

# Tunable Metasurface based on Silicon Doped Indium Oxide

Hongwei Zhao<sup>1</sup>, Ran Zhang<sup>2</sup>, Hamid T. Chorsi<sup>1</sup>, Wesley Britton<sup>2</sup>, Yuyao Chen<sup>2</sup>, Prasad P. Iyer<sup>1</sup>,  
Jon A. Schuller<sup>1</sup>, Luca Dal Negro<sup>2,3</sup>, and Jonathan Klamkin<sup>1</sup>

<sup>1</sup> Electrical and Computer Engineering Department, University of California Santa Barbara, Santa Barbara, CA 93106, USA

<sup>2</sup> Electrical and Computer Engineering Department and Photonics Center, Boston University, Boston, Massachusetts 02215, USA

<sup>3</sup> Division of Material Science and Engineering, Boston University, Boston, Massachusetts 02215, USA  
hwzhao@ece.ucsb.edu

**Abstract:** A tunable metasurface based on silicon doped indium oxide has been investigated. The amplitude of reflected light was actively tuned with a gate bias, demonstrating 57% reflectance change and 366 nm of resonance wavelength shift. © 2019 The Author(s)

**OCIS codes:** (160.3918) Metamaterials; (050.6624) Subwavelength structures; (240.6680) Surface plasmons.

## 1. Introduction

Transparent conducting oxides (TCOs) have drawn significant attention due to their fabrication simplicity and electrical tunability in the near- and mid-infrared wavelength range [1]. Gate-tunable metasurfaces and optical modulators based on tin doped indium oxide (ITO) have been widely reported for engineering light amplitude and phase [2-4]. Silicon doped indium oxide (ISO) is an alternative TCO candidate for transparent electrodes, compact modulators and tunable metasurfaces [5]. In this work, gate-tunable metasurfaces based on ISO were fabricated and characterized. A maximum change in the reflectance ( $\Delta R/R$ ) of 57% and up to 216 nm of resonance wavelength shift were measured.

## 2. Fabrication of the Metasurface Structure

As shown in Fig. 1, the metasurface consists of a reflecting substrate, a 20-nm-thick ISO film, a 40-nm-thick hafnium dioxide ( $\text{HfO}_2$ ) film, and 50-nm-thick subwavelength gold resonator arrays. The resonator arrays are designed with a period ( $d$ ) of  $1 \mu\text{m}$  and width ( $w$ ) of 405 nm.

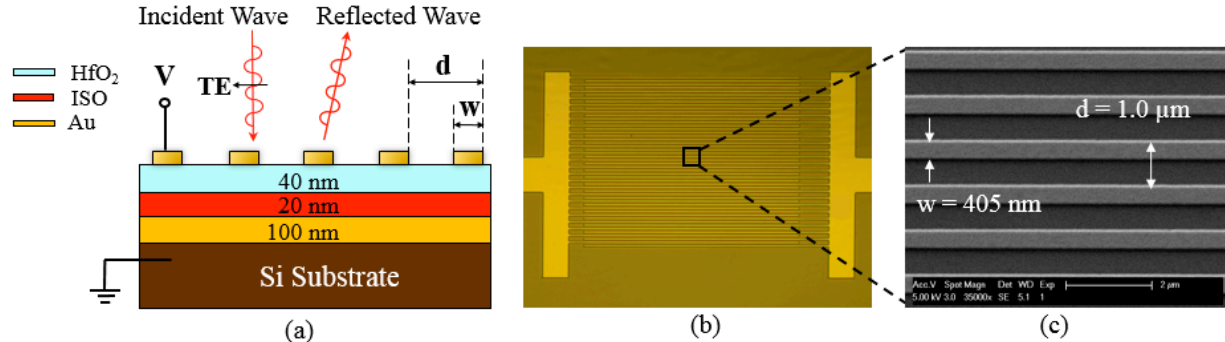


Fig. 1. (a) Cross-section schematic of the ISO metasurface; (b) Top view of the fabricated metasurface structure; (c) Scanning electron micrograph image of the metallic grating arrays.

