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

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A new way to make low driving voltage electroabsorption modulator based on band-filling effect is demonstrated. The electroabsorption modulator composed of InAlGaAs quantum wells is bonded on silicon-on-insulator wafer. The band-filling effect happens when electroabsorption modulator is worked at forward bias. In this way, the exciton absorption blue shifts and the absorption intensity almost keeps same. We fabricated an 80 μm long compact electroabsorption modulator. In the static transmission performance, we can achieve extinction ratio more than 20dB with only 100mV bias variation. In the high speed transmission performance, we showed a 1.25Gbps electroabsorption modulator, with only 50mV peak to peak driving voltage and the dynamic extinction ratio is 6.3dB. This indicates that the present band-filling effect in electroabsorption modulator provides a novel method for low driving voltage optical modulator.

Electroabsorption modulator (EAM) based on quantum-confined Stark effects (QCSE) in multi-quantum wells (MQWs) has high speed, low energy consumption and high extinct ratio with small size features.1, 2 These features makes EAM been successfully used in long distance optical communication system. And, besides that, EAM also can be used as high speed photodetector. 3 This dual function property makes EAM advantage in the compact optoelectronic oscillators (OEO).4 Recently, silicon photonics integrated with electronic device fabricated in CMOS production lines have become a promising way in short distance optical communication and single chip OEO system.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 digital logical CMOS driver is still missing. Recently, sub 100mV driving voltage silicon modulator based on tuning resonant wavelength in *\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_*

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high Q microring resonator or photonic crystal cavity have been demonstrated.9, 10 However, they are sensitive to fabrication imperfects and cannot be used as photodetectors. For EAM, it is a challenging to reduce the driving voltage without increase the modulator size and insertion loss. Even though using 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 desired to find a new simple way to reduce the driving voltage without increase additional fabrication procedure.

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

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

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

The fabrication process of this EAM is simpler than our previous laser, modulator fabrication process.7, 8 Thanks to the high selective wet etching process, we can directly use photoresist mask instead of SiN hard mask to define the III/V waveguide. In this way, we don’t need to deposit or etch 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 width and the slab height is 160 nm. The silicon ridge waveguide is planarized with silica. After bonding and removing InP Substrate, the pattern on InGaAs layer is defined by wet-etching with the photoresist mask. Then the p-InP waveguide is defined by last step InGaAs pattern though wet etching. Its cross section becomes an upside down trapezoid with a width of 2.5 µm at top and 1.5 μm width at bottom. The intrinsic layer is defined by a 5 μm width photoresist mask. Though under-etching process, the intrinsic region is reduced to 1.5 μm width. A 0.1 µm thick Ni/Ge/Au alloy was deposited on n-InP for n-contacts. Then the unwanted n-InP is removed away 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 on 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 the top-view 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 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 in multi-quantum wells is around 24%. 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 keeps straight in the bi-level taper. In the first level, the mode is converted from the silicon ridge waveguide to III-V waveguide without 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 p-InP layer laterally tapered from 0.2 µm to 2.5 µm and the intrinsic layer keeps 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

EAM with InAlGaAs quantum wells has a strong exciton absorption peak at 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 contains exciton transition, to simplify calculation the absorption spectra and the shift of absorption edge for the EAM.16 The material parameters of MQW, such as effective electron/hole mass, Luttinger paramenters, band energy level et. al., 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\** in average matrix element is 0.0064 *m0*,16 where *m0* is the electron mass.

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



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

We firstly measure the EAM’s static performance with different bias at 1.55 μm, shown in Fig. 4(a). The measurement results is normalized to a straight waveguide with same grating couplers. The insertion loss of the EAM with is around 5dB, larger than the simulation results. We think that it mainly comes from the width of the intrinsic region is larger than designed values 1.5 μm, shown in Fig. 1(c). In this case, the bi-level taper coupler will excite high 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 changes bias voltage. In the reverse bias, the absorption variation is caused by continuum transitions absorption. The extinction ratio is around 4dB with voltage changing from -1V to -2V. In the forward bias, the absorption variation is caused by exiton 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 exiton absorption peak intensity and shifts are in good agreement with the simulation results shown in Fig. 3. In the forward bias, the exciton absorption peak shifts rate is around 50 nm/V to the short wavelength, without reduce absorption intensity. So in this way, 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 voltage. 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 generated and attenuated to a level of 50 mV swing, is applied to EAM sample via a bias bee under a forward bias 0.6 V. The modulated light is coupled out to a fiber though a grating coupler and amplified by an erbium-doped fiber amplifier (EDFA). The amplified spontaneous emission caused by 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 ratios is 6.3 dB which is twice larger than the low voltage driving silicon modulator based on tuning resonant wavelength with same peak-to-peak voltage. The method to calculate the energy consumption for the EAM is presented in reference [1]. Due to the cross-section of our 80 μm long EAM is same to our pervious 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 EAM with lump electrode worked at reverse bias is limited by the RC time constant.1, 8 However, for the EAM worked at forward bias, the rise and fall time is limited by the carrier lifetime in MQW. Though using modulation-doped MQW, 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 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 electroabsorption modulator based on band filling effect. The electroabsorption was bonded on silicon-on-insulator though a bi-level taper coupler. With 100mV bias variation, the DC extinction ratio can be more than 20dB. The exiton absorption peak shifts and intensity variation are in good agreement with 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 improvement 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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