Voltage-controlled active mid-infrared plasmonic devices
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We demonstrate active voltage-controlled spectral tuning of mid-infrared plasmonic structures. Extraordinary optical transmission gratings were fabricated on n-doped GaAs epilayers with a HfO2 gate dielectric between the grating and the doped semiconductor. The permittivity of the GaAs was tuned by depleting charge carriers below the top grating gate upon the application of a reverse bias to the gate. Devices were characterized both electrically and optically, and resonant transmission peak spectral and transmitted intensity shifts were achieved. Possible applications for, as well as the limitations of, the demonstrated technology are discussed. © 2011 American Institute of Physics. [doi:10.1063/1.3600230]

I. INTRODUCTION

Surface plasmons (SPs) are hybrid excitations consisting of collective charge oscillations of electrons in a metal coupled to an electromagnetic (EM) wave, which can either propagate along a planar metal/dielectric interface,1,2 or alternatively, can be localized at such interfaces with non-planar geometries.3,4 For typical plasmonic metals (such as Ag and Au), in the visible and near-IR spectral range, the SP can be coupled to an electromagnetic (EM) wave, which can either propagate along a planar metal/dielectric interface1,2 or alter-actively, mechanical control,15 or more technologically, can be localized at such interfaces with non-planar geometries.3,4 For typical plasmonic metals (such as Ag and Au), in the visible and near-IR spectral range, the SP excitation is tightly bound (with a subwavelength length-scale) to the metal/dielectric interface, making plasmonics an important subfield of nanophotonics. The vast majority of existing plasmonic structures are passive, designed for waveguiding,5,6 filtering,7,8 focusing,9 or steering10,11 light, with applications in the fields of sensing, security, and optical interconnects and computing. However, there has recently been significant interest in developing tunable plasmonic structures, where the optical properties of the device can be actively controlled by temperature tuning,12 optical excitation,13,14 mechanical control,15 or more technologically appealing, by the application of voltage.16,17 Development of a rapidly and broadly tunable plasmonic device would add an important and enabling capability to existing plasmonic technologies.

For planar metal/dielectric interfaces, the SP can be quantitatively described by solving Maxwell’s Equations for a wave propagating along the interface, yielding the dispersion relation

\[ k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}, \]

which describes the SP wavevector \(k_{sp}\) at the interface for a given excitation frequency \(\omega\) and metal and dielectric permittivities, \(\varepsilon_m\) and \(\varepsilon_d\), respectively.12 Because of the in-plane momentum mismatch between incident free-space photons and the SP defined by Eq. (1), coupling to SPs from free space photons with in-plane wavevectors \(k_x(\theta) = (\omega/c) \sin \theta\) (where \(\theta\) is the angle of incidence as measured from normal) requires an additional momentum component, which can be acquired through prism coupling configurations (Kretschmann18 or Otto19) or alternatively, by a discrete or periodic modulation of the dielectric or metal material. In the latter case, a periodic modulation of the metal film results in an additional grating momentum term \(G = 2\pi/\Lambda\), where \(\Lambda\) is the periodicity of the metal modulation. For a plasmonic structure with a periodic modulation in the \(x\) direction, the coupling condition to a SP propagating along the \(x\)-direction reads:

\[ k_{sp} = \frac{\omega}{c} \sin \theta = \frac{2\pi}{\Lambda}, \]

For such a structure, tuning the permittivity of the dielectric material alters the SP dispersion relation, shifting the resonant coupling frequency to the SP mode, and thus shifting the macroscopic spectral properties of the structure.

In the mid-infrared (mid-IR) spectral range \((\lambda = 3–30 \ \mu m)\), SP modes are less tightly bound to the metal/dielectric interface, though they can propagate for much longer distances, when compared to their visible/near-IR counterparts.20 The mid-IR is a technologically important spectral range, especially for sensing and security applications, and the development of actively tunable mid-IR plasmonic devices is especially attractive for a number of these applications. Furthermore, many semiconductors are transparent in the mid-IR, allowing for the investigation of metal/semiconductor plasmonic structures which can be integrated with semiconductor-based electronics, optical sources, or detectors. The integration of semiconductors with metal-optics offers the potential for large permittivity tuning by control of charge carrier densities in the semiconductor material, giving an intriguing tuning mechanism for active control of mid-IR metal/dielectric structures.

