Ultra-compact modulators based on novel
CMOS-compatible plasmonic materials

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Abstract: We propose several planar layouts of ultra-compact plasmonic waveguide modulators that utilize alternative CMOS-compatible materials. The modulation is efficiently achieved by tuning the carrier concentration in a transparent conducting oxide layer, thereby tuning the waveguide either in plasmonic resonance or off-resonance. Resonance significantly increases the absorption coefficient of the plasmonic waveguide, which enables larger modulation depth. We show that an extinction ratio of 86 dB/µm can be achieved, allowing for a 3-dB modulation depth in less than one micron at the telecommunication wavelength. Our multilayer structures can potentially be integrated with existing plasmonic and photonic waveguides as well as novel semiconductor-based hybrid photonic/electronic circuits.

1. Introduction

Plasmonics enables the merging between two major technologies: nanometer-scale electronics and ultra-fast photonics [1]. Metal-dielectric interfaces can support the waves known as surface plasmon polaritons (SPPs) that are tightly coupled to the interface, and allow manipulation of light at the nanoscale, overcoming the diffraction limit. Plasmonic technologies can lead to a new generation of fast, on-chip, nanoscale devices with unique capabilities [2,3]. To provide the basic nanophotonic circuitry functionalities, elementary plasmonic devices such as waveguides, modulators, sources, amplifiers, and photodetectors are required. Various designs of plasmonic waveguides have been proposed to achieve the highest mode localization and the lowest propagation losses [3]. In addition to waveguides, modulators are the most fundamental component for digital signal encoding and are paramount to the development of nanophotonic circuits. In this regard, opto-electronic modulators can be designed to achieve ultra-fast operational speeds in the 10’s of GHz. Many plasmonic waveguide and modulator structures have been proposed and experimentally verified, but most of these structures use metals such as gold or silver, which are not CMOS compatible [4-22].

The promising development of chip-scale plasmonic devices with traditional noble metals is hindered by challenges such as high losses, continuous thin film growth, and non-tunable optical properties. Moreover, noble metals as plasmonic building blocks are not compatible with the established semiconductor manufacturing processes. This limits the ultimate applicability of such structures for future consumer devices. Recently, there have been efforts towards addressing the challenge of developing CMOS compatible material platforms for integrated plasmonic devices [23]. Similar to the advances in silicon technologies that led to the information revolution worldwide, the development of new CMOS compatible plasmonic materials with adjustable/tunable optical properties, could revolutionize the field of hybrid photonic/electronic devices. This technology would help to address the needs for faster, smaller and more efficient photonic systems, renewable energy, nanoscale fabrication, and biotechnologies. These new materials can bring exciting new functionalities that cannot be achieved with traditional metals.

Pioneering works in the search for new plasmonic materials [23,24] have suggested new intermediate carrier density materials such as transparent conducting oxides (TCOs) and transition metal nitrides as promising plasmonic building blocks with low loss, extraordinary tuning and modulation capabilities, and compatibility with standard semiconductor technology [25-32]. While many materials have been suggested as replacements for the traditional plasmonic metals, CMOS-compatible titanium nitride (TiN) is one of the best candidates [28,29]. Moreover, TiN is very thermally stable, bio-compatible, extremely hard (one of the hardest ceramics) and chemically stable; in particular, it does not oxidize like silver or copper. It was also shown that TiN provides higher mode confinement in comparison to gold [27]. This makes TiN a very promising material for telecommunication-range plasmonic waveguides.

One important advantage of TiN is that it can be grown epitaxially on many substrates including [100]-silicon, forming ultra-smooth and ultra-thin layers [29,33]. A final benefit of transition metal nitrides is that they are nonstoichiometric materials. Hence their optical properties depend greatly on the preparation conditions and can be
varied based on the desired performance. In this study, we use the optical constants of TiN films optimized for plasmonic applications. The films were deposited at high temperature (800 °C) using reactive DC magnetron sputtering. This high temperature sputtering process is not utilized in the current semiconductor manufacturing processes for TiN deposition. Hence, optimization of the low temperature (less than 400 °C) deposition process used in CMOS industry is needed for TiN to suit plasmonic applications.

