High-Speed Transmission Control in Gate-Tunable Metasurfaces Using Hybrid Plasmonic Waveguide Mode

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Dynamic control of light based on gate-tunable metasurfaces has revolutionized traditional optoelectronic devices due to its unprecedented compactness and versatile functionalities. However, these devices are typically based on metal-insulator-metal geometries that enable field-effect modulation of only reflected light. Transmittance modulation techniques based on dielectric metasurfaces, despite their large modulation depth, have a disadvantage of low modulation speed due to high resistance of dielectric materials. Here, a high-efficiency transmittance modulator that enables high switching speed, as well as large modulation depth, is demonstrated using indium-tin-oxide-based metasurfaces. To realize these devices, the hybrid plasmonic waveguide mode is used which allows electromagnetic energy storage within the nanoscale permittivity-tunable region between metal and high-refractive dielectric layers. Experimental measurements reveal a change in the transmittance (≈33%) by applying 6 V gate bias, and a fast modulation speed (≈826 kHz of 3 dB cut-off frequency). This work provides a promising avenue for developing ultracompact optical components such as dynamic holograms, lenses with active focal lengths, or spatial light modulators.

1. Introduction

Dynamic control of constitutive properties of light such as phase, intensity, polarization, or spectrum using tunable metasurfaces has introduced a new route towards miniaturization of optical devices far beyond the limit of current optoelectronic technologies.[1–10] The integration of passive metasurfaces with active materials enables the construction of tunable, highly compact devices with additional functionality.[11–15] Based on the field-effect modulation mechanism, the formation of charge accumulation or depletion region by gate bias, metal-oxide-semiconductor (MOS) combined metasurfaces have been used for controlling the complex refractive index of materials, resulting in modulation of the optical output. Significant efforts have been made to create field-effect-based optical modulators that operate from THz to visible frequencies. Among various electro-optical materials including transparent conducting oxides (TCOs),[4–8] graphene,[16–21] transition metal dichalcogenide,[22–24] and highly doped semiconductors,[25–27] TCO-based modulation is particularly useful for application in telecommunication systems because of its operation feasibility at near-infrared frequencies with high speed modulation and low power dissipation. This is possible due to their relatively large plasma frequency (=6 eV) that places the epsilon-near-zero (ENZ), which is the wavelength in which their real part of dielectric permittivity is between –1 and 1, in the near-infrared range. To achieve large modulation depth, most TCO-based metasurfaces have been designed to operate in ENZ region, therefore attaining strong electric-field enhancement.[4,8,28–31]

However, charge accumulation or depletion occurring at extremely small region has limited the efficiencies of such modulators. To overcome this inherent restraint, metal-insulator-metal (MIM) cavities including the nanoscale metal-oxide-semiconductor (MOS) configuration have been utilized in forming gap plasmon resonance, which couples to the ENZ region in TCO, leading to extremely high modal confinement that enhances light-matter interaction.[4–6,8,32] Based on such features, a number of reports have demonstrated dynamic control of phase, intensity, polarization, or spectrum of reflected light in MIM geometries by means of gate bias with high modulation speed.[4–6,8,9,28,32] In contrast to reflection-type gap
plasmon resonators, electrically tunable transmittance modulators with high switching speed at near-infrared wavelength region have not yet been reported, to the best of our knowledge. Transmission modulation is essential for the implementation of ultracompact optoelectronic systems because additional optical elements such as beam splitters or polarizers to separate incident and reflected light from each other are required in reflectance modulators. Previously reported transmittance modulators based on dielectric metasurfaces exhibited strong resonances without absorption loss by metal, but the reduction of switching speed is inevitable due to high resistance of dielectric materials that lead to large RC (circuit resistance × circuit capacitance) time constant.\(^7\)\(^13\) \(^\text{13}\)\(^\text{13}\) The development of a transmittance modulator with high switching speed would be beneficial in designing ultracompact optical components such as high-resolution transmission-type spatial light modulators for real-time hologram display, lenses with reconfigurable focal lengths, and pixels for transparent display.

In this work, we propose electrically-tunable transmittance modulators that are compatible with fast AC gate bias at near-infrared wavelengths. The devices are constructed from plasmonic metasurface which consists of indium tin oxide (ITO) layer as an active material on a high-index silicon waveguide. We utilize the coupled hybrid mode between the plasmonic and dielectric waveguide modes that enables energy storage across the ITO layer between the waveguide and metal. This strongly confined mode offers enhanced light-active material interaction, resulting in \(\approx 33\%\) change in the transmission. In respect to switching speed, our transmission modulator shows \(\approx 826\) kHz of the 3 dB cut-off frequency.