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In this work, the plasmonic structure we investigate is the extraordinary optical transmission (EOT) grating, first demonstrated by Ebbesen et al. (1998), which consists of a metal film periodically perforated with a square array of subwavelength apertures. At certain wavelengths, more light passes through EOT gratings than is predicted by classical aperture theory. We chose to utilize EOT gratings as our active plasmonic device structure for their distinct spectral resonances, so that active control of the plasmonic structure would result in a clear and readily observable spectral shift in the transmission through the structures.

For our tuning mechanism, we controlled the free carrier concentration of a doped semiconductor dielectric at the interface between the semiconductor and our metal EOT grating. The frequency-dependent permittivity of doped semiconductors can be expressed, using a simple Drude model, in terms of the free electron plasma frequency, as

$$\varepsilon(\omega) = \varepsilon \left(1 - \frac{\omega_p^2}{\omega^2 + i\gamma \omega}\right), \quad \omega_p^2 = \frac{ne^2}{\varepsilon_0 m^*},$$

where $n$ is the carrier concentration, $e$ the charge of an electron, $\varepsilon$ the background dielectric constant of the semiconductor, $\varepsilon_0$ the permittivity of free space, $m^*$ the electron effective mass in the semiconductor, and $\gamma$ is the damping term.

In previous work, tuning of mid-IR EOT gratings has been demonstrated by fabricating passive EOT grating structures above separate doped GaAs epilayers of varying thickness and doping, grown by Molecular Beam Epitaxy (MBE). In the present work, we tune the carrier concentration in a single device by applying a bias across the semiconductor to deplete charge carriers. By changing the carrier concentration, we thus alter the dielectric constant of the semiconductor (Eq. (3)), which in turn tunes the plasmonic resonance (Eqs. (1) and (2)). Such voltage-controlled carrier depletion device has been investigated in the THz frequency range, where a Schottky gate structure was demonstrated to modulate losses in an EOT grating (though not the spectral peak position).

In the mid-IR, the higher doping concentrations required for tuning makes a metal oxide semiconductor (MOS) capacitor (as opposed to a Schottky gate) the preferred structure to use for our active devices as leakage currents can be minimized. The basic representation of a p-type MOS-capacitor (n-type substrate) and its energy band diagram is shown in Fig. 1, along with a schematic for our device, in which an EOT grating is built into the top contact of the MOS design. No different than a traditional MOS device, a reverse-bias applied to the top gate of our device will push electrons in the semiconductor away from the interface, depleting the highly doped n-GaAs and changing the permittivity of the material underlying the top metal gate and gate dielectric.

II. FABRICATION

All of the devices were fabricated upon GaAs wafers with a highly n-type doped ($1.2 \times 10^{18}$ cm$^{-3}$), 1.2 $\mu$m-thick epilayer grown using a Varian Gen II MBE system. The high

FIG. 1. (Color online) (a) Schematic of our voltage-tunable EOT grating device (b) Schematic of accumulation, depletion, and inversion in a standard MOS structure (c) Energy band diagram for a p-MOS capacitor in depletion, where $E_c$ is the conduction band, $E_v$ is the valence band, $E_f$ is the Fermi level, $\phi_s$ the semiconductor surface potential, and $\phi_f$ is the energy spacing between $E_f$ and $E_i$, the midgap intrinsic energy level.
doping of our GaAs epilayers was designed to give a large shift in the GaAs permittivity as we deplete the doped material below the EOT top gate. The devices were fabricated by first etching a mesa (250 × 400 μm²) in the doped GaAs. Next, following a HF dip to remove the native oxide on the Ga surface, a thin film of HfO₂ was deposited on the sample using atomic layer deposition (ALD). The deposited Hafnia was then removed with a wet etch everywhere except on top of the mesa, before being annealed for 60 s at 700 °C in forming gas ambient. The sample was then patterned with top and bottom gold contacts, above and around the mesa, respectively. Initially, solid top gate MOS-capacitors were fabricated in order to characterize the electrical properties of our Hafnia gate dielectric. The tunable mid-IR plasmonic devices utilized top contacts with an EOT grating (square array periodicity Λ = 3.0 μm) patterned into the top gate. Figure 2 shows scanning electron and optical micrographs of the fabricated tunable EOT samples.

