**Low Driving Voltage Electroabsorption Modulator Based on Band Filling Effect**

Qiangsheng Huang,1,2 Yingchen Wu,2,3 and Keqi Ma,1 Jianhao Zhang,1 Weiqiang Xie,2 Xin Fu,1 Yaocheng Shi,1 Jianxin Cheng,4 Kaixuan Zhang,4 Chenzhao Zhang,4 Gunther Roelkens,2 Dries Van Thourhout,2 Liu Liu,4 Jianjun He,2 and Sailing He1, 4

1 *Centre for Optical and Electromagnetic Research, Zhejiang Provincial Key Laboratory for Sensing Technologies, Zhejiang University, Hangzhou, 310058, China*

2 *Photonics Research Group, Department of Information Technology, Ghent University-IMEC, Ghent B-9000, Belgium*

3 *State Key Laboratory of Modern Optical Instrumentation, Centre for Integrated Optoelectronics, Department of Optical Engineering, Zhejiang University, Hangzhou, China 310027*

4 *ZJU-SCNU Joint Research Center of Photonics, Centre for Optical and Electromagnetic Research, South China Academy of Advanced Optoelectronics, Science Building #5, South China Normal University, Higher-Education Mega-Center, Guangzhou 510006, China*

In this paper, a new method for realizing a low driving voltage electroabsorption modulator based on the band-filling effect is demonstrated. The electroabsorption modulator is fabricated using the BCB bonding technique on a silicon-on–insulator platform. When the electroabsorption modulator is forward biased, the band-filling effect occurs, which leads to a blue shift of the exciton absorption spectrum while the absorption intensity stays almost the same. The length of the electroabsorption modulator is only 80 μm. In static performance, we can get an extinction ratio of more than 20dB within 100mV bias variation. In dynamic performance, we can achieve a 1.25Gbps modulation with a 6.3dB extinction ratio using only a 50mV peak to peak driving voltage. The band-filling effect provides a novel method for realizing ultra-low-driving-voltage electroabsorption modulators.

Quantum-confined Stark effects (QCSE) based electroabsorption modulators (EAM) have high speed, low energy consumption and relatively high extinction ratio with small footprint size.1, 2 These features makes EAM widely used in long distance optical communication systems. In addition, EAMs can also be used as high speed photodetectors.3 This dual function property makes EAMs advantageous in compact optoelectronic oscillators (OEO).4 Recently, silicon photonics integrated with electronic devices fabricated in CMOS production lines have become a promising technology in short distance optical communication and single chip OEO systems.5,6 High speed EAM has also been successfully used in silicon photonic circuits though hybrid bonding technology.1, 7, 8 However, an EAM directly driven by low voltage from a digital logical CMOS driver is still missing. Recently, a sub 100mV driving voltage silicon modulator based on tuning resonant wavelength in a *\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_*

***a) Author to whom correspondence should be addressed. Electronic mail: sailing@kth.se.***

high Q microring resonator or photonic crystal cavity has been demonstrated.9, 10 However, they are sensitive to fabrication imperfections and cannot be used as photodetectors. For EAMs, it is challenging to reduce the driving voltage without an increase in the modulator size and insertion loss. Even when using a complex slow-light Bragg reflector waveguide to enhance light-matter interaction, it is still hard to reduce the driving voltage below 100 mV and integrate with silicon photonics.11 Therefore, it is desirable to find a new, simple way to reduce the driving voltage without requiring additional fabrication procedures.

Band-filling effect in modulation-doped MQWs has been studied in the 1980s.12 The band-filling effect, in which the conduction subbands are filled with two-dimensional (2D) electron gas, results in a blue shift of the absorption edge. By controlling the bias voltage, electron concentrations in the MQWs region can be adjusted. In this way, the MQWs absorption edge can be controlled by bias voltage though the band-filling effect. This effect has been used in 100mV driven Q-switching lasers through electrooptical phenomena in a modulation-doped quantum well.13 However, there is still a lack of an EAM based on the band-filling effect.

In this paper, we demonstrate a new type low driving voltage EAM based on the band-filling effect at 1.55 μm. The EAM is bonded on a silicon-on-insulator (SOI) wafer, which makes it a promising direct digital CMOS driven modulator.

Fig. 1(a) and (b) show the cross-section view and the three-dimensional view, respectively, for the EAM integrated on SOI using BCB adhesive bonding technology.7 It consists of a silicon ridge waveguide, a thin bonding layer and a III/V p-i-n structure. The silicon ridge waveguide is fabricated on a 380nm-thick silicon layer. The thin bonding layer includes around 30nm BCB layer and around 15 nm silica layer. At the top of the III/V p-i-n structure, there is a 100nm p-InGaAs (1.5×1019 cm-3) layer connected with the source metal. Below it, there is a 1.5 μm gradually-doped (2×1018 to 1×1018 cm-3) p-InP. In the intrinsic region, a multiple-quantum-well (MQW) stack is sandwiched between two separate confinement heterostructure layers of In0.52Al0.16Ga0.32As. There are 10 compressive In0.65Al0.09Ga0.26As wells and 11 tensile In0.42Al0.17Ga0.39As barriers composing the MQW. At the bottom of the III/V structure, a 150nm thin n-InP (3×1018 cm-3) layer is connected with the ground metal. Detailed epitaxial layers are shown in Fig. 1(a).

