Design of Traveling Wave Electrode for High-speed Silicon Modulators

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Abstract: We design a traveling wave electrode to drive carrier-depletion-based silicon modulators. By optimizing the electrode on top of the active region and the connection transmission line, the impedance can be matched to 50 Ohm. The 3-dB bandwidth of the modulator can be up to 40 GHz, mainly limited by the velocity mismatch.

OCIS codes: (230.0230) Optical devices; (230.2090) Electro-optical devices; (230.4110) Modulators; (230.7020) Traveling-wave devices

1. Introduction

Silicon optical modulators have been rapidly developed during the past several years. Multiple modulator structures have been reported, including Mach-Zehnder [1], microring [2], and microdisk [3]. Many modulation mechanisms have been employed, including carrier injection, accumulation, and depletion [4]. Among these mechanisms, the method using carrier depletion in a reverse-biased p-n junction has shown superior performances with high operation speed and low power consumption. Essentially, a modulator driven by a traveling wave electrode can provide high operation bandwidth, mainly limited by three factors: 1) the velocity matching between the optical carrier and the microwave; 2) the impedance matching; and 3) the microwave attenuation [5]. In order to increase the transmission efficiency and operation bandwidth, the impedance of the traveling wave electrode should be 50 Ohm to match most RF and microwave interfaces to reduce reflection.

Here, we design a traveling wave electrode to drive carrier-depletion-based silicon modulators. Finite element method (FEM) simulation results show that our traveling wave electrode can achieve an impendence of around 50 Ohm with a reflection coefficient (S_{11}) of below -35.82 dB and a transmission coefficient (S_{21}) of above -0.80 dB over the frequency ranging from 1 GHz to 100 GHz. With impedance-matched, the 3-dB modulation bandwidth is mainly limited by the velocity mismatch and a 40 GHz bandwidth can be achieved. We also optimize the connection part between the pad and the traveling wave electrode. The impedance of the connection transmission line in this part is around 50 Ohm in the frequency ranging from 1 to 69 GHz, after which the impedance increases rapidly, resulting in a 3-dB bandwidth of 69 GHz.

2. Configuration and simulation

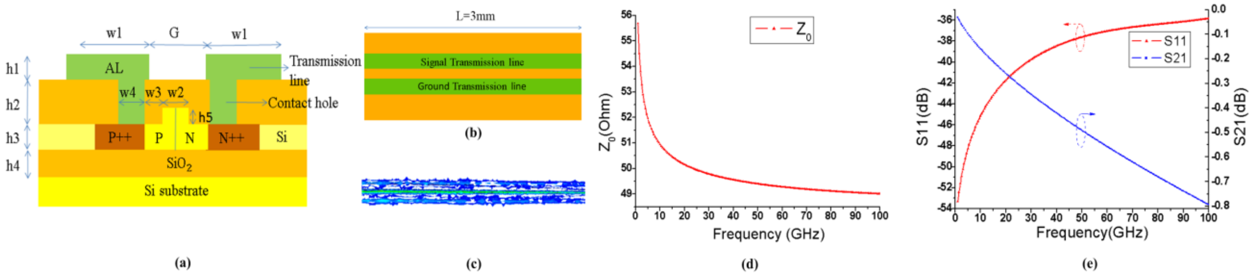


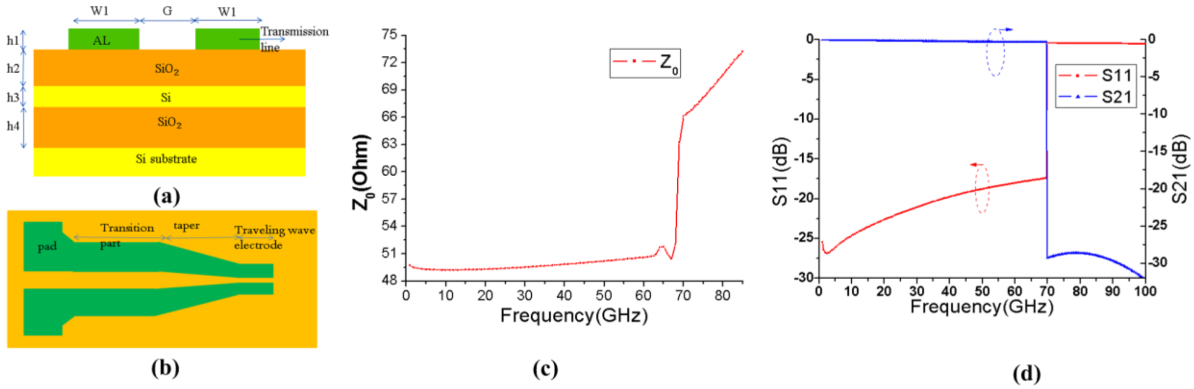
Figure 1 (a) Cross section of the traveling wave electrode. (b) Top view of the traveling wave electrode. (c) Electric field distribution in the traveling wave electrode. (d) Characteristic impedance of the traveling wave electrode. (e) S_{11} and S_{21} parameters.

