid waveguides has been proposed in the form of ENZ absorption modulators [6], switching between a low loss dielectric state and the lossy ENZ state of the TCO film. Electro-optical ENZ based phase modulators has also been proposed [10]. These articles converge in pointing out the importance high mobility TCOs as a requisite to design efficient modulators, signalling CdO as an ideal candidate. However, future perspectives on TCOs such as CdO are limited due to their scarcity or toxicity. In this regard, more eco-friendly alternatives such as AZO are investigated in this article to bridge the gap between current TCO research and their future applicability as optical switches and modulators. Here we present an ENZ-based all-optical amplitude switch built on a TCO/Si hybrid waveguide operating near the third telecom window with ultrafast switching time—tens of femtoseconds—and picojoule energy consumption. The impact of the TCO's carrier density and mobility on the performance of the switch, including energy consumption arguments, is investigated by selecting two TCOs with different properties (ITO and AZO) and calculating a suitable figure of merit (FOM) to gain insight into the underlying physical mechanisms as well as to predict the optimal material and experimental requirements to design efficient devices.

RESULTS

Near resonant values of the TCO refractive index need to be considered in the design for an efficient operation. The relative permittivity of TCOs in the NIR region under intraband excitation can be described by a Drude model with a nonparabolic electron band. The nonparabolicity introduces electron effective mass dependence on energy, defining an electron temperature-dependent effective-mass contribution that can be used to interpret the cause of the nonlinearity and to provide functional relationships between the refractive index, the wavelength and the excitation energy. Such relationships are numerically calculated for ITO and AZO with reported parameters [11] and

the expression of the nonparabolic Drude model [12] taken from literature. From the perspective of design, the two most important parameters of a TCO described by a Drude model are carrier concentration N and mobility μ. Here N is taken as a variable. Thus, the selected materials will be defined by their mobility, having a value of 15 $cm^2 V^{-1} s^{-1}$ for ITO and 50 $cm^2 V^{-1} s^{-1}$ for AZO. While N controls the position of the ENZ (temperature and wavelength), μ has an effect on the shape of the resonance.

Then, the permittivity values are used to calculate the first TM mode of the ultra-thin TCO film/Si hybrid waveguide shown in Figure 1(a). All-optical phase switching is attained by employing a pulsed pump and a continuous wave (CW) probe configuration that, upon pump absorption, raises the electron temperature up to several thousands of Kelvins and, in this way, switches the device's state from a low loss state to a high loss state (tuned at the ENZ temperature). High losses are produced by the strong modal confinement withing the lossy TCO film. In general, switch's ON-state is activated at the ENZ temperature (T_e^{ENZ}) and its value depends on TCO's carrier concentration and wavelength. In the contour maps of Figure 1(b-c) the color bar values of ER are defined as the OFF-state losses (T_e = 300 K) minus the ON state losses (*i.e. ER = Loss (300K) - Loss (T_e)* in dB/µm units). The maps were calculated at a fixed wavelength of 1550 nm. In such plots the position of the ENZ resonance as a function of carrier concentration N is shown as a dotted line. In the case of AZO, the room temperature ENZ (T_e = *300 K*) is located at $N = 0.9x10^{21}\ cm^{-3}$. This means that losses are maximal at 1550 nm for this particular value of N and T_e and that, upon absorption of pump power, the system would detune from being resonant at the ENZ as temperature rises, therefore decreasing losses (this is the reason why ER is negative around this region). To operate the device inversely (ER positive) the value of N should be increased to detune the ENZ resonance from T_e = *300 K*. It follows that, the higher the value of N the greater the ER of the device and the lower the insertion losses (*IL = Loss (300K)*). However, the required value of ΔT_e also scales and, consequently, the energy consumption of the switch. In this context, the FOM = $ER/\Delta T_e$ can be introduced to compare the performance of both materials. This results in the maps of Figure 1(d-e). Such maps reveal a fivefold difference between ITO and AZO materials (see maximum FOM values in Table 1), implying the superior switching performance of AZO in terms of energy efficiency. Another metric that can be obtained is the bandwidth of the device. Figure 1(f-g) was calculated by sweeping the wavelength for a given value of N and T_e (in this case, the pair of values that maximizes the FOM) revealing that the hybrid waveguide loaded with ITO has a much broader response.

