A High Speed Mach-Zehnder Silicon Evanescent Modulator Using Capacitively Loaded Traveling Wave Electrode

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Abstract

We demonstrate a traveling-wave Mach-Zehnder silicon evanescent modulator that implements a slotline design for the electrodes. The device has a modulation efficiency of 1.6V-mm and modulation bandwidth of 20 GHz.

I. Introduction

Realizing optical modulators in silicon are crucial to developing future optical communication systems in silicon. Among the various devices to be developed on a Si platform, active devices such as modulators are one of the most challenging to realize because of the lack of efficient electro-opto (EO) effects in silicon. In order to overcome this problem various structures and effects are utilized. Some of these approaches are described below.

Micro-ring modulators are of great interest due to their ultra compact footprint and low drive voltage. The radius of these modulators can be as small as 5 µm with only 1.8 V voltage difference required to shift the resonant frequency resulting in a 17 dB extinction ratio (ER) [1]. High speed operation up to 12.5 G/s using pre-emphasized electrical signal was also demonstrated. However, due to the nature of the ring structure, the optical bandwidth of the ring modulator is generally smaller than 1 nm. Furthermore, the device is also very sensitive to environment temperature, bias condition, and fabrication variations. Any error can result in undesired shift of the resonant frequency; hence extra components such as thermal heaters are usually applied for tuning purpose [2].

Another approach to realize modulators on Si is to use electroabsorption (EA). A SiGe electroabsorption modulator (EAM) based on the Franz-Keldysh and quantum confined Stark effects were reported recently [3,4]. The waveguide SiGe EAM demonstrated in [4] has small footprint, ~50 µm in length and low energy consumption per bit, but the absorption coefficient in SiGe multiple quantum wells (MQW) is lower than InP MQW resulting in lower efficiency. The additional absorption caused by the indirect bandgap of Ge also introduces higher propagation loss than that in III-V material at zero bias. A third scheme to implement a silicon modulator is through a Mach-Zehnder (MZ) interferometer. A Mach-Zehnder modulator (MZM) utilizing carrier depletion inside the silicon waveguides with 1 dB ER at 40 Gb/s has been demonstrated with a modulation efficiency of 40 V-mm [5]. To overcome the trade offs between modulation efficiency and high speed performance, we demonstrated modulators on a hybrid silicon evanescent platform. An EAM was first demonstrated with 10 dB DC extinction ratio (ER) at a bias of -5 V. It had a 16 GHz modulation bandwidth and 30 nm optical bandwidth [6]. A 10 dB ER at 10 Gb/s makes this hybrid EAM very competitive for high speed modulation. Subsequently, a MZM on the hybrid platform was demonstrated having 6.3 dB ER at 10 Gb/s, low drive voltage (4V for a 500 µm device) and large optical bandwidth (~100nm) simultaneously [7]. In this paper, we present a traveling wave MZM modulator with improved traveling
wave electrode (TWE) design to decrease the electrical loss and device capacitance so that that higher bandwidth operation can be achieved.

II. Device Design and Fabrication

The MZM is fabricated on the hybrid silicon platform [8], and more details about the material parameters can be found in [7]. Our earlier MZM design incorporated a coplanar waveguide (CPW) electrode design and had a voltage length product of 2 V-mm and modulation bandwidth up to 8 GHz limited by the RC constant. In general, CPW is a very common TWE design to provide the necessary electrical signal for modulation. However, this design is not applicable if there is a highly doped semiconductor near the electrodes because the skin depth varies with frequency. Once the electrical fields penetrate into the semiconductor, they will suffer the loss from the doped material. Hence, it is important to ensure that the electrical fields do not overlap with the doped semiconductor. In order to decrease the overlap between electrical fields and the doped semiconductor, the cladding layer in this case, a different TWE design should be used. One of the options that has been widely demonstrated for high speed operation is capacitively loaded (CL) TWE [9,10]. The small pads extended from the transmission line can provide the necessary electrical signal to drive the device while the TWE is kept away from the semiconductor. The loaded sections (small pads) are capacitive if the Bragg frequency of each periodic section is much larger than the highest frequency of interest. In this paper, a CL TWE based on a slotline architecture is preferred over a CPW because it can be configured in a push-pull configuration for high speed operation. The device capacitance is reduced to half with the push-pull scheme by serially connecting the diodes on both arms. In the top view of the device shown in Fig. 1(a), the AC signal travels along the slotline and the bias voltage is applied using a probe pad connected to the n-contact layer. The 250 µm modulation length of the device (Lm) is composed by two loaded section (L) of 125 µm with a 140 µm periodicity (Lp), which results in a total length of 280 µm. The filling factor defined by L/Lp is around 0.9. Additionally, two adiabatic tapers, as shown in Fig 1(c), are added between passive and hybrid sections to minimize reflection and increase coupling efficiency. The cross section of the loaded region is depicted in Fig. 1(b). The signal and ground of the slotline are on top of each arm, respectively. The two arms have a common ground by connecting the n-contact layer together. The cladding mesa is 4 µm wide, and the QW/SCH layers are intentionally undercut to 2 µm to reduce the device capacitance. The silicon waveguides have a height of 0.47 µm, a slab height of 0.2 µm, and a width of 1 µm. In order to have less cross talk, the silicon waveguides are etched down to the buried oxide layer around the MMI (Fig. 1(c)), hence the optical signals are completely isolated between the two arms of the MZI. The SEM of the fabricated device is shown in Fig. 1(d).