2. Results and Discussion

A schematic illustration of the proposed transmission modulator is depicted in Figure 1a. Au nanoslit array with 900 nm periodicity and 120 nm width is patterned on an Al\(_2\)O\(_3\)/ITO/amorphous silicon (a-Si) stack grown on a quartz substrate. The thicknesses of each Au pattern and underlying Al\(_2\)O\(_3\), ITO, and a-Si layers are 40 nm, 10 nm, 20 nm, and 140 nm, respectively. The metasurface based on a MOS structure features a charge accumulation layer within the dielectric spacer of each nano-resonator. In this configuration, the ITO layer serves both as an active material and electrode for applying voltage. Spatial distribution of accumulated carrier concentration in ITO varies depending on the applied bias, changing the complex refractive index of the region.\(^14\)\(^\text{14}\) Under normal illumination with transverse magnetic (TM) polarization state, transmission can be electrically controlled via strong field confinement within the active material, enhancing light-matter interaction (Figure 1a).

A scanning electron microscope (SEM) image of the fabricated device is shown in Figure 1b. Fabrication details can be found in Experimental Section. Au nano-antennas are electrically connected to the external Au electrode for voltage application.

In order to comprehend the change in refractive index and accumulated charges according to the applied bias, the carrier distribution in ITO layer was calculated with the Poisson equation using a one-dimensional MOS capacitor model consisting of Au, Al\(_2\)O\(_3\), and ITO (The inset of Figure 1c). The carrier distribution is a function of the distance from the Al\(_2\)O\(_3\)/ITO interface for different applied voltages. In our calculations, it is assumed that the DC dielectric constant of gate insulator

![Figure 1](image-url)

**Figure 1.** An electrically tunable metasurface capable of achieving transmission control with high switching speed. a) Schematic of the plasmonic metasurface device constructed from a nanoscale MOS capacitor with high-refractive-index material. Applied voltage between the Au pattern and ITO layer results in the formation of charge accumulation at the Al\(_2\)O\(_3\)/ITO interface. Transmission is controlled by electrically tuning of the carrier density of ITO material. Unit cell dimensions are selected as follows: periodicity of nanoslit \(p = 900\) nm, width of nanoslit \(w = 120\) nm, and thickness of Au nanoslit, Al\(_2\)O\(_3\), ITO, and a-Si are \(t_p = 40\) nm, \(t_s = 10\) nm, \(t_{ps} = 20\) nm, and \(t_{so} = 140\) nm, respectively. b) Scanning electron microscopy images of the Au nanopattern and contact (left panel), and the close-up of the nano-pattern (right panel). c) Field-effect modulation based on the nanoscale structure of MOS. Dielectric permittivity of ITO changes due to the formation of charge accumulation region. Spatial distribution of the carrier density (top panel) and real part of dielectric permittivity of ITO at wavelength of 1500 nm (bottom panel) are shown as a function of distance from Al\(_2\)O\(_3\)/ITO interface and applied voltages. Black contour indicates the region where the real value of the dielectric permittivity of ITO is between \(-1\) and 1, representing the ENZ region.
(Al₂O₃) is 9.1, the work function of gate electrode (Au) is 5.1 eV, and the carrier density of ITO is $N = 3 \times 10^{20}$ cm⁻³. As shown in Figure 1c (top), charge accumulation region at near oxide/semiconductor interface is generated by external electric field within about 2 nm from the interface. In our work, the range of voltage application is extended from 0 V to 8 V compared to Atwater group's⁶ due to the two-fold increase in the insulator thickness, meaning that the device can withstand higher applied bias without dielectric breakdown. However, since a larger applied voltage is required to accumulate the same amount of charge, the maximum amount of charge accumulation would be similar. Figure 1c (bottom) shows the real part of the dielectric permittivity calculated for different applied biases as a function of the distance from the Al₂O₃/ITO interface at a target wavelength of 1500 nm. It is difficult to measure directly the permittivity of charge-accumulated region since its thickness is very thin. To solve this problem, above all, we obtained optical parameters such as refractive index $n$ and absorption coefficient $\kappa$ of ITO by ellipsometry measurement with no applied voltage. Due to the capacity of ITO to support high carrier density, the dielectric permittivity of ITO can be well fitted by the Drude model, which is given by $\varepsilon_{ITO} = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i \Gamma \omega}$, where the plasma frequency is $\omega_p = (Ne/m^*e^2)^{1/2}$. Here, $\varepsilon_\infty$ is dielectric permittivity at infinite frequency, $\Gamma$ is damping constant, $N$ is carrier density, and $m^*$ is electron effective mass. In this equation, all parameters can be determined by fitting the curve to obtained $n$ and $\kappa$. Thus, the permittivity of ITO can be controlled by adjusting $N$, which is crucial mechanism of field-effect modulation based on ITO layer. $N$ of ITO is adjustable by changing the ratio of Ar:O₂ during sputtering. This is because In₂O₃ has point defects that consist of oxygen vacancies or the interstitial indium atoms, giving rise to free electrons in reduction environment. The related chemical equations of In₂O₃ during the annealing process are indicated by Equations (1) and (2).