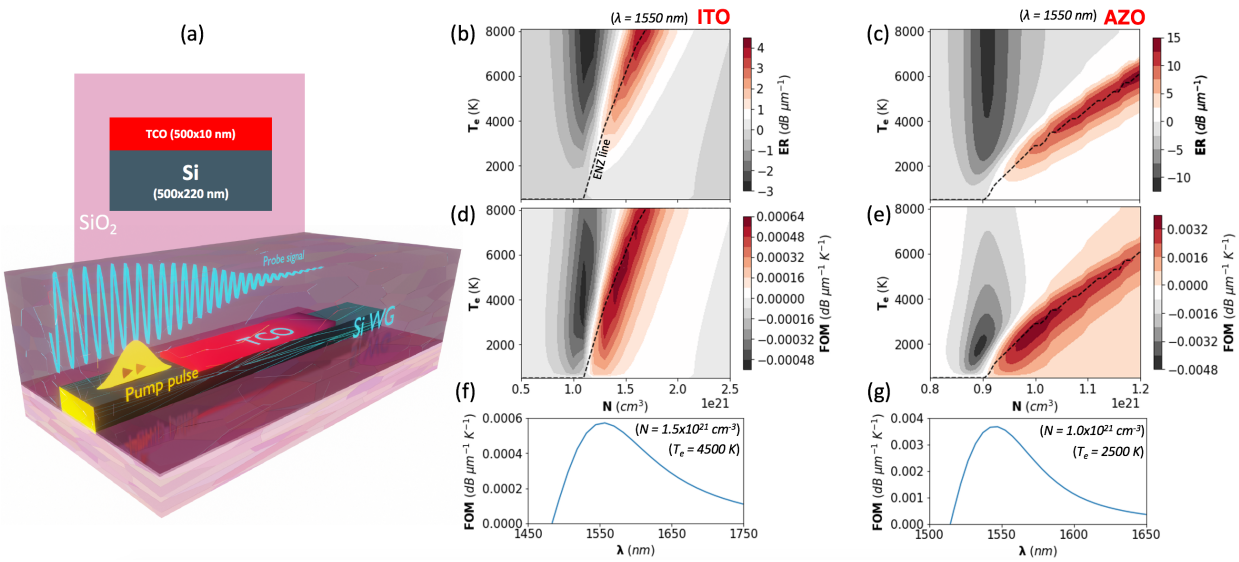

Fig. 1. (a) Cross section and sketch of the all-optical switch based on a hybrid TCO/Si waveguide. (b), (c), (d), (e) Contour maps of the ER and FOM as a function of T_e and N calculated at a fixed wavelength of 1550 nm. (f), (g) Dependence of FOM with wavelength for a given value of N and T_e.

Another important analysis that can be performed with our device is to balance the energy requirements and optical losses of the switching process. The transient evolution of the TCO can be described through a Two-Temperature Model (TTM). Such models are typically used to evaluate the energy transfer following ultrafast photoexcitation. In our case, the FOM can be redefined as $FOM = ER/E_s$. Here E_s is the switching energy required to produce the increment ΔT_e. In Table 1 the FOM with energy units was calculated with a pump pulse of 100 fs. Required powers were of 3 W and 0.5 W to reach $\Delta T_e = 4500\ K$ in the case of ITO and $\Delta T_e = 2500\ K$ in the case of AZO. All modelling parameters and equations were taken from [7] and [9].

	ER (dB/μm)	IL (dB/μm)	FOM (dB μm^{-1} K^{-1})	FOM (dB μm^{-1} pJ^{-1})	Bandwidth (nm)
AZO/Si	4	1	0.0006	5	80
ITO/Si	15	2	0.0032	130	180

Tab. 2. Maximum values of the FOM and ER, IL corresponding to maximum ER point and optical bandwidth.

DISCUSSION

Through analysis of nonparabolic Drude model equations the large nonlinear response TCOs under ENZ regime has been explored. We calculate a FOM that compares TCOs at their peak performance. For moderate mobility ranges, 15 – 50 $cm^2 V^{-1} s^{-1}$, large values of ER can be obtained (up to 15 dB/μm in the case of AZO, Table 1). The IL associated with the maximum ER configuration are also reported in Table 1. When compared with ultrahigh mobility materials such as CdO (>300 $cm^2 V^{-1} s^{-1}$) on similar hybrid Si waveguide switching devices, having a maximum ER of 20 dB/μm [9], we can therefore conclude that pursuing exceptionally low loss ENZ materials is not pivotal in the design of efficient amplitude switches. On the contrary, device performance should be balanced with energy consumption. Indeed, when FOM takes into account the energy consumption argument, the comparison between high mobility TCOs (200 dB μm^{-1} pJ^{-1} for CdO [9]) and moderate mobility TCOs (130 dB μm^{-1} pJ^{-1} for AZO in Table 1) become less prominent. Still, TCOs with even lower mobilities present huge performance gaps that renders materials such as ITO unfeasible to develop efficient all-optical integrated devices (5 dB μm^{-1} pJ^{-1} for ITO in Table 1). Another relevant consideration is optical bandwidth because as mobility is increased the value of bandwidth decreases (Table 1). In this scenario, high mobility TCOs might offer worst performance depending on the application.

In conclusion, TCO are materials with tremendous potential for integrated photonics. To date, all-optical switching between high-low loss ENZ modes exhibit the highest switching efficiency in current literature [9]. Apart from their remarkable nonlinear response due to their NZI condition, TCOs can be readily integrated into current nanophotonic circuitry without costly fabrication procedures and their optical properties can be flexibly tuned during fabrication time or even electro-optically during run time. However, such flexibility requires the development of computational tools and predictive knowledge to tackle the many possibilities that arise during design. That is the reason why comparative analysis such as the one conducted on this paper may help to pave the road towards next generation all-optical switches based on TCOs.

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