New intermediate carrier density materials offer the prospect of additional exotic properties beyond tailor able optical properties, lower losses and integration advantages [23]. TCOs can provide extraordinary tuning and modulation of their complex refractive indices, because their carrier concentrations can be changed over several orders of magnitude by applying an electric field [17,19,34]. Therefore, they are promising candidates for adding electro-optical capabilities to plasmonic devices [17,19]. In particular, a unity-order index change in a 5 nm thin Indium-Tin-Oxide (ITO) layer was demonstrated for a metal-insulator-metal (MIM) structure [34]. Tunability is accomplished by applying a bias, resulting in an electric field across the TCO layer. The resulting electric field causes a charge accumulation, or depletion, in the TCO layer (depending on the direction of electric field) which in turn changes the plasma frequency of the TCO, and consequently, its permittivity. The modulating speed is only RC limited and is expected to exceed 10’s of GHz.

Several layouts of Si photonic modulators using a TCO as a dynamic layer were proposed [19,35]. The modulation can be characterized by the extinction ratio (ER), which shows how deep one can modulate a propagating wave per unit length of the absorption modulator. An extinction ratio of 1 dB/µm was demonstrated for a plasmonic modulator utilizing a metal-oxide-ITO stack on top of a silicon photonic waveguide [19]. Under an applied bias, the carrier concentration is changed from 6.8×10²⁰ to 1×10³⁹ cm⁻³, and the propagation length is varied from 1.3 to 34 µm. However, because this structure uses a photonic mode, the miniaturization level of such a device is limited. Very high ER (up to 20 dB/µm) was achieved utilizing the epsilon-near-zero properties of Aluminum-Zinc-Oxide (AZO) [35]. Because of the small absolute value, a large portion of the field is localized within the layer and provides more efficient modulation.

ITO has also been implemented in an MIM waveguide structure to demonstrate a subwavelength plasmonic modulator [17], for which a five percent change in the average carrier density (from 9.25×10²⁰ to 9.7×10²⁰ cm⁻³) was studied. The structure operates close to the surface plasmon resonance and an ER up to 2 dB/µm was theoretically predicted. The proposed design can be made extremely compact. However, due to the high confinement achievable in the MIM structure and the high losses associated with both the metal and ITO layers, the propagation length in this system was limited to approximately 0.5 µm.

ITO, and many other TCOs, may be deposited at relatively low temperatures (less than 300°C), which makes it possible to integrate them with standard silicon process despite the fact that they are not available in CMOS production lines. Similar techniques have been used to include lithium niobate crystals or electro-optic polymers on CMOS produced photonic chips [36]. Similar to other TCOs, ITO’s properties depend strongly on fabrication conditions such as the annealing environment and temperature [24,28]. Since ITO provides a wide tunability of optical properties, the ITO layer optimization can be used to achieve better modulator performance (decreased losses in the structure) [37]. Periodic patterning of the active layer can provide further improvements allowing for propagation lengths of approximately 2.5 µm [37]. Ultra-compact designs can be achieved in a modulator layout based on an MIM waveguide with a very small (5 nm) gap [18]. Very small gap size leads to a very efficient change of the carrier concentration in a 2.5-nm-thick ITO layer. However, the practical implementation of the proposed device [18] is challenging.

In this paper, we will focus on developing active plasmonic devices that are compatible with CMOS processing techniques to allow for easy integration with current nanoelectronic devices (Fig. 1). We will suggest a variety of plasmonic modulator structures using transparent conducting oxides, which may serve as both the plasmonic material and as a dynamic element. In the design of the structures, both the device performance and its fabrication complexity are taken into account. We will numerically study these modulator geometries and compare their performance from different points of view. Modulation depth, propagation losses, mode size and their trade-off will be analyzed. Finally, we will investigate the integration of the modulator geometries with plasmonic waveguides, and compare their performance and fabrication complexity.

2. Multilayer structures

An example geometry of the proposed electro-optic plasmonic modulator integrated with stripe waveguides is shown in Fig. 1, along with the symmetric, long ranging SPP (LR-SPP) excitation mode, its direction of propagation through the structure, and the applied voltage for modulation. The waveguide sections are composed of a lower dielectric cladding (Fig. 1 shown in red) with a metal strip (grey) and a top dielectric cladding (red). This configuration allows for the LR-SPP mode to be utilized for low loss connections to and from the modulator. The
modulator section is composed of a lower dielectric layer (Fig. 1 shown in red), a TCO layer used as both a plasmonic layer and an electrode (light blue), a dielectric layer to provide electrical insulation (light orange), and a top electrode (pink). However, we investigate two other modulator configurations in this paper, which will be discussed in the subsequent sections.

