A Hybrid Silicon–AlGaInAs Phase Modulator
Hui-Wen Chen, Student Member, IEEE, Ying-Hao Kuo, and John E. Bowers, Fellow, IEEE

Abstract—We demonstrate a carrier depletion phase modulator based on the hybrid silicon evanescent platform. A low temperature and robust bonding process is employed to transfer III–V epitaxial layers to patterned silicon waveguides. An external electric field is applied across the doped multiple quantum wells so that carriers are depleted, resulting in an index change. The device has a voltage-length product, \( V_L \), of 4 V-mm at 1550 nm. An optical bandwidth of 100 nm with an extinction ratio over 10 dB is achieved. The device can handle optical power up to 28 mW.

Index Terms—Hybrid integrated circuits, modulation, silicon-on-insulator (SOI) technology.

I. INTRODUCTION

Silicon photonics is receiving attention due to potential to realize low cost photonic integrated circuits by utilizing the manufacturing infrastructure of CMOS electronics. Several key components have been successfully demonstrated on the hybrid silicon evanescent platform [1], such as lasers [2]–[4], amplifiers [5], and detectors [6]. Optical modulators, another key element in optical communication systems, have also been demonstrated in silicon. Carrier depletion phase modulators in a Mach–Zehnder interferometer (MZI) configuration [7] can achieve high-speed amplitude modulation since it is not limited by the slow carrier injection, but the index change introduced by such devices is generally small. The concern of propagation loss results in low concentration of carriers depleted in the junction and hence limits the index change. On the other hand, ring resonator configurations using carrier depletion [8] can be very efficient in modulation due to small index changes required for shifting the resonant frequency. Its narrow bandwidth (1 nm) in conjunction with the difficulty to maintain the operation wavelength makes integration of these devices in a wavelength-division multiplexing (WDM)-based photonic integrated circuits (PICs) relatively challenging. Earlier this year, we demonstrated an electroabsorption silicon evanescent modulator based on the quantum confined Stark effect (QCSE) [9]. By utilizing QCSE, the device can provide efficient high-speed modulation with a small device footprint. However, it is still rather sensitive to temperature and has a restricted optical bandwidth compared to MZI modulators. Here, we report a silicon evanescent phase modulator utilizing carrier depletion in multiple quantum wells (MQW). When used in an MZI device configuration, the amplitude modulation optical bandwidth (100 nm) is much larger than the EAM and ring resonator counterparts. In addition, the efficient carrier depletion in the MQWs leads to a ten-fold reduction in device footprint over their silicon MZI modulator counterparts.

II. DEVICE STRUCTURE AND FABRICATION

The silicon evanescent phase modulator, illustrated in Fig. 1, is a hybrid structure consisting of III–V MQWs bonded to silicon waveguides fabricated on a silicon-on-insulator (SOI) wafer. The structure is listed in Table I and contains 15 compressive MQWs with 16 tensile barriers and two separate confinement heterostructure (SCH) layers to achieve strain balance. The photoluminescent (PL) peak of the MQWs is designed at 1.36 \( \mu \)m to ensure low absorption at the operating wavelength (1.55 \( \mu \)m). Both the top SCH layer and MQW are doped in order to introduce free carriers [10]. The thickness and doping of the top SCH layer is carefully designed to be completely depleted in the absence of an externally applied electric field. Thus, all applied bias voltage will be used to deplete carriers in the MQW region rather than the SCH layer. The compositions of wells and barriers are chosen to have

Table I

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material and Composition</th>
<th>Doping</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Contact</td>
<td>In(<em>{0.53})Ga(</em>{0.47})As</td>
<td>P – 1e19</td>
<td>0.1 ( \mu )m</td>
</tr>
<tr>
<td>Cladding</td>
<td>InP</td>
<td>P – 1e18</td>
<td>1.5 ( \mu )m</td>
</tr>
<tr>
<td>SCH</td>
<td>In(<em>{0.53})Ga(</em>{0.47})As 0.30%As, 1.3 ( \mu )m</td>
<td>N – 1e17</td>
<td>0.1 ( \mu )m</td>
</tr>
<tr>
<td>QW ((\lambda_p=1.36 \mu m))</td>
<td>In(<em>{0.53})Ga(</em>{0.47})As 0.31%As, 0.31%As, 0.41%As (15x)</td>
<td>N – 1e17</td>
<td>8 nm</td>
</tr>
<tr>
<td>SCH</td>
<td>In(<em>{0.53})Ga(</em>{0.47})As 0.30%As, 1.3 ( \mu )m</td>
<td>N – 3e18</td>
<td>0.05 ( \mu )m</td>
</tr>
<tr>
<td>N Contact</td>
<td>InP</td>
<td>N – 3e18</td>
<td>0.11 ( \mu )m</td>
</tr>
<tr>
<td>Super lattice</td>
<td>In(<em>{0.53})Ga(</em>{0.47})As 0.32%P 0.67% (2x)</td>
<td>N – 3e18</td>
<td>7.5 nm</td>
</tr>
<tr>
<td>InP (2x)</td>
<td></td>
<td>N – 3e18</td>
<td>7.5 nm</td>
</tr>
<tr>
<td>Bonding</td>
<td>InP</td>
<td>N – 3e18</td>
<td>10 ( \mu )m</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic cross section of the hybrid waveguide.
shallower $\Delta E_c$ compared to electroabsorption modulators (EAM) and lasers for more efficient carrier depletion.