The fabrication process of this EAM is simpler than that of our previous laser/modulator.7, 8 Thanks to the highly selective wet etching process, we can directly use a photoresist mask instead of a SiN hard mask to define the III/V waveguide. In this way, we do not need to deposit or etch the SiN layer by PECVD or ICP-RIE. The SOI is fabricated through an ePIXfab Multi Project Wafer run.15 The silicon ridge waveguide is 1.5 μm wide, and the slab height is 160 nm. The silicon ridge waveguide is planarized with silica. After bonding and removing the InP substrate, the pattern on the InGaAs layer is defined by wet-etching with the photoresist mask. Then the p-InP waveguide is defined by a last step InGaAs pattern through wet etching. Its cross section becomes an upside down trapezoid with a width of 2.5 µm at the top and 1.5 μm width at the bottom. The intrinsic layer is defined by a 5 μm wide photoresist mask. Through an under-etching process, the intrinsic region is reduced to 1.5 μm in width. A 0.1 µm thick Ni/Ge/Au alloy is deposited onto the n-InP for n-contacts. Then the unwanted n-InP is removed by wet-etching. A 2.5 µm thick DVS-BCB is used for passivation and planarization. The DVS-BCB is etched away in the via-holes for metal connection. A 1 μm thick Ti/Au alloy is deposited onto the p-InGaAs and n-contacts for 100 μm pitch ground-signal-ground (GSG) metal contact. Fig. 1(c) shows the fabrication results for the cross section of the III-V/Si hybrid waveguide. Fig. 1(d) shows a top-down photograph for the lump electrode EAM.

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FIG. 1. (a) Cross-section view for the EAM bonded on SOI. (b) Three-dimensional sketch of the EAM bonded on SOI. (c) SEM image of the cross-section view of the III-V/Si hybrid waveguide. (d) Top image of the III-V/Si hybrid integrated EAM.

Fig. 2 (a) also shows the simulated fundamental optical mode for the EAM bonded on the silicon waveguide. The optical power confinement factor in multi-quantum wells is around 24% (distribution rather than confinement?). The mode conversion from the silicon ridge waveguide to the EAM waveguide is achieved by a 45 µm long bi-level taper.8,14 The silicon ridge waveguide remains straight in the bi-level taper. In the first level, the mode is converted from the silicon ridge waveguide to a III-V waveguide without a thick p-InP layer, with the intrinsic layer width laterally tapered from 0.2 μm to 1.5 μm. The second level taper transforms the optical mode into the full III-V waveguide mode, with the p-InP layer laterally tapered from 0.2 µm to 2.5 µm and the intrinsic layer kept the same. The simulation coupling efficiency between the silicon ridge waveguide and EAM waveguide is around 98%.



FIG. 2. (a) Mode profile of the III-V/Si hybrid waveguide. (b) Mode transformation in the 45μm long bi-level taper

The EAM with InAlGaAs quantum wells has a strong exciton absorption peak at the absorption spectra edge due to its large conduction band offset.2 Since the band-to-band continuum transition energy (which is above the exciton transition energy) has a small influence on the absorption edge, we adopt a theoretical model only containing exciton transition, in order to simplify calculation of the absorption spectra and the shift of the absorption edge for the EAM.16 The material parameters of MQW, such as effective electron/hole mass, Luttinger parameters, band energy level, etc., are taken from reference [17], according to the mole fraction of each element. The half-linewidth for the absorption peak varies from 1 meV at zero electric field to 1.4 meV at 42 KV/cm. The effective mass *m\** of the average matrix element is 0.0064 *m0*,16 where *m0* is the electron mass.

The simulated exciton absorption spectra for the 80 μm long EAM is shown in Fig. 3. Due to the p-i-n structure, there is a built-in electric field in 0 V. The zero electric field in the intrinsic layer is achieved at a forward bias of 0.6 V. Below 0.6 V, the absorption spectra for the EAM is calculated based on QCSE. The exciton absorption peak red shifts with increasing applied electric field. Due to decreasing electron-hole overlap integral with increasing electric field, the absorption magnitude decreases. Above 0.6V, the absorption spectra for the EAM is calculated based on the band-filling effect. The exciton absorption peak blue shifts with current injected into the conduction band. Because the electron-hole overlap integral remains almost constant with increases in current density, the absorption does not decrease in magnitude. The exciton transition energy shift *ΔE* is given by: *ΔE = (1+me/mh)EF*, where *EF* is the fermi energy, and *me*and *mh* are the electron and hole mass, respectively.12 When *EF* is much higher than the lowest conduction subbands *E1*, *EF* is linear with carrier density in the quantum well.18 Because the carrier density is proportional to the injected current, and the injected current is directly related to the applied voltage, the absorption peak shifts are directly proportional with the applied voltage. In this way, by modulating the applied voltage, we can modulate the output optical power.