This proposed geometry provides several benefits when compared to other potential structures. The utilization of an electrical control system allows for the device to be easily integrated into traditional CMOS control circuitry. Also, due to the plasmonic nature of the modulator, the device can achieve a very small footprint that cannot be realized in traditional photonic elements. Secondly, the multilayer structure which forms the modulation, can achieve an extremely high absorption coefficient when this layer is modulated into resonance by an applied field. Therefore, a very small length is required to achieve 3-dB modulation of the signal. Due to these advantages, the proposed modulator configuration shows great promise for a CMOS compatible, on-chip electro-optic modulator.

Due to obvious fabrication and integration advantages we consider modulators based on the strip waveguide geometry, as discussed in the previous section [6,7]. Stripe waveguides have low loss but have poor mode localization [6]. However, the relatively simple planar fabrication process provides an advantage to utilize the structure in realistic devices. Here we consider only the one-dimensional planar layout as an estimate of a stripe waveguide. In realistic structures, a finite-wide stripe waveguide will be used, and the propagation losses will depend on the geometrical parameters of the stripe. However, the performance is only marginally different from the one-dimensional structure, and the main dispersive features will be captured [5,38]. Therefore, for the purposes of this paper, the estimates provided by assuming a one-dimensional structure are suitable for the comparison of the various modulator geometries suggested.

The main element of the structure is the TCO layer. Since the TCO can possess plasmonic properties at telecom range, a thin TCO layer can guide the plasmonic mode as well as control the signal propagation. TCOs such as ITO, Gallium Zinc Oxide (GZO), and AZO have very similar properties and allow for an efficient change of carrier concentration. We chose GZO as it has shown the ability to achieve the highest plasma frequency of the three [39]. The permittivity of the GZO layer was taken from [39] and a carrier concentration in the GZO was determined using a Drude-Lorentz model fitting: \( N_0 = 9.426 \times 10^{20} \text{ cm}^{-3} \). To estimate the modulator performance, we assume that under an applied voltage, the carrier concentration can be either decreased or increased by a factor of 2 (\( N = 0.5N_0 \ldots 2N_0 \)). The calculated permittivity of GZO for these carrier concentrations is shown in Fig. 2a.

Including a TiN layer increases the mode localization, which influences the modulator’s performance. Moreover, the TiN layer can also serve as a second electrode to apply bias to the GZO active layer. The permittivity of TiN is taken as experimentally measured \( \varepsilon_{\text{TiN}} = -83.3 + 21.3i \) at \( \lambda = 1.55 \mu\text{m} \) (Fig. 2b). The TiN film was deposited at 800ºC and the optical properties of 20 nm thin film was measured using spectroscopic ellipsometer (J.A. Woollam Co). High deposition temperature poses some fabrication and integration restrictions which must be taken into account. The materials beneath the TiN layer must withstand the TiN-deposition and etch conditions without degradation. Since the properties of the TCO degrade at high temperatures, the TCO layer must be deposited only after the deposition and patterning of the TiN layer.
The simplest structure is shown in Fig. 3i-a where modulation is achieved by applying a bias across the GZO layer. For this structure, the zinc oxide (ZnO) layer serves as one electrode while the GZO film itself is the second. A dielectric layer between the TCO film and second conductive layer is required to provide electrical insulation. This layer should be made as thin as possible to reduce the voltage required to modulate the GZO carrier concentration.

For the design in Fig. 3i-a, a thick Si$_3$N$_4$ layer can be utilized, for example, on a silicon substrate. It is also preferable to have materials with similar indices on the top and bottom of the plasmonic layer. In this case, the conditions are similar to those required for long-range SPP mode propagation, and the mode losses are lower [6].

Furthermore, we studied designs that include TiN layers (Fig. 3b,c). The addition of the layer allows for the modulator to be easily integrated with external strip waveguides. It also provides tighter field confinement, which will result in a larger attenuation of the signal during modulation. Both layouts with a thick and thin TiN layer are studied. On the structures shown in Fig. 3, the central layers (TiN, silicon nitride insulation, and GZO) remain in the same configuration.