The fabrication of the modulators follows a standard process of for silicon evanescent devices [11]. First, the III-V epitaxial chip is bonded to a silicon-on-insulator wafer using vertical outgassing channel (VOC) [12] at 300 °C for 3 hours. After removing the III-V substrate, the cladding mesa can be defined by using a self-aligned process. In order to have electrical isolation between each loaded section, the metal on top of the mesa is removed for unloaded regions, and then proton implantation is applied to damage the doping concentration of both p-contact and p-cladding layers such that modulation sections can be defined without disturbing the optical mode. Next, the under-cut is created by a wet etching process, while circular patterns are used as a reference to monitor the etching distance. The electrical isolation between different devices is achieved by removing all the III-V materials on top of passive regions. A stack of n-metal is then deposited to form the ohmic contact. Next, the device is passivated using a thick polymer to have better mechanical support and reduce parasitic capacitance. Finally, a 3 µm thick probe metal is electroplated to reduce electrical loss and achieve better sidewall coverage.

III. Experimental Results

To explore the DC characteristics of the MZM, lensed fibers are used to couple the light in and out of a seven degree angled silicon waveguide. The normalized transmission as a function of reverse bias for two devices is shown in Fig. 2. Due to the phase difference generated from fabrication errors between the two arms, the bias condition at the other arm is adjusted to have peak transmission at no voltage supplied to the tested arm. As can be seen, the Vπ of a 250 µm and a 500 µm long modulators are 6.3 V and 4.8 V, respectively. This results in voltage length products of 2.4 V-mm and 1.6 V-mm, respectively. The number does not scale linearly with length because index change from effects other than carrier depletion, such as quantum confined Stark effect (QCSE) and Kerr effect are more obvious at higher bias voltages. Consequently, a shorter device operating at high bias will experience extra index shift resulting in larger modulation efficiency. In contrast, the loss also increases with bias so that loss imbalance between two arms can lead to a worse ER. The ER
of a 250 µm and a 500 µm long modulator are 12.2 dB and 18.4 dB, respectively.

The high speed performance of the CL TWE modulator is also of great interest. The electrical $S_{21}$ of a 250 µm modulator, displayed in Fig. 3 in the black curve, was first measured using an Agilent E8364A PNA network analyzer with a 3 V bias across the diode. The inset of Fig. 3 illustrates the circuit model for the device under test. The transmission curve indicates a 3 dB cutoff frequency around 25 GHz, which is about three times larger than the previously demonstrated device [7]. A 35 Ω characteristic impedance of the device under push-pull operation is also extracted from full four-port S parameter measurement. The modulation bandwidth of this device was also measured using an Agilent E8703A Lightwave component analyzer. Due to the limited bandwidth of the equipment, the experimental modulation response can only show up to 20 GHz with a 2 dB insertion loss. The apparent peaking at 20 GHz is probably due to the termination at an impedance higher than the transmission line impedance. We are in the process of measuring the modulation bandwidth utilizing a PNA and a high speed photodetector so that the exact 3 dB cutoff frequency can be determined.

**IV. Conclusions**

A silicon evanescent MZM with modulation efficiency of 1.6 V-mm and 12.2 dB extinction ratio is demonstrated. This device has an electrical bandwidth of 25 GHz and a modulation bandwidth over 20 GHz. The MZ structure has the potential for large signal modulation at higher frequency and can be used in an optical interconnect in future silicon based optical networks.

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**V. References**