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0.3 V drive voltage GaAs/AlGaAs substrate removed Mach–Zehnder intensity modulators

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Push-pull driven Mach–Zehnder intensity modulators with a record low drive voltage of 0.3 V were realized in substrate removed very compact GaAs/AlGaAs optical waveguides at 1.55 μm. The modulator electrode is 7 mm long, corresponding to a drive voltage length product of 0.21 V cm. The modulation is due to linear electro-optic and carrier depletion effects and has a high speed potential. The propagation loss was 8 dB/cm, making moderately long devices possible. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2931057]

Modulators are essential building blocks for fiber optic communications, rf photonics, on chip interconnects, and instrumentation.[1] All these applications require low cost, low drive voltage external modulators with preferably wide bandwidth. Low drive voltage is particularly important since drive power is proportional to its square and power becomes more difficult to generate with increasing frequency. Hence, one of the current research objectives is to realize modulators with subvolt drive voltage. This work reports a technology based on compound semiconductors and substrate removal processing to deliver very low drive voltage modulators. Compound semiconductors have relatively small electro-optic coefficients but have high index of refraction. High refractive index significantly increases electro-optic efficiency while making strong optical confinement possible. Furthermore, high quality epitaxial growth and advanced processing techniques enable flexibility in designing and fabricating original structures. Utilizing these properties, we have demonstrated bulk GaAs/AlGaAs modulators with a drive voltage of 3.7 V cm.[2] In this paper, we present an original approach that reduces the drive voltage by more than an order of magnitude to 0.3 V in a Mach–Zehnder intensity modulator using substrate removed very compact optical waveguides. This is the lowest drive voltage reported for any optical modulator.

The device reported is a Mach–Zehnder intensity modulator with the input and output y branches separating the arms of the interferometer. The arms are 7 mm long. Figure 1 shows the cross sectional schematic of the modulator arms, which are identical phase modulators. The total thickness of the epilayer is 0.25 μm. The 1.4 μm wide rib waveguides are defined by evaporating 60 nm thick silicon on the epilayer. Due to substrate removal, this design creates a very strongly confined optical waveguide with calculated mode size of $0.5 \times 1.5\ \mu\text{m}^2$. The epilayer contains a p-i-n junction. The p and n layers are 20 nm thick $1 \times 10^{18}\ \text{cm}^{-3}$ doped GaAs quantum wells (QWs). The i region consists of 120 nm undoped GaAs and two 15 nm undoped $Al_{0.5}Ga_{0.5}As$ layers. Ohmic contacts are made to these QWs on either side of the optical waveguide. The doped QWs serve two functions. First, they confine free carriers. As a result, overlap of the optical mode with free carriers is the overlap of the optical mode with these QWs. In the present design, this is about 5% for each QW, resulting in a low additional loss due to doping. This makes a moderately long device possible. Secondly, doped QWs act as built in electrodes connected to the external Ohmic contacts. The voltage drop along the doped QW is very low since the reverse conduction current of the junctions is very small. Therefore, the i region consisting of GaAs and $Al_{0.5}Ga_{0.5}As$ barriers experience a uniform vertical electric field. To a very good approximation, this field is the external reverse bias voltage divided by the thickness of the i region. Since the total i-region thickness is only 0.15 μm, a large electric field can be created with very low external voltage. This large electric field overlaps very well with the optical mode due to strong optical confinement resulting from the substrate removal. This creates a large index change due to linear electro-optic (LEO) and quadratic electro-optic (QEO) effects. Furthermore, even the slight depletion of the QWs creates an additional index change due to plasma (PL) and band filling (BF) effects.[3] This makes very efficient modulation possible. In the fabrication, first, 1.4 μm wide optical waveguides are defined by silicon lift-off based on electron beam lithography and evaporation. Next, the epilayer is etched about 150 nm to have access to the p-QW. Then, Ohmic contacts are formed to the n- and p-QWs. This is followed by a mesa etch to remove the epilayer in between individual devices and arms of the interferometer. Next, the wafer is glued to a transfer substrate with benzocyclobutane (BCB) and the growth substrate is removed as described elsewhere.[2] Finally, the p-QW under the n contact is etched.