In this paper, we consider two main groups of the devices, one with low-index cladding (Fig. 3i) and another with high-index cladding (Fig. 3ii). Further in the text, ZnO, LP-CVD Si$_3$N$_4$ and PE-CVD silicon nitride (denoted in subsequent text by SiN), will be referred to as low-index materials. As we are interested in operation at the telecom wavelength of $\lambda = 1.55 \ \mu m$, the refractive indices used in the calculations are the following: $n_{ZnO} = 1.93$ [40], $n_{SiN} = 1.76$ (experimental characterization of samples after PE-CVD process) and $n_{Si3N4} = 1.97$ (after LP-CVD process). It should be mentioned that LP-CVD Si$_3$N$_4$ requires high temperature deposition which may degrade the properties of TCO layer. Hence, only PE-CVD SiN can be deposited after the TCO layer.

Furthermore, a high-index material can be utilized as a cladding. In this work, we consider silicon as a high-index cladding $n_{si} = 3.48$ [41]. While amorphous silicon would be deposited as the upper cladding layer, for this investigation, we consider crystalline silicon and amorphous silicon to be identical in their optical properties at $\lambda = 1.55 \ \mu m$. In particular, the next three structures (Fig. 3ii) are similar to the first three but with silicon layers as a top and bottom cladding. In these cases, either the silicon or TiN layer can be used as a second electrode.

### 3. Performance of the modulators

With all these considerations, six basic geometries were chosen as templates for modulator designs, operating at the telecom wavelength of $\lambda = 1.55 \ \mu m$. The dispersion equation was solved for the one-dimensional multilayer structures with varying carrier concentrations in the GZO. The thickness of all thin layers (GZO, TiN, SiN, Si$_3$N$_4$) is 10 nm. The top and bottom layers are assumed to be infinitely thick. Thus, we will refer to structure in Fig. 3a as “thick TiN” and Fig. 3b as “thin TiN”. The structures in Fig. 3c are referred to as “without TiN”.

At a particular carrier concentration, the GZO permittivity value satisfies the condition to achieve a plasmonic resonance in the multilayer structures, resulting in a significant increase in the absorption coefficient $\alpha_{max}$ (Fig. 3d). Therefore, the absorption coefficient $\alpha$, in the waveguide structure, strongly depends on carrier concentration $N$: $\alpha = \alpha (N)$. $\alpha_{max}$ is lower for structures without TiN, higher for a thick TiN layer and the highest with a thin TiN film (Table 1).

Modes of the structures with a GZO layer only (in Fig. 3a) have a quasi-symmetric electric field distribution. Adding a TiN layer increases the absorption coefficient of the multilayer structure because of the ohmic losses. Moreover, the structure with a thin TiN layer and low-index cladding (Fig. 3i-c) supports only the mode with a quasi-asymmetric electric field profile, while the structure with the high-index cladding (Fig. 3ii-c) supports both...
quasi-symmetric and quasi-asymmetric. In the quasi-asymmetric mode, the field is mostly localized near the waveguide (in contrast to quasi-symmetric mode, where the field is mostly spread outside the waveguide) such that the losses are even higher [42]. In this case, \( \alpha_{\text{max}} \) reaches 28 and 132 dB/\( \mu \)m for the low- and high-index cladding, respectively.

Fig. 3. Multilayer structures. Waveguide layers (GZO and TiN) are sandwiched or covered with (i): low-index materials, (ii): silicon as a high-index material. Further in the text, we will refer to designs (a) as “without TiN”, (b) as “thick TiN”, (c) as “thin TiN”. (d) Absorption coefficients \( \alpha \) for various carrier concentrations of GZO. Structures with high-index cladding (ii) show much higher absorption than structures with silicon nitride cladding (i). Notation “sym” and “asym” correspond to quasi-symmetric and quasi-asymmetric SPP modes respectively. (f) Mode size of the modulator structures versus carrier concentration in the GZO film. The absorption maximum is accompanied by highest mode localization. At lower carrier concentrations of GZO, modes are more spread-out because of the smaller magnitude of real permittivity of GZO.

