Hybrid Silicon Evanescent Modulators

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We review a range of modulators on silicon from groups around the world. We describe in detail high frequency, high power electroabsorption and Mach-Zehnder modulators on silicon waveguides with low drive voltages.

Silicon-based modulators are of interest because of their potential to be manufactured in high volume and at a low cost using standard CMOS processing technology. These modulators typically utilize the electroabsorption (EA) and electro-optic (EO) effects inside the silicon waveguide to deliver the necessary phase shift (or extinction ratio) needed for modulation. Exciting results have recently been reported to modulate light in silicon include electroabsorption modulators (EAM) based on the Franz-Keldysh effect in strained SiGe[1], and Mach Zender (MZ) or ring modulators based on carrier effects [2]. Silicon ring modulators that utilize carrier injection to introduce index shift have the advantage of being small and can operate up to 12.5 Gb/s by applying pre-emphasized electrical signals [2]. Their bandwidth is fundamentally limited by carrier life time (~ns) due to the relatively slow recombination process and the optical bandwidth of such a structure is narrow because of the inherent resonant nature of the ring structure. Mach-Zehnder modulators (MZM) with refractive index shift introduced by the carrier depletion effect can increase the electrical bandwidth up to 40 Gb/s and have reasonable optical bandwidths at the expense of higher voltage-length products: 40 V-mm [3]. The tradeoff between bandwidth and modulation efficiency is more difficult compared to conventional III-V modulators [4,5]. Therefore, our motivation is to combine III-V layers on silicon waveguides to realize modulators that can simultaneously achieve high bandwidth, large modulation efficiency, high power, wide optical bandwidth and low drive voltage. We describe two different modulators on the hybrid silicon evanescent platform [6], where the EA or EO effect is introduced through the III-V material. The EAM is based on the quantum confined Stark effect (QCSE) and has a 10 dB extinction ratio (ER) at -4 V, a 16 GHz bandwidth, and 30 nm optical bandwidth, sufficient for C-band application [7]. Additionally, we demonstrated a MZM with a 1.5 V-mm modulation efficiency, a 8 GHz bandwidth, and over 100 nm optical bandwidth by using carrier depletion effect in offset multiple quantum wells (MQW) [8]. The bandwidth, as mentioned, is not limited by physical effects in the material and can be improved by implementing an appropriate electrode design as described in [2]. These hybrid silicon modulators can be integrated with tunable lasers to generate data streams at multiple wavelengths, and can be applied to WDM systems.

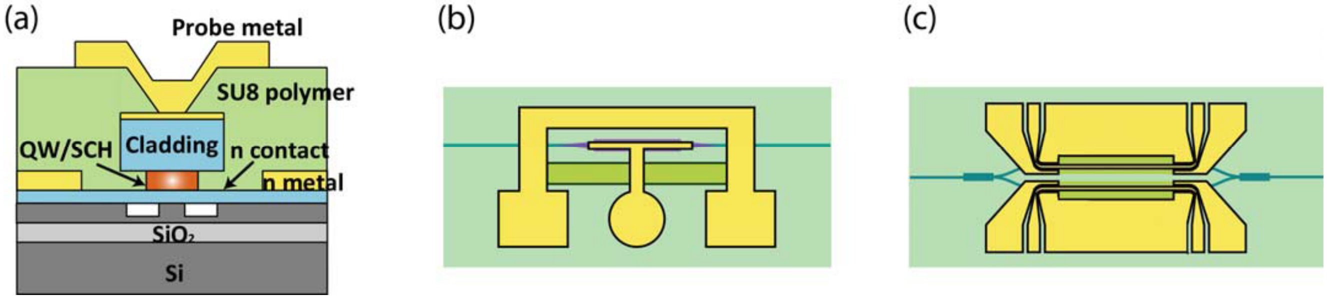

Figure 1: (a) Cross section of both EAM and MZM at the hybrid section. (b) Schematic top view of an EAM. (c) Schematic top view of a MZM.

The device cross section is similar for both EAM and MZM as shown in Fig.1 (a). A III-V epitaxial material was first bonded to a silicon on insulation wafer using a vertical outgassing channel technique for low temperature bonding [9]. This is followed by a standard lithographic process to define cladding mesa, metal contacts and passivation layers. Two techniques were used to get better high speed performance. First, the QW and separate confinement heterostructure (SCH) layers were under-cut to 2 µm so that the total device capacitance is reduced while the cladding mesa is maintained at 4 µm for low contact resistance and a large tolerance for lithographic alignment. Next, a 5 µm thick polymer was applied to provide additional mechanical support to the thin bonding layer and to reduce the parasitic capacitances and implement the desired electrode design. In addition, two 60 µm long tapers are added to minimize the optical reflection and increase coupling efficiency due to the mode mismatch between the passive and hybrid sections.

