Silicon electro-optic modulator with high-permittivity gate dielectric layer

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A high-permittivity (high-k) material is applied as the gate dielectric layer in a silicon metal-oxide-semiconductor (MOS) capacitor to form a special electro-optic (EO) modulator. Both induced charge density and modulation efficiency in the proposed modulator are improved due to the special structure design and the application of the high-k material. The device has an ultra-compact dimension of 691 μm in length.

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Silicon electro-optic (EO) modulator is a critical component for enabling optical interconnection systems on a microelectronic chip[1]. According to the free carrier plasma dispersion effect, a change of the refractive index can be achieved by changing the carrier density. Carrier injection in forward biased PIN structure, carrier depletion in reverse biased PIN structure, and carrier accumulation in metal-oxide-semiconductor (MOS) structure can all change the charge density.

In conventional silicon EO modulators based on MOS capacitor, an induced charge layer only occurs around the silica gate dielectric area while a positive voltage is applied. The layer is very thin[2] and the carrier density change is small, which results in a small refractive index change and a low modulation efficiency. Although double-MOS structure modulators have been proposed and the device length has been reduced considerably, they are still in the level of millimeters[3,4]. In this letter, an ultra-compact silicon EO modulator based on MOS capacitor with high permittivity (high-k) gate dielectric is designed and demonstrated. The device is only 691 μm in length.

The high-k gate dielectric silicon EO modulator based on MOS capacitor proposed here is designed using high-k gate dielectric as a substitute for silica gate dielectric. The diagram of the cross-section view is shown in Fig. 1. It comprises an inverted p-type doped silicon rib and an n-type doped silicon rib with a high-k gate dielectric layer sandwiched between them. The material which has a larger permittivity than silica is called high-k material. With different fabrication processes, a material may have different permittivities. In this structure, HfO_2 fabricated by electron-beam evaporation (EBE) is selected since it has a high permittivity of 19[5].

At a wavelength of 1.55 μm, the refractive index change caused by the charge density change is given by[6]

$$\begin{aligned}\Delta n &= \Delta n_{\mathrm{e}} + \Delta n_{\mathrm{h}} = -8.8\times10^{-22}\Delta N_{\mathrm{e}} \\ &\quad -8.5\times10^{-18}(\Delta N_{\mathrm{h}})^{0.8}, \qquad (1)\end{aligned}$$

where Δn_{e} and Δn_{h} are index changes caused by the density changes of electron and hole, ΔN_{e} and ΔN_{h} are the density changes of electron and hole, respectively.

In a MOS structure modulator, when a positive voltage is applied to the MOS capacitor, the larger the permittivity of the gate dielectric material, the larger the carrier density change and the thicker the induced charge layer. According to Eq. (1), a larger refractive index change can be reached with a larger carrier density change. A thicker induced charge layer will enhance the overlapping between the optical field and carrier density changing region. These result in a larger effective refractive index change. Compared with the silica's permittivity of 3.9, the larger permittivity of HfO_2 will improve the

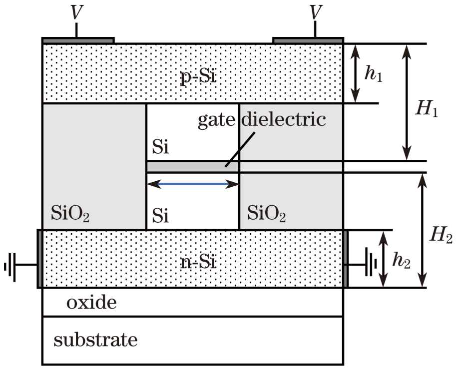

Fig. 1. Cross section of the silicon EO modulator with high-k gate dielectric.

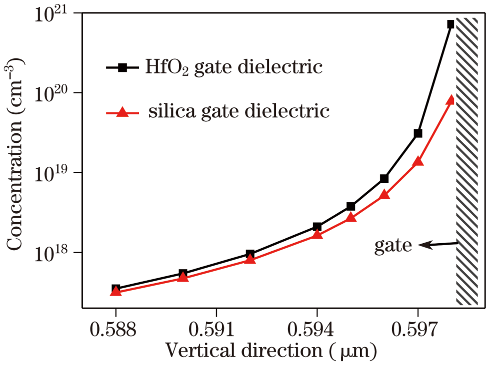

Fig. 2. Hole concentration above the gate dielectric.

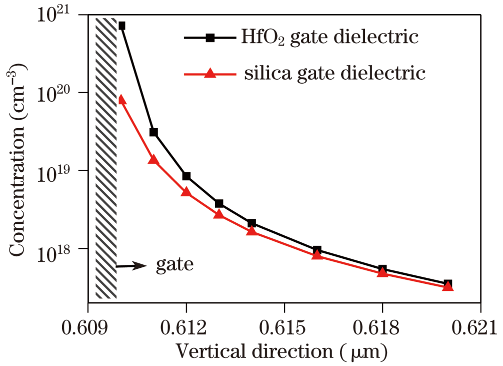

Fig. 3. Electron concentration under the gate dielectric.

