Optics Communications 381 (2016) 18–23

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Nanoscale field effect optical modulators based on depletion of epsilon-near-zero films

Zhaolin Lu *, Kaifeng Shi, Peichuan Yin

Microsystems Engineering, Kate Gleason College of Engineering, Rochester Institute of Technology, Rochester, NY 14623, USA

ARTICLE INFO

Article history:
Received 18 March 2016
Received in revised form
14 June 2016
Accepted 20 June 2016

Keywords:
Epsilon-near-zero
Plasmonic modulator
Electro-absorption modulator
Field effect optical modulator
Depletion

ABSTRACT

The field effect in metal-oxide-semiconductor (MOS) capacitors plays a key role in field-effect transistors (FETs), which are the fundamental building blocks of modern digital integrated circuits. Recent works show that the field effect can also be used to make optical/plasmonic modulators. In this paper, we report the numerical investigation of field effect electro-absorption modulators each made of an ultrathin epsilon-near-zero (ENZ) film, as the active material, sandwiched in a silicon or plasmonic waveguide. Without a bias, the ENZ films maximize the attenuation of the waveguides and the modulators work at the OFF state; on the other hand, depletion of the carriers in the ENZ films greatly reduces the attenuation and the modulators work at the ON state. The double capacitor gating scheme with two 10-nm HfO_2 films as the insulator is used to enhance the modulation by the field effect. The depletion requires about 10 V across the HfO_2 layers. According to our simulation, extinction ratio up to 3.44 dB can be achieved in a 500-nm long Si waveguide with insertion loss only 0.71 dB (85.0% pass); extinction ratio up to 7.86 dB can be achieved in a 200-nm long plasmonic waveguide with insertion loss 1.11 dB (77.5% pass). The proposed modulators may find important applications in future on-chip or chip-to-chip optical interconnection.

1. Introduction

With the successful demonstration of ultracompact lasers, detectors, and waveguides, the development of ultracompact optical modulators becomes one of the priority tasks for photonic integration. The existing techniques include electro-optical (EO) modulators based on linear EO effect in materials such as $LiNbO_3$ and free carrier plasma dispersion effect [1], as well as electro-absorption (EA) modulators based on Franz-Keldysh effect [2] and quantum-confined Stark effect [3]. However, they suffer either large dimensions or difficult integration.

The most widely discussed EO modulators in academia these years are Si modulators based microrings [4–6]. The dimensions of Si modulators with high-Q microring can reduce down to a few micrometers. However, they suffer thermal instability. Even for the recently developed athermal modulators, they work well only within 7 °C [7]. Seeing that thermal heaters are required to maintain the temperature on microring modulators, it is ironical that optical interconnection was initially proposed as a paradigm to decrease the power consumption of integrated circuits.

* Corresponding author.
E-mail address: zhaolin.lu@rit.edu (Z. Lu).

http://dx.doi.org/10.1016/j.optcom.2016.06.057

2. Theory of operation

Compared to the *pn* or *pin* structures in microring modulators, optical modulators may be also realized based on the MOS structure, which roughly functions as a parallel capacitor. When a bias voltage is applied across the oxide layer, charge is induced at metal and semiconductor surfaces. The field-induced charge per unit area in the MOS capacitor can be calculated according to

$$Q_s = \varepsilon E \approx \varepsilon\left(\frac{V}{d}\right), \tag{1}$$

where ε is the DC or RF permittivity of the insulator, and E is the applied electric field across the insulator layer with thickness d. According to the bias polarity and strength, a MOS structure may work in three well-known modes: accumulation, depletion, and inversion. Generally speaking, accumulation induces more majority carriers, and the accumulation layer becomes more electrically conductive and more optically absorptive, whereas depletion removes free carriers, and the optical absorption by free carrier in the depletion layer can reduce to a negligible level. The inversion between electron and holes requires slow thermal excitation; thus, inversion is insignificant for high speed optical modulation. The accumulation layer thickness can be estimated as $l_{ac} \approx \pi L_D/\sqrt{2}$, where L_D is the Debye length of the semiconductor. The depletion layer thickness can be estimated by

$$w_d = \frac{Q_s}{eN_0} \quad (.(2)$$

Dionne et al. demonstrated a field effect optical modulator (FEOM) based on crystalline silicon sandwiched into two silver films [8], where the modulating electric field can switch the waveguide between guiding and cut-off states. Feigenbaun et al. investigated an FEOM based on conductive oxide (COx) [9], which is the first experimental demonstration of COx as active material for optical modulation. In particular, unity-order refractive index change in the COx accumulation layer was measured based on the ellipsometry method. The result is very promising and many works have followed this work, including numerical studies reported in Refs. [10–16]. Experimental demonstrations of COx as active material for EA/EO modulation are also reported [17–19]. Modulation extinct ratio is reported 1 dB/μm in Ref. [17], and 2.71 dB/μm in Ref. [18].

We are interested in EA modulation based on ENZ materials. Epsilon-near-zero materials [20–22] were initially proposed for microwave applications to improve the directivity of antennas [23], super coupling [24–26], and super tunneling [27], etc. We noticed that ENZ can also be achieved in graphene [28] and COx [11] for near-infrared applications. In particular, when a thin ENZ film is sandwiched in a single mode dielectric or plasmonic waveguide, very strong electric field can be excited in the ENZ film for the transverse magnetic (TM) mode. The structure was named as the “ENZ-slot” waveguide [11,28,29], which is the extreme case for the slot waveguide [30]. The greatly enhanced electric field leads to greatly enhanced light absorption [11,28].