\[
\begin{align*}
\text{In}_2\text{O}_3 & \rightleftharpoons 2\text{In} + 3\text{V}_0^+ + 3\text{e}^- + \frac{3}{2}\text{O}_2 \\
\text{In}_2\text{O}_3 & \rightleftharpoons 2\text{In}^+ + 2\text{e}^- + \frac{3}{2}\text{O}_2
\end{align*}
\]

In Equations (1) and (2), $V_0^+$ and $\text{In}^+$ are oxygen vacancies and interstitial indium atoms, and $e^-$ is the carrier electron. If the rate of $O_2$ is higher during annealing process, the reverse reactions of Equations (1) and (2) occur more actively, thus decreasing the number of free electrons, and consequently, $N$. The samples for ellipsometry measurements were prepared by depositing 50 nm of ITO on a silicon wafer. In the sputter chamber, there are two valves for Ar and O₂ to control the flow rate, where we fixed the flow rate of Ar as 20 sccm and changed the flow rate of O₂ gradually from 0.1 to 0.3. Figures 2a–b show the measured refractive index of ITO and the absorption coefficient for different O₂ flow rate, respectively. As expected, the refractive index increases with the flow rate of O₂, as the decrease in $N$ reduces the value of the plasma frequency in the Drude equation. We chose the condition of which the flow rate of O₂ and Ar are 0.2 and 20, respectively (red line), and the corresponding Drude parameters were determined by fitting, based on the measured optical values. The carrier density of ITO incorporated by modulator is $N = 3 \times 10^{20}$ cm⁻³, dielectric permittivity at infinite frequency $\varepsilon_\infty$ is 4.4, and electron effective mass is 0.22 $m_e$. We use literature value for the damping constant $\Gamma$ as $1.8 \times 10^{14}$ rad Hz. The chosen values result in good agreement between the calculated and measured values at the wavelength region of interest. Note that real part of the dielectric permittivity of ITO layer is positive due to $N = 3 \times 10^{20}$ cm⁻³ at target wavelength of 1500 nm with no applied bias according to the Drude equation.⁵ When the applied bias increases from 0 V, the dielectric permittivity value of the ITO layer near the Al₂O₃/ITO interface decreases with the accumulation of charge. At bias above 2 V, the dielectric permittivity enters the ENZ region, and changes its sign upon further bias.

The electrically-tunable refractive index layer due to charge accumulation, however, is confined to the ultrathin region (within ~3 nm, according to Figure 1c) at the Al₂O₃/ITO interface. To achieve a transmission modulator with large modulation depth, the following points should be fulfilled: i) strong field confinement within the active material for enhancing light-matter interaction and ii) reduction of unwanted absorption loss, or reflection by metallic structures to obtain sufficient transmittance. On this basis, we utilize a hybrid plasmonic waveguide configuration that consists of a a-Si layer separated...
from the metal layer by a nanoscale dielectric gap.\textsuperscript{[35]} Si is not only transparent at the operating frequency, but also has a high refractive index, providing a larger effective mode index (see Supporting Information 1). The coupling between the plasmonic mode by surface plasmon polaritons (SPPs) excited at the metal/dielectric interface and a-Si waveguide mode enables electromagnetic energy storage, as in an optical capacitor. In both SPP and waveguide geometries, the electric-field components normal to the material interfaces are dominant, resulting in strong energy confinement in the gaps due to the continuity of the displacement field. The geometry-dependent behavior of the hybrid mode is demonstrated in Figure 3a, where the dependence of the effective indices of hybrid mode $n_{\text{hyb}} (t_{\text{Si}}, t_{\text{o}})$, pure waveguide (without metal region) and SPP modes (with no waveguide), on the thickness of a-Si ($t_{\text{Si}}$) and Al$_2$O$_3$ ($t_{\text{o}}$) layers in the proposed configuration (see Figure 1a) is shown ($t_{\text{s}}$ is fixed as 20 nm). Evidently, pure SPP mode is invariable with $t_{\text{Si}}$ or $t_{\text{o}}$ while pure waveguide mode depends solely on $t_{\text{Si}}$. When the $t_{\text{Si}}$ is either very large or small, $n_{\text{hyb}}$ approaches that of pure waveguide or SPP mode, implying that the hybrid mode can be described as a superposition of the waveguide and the SPP modes.\textsuperscript{[35]} The results show that the effective index of hybrid mode is always larger than those of the pure waveguide and SPP modes, which leads to large modulation depth (see Supporting Information 1).