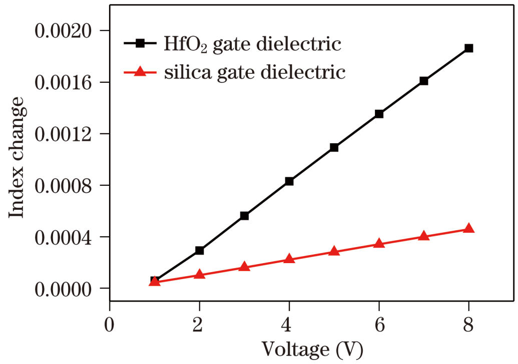

Fig. 4. Effective refractive index changes of modulator with HfO_2 gate dielectric and modulator with silica gate dielectric.

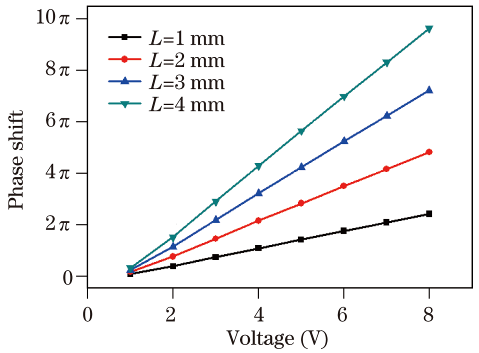

Fig. 5. Phase shift versus driving voltage. L is the length of the active region.

performance of the modulator. So a HfO_2 gate dielectric modulator will have a larger refractive index change and a higher modulation efficiency than conventional modulators with silica gate dielectric.

The semi-vector beam propagation method (BPM) is used to analyze the optical field amplitude distribution. We use a commercially available simulation package, ATLAS from SILVACO, to analyze the carrier distribution and do relevant electrical calculations. ATLAS is a modular and extensible framework for one-, two-, and three-dimensional semiconductor device simulation. It physically predicts the device electrical characteristics with certain parameters and boundary conditions by solving semiconductor physics equations related to the device physical structure, such as Poisson's equation and the charge continuity equations[7].

As shown in Fig. 1, W, h_1, H_1, h_2, and H_2 denote the waveguide width, p-Si slab height, p-Si rib height, n-Si slab height, and n-Si rib height, respectively. After simulations, the optimized structure parameters are obtained as W=1 μm, h_1=0.3 μm, H_1=0.3 μm, h_2=0.3 μm, H_2=0.3 μm. The doping concentrations of p-Si and n-Si are both 1×10^{19} cm^{-3}. The light doping concentrations above and under the gate dielectric are both 5×10^{16} cm^{-3}. The thickness of the gate dielectric is 12 nm. Figure 2 shows the hole concentration above the gate dielectric. Figure 3 shows the electron concentration under the gate dielectric. It can be seen that the charge density and charge layer of the modulators with HfO_2 gate dielectric are larger than those of modulators with silica gate dielectric. Figure 4 shows the effective refractive index changes of the modulator with HfO_2 gate dielectric and a modulator with silica gate dielectric. The incident light wavelength is 1.55 μm with a transverse electric (TE) like fundamental mode. It is obvious that with the same structure, the refractive index change of modulator with HfO_2 gate dielectric is much larger. This means a higher modulation efficiency and a much shorter device length.

Figure 5 shows the dependence of the phase shift on the applied gate voltage under different lengths of the active region. We use the product of $V_\pi \cdot L_\pi$ to represent the phase modulation efficiency of the device. The smaller $V_\pi \cdot L_\pi$ is, the higher the modulation efficiency is. In conventional silicon MOS modulators with silica gate dielectric, the $V_\pi \cdot L_\pi$ is about 1 V $\cdot$ cm[4,8] or even larger[2]. Here a higher phase modulation efficiency corresponding to $V_\pi \cdot L_\pi$ =0.37 V $\cdot$ cm is achieved. When the voltage is 5 V, L_π is only 691 μm, which is much shorter than the millimeter level length of conventional modulators with silica gate dielectric. The rise time of this structure is 0.039 ns and the fall time is 0.03 ns, which are comparable with those in silicon modulators with silica gate dielectric.

In conclusion, a silicon EO modulator based on MOS capacitor with high-k gate dielectric layer is proposed. Both the induced charge density and the induced charge layer are enlarged by using a high-k gate dielectric material. The $V_\pi \cdot L_\pi$ value of the device is 0.37 V $\cdot$ cm, and the modulation speed is 14 GHz. The device is compact and shows a higher modulation efficiency.

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