Our previous work reported EA modulators based on ENZ-slot waveguides by accumulation [11]. However, the electron density in the accumulation layer nearly exponentially decays with distance, which leads to very non-uniform optical dielectric constant across the accumulation layer. Our recent experiment shows that both accumulation and depletion play an important role in the optical modulation [31,32]. Herein, we propose EA modulators each based on the depletion of an ENZ thin film. In contrast to accumulation, the initial film can be designed with uniform carrier concentration and uniform ENZ optical dielectric constant. The depletion can greatly remove the carriers. Thus, optical modulation can be achieved between ENZ and depletion with very large extinction ratios. As examples, we consider EA modulators based on the metal-insulator-metal waveguide and Si waveguide platforms, respectively.

3. Design and simulation

The challenge of this approach is that it requires high-k oxide and an ultrathin ENZ film. To overcome this, we employ the double capacitor gating scheme, as illustrated in Fig. 1(a), where the same gate voltage can induce depletion layers simultaneously on top and bottom sides of the ENZ film. The ultrathin film may be 2D semiconductor or COx. As an example, we first consider an optical modulator based on “metal-insulator-COx-insulator-metal” (MICIM), where a widely used COx, indium tin oxide (ITO) works at ENZ, and the metal layer is assumed to be Au owing its chemical stability and low absorption at near-infrared frequencies. Fig. 1 (a) illustrates the MICIM structure to be investigated. Electro-absorption modulators based on the MICIM structure were investigated in our recent experiment [33]. According to the Drude model, the optical dielectric constant of COx can be approximated

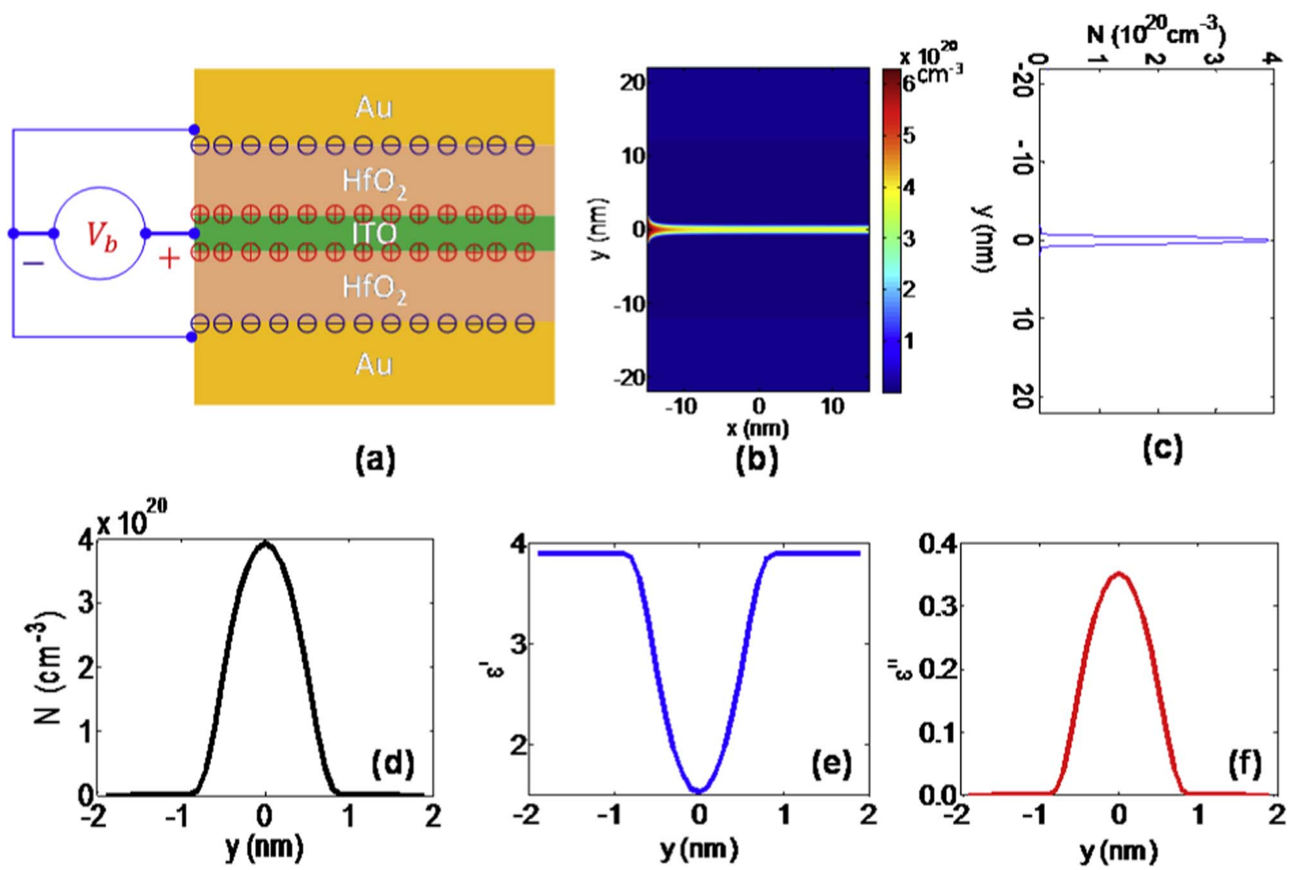

Fig. 1. (a) Illustration of the metal-insulator-COx-insulator-metal structure working at the depletion mode. (b–d) FEM simulation of the residual electron distribution in the ITO film. (e) The real part of the ITO complex dielectric constant (ε') of ITO. (f) The imaginary part of the complex dielectric constant (ε'') of ITO.