The cross section of the traveling wave electrode is shown in Fig. 1 (a). The device is made on a silicon-on-insulator (SOI) wafer with a buried oxide thickness of 2 μm and a top silicon thickness of 220 nm. The silicon waveguides have a width of 0.5 μm and a slab thickness of 110 nm. The transmission line is made of aluminum with a thickness of 0.75 μm and a width of 12 μm. The gap separation between the signal and ground lines is 1.5 μm. The contact holes have a height of 0.6 μm and a width of 1 μm. The distance from the rib edge to the contact hole is 2 μm. The top view of the traveling wave electrode is shown in Fig. 1 (b). The length of the electrode is assumed to be 3 mm for use in Mach-Zehnder modulators. The commercial software HFSS was employed to perform simulations of the traveling wave electrode. The electric field distribution in the electrode is shown in Fig. 1 (c). In order to reduce reflection and increase transmission efficiency, characteristic impedance of the structure was optimized to match 50 Ohm. It can be seen from Fig. 2 (d) that the impedance of the electrode is around 50 Ohm. Because of the impedance match, the transmission efficiency is high. S-parameters (S_{11} and S_{21}) over the frequency ranging from 1 GHz to 100 GHz are illustrated in Fig. 1 (e). It can be clearly seen that S_{21} is above -0.80 dB and S_{11} is below -35.82 dB. The microwave transmission loss thus can be negligible, and therefore, the modulator 3-dB bandwidth is mainly determined by the velocity mismatch between the optical carrier and the microwave, which is given as [6]

$$f_{3dB} = \frac{0.18}{l|n_m - n_0|}$$

where n_m is the microwave refractive index, n_0 is the group refractive index of the optical mode, and l is electrode length. The parameters that we used are $n_0 = 3.48$ at 1.55 μm and l = 3 mm. The microwave propagation constant can be obtained from HFSS simulations, and hence we get $n_m = 1.96$ at 40 GHz. The 3-dB bandwidth of the modulator is then calculated to be about 40 GHz.

In most of the demonstrated silicon optical modulators, metal pads interfacing with external microwave cables are put close to the electrodes. The distance is shorter than the microwave wavelength, and hence no transmission line is needed for the connection. However, in integrated optoelectronic chips, where hundreds or thousands of optical components are put together, the metal pads can only be positioned at the chip edges far from the devices. Therefore, long transmission lines are essential and impedance match should be taken into account. The cross sectional and top views of the transmission line for connection are depicted in Fig. 2 (a) and (b), respectively. The transmission line is gradually widened to terminate with metal pads. The transmission line has a width of 120 μm and a gap separation of 20 μm between the signal and ground lines. It does not have contact holes but sees the 110-nm-thick silicon slab under the 600-nm-thick silica upper cladding. Figure 2 (c) shows the simulated characteristic impedance of the transmission line. It can be seen that Z_0 is about 50 Ohm ranging from 1 GHz to 69 GHz, matched with that of the electrode. The transmission is high and reflection is low below 69 GHz (S_{11} below -17.50 dB and S_{21} above -0.30 dB), and exceeding that, they both experienced a rapid change as shown in Fig. 2 (d). Hence, the 3-dB bandwidth of the transmission line is around 69 GHz.



(a) (b) (c) (d)

Figure 2 (a) Cross section of the transmission line. (b) Top view of the transmission line connecting to metal pads. (c) Characteristic impedance of the transmission line. (d) Transmission (S_{21}) and reflection (S_{11}) frequency responses.

3. Conclusion

We presented numerical studies of a traveling wave electrode for high-speed silicon modulators. The simulation results show that the electrode has good performances in transmission efficiency when the characteristic impedance is optimized to 50 Ohm. Based on this traveling wave electrode, the Mach-Zehnder modulator can have 3-dB bandwidth of 40 GHz, limited by the velocity mismatch between microwave and optical carrier. We also optimized the transition line between the electrode and the metal pads. The results show it has high transmission efficiency with a 3-dB bandwidth of 69 GHz. Therefore, our high-speed electrode and transmission line design can be applied to 40 GHz Mach-Zehnder modulators.

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