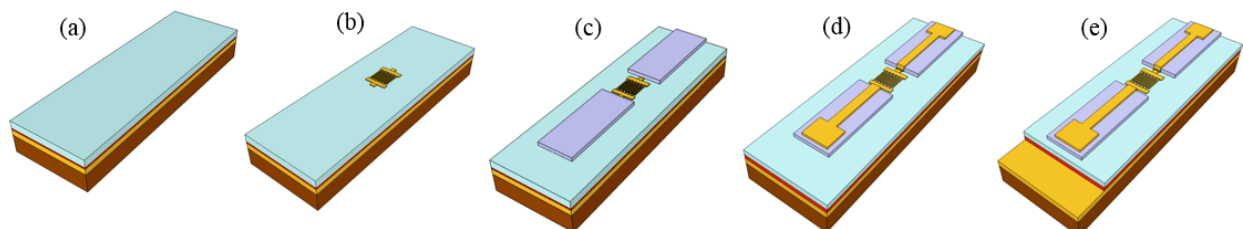


Fig. 2. Fabrication process flow of the metasurface structure. (a) Deposition of all underlying thin films including Au, ISO, and  $\text{HfO}_2$ ; (b) Formation of metallic grating arrays using EBL and a metal lift off process; (c) Deposition and patterning of passivation  $\text{SiO}_2$ ; (d) Formation of metal contacts; (e) Patterning and etching of all films to expose underlying Au for contact.

The fabrication process flow is illustrated in Fig. 2. Firstly, titanium (Ti) and gold (Au) metal layers with thickness of 5 nm and 100 nm, respectively, were deposited using electron beam evaporation onto the silicon (Si) substrate. Then, the ISO thin film was sputter deposited onto the metallic reflecting layer. Using atomic layer deposition

(ALD), the  $\text{HfO}_2$  dielectric layer was deposited. The gold resonator arrays were realized using electron beam lithography (EBL) and metal lift off. Silicon dioxide ( $\text{SiO}_2$ ) was deposited and patterned for passivation. On top of this, metal pads were deposited, again using electron beam evaporation and liftoff. The metal pads comprise a 15-nm-thick Ti sticking layer and a 50-nm thick layer of Au. Lastly, the  $\text{HfO}_2$  and ISO layers were patterned and etched to expose the reflecting metal layer for electrical contact.

### 3. Experimental Results

Reflection spectra were measured with a Fourier Transform Infrared (FTIR) spectrometer coupled to a 36X objective microscope. Light reflected from the sample was detected with a liquid nitrogen cooled mercury cadmium telluride (MCT) detector. A clean Au substrate was used as a reference. A gate bias was applied to the metallic grating arrays using the larger contact pads while the reflecting substrate was connected to ground.