Furthermore, we analyzed the size of the mode in all the proposed structures. In the case of a single interface, the 1/e point of the electric field corresponds to an 86% localization of electrical energy (1-e\(^{-2}\) portion). To estimate the
mode size of our multilayer structures, which have a complicated field profile, we define the mode size such that 86% of electrical energy is localized within the region (Fig. 4). Similar to other long-range SPP based waveguides, the structure suffers from low mode localization. It can be seen from Fig. 3f that structures without TiN have lower mode localization in comparison to those with TiN. Moreover, utilizing a high-index cladding significantly decreases mode size. In all cases, a decrease of $\alpha$ at lower $N$ is accompanied by significant increase of mode size.

![Fig. 4. Depiction of the mode profile for the geometry Fig. 3 i-c showing the definition of mode size. Due to the complexity of the structure and high concentration of electrical energy in the GZO layer, the traditional definition of mode is cannot be utilized as this would simply define the mode size as the thickness of the GZO layer. Here we define mode size as the distance which encompasses 86% of the electric field energy, a condition similar to that of the 1/e definition for single interface waveguide.](image)

At some particular carrier concentration in GZO, the absorption coefficient reaches a maximum value $\alpha_{\text{max}}$. The extinction ratio $\text{ER}$, or modulation depth, can be defined as

$$\text{ER} = 8.68 \left( \alpha_{\text{max}} - \alpha_{\text{min}} \right),$$  

where $\alpha_{\text{min}}$ is propagation loss in the transmissive state. Here we do not specify which states correspond to voltage on and voltage off states. It depends on how GZO layers are deposited and which carrier concentration is chosen as an initial value.

Either increasing or decreasing $N$ from $N_0$ results in modulation of $\alpha$. However, because of the large mode extension, or delocalization, at lower $N$, it is more preferable to operate at higher $N$ (see Fig. 3f for small carrier concentrations). Thus, $\alpha_{\text{min}}$ is defined by

$$\alpha_{\text{min}} = \alpha(2N_0).$$

Eq. (2) is valid for all the proposed structures apart from $\text{Si}_3\text{N}_4/\text{GZO/}\text{SiN/ZnO}$ (Fig. 3 i-a). This is because with the low-index cladding and absence of TiN, a localized mode exists only for a narrow range of $N = 5 \times 10^{20}$ to $8 \times 10^{20}$ cm$^{-3}$. Modes larger than 10 $\mu$m are considered delocalized and the corresponding values for $N$ will not be used in subsequent calculations. Thus, for this layout, $\alpha_{\text{min}} = \alpha(N = 8 \times 10^{20}$ cm$^{-3}$) is defined. While operation in this narrow range of $N$ can be more preferable as it does not require a large change of $N$, it provides less tolerance to fabrication or design imperfections.

Similar to the value of $\alpha_{\text{max}}$, the $\text{ER}$ is lower for the structures without TiN, higher for a thick TiN layer and the highest with a thin TiN film (see Table 1 for a comparison of values). The $\text{ER}$ is 1.8-16 dB/$\mu$m for a silicon nitride cladding, and 24-86 dB/$\mu$m for a silicon cladding. In the latter case, less than a 35-nm-length active section is required to achieve 3 dB modulation.

A figure of merit $\text{FoM}$ for such multilayer modulator structures can be defined as

$$\text{FoM} = \frac{\text{ER}}{\alpha_{\text{min}}}.$$  

It reflects a trade-off between the modulation depth and the loss of the signal in the transmissive state ($\alpha_{\text{min}}$). While the structures with a thin TiN layer provide the strongest resonance, $\alpha$ is also relatively high at large $N$. Such structures give the lowest performance.

The highest $\text{FoM}$ is provided by structures without TiN. However, the lowest absorption in the transmissive state is accompanied by lowest mode localization (up to 10 $\mu$m). In Table 1 we summarize the ranges of mode extensions. In most cases, the minimum value corresponds to plasmonic resonance and the maximum to a carrier concentration $N = 2N_0$ (structure on Fig. 3i-a is an exception).