The thickness of a-Si determines the operation wavelength in which the coupled hybrid mode is attained. Figure 3b demonstrates this in a map of transmission as a function of incident wavelength and the thickness of a-Si. The resonant wavelength of maximum transmittance red-shifts as the thickness of a-Si increases, resulting in the rise in effective mode index of hybrid mode as shown in Figure 3a. To obtain the resonance wavelength of 1500 nm, the thickness of a-Si was optimized to be 140 nm. As expect, full-field simulations show that highly confined hybrid modes can be excited between dielectric gap (Al$_2$O$_3$ and ITO) by TM-polarized top illumination, enhancing light-active material interaction (Figures 3c,d). Figures 3e–f give an intuitive understanding of field-effect modulation, where the distribution of the $z$-component of the electric field ($E_z$) at different applied bias at the wavelength of 1500 nm is shown. As one can see from the field distribution of the magnified region in Figure 3d with no voltage bias (Figure 3e), ITO can be optically considered as a dielectric material like Al$_2$O$_3$, since its real part of the dielectric permittivity is positive. On the other hand, when the applied voltage is 8 V (Figure 3f), enhanced $E_z$ at the accumulation layer is observed due to the continuity of the normal component of electric displacement ($\varepsilon_\perp E_z$) at the Al$_2$O$_3$/ITO interface. For this case, the charge accumulation layer in ITO becomes optically metallic, as the real part of the dielectric permittivity is negative.

Based on the complex dielectric permittivity of ITO, which is a function of position and applied voltage, the transmission spectra are numerically calculated for different applied biases as shown in Figure 4a (Supporting Information 2). The maximum transmittance at the resonance wavelength decreases with increasing applied bias. This is due to rise in reflectance by optically metallic property (the real part of dielectric permittivity
is negative) of the charge accumulation layer, and the energy loss from the charge accumulation layer, of which the imaginary part of dielectric permittivity increases. Note that drastic transmission modulation is observed within voltage regions where the real part of dielectric permittivity is in the ENZ region. Namely, transmission modulation between 4 and 6 V of applied bias is larger than those between 0 to 2 V, or 6 to 8 V. We also observe a blue shift of the resonance when the applied bias increases from 0 to 5 V, and a red shift for applied voltages larger than 5 V. This is because charge accumulation leads to the optically metallic state, thus, effective thickness of dielectric spacer (Al\textsubscript{2}O\textsubscript{3} and ITO) decreases and effective index of hybrid mode (Figure 3a) increases, resulting in the shift of resonance to longer wavelengths. Figure 4b shows measured transmission spectra for different applied voltages (see Supporting Information 3 for measurement setup). The voltage was only applied up to 6 V since the 10 nm Al\textsubscript{2}O\textsubscript{3} layer we fabricated undergoes electrical breakdown at around 6 V. The resonance shift, the maximum transmission, and the wavelength at the resonance show good agreement with simulation results. It is clear that the transmittance modulation is achieved with applied bias. The transmittance change at the resonant wavelength (defined as the difference between transmittance normalized to the transmittance without applied voltage, $\Delta T/T = (T(V)-T(0))/T(0)$) is $\approx 33\%$ from 0 to 6 V of applied. The transmission change demonstrated in our device is comparable to previously reported results in reflectance or transmittance modulations.[4,5,8,19]

To characterize the electrical properties of the fabricated sample, electrical impedance spectroscopy was measured by applying 10 mV AC input with frequencies ranging from 1 Hz to 1 MHz. The absolute value and phase angle of the complex impedance are shown in Figure 4c. Measured resistance is $\approx 210$ M$\Omega$ at the DC environment, implying that the leakage current from the device is smaller than 1 nA. Over 100 Hz, capacitive behavior begins to occur, and the phase angle of the impedance becomes nearly $-90$ degrees. To demonstrate the dynamic control of transmission with fast AC input signals, an InGaAs amplified photodetector is used to detect the temporal changes of the transmittance upon application of 2 V bias (max: 2 V, min: 0 V) to the device with frequencies ranging from 100 Hz to 10 MHz. The inset in Figure 4d shows the applied voltage trigger (blue) for a square pulse with frequency of 500 kHz.