III. OPTIMIZATION

An Agilent B1505 A test station was used for measuring the current-voltage (I-V) and high frequency (1 MHz) capacitance-voltage (C-V) characteristics of the solid top gate structures, in order to characterize, and ultimately optimize, HfO₂ deposition and post-deposition processing. For the highest quality HfO₂ gate dielectrics deposited, low current densities (J < 50 μA/cm²) were achieved for applied biases between −3 and 2 V. Poorer quality HfO₂ devices broke down at much lower voltages, sometimes immediately upon applying a bias, suggesting the formation of pin holes in the insulating Hafnia during deposition. Electrical testing was performed on numerous samples with a range of Hafnia thicknesses as well as varying annealing temperatures and times in order to determine the ideal Hafnia layer thickness and anneal process that minimized leakage current and maximized depletion at reasonable biases (<5 V). Figure 3 shows the I-V and C-V curves for a high quality 20 nm thick HfO₂ dielectric layer grown on highly n-doped GaAs, annealed at 700 °C for 60 s.

For accumulation (positive gate voltages), the sample acts as a simple parallel plate capacitor, allowing us to calculate the permittivity of the Hafnia from the measured capacitance (C) and the thickness of the deposited Hafnia (d), using the simple relation \( C_{ox} = A \varepsilon_{ox}/d_{ox} \). The C-V results were consistent across samples of varying Hafnia thicknesses, yielding a HfO₂ permittivity of \( \varepsilon_{ox} \approx 16.3 \varepsilon_0 \), within the range found in the literature.²⁶,²⁷

IV. RESULTS

Following characterization of solid top-contact MOS capacitors, devices with EOT grating top contacts were fabricated (using the optimized Hafnia deposition and anneal recipe), wire-bonded, and fixed to a copper transmission mount. Samples were optically characterized at low temperature (~80K) in a vacuum cryostat. The samples were biased (DC) with a Keithley 2420 Source Meter during optical testing and current flow was monitored to prevent thermal heating of the sample, which can shift the permittivity of the GaAs.¹¹ Broadband mid-IR light (500–4000 cm⁻¹) from the internal globar source of a Bruker V80 Fourier Transform Infrared (FTIR) spectrometer was focused through the window of the cryostat and onto the EOT grating using a 8 in. focal length ZnSe lens. Transmitted light was collected, collimated and refocused onto an external HgCdTe (MCT) detector with a pair of ZnSe lenses. Transmission spectra were collected for a range of applied reverse biases \( V_R = 0 \) to −4.8 V. All spectra collected were normalized to a background transmission spectra with no sample in place.

For \( V_R = 0 \) V, the mid-IR transmission spectra showed characteristic EOT transmission peaks with resonant transmission near \( \lambda = 10 \mu m \), as predicted by the SP dispersion and momentum matching relations (Eqs. (1) and (2)). As the reverse bias was increased from \( V_R = 0 \) V to \( V_R = −3.6 \) V, the resonant transmission peak red-shifted slightly, as shown in Fig. 4, and quantified in Fig. 5. At biases of approximately \( V_R \approx −3.6 \) V the spectral tuning of the transmission reached...
the tuning mechanism of our device: as the carriers are depleted from the GaAs/HfO$_2$ interface, the interaction between these absorbing carriers and the most intense region of the SP mode is decreased, lowering the losses, and increasing transmission through the device. As the reverse bias is increased above $V_R = -3.6$ V, the peak transmission intensity begins to decrease, as seen in Fig. 5.

**V. DISCUSSION**

Both the blueshift and the decrease in transmission intensity of the transmission peak for $|V_R| > 3.6$ V suggests the possibility of inversion at the GaAs/HfO$_2$ surface. The inversion of the GaAs/HfO$_2$ surface would bring mobile holes to the GaAs/HfO$_2$ interface, spectrally shifting the transmission peak back toward its unbiased position and introducing loss into the strongest part of the SP mode. However, the GaAs surface is notoriously difficult to invert, and significant effort has been made to develop processes and materials for the fabrication of inversion mode GaAs FET structures. Because our Hafnia layer was grown with only a HF dip clean, and no surface passivation, the likely presence of large numbers of GaAs/HfO$_2$ interface states makes it unlikely that inversion would be achievable for any AC capacitance measurement (as can be seen from Fig. 3(b). However, because our optical characterization is effectively a DC biased measurement, it is conceivable that in such measurements, inversion of the GaAs surface is possible. A quasi-static CV measurement was attempted in an effort to demonstrate inversion at our GaAs/HfO$_2$ interface. However, results from this measurement were inconclusive due to leakage current through the Hafnia gate dielectric. This current, while weak enough to avoid thermal tuning of the plasmonic structure’s optical properties, was strong enough to obscure the capacitive charging current whose accurate measurement is necessary to obtain quasi-static CV data. Therefore, although it is suggested by our optical experiments, inconclusive quasi-static CV measurements prevent us from claiming inversion of the GaAs/HfO$_2$ interface.