Calculations show that the high-index cladding designs possess the highest performance. Working with a 2x change in the carrier concentration of GZO, the studied plasmonic modulator can outperform previously proposed
designs. For example, deeply subwavelength MIM structures were analyzed and a corresponding ER up to 12 dB/µm was theoretically predicted [17,18]. However, such high values are accompanied by high losses in transmittive state. The ratio of the absorption coefficients in the two states, FoM, is on order of 1. In our case, because of the possibility to detune from the plasmonic resonance, the absorption coefficient in the transmittive state can be relatively low. Utilizing a high index cladding makes the resonance more pronounced and the required change of carrier concentration is smaller. This structure also achieves transmittive state losses down to 0.06 dB/µm, which produced the highest FoM = 400. Thus, the Fig. 3ii-a geometry with high-index silicon claddings and without TiN, provides the highest performance for an ultra-compact plasmonic modulator.

Table 1. Summary of the characteristics of different structures. Performance comparison for planar modulator designs. Designs utilizing high-index materials show the highest performance.

| Structure (layers bottom to top) | $N(n_{\text{max}})$, $10^{20}$ cm$^{-3}$ | $\alpha_{\text{max}}$, dB/µm | $\alpha_{\text{min}}$, dB/µm | ER, dB/µm | FoM | Mode size, µm |
|----------------------------------|----------------------------------|----------------------------|------------------------------|------------|-----|---------------|
| Si$_3$N$_4$/GZO/SiN/ZnO (Fig. 3i-a) | 6.13 | 1.95 | 0.114 | 1.8 | 16 | 1.6 – 10 |
| TiN/Si$_3$N$_4$/GZO/SiN (Fig. 3i-b) | 6.13 | 8.4 | 0.55 | 8 | 15 | 0.5 – 1 |
| Si$_3$N$_4$/TiN/Si$_3$N$_4$/GZO/SiN (Fig. 3i-c) | 6.41 | 28 | 12.2 | 16 | 1.3 | 0.2 – 0.3 |
| Si$_3$N$_4$/GZO/Si (Fig. 3ii-a) | 6.79 | 24 | 0.060 | 24 | 400 | 0.09 – 6 |
| TiN/Si$_3$N$_4$/GZO/Si (Fig. 3ii-b) | 7.82 | 60 | 4.2 | 56 | 13 | 0.03 – 0.2 |
| Si/TiN/Si$_3$N$_4$/GZO/Si (Fig. 3ii-c, asym) | 9.00 | 132 | 46 | 86 | 1.9 | 0.04 – 0.09 |
| Si/TiN/Si$_3$N$_4$/GZO/Si (Fig. 3ii-c, sym) | 6.60 | 46 | 0.29 | 46 | 160 | 0.06 – 1.3 |

The extinction ratio for the investigated structures was found to be 1.8-16 dB/µm for a silicon nitride cladding, and 24-86 dB/µm for a silicon cladding. It is one of the highest values reported so far for both theoretical predictions and experimental demonstration for plasmonic modulators.

4. Waveguide and modulator integration

Efficient modulators allow a 3 dB modulation depth within a one-micron length plasmonic modulator. Thus, these devices can be very short and considered as a small section of a larger plasmonic waveguide. To couple into these devices, several possible integration schemes can be studied. Modulator structures can be fabricated on top of a plasmonic waveguide. Here we consider 10-nm thin TiN layer, which supports the LR-SPP. In a silicon nitride cladding, the propagation length in such waveguides is 5.5 mm. By limiting the GZO to only a small section required for modulation, the added propagation losses in the GZO dynamic layer are avoided in the remainder of the waveguide. To achieve this, the GZO can either be added directly on top of the TiN layer or used as the plasmonic material in replacement of the TiN (Fig. 5). In the latter case, GZO serves as both a waveguide and dynamic element.

The designs with thick TiN layers (Fig. 3b) could be integrated with a single-interface waveguide. However, such waveguides have significantly higher losses in comparison with thin TiN layers. Therefore, their applications are limited. For this reason, these geometries will not be considered in the following analysis.