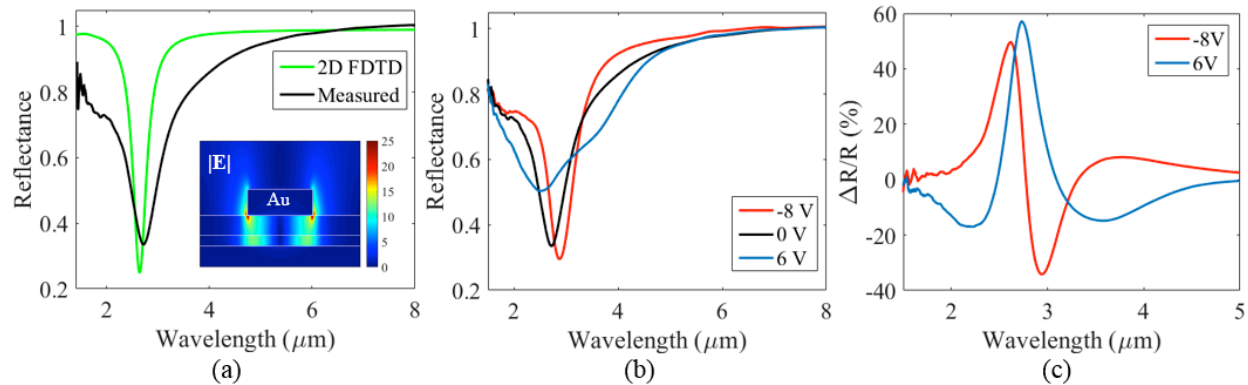


Fig. 3. Reflectance spectrum without bias and the simulated electrical field distribution ( $|E|$ ) at the resonance wavelength; (b) Electrically tuning of reflectance from metasurface; (c) Relative reflectance change:  $\Delta R/R = [R(V) - R(0)] / R(0)$ .

Metasurface reflection spectra are shown in Fig. 3. A 2D-finite different time domain (FDTD) solver was used to calculate the reflectance spectrum without bias. The near-normal incidence TE-polarized (in-plane electric field perpendicular to the resonators' long axis) light resonantly couples to surface plasmons, producing a dip in reflectance (Figure 3(a)). Simulated (2.64  $\mu\text{m}$ ) and measured (2.72  $\mu\text{m}$ ) resonance wavelengths show good agreement. The simulated electric field distribution ( $|E|$ ) on resonance is shown in the figure inset, and demonstrates significant field intensity in the underlying ISO layer. Figure 3(b) shows the reflectance spectrum for applied biases of -8 V, 0 V, and 6 V, demonstrating the tunability of the metasurface structure. Figure 3(c) plots the relative reflectance change,  $\Delta R/R = [R(V) - R(0)] / R(0)$ , defined as the normalized ratio of the change in reflectance with and without bias. A maximum  $\Delta R/R$  of 57% was achieved at a wavelength of 2.73  $\mu\text{m}$ . A resonance wavelength shift of -216 nm was demonstrated with a bias of +6 V. With a bias of -8 V, the resonance wavelength shift measured was +150 nm and  $\Delta R/R$  was 50% at a wavelength of 2.6  $\mu\text{m}$ .

### 4. Conclusions

We have demonstrated a tunable metasurface based on ISO. A reflectance change of 57% was measured at a wavelength of 2.73  $\mu\text{m}$ . A total resonance wavelength shift of 366 nm was observed with a change in bias from -8V to +6V. This new TCO material shows promise for tunable metasurface applications.

Portion of this work was supported by the National Science Foundation (ECCS 1709704).

- [1] V. E. Babicheva, N. Kinsey, G. V. Naik, M. Ferrera, A. V. Lavrinenko, V. M. Shalaev, and A. Boltasseva, "Towards CMOS-compatible nanophotonics: Ultra-compact modulators using alternative plasmonic materials," *Opt. Express*, vol. 21, no. 22, 2013.
- [2] H. W. Lee, G. Papadakis, S. P. Burgos, K. Chander, A. Kriesch, R. Pala, U. Peschel, and H. A. Atwater, "Nanoscale Conducting Oxide PlasMOStor," *Nano Lett.*, vol. 14, no. 11, pp. 6463–6468, Nov. 2014.
- [3] H. Zhao, Y. Wang, A. Capretti, L. Dal Negro, and J. Klamkin, "Broadband electroabsorption modulators design based on epsilon- near-zero indium tin oxide," *IEEE J. Sel. Top. Quantum Electron.*, vol. 21, no. 4, pp. 192–198, Jul. 2015.
- [4] J. Park, J. H. Kang, S. J. Kim, X. Liu, and M. L. Brongersma, "Dynamic reflection phase and polarization control in metasurfaces," *Nano Lett.*, vol. 17, no. 1, pp. 407–413, Jan. 2017.
- [5] W. A. Britton, R. Zhang, S. Shrestha, Y. Chen, N. Yu and L. Dal Negro, "Indium silicon oxide thin films for infrared metapotonics", *Appl. Phys. Lett.*, accepted for publication.