The tuning of our plasmonic devices is limited by the maximum depletion width achievable in our structures. For an ideal n-doped GaAs MOS capacitor, the maximum depletion depth corresponds to the onset of inversion, when the surface potential $\phi_{t_{\text{max}}} = 2\phi_f$. The predicted low-temperature maximum depletion width in the doped GaAs, for our samples, is $x_d = 43$ nm, calculated using

$$x_d = \sqrt{\frac{4\varepsilon_0\phi_f}{eN_d}} \quad (4)$$

where $\phi_f = E_f - E_i$ (see Fig. 1(c)) and $N_d$ is the donor dopant concentration. For a highly doped sample such as ours, this corresponds to a surface potential approximately equal to the GaAs bandgap (at low temperatures $\phi_{t_{\text{max}}} \approx E_g = 1.52$ eV). Excluding oxide and interface charging, the ideal threshold voltage for inversion in our structures was estimated to be $V_T \approx -1.74$ V. However, the presence of oxide charge and interface states in our sample should result in a shift in the ideal threshold voltage. Using values found in the literature, the expected shift would be on the order of

![Figure 4](image_url)

**FIG. 4.** (Color online) Transmission spectra taken on voltage-tunable EOT device. Measurements taken at 77K for reverse biases of magnitude $V_R = 0, 0.8, 2.4, 3.6$, and 4.8 V. Spectra are normalized to allow comparison of spectral shifts.

![Figure 5](image_url)

**FIG. 5.** (Color online) Change in peak transmission intensity (red, left axis) and spectral peak position (blue, right axis) of active mid-IR EOT grating device as a function of the magnitude of the applied reverse bias.
$|\Delta V_T| \approx 0.75 - 1.5 V$, putting the maximum depletion of our samples in the range of $V_G \approx -3 V$, in good agreement with the gate bias associated with the maximum spectral shift seen experimentally for our devices.

The maximum depletion width of the doped GaAs ($d_{\text{max}} = 43 \text{ nm for our samples}$) is the limiting factor that prevents broader tuning in our devices. The spatial extent of the SP electric fields in bulk GaAs reaches a penetration depth of approximately $\delta_{\text{GaAs}} \sim 10 \mu m$ for $\lambda \sim 10 \mu m$. Thus the overlap of the plasmonic mode with the region of tunable dielectric is minimal. In fact, a simple calculation of the expected shift in the resonant transmission wavelength of our device, using a fixed SP mode profile, and calculating a weighted effective permittivity for the depleted and unbiased states allows for transmission of incident light and one contact was fabricated and small spectral shifts in transmission intensity shifts, were observed and attributed to the control of carrier concentrations at the MOS interface. The minimal magnitude of the spectral shifts was attributed to weak spatial overlap between the optical mode and the tunable dielectric material. However, the small tuning range in our devices is near the value required to switch such devices between a state allowing for transmission of incident light and one which allows coupling to propagating surface waves. For future device designs, where the optical mode can be confined to a smaller region of the tunable dielectric, larger tuning ranges of mid-IR plasmonic devices based on the carrier depletion tuning mechanism may be achievable.

VI. CONCLUSION

In conclusion, we demonstrate active voltage control of mid-IR plasmonic EOT gratings using a carrier depletion tuning mechanism. MOS-capacitors with EOT grating top contacts were fabricated and small spectral shifts in transmission resonances ($< 3 \text{ cm}^{-1}$), as well as transmission intensity shifts, were observed and attributed to the control of carrier concentrations at the MOS interface. The minimal magnitude of the spectral shifts was attributed to weak spatial overlap between the optical mode and the tunable dielectric material. However, the small tuning range in our devices is near the value required to switch such devices between a state allowing for transmission of incident light and one which allows coupling to propagating surface waves. For future device designs, where the optical mode can be confined to a smaller region of the tunable dielectric, larger tuning ranges of mid-IR plasmonic devices based on the carrier depletion tuning mechanism may be achievable.

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