The top view of a typical EAM with metal contact is illustrated in Fig.1 (b). By changing the length of the absorber, the applied bias required to achieve a certain ER varies as shown in Fig. 2(a). The frequency response of a 100 µm EAM exhibits a

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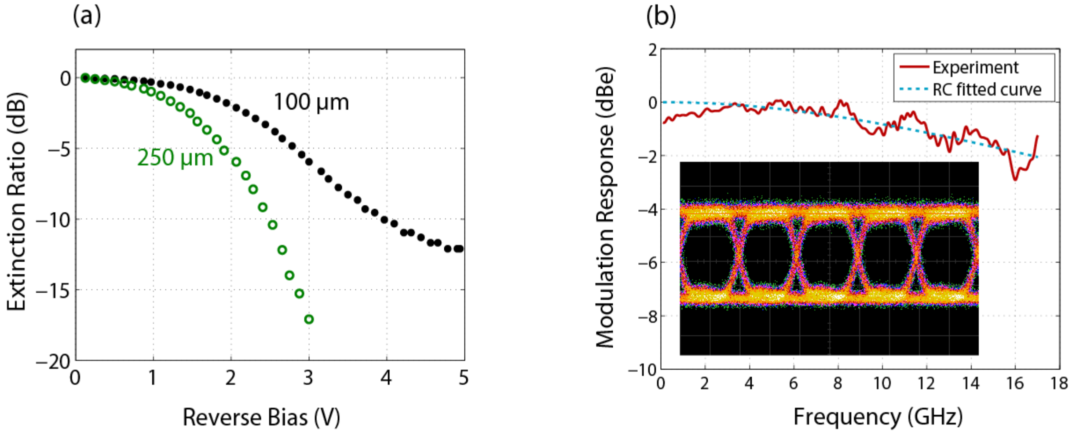

Figure 2: (a) DC characteristic of two EAMs with different length. (b) Frequency response and 10 Gb/s eye diagram with 2^{31}-1 PRBS.

16 GHz bandwidth which agrees with the theoretical RC limited curve. The 10 Gb/s signal has an ER of 11 dB at 3.2 V swing as shown in the inset of Fig.2 (a).

A 500 µm MZM is shown in Fig.1 (c) with coplanar waveguides (CPW) in order to achieve high speed performance. As can be seen from Fig. 3, it has a modulation efficiency of 1.5 V-mm. The extinction ratio (ER) is 12 dB for a dc bias of -1.6 V applied to the other arm. The bias dependence in ER is due to the loss imbalance introduced between the two arms since the quantum-confined Stark effect (QCSE) becomes more significant for applied voltages greater than 3V. Fig. 3(b) shows the small signal response with 25 Ω termination, which indicates a 3dB cutoff frequency of 8 GHz. The 10 Gb/s pseudorandom bit sequence (PRBS) NRZ response is shown in the inset of Fig.3 (b) and is measured to have 6.3 dB ER at 3 V swing.

The results of the EAM and MZM both show the potential for high speed modulation and can be used for future optical interconnects. The bandwidths of both the EAM and MZM are currently RC limited. However, this can be improved by applying the proper traveling wave electrode design and termination.

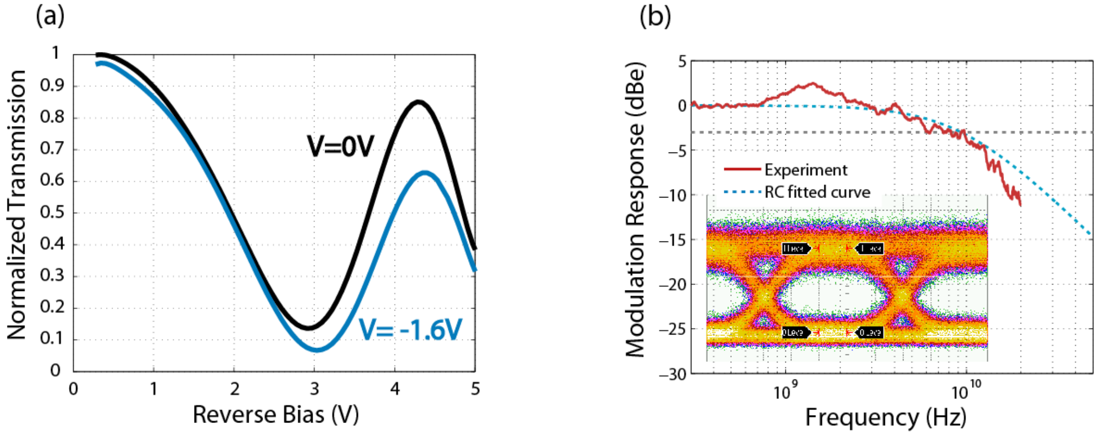

Figure 3: (a) DC characteristic of a 500 µm MZM. (b) Frequency response and 10 Gb/s eye diagram with 2^{31}-1 PRBS.

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