FIG. 3. The simulated exciton absorption spectra (dB) for the 80 μm long EAM with different bias voltages. The largest absorption intensity is more than 20dB.

We first measure the EAM’s static performance with different biases at 1.55 μm, shown in Fig. 4(a). The measurement results are normalized to a straight waveguide with the same grating couplers. The insertion loss of the EAM is around 5dB, larger than the simulation results. We think that it mainly comes from the width of the intrinsic region being larger than the designed value of 1.5 μm, shown in Fig. 1(c). In this case, the bi-level taper coupler will excite higher order modes and cause unwanted reflection during mode transformation, especially in the first level taper.14 Fig. 4(a) shows that there are two absorption variation sections when we change the bias voltage. In the reverse bias, the absorption variation is caused by continuous transition absorption. The extinction ratio is around 4dB with the voltage changing from -1V to -2V. In the forward bias, the absorption variation is caused by exciton transition absorption. The extinction ratio is more than 20dB with only 100mV bias variation. Furthermore, we measure the normalization absorption spectra with bias variation. The exciton absorption peak intensity and shifts are in good agreement with the simulation results shown in Fig. 3. In the forward bias, the shift rate of the exciton absorption peak is around 50 nm/V to the short wavelength, without a reduction in absorption intensity. Thus, we can achieve a low driving voltage EAM in the forward bias.



FIG. 4. (a) The bias dependent normalized transmission for the 80 μm long EAM at 1.55 μm. (b) The exciton absorption spectra (dB) with different bias voltages. The largest absorption intensity is more than 20dB.

Then, we measure the high speed performance of the EAM at 1.55 μm. A non-return-to-zero (NRZ) 231-1 pseudorandom bit sequence (PRBS) pattern is generated and attenuated to a level of 50 mV swing, and then applied to an EAM sample via a bias bee under a forward bias of 0.6 V. The modulated light is coupled out to a fiber through a grating coupler and amplified by an erbium-doped fiber amplifier (EDFA). The amplified spontaneous emission caused by the EDFA is filtered out by a narrow optical filter. After that, we can measure the eye diagrams from a Tektronix 8300A digital series analyzer. The 1.25 Gbps eye diagram of the EAM is shown in Fig. 5(a). The dynamic extinction ratio is 6.3 dB, which is twice as large as the low voltage driving silicon modulator based on tuning resonant wavelength with the same peak-to-peak voltage. The method to calculate the energy consumption for the EAM is presented in reference [1]. Because the cross-section of our 80 μm long EAM is the same as our previous 100 μm long modulator,8 the junction capacitance is around 116fF. The transient energy consumption for this EAM is 0.29 fJ/bit. The transient energy consumption can be further reduced by narrowing the intrinsic layer width to decrease the junction capacitance. The DC energy consumption at 1.25Gbps is 110fJ/bit. The DC consumption can be reduced by increasing the modulator speed.

Fig. 5(b) shows the high speed performance for the identical EAM at reverse bias. The speed of the EAM with a lump electrode working at reverse bias is limited by the RC time constant.1, 8 However, for the EAM working at forward bias, the rise and fall time is limited by the carrier lifetime in MQWs. Through using modulation-doped MQWs, 12, 13 we can shift the work point to the reverse bias. In this way, we can reduce the carrier lifetime and increase the EAM speed based on the band filling effect.



FIG. 5. Measured 231-1 PRBS NRZ eye diagrams at 1.55 μm (a) 1.25 Gbps at forward bias 0.6V. (b) 12.5 Gbps at reverse bias -1.5V.

In summary, we have demonstrated a new type of electroabsorption modulator based on the band filling effect. The electroabsorption was bonded on silicon-on-insulator and coupled with a silicon waveguide through a bi-level taper coupler. With 100mV bias variation, the DC extinction ratio can be adjusted more than 20dB. The exciton absorption peak shifts and intensity variation are in good agreement with the simulation results. A clear open eye diagram is obtained at 1.25 Gbps with a dynamic extinction ratio of 6.3 dB. The peak to peak driving voltage is only 50 mV. The speed of the present device is limited by carrier lifetime and can be further improved by using modulation-doped multi-quantum wells. The insertion loss and transient energy consumption can be further improved with optimized fabrication processes.

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