The cladding mesa width is 4 $\mu$m while the QW and SCH layers are undercut to 2.8 $\mu$m to reduce the device capacitance (Fig. 1). Silicon waveguides were fabricated with a waveguide height of 0.48 $\mu$m and slab height of 0.24 $\mu$m. The width of the waveguide is 1 $\mu$m in the modulation section and 1.5 $\mu$m in passive regions. This leads to a QW confinement factor of $\sim$15%. A 60-$\mu$m hybrid taper, laterally tapered in both the silicon and III–V epitaxial layers, is added to minimize reflections and adiabatically transform the optical mode between the passive silicon waveguides and the hybrid waveguide structure. Two $1 \times 2$ MMIs are used for splitting and combining of light into the two arms of the MZI.

The silicon evanescent device fabrication flow consists of silicon waveguide formation, low temperature wafer bonding, and post-bonding fabrication. In this paper, we used a 4-hour bonding technique utilizing vertical outgassing channels (VOC) [11]. The array of $6 \times 6$ $\mu$m VOCs with 50-$\mu$m spacing assists in quenching $H_2$ outgassing during bonding.

After bonding, the mesa structure is fabricated using a self-aligned dry etch process [6]. A stack of Pd–Ti–Pd–Au p-contacts is used as the hard mask with a following selective wet etch to create the undercut. The sample is then dipped into a mixture of HCL–H$_2$O to remove native indium oxide on the surface of the QW/SCH layers to avoid current leakage before depositing Ni–Au–Ge–Ni–Au n-contacts. A 4-$\mu$m-thick polymer is used to provide additional mechanical support to the thin bonding layer and to separate the metal pad from the underlying ground in order to implement the desired microstrip line design and to minimize parasitic capacitances.

III. EXPERIMENT AND RESULTS

The index shift of the material was observed by measuring the resonant spectrum of the Fabry–Pérot (FP) cavity formed by a straight hybrid waveguide with polished facets. TE-polarized light from a tunable laser is coupled into a 1.7-mm-long silicon waveguide with 1-mm-long hybrid section. The device is operated under different reverse bias while the laser wavelength is swept at speed of 500 nm/s. In order to examine wavelength dependence, the center wavelength is selected from 1525 to 1625 nm with 25-nm spacing. Output light is then collected into a lensed fiber and detected by an InGaAs photodetector to record the FP spectrum for further analysis. The experimental data shows that higher bias delivers higher index shift, which is a result of both the carrier depletion effect and QCSE. More carriers are depleted with stronger external electrical field while shorter wavelengths are affected more by QCSE since they are closer to the absorption edge. The results also indicate that shorter wavelengths are affected more by QCSE since they are closer to the absorption edge. The same phenomenon can be observed by measuring the photocurrent from devices with an antireflection (AR) coating device as shown in Fig. 2. The absorption edge (3-dB absorption) shifts into the $C$-band with reverse bias larger than $-3$ V.

In order to investigate the mechanism of index shift inside doped AlGaInAs MQWs, an epitaxial III–V material with undoped MQW was fabricated and measured for comparison. As shown in Fig. 3, an undoped MQW has a smaller index change at 1 V because there is no carrier depleted from the MQW. When the bias voltage increases, QCSE begins to take account and thus the slopes between these two curves are almost identical. Meanwhile, the combination of carrier depletion effect and QCSE for doped MQW structure creates a more linear response between the index shift and bias voltage.

MZI modulators based on offset doped MQWs were also fabricated and tested. Fig. 4 presents the modulation efficiency and extinction ratio (ER) at different wavelengths for the device with 1-mm hybrid section. Lower $V_\pi$ at shorter wavelength is consistent with results from FP measurement. A calculated $V_\pi$ curve based on band filling [12] and plasma effects is shown in Fig. 4. The discrepancy between theoretical values and experimental data at shorter wavelengths is due to the influence of QCSE. The optical bandwidth is over 100 nm for ER greater than 10 dB. The
ER is limited to 14 dB mainly due to the loss imbalance between the two arms of the MZI introduced by QCSE.

The 1-mm MZI modulator was tested at $-3$ V to determine high-speed performance as well. The device capacitance is 2 pF. The optical response shows a 3-dB cutoff at 2.5 GHz with a 50-Ω cap termination. This agrees with the 3-dB theoretical cutoff frequency of $\sim 2.4$ GHz calculated from the series resistance (8Ω) and termination resistance. The high-speed performance can be improved with a better microwave design, such as periodic loading, and a termination between 10 to 20 Ω [13].

Power handling is important for MQW-based devices. We measured the index change under different input power from $-3.5$ to 5.5 dBm. The modulation efficiency measured from the FP test shows little variation. Photocurrents collected from an AR-coated device are investigated as well as a function of optical input. The device is soldered to a copper substrate to improve heat dissipation. The experimental results are shown in Fig. 5, where photocurrent is measured at several reverse bias conditions for different input power levels. The device suffered destructive breakdown at 28-mW input power at $-5.5$-V bias. A 1-dB saturation at 28-mW input can be observed at all biases, which implies that current saturation is not dominated by a screening effect. This saturation can be attributed to free carrier absorption inside silicon [14].

IV. CONCLUSION

A silicon evanescent phase modulator capable of handling high optical powers with broad optical bandwidth has been demonstrated. The modulator operates over the entire C-band part of the L-band from 1500 and 1600 nm with an extinction ratio of 10 dB allowing for use in WDM optical networks. The combination of carrier depletion and QCSE delivers a linear modulation response from 0 to $-5$ V. The modulator exhibits a $V_L$ of 4 V-mm at 1550 nm and below 6 V-mm within a 150-nm range. This efficient carrier depletion phase modulator can be integrated in coherent communication links or as MZI switches with lasers, amplifiers, and photodetectors on silicon to make compact high-speed optical interconnects.

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REFERENCES