Figure 4. a) Simulated and b) measured transmittance spectra of the active metasurface for different voltage bias. c) Measured impedance of the transmission modulator. The absolute value (blue) and phase angle (red) of the impedance are plotted as a function of frequency. d) Frequency characteristics. The normalized modulation depth exhibits a 3 dB cut-off frequency around 826 kHz. The inset in Figure 3d shows the temporal transmission changes (red) upon voltage trigger (blue) from 0 to 2 V with frequency of 500 kHz.
Moreover, our device is expected to have a larger modulation depth, if the Al$_2$O$_3$ is used as an insulator replaced with a lamina-
tion of Al$_2$O$_3$ and HfO$_2$, leading to a higher DC constant and
larger breakdown voltage.

3. Conclusion

In summary, we have demonstrated an electrically tunable metasurface in the near-infrared wavelength region with high
switching speed. The transmittance is controlled by gate-tunable optical permittivity modulation in ENZ region. The
hybridization of the fundamental mode of a Si waveguide with the SPP of a dielectric-metal interface enables strong field conf-
finement within an active material. A transmittance change of ≈33% was measured by applying 6 V gate bias. A fast modula-
tion speed of a 3 dB cut-off frequency around 826 kHz was also
achieved. Considering that the current and previous research on intensity modulation with high switching speed is mostly
focused on reflection-type devices, we emphasize that our approach towards improved transmittance modulators may
contribute to the implementation of ultra-compact optoelec-
tronic and Si-based photonic systems.[36–38]

4. Experimental Section

Sample Fabrication: The proposed device was fabricated via standard thin film deposition processes and e-beam lithography techniques. Each
layer was stacked in order from bottom to top. First, a 140 nm-thick amorphous Si layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) on a quartz glass substrate (P5000, AMAT). Then,
a 20 nm-thick ITO layer was sputtered on the silicon by DC magnetron sputtering in Ar-O$_2$ plasma. The target source was indium oxide (In$_2$O$_3$)
and tin dioxide (SnO$_2$) of a 90 to 10 weight percent ratio. Sputtering was
carried out at a chamber pressure of 6.5 mTorr, with a sputtering power
of 2 kW, while maintaining the ratio of the partial pressure of Ar-O$_2$ at
20:0.2. Next, a 10 nm of Al$_2$O$_3$ was deposited by atomic layer deposition (ALD) method. Subsequently, Au nanoslit array was patterned by lift-off
process on the stack. Lift-off was carried out by using bilayer e-beam
resist to achieve undercut profile that was required for reliable nano-
patterning. Positive resist PMMA was used for both layers in the
biliayer process. Bottom PMMA (MicroChem Corp., PMMA 495K A2) and
top PMMA (MicroChem Corp., PMMA 950K A2) have different
molecular weight of 495 and 950 K, respectively, and all were 2% wt
solution in anisole. The bottom PMMA was spin-coated at a speed of
2000 rpm for 45 s and baked at a temperature of 180 °C for 5 min.
Successively, PMMA was once more spin-coated at a speed of 3000 rpm
for 45 s and baked under the same conditions abovementioned.
With this e-beam resist, the patterning was executed by e-beam
lithography equipment (JEOL, JBX-6300FS) at an acceleration voltage
of 100 keV with a dosage of 760 μC cm$^{-2}$. After the exposure process,
the development of the resists was carried out by manually agitating in
MIBK/IPA (1:3) for about 60 s. Then, Au layer of 50 nm was deposited by
thermal evaporator (the rate was 0.1 nm s$^{-1}$). Lastly, the sample was
soaked in acetone for 24 h followed by sonication for 10 s to get rid of
residuals.

Supporting Information

Supporting Information is available from the Wiley Online Library or
from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

fast switching speed, hybrid plasmonic waveguide mode, indium tin
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