Since the mode in the modulator section in Fig. 3c is quasi-asymmetric, it must be excited by the asymmetric mode of a strip-waveguide. Besides the challenge of excitation of asymmetric mode, it has much higher propagation...
losses. Furthermore, for the design in Fig. 3b,c, a thin layer of Si$_3$N$_4$ on top or beneath TiN is needed to insulate the GZO layer. However, realization of the designs with Si/TiN/Si$_3$N$_4$/Si waveguides encounters an issue. Because of the drastic difference between refractive indices of Si and Si$_3$N$_4$, it does not support the symmetric mode. It cannot be easily replaced by a Si/TiN/Si waveguide, as the thin Si$_3$N$_4$ layer (or a more advanced method of electrical isolation such as p-n junction doping) is required to maintain electrical isolation in the active section. Thus, from the integration point of view, the best modulator structures are those without TiN (Figs. 3a and 5). As we showed in the previous section, these structures also give the highest performance in terms of modulation depth and propagation losses.

Similar to the previous sections, we perform calculations for one-dimensional structures as their properties are close to those of finite-width. The coupling losses $\gamma$ for a single interface was calculated by following equation

$$
\gamma = \frac{4\beta_1\beta_2}{(\beta_1+\beta_2)^2} \left( \int E_1^* E_2' dz \right)^2
$$

where $\beta_1$ ($E_1$) and $\beta_2$ ($E_2$) are the mode indices (electric field) of the waveguide and waveguide modulator, respectively. Eq. (4) it takes into account both the mode overlap integral and the Fresnel coefficients at the boundary region.

We calculated the coupling losses for the two designs shown in Fig. 5, and the results are shown on Fig. 6. With regards to the scheme in Fig. 5i (the silicon nitride cladding), there is an interplay of two major effects. First, coupling losses are increased at the plasmonic resonance because of the high field localization in the GZO layer. This greatly reduces the mode overlap (Fig. 7i). Second, coupling losses are increased at lower and higher carrier concentration in GZO due to the mode extension outside the waveguide where GZO no longer supports a plasmonic mode (similar to Fig. 3 i-f for the geometry “without TiN” where the usable carrier concentration is between approximately 5 and $8\times10^{20}$ cm$^{-3}$). As a result, coupling losses vary by only 5 dB across the modulation range.

For the scheme employing a high-index silicon cladding (Fig. 5ii), the coupling loss in the transmissive state monotonically increases as the carrier concentration decreases towards the maximum in the modulator absorption (similar to the first effect for the low-index cladding). However, because of the mode mismatch at the low-to-high index interface between the waveguide and modulator (Fig. 7i), coupling losses are higher at the GZO plasmonic resonance. This effect can be beneficial for modulator performance in specific applications as it provides additional losses in the resonant state and fewer losses in the transmissive state.

![Fig. 6. Single interface coupling loss (between waveguide and modulator sections) versus carrier concentration in the GZO layer. This is shown for both the low-index silicon nitride and high-index silicon cladding. The significant increase of coupling losses corresponds to mode extension outside the waveguide. For the high-index cladding, the coupling losses is large because of the mode size mismatch between the Si$_3$N$_4$/TiN/Si$_3$N$_4$ waveguide and modulator with silicon cladding. For the low-index cladding, we consider only the values of N which correspond to mode size less than 10 µm.](image-url)
Fig. 7. Example mode profiles in the two integrated modulator geometries: (i) low-index and (ii) high-index claddings. Note that the field decay outside the strip waveguide is slow and therefore appears constant in this graph. The carrier concentration in the GZO layer used for the calculations corresponds to the maximum absorption in the modulator, i.e. plasmonic resonance in the layer. Under these conditions the majority of the field is localized within the GZO layer.

5. Conclusion

In this paper, we have analyzed several multilayer structures with alternative plasmonic materials to be utilized in ultra-compact plasmonic modulators. Applying an electric field across the TCO layer allows for the permittivity to be tuned, resulting in a change of the absorption coefficient of the waveguide. Therefore, active modulation is achieved. Numerous modulator layouts are investigated and the typical trade-off between compactness and propagation loss is analyzed. Amongst all the reported structures, one stands out with a remarkable FoM = 400. This figure of merit takes into account both the modulation depth (ER = 24 dB/µm) and the propagation losses in the transmissive state (α = 0.06 dB/µm). The corresponding geometry may allow for ultra-compact modulation with effective length much less than 1 µm. The proposed approach based on the cost-effective planar fabrication processes and the ability to easily integrate with existing semiconductor systems could enable new devices for applications in on-chip optics, sensing, optoelectronics, data storage, and information processing.

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