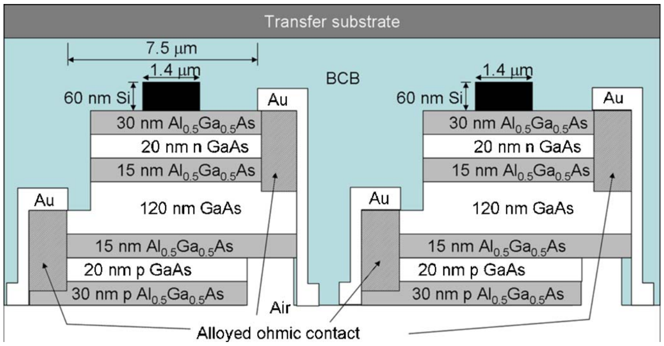

FIG. 1. (Color online) Cross sectional schematic of the arms of the Mach–Zehnder intensity modulator.

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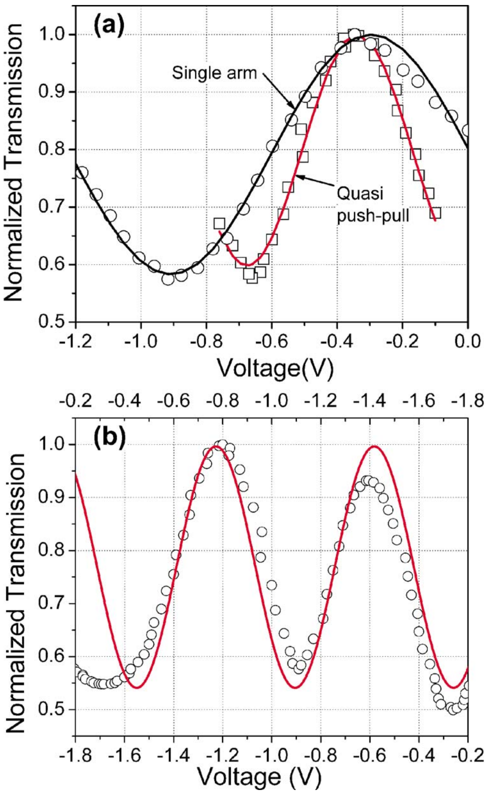

FIG. 2. (Color online) Normalized transmission of Mach–Zehnder intensity modulator with 7 mm long electrodes. (a) Comparison between single arm and quasi-push-pull drive, and (b) quasi-push-pull drive. Open circles and the smooth curves show data and its curve fit using Eq. (1), respectively. For quasi-push-pull drive, the bias voltage is −1 V. The voltage axis for quasi-push-pull drive shown in (a) is shifted to match the peaks for easier comparison. In (b), the lower and upper horizontal axes show the total voltage across two arms of the modulator, respectively.

After fabrication, both ends of the modulators are cleaved and transmission characteristics were measured at 1.55 μm. Lensed fiber was used for input coupling. The output was collimated with a microscope objective and projected to a photodetector. The arms can be biased independently. The normalized transmission of the modulator, only when one arm is reverse biased, is shown in Fig. 2(a). Even though both arms can be biased independently, true push-pull operation is not possible since reversing the bias voltage polarity would forward bias one of the arms. However, a quasi-push-pull scheme can be utilized by applying V_B+V to one arm and V_B-V to the other, where V_B is a fixed bias voltage and V is the modulating voltage. If $|V_B| \geqslant |V_{\text{peak}}|$, the reverse bias across the arms will swing between V_B+V_{peak} and V_B-V_{peak}. Therefore, the voltage swing across one arm will be $2V_{\text{peak}}$. Furthermore, when voltage across one arm increases, voltage across the other arm decreases, and neither arm is forward biased. Therefore, the required modulating voltage amplitude is reduced by a factor of 2 as in true push-pull operation. The result of such a measurement is shown in Figs. 2(a) and 2(b). Based on both measurements shown in Fig. 2, V_π is very low. Modulation efficiency decreases when the reverse bias across either arm exceeds 1.6 V. This is due to the depletion of QWs, as discussed below. The extinction ratio is about 3 dB, mainly due to unmodulated light trapped in BCB between the epilayer and transfer substrate. This stray light can be reduced by improving coupling efficiency using mode transformers.

In the presence of this stray light, the transmission characteristics of a Mach–Zehnder modulator can be expressed as

$$\frac{P}{P_{\text{max}}} = (1 - r_{\text{ex}})\cos^2\left(\frac{\pi}{2}\frac{V}{V_\pi} + \delta\right) + r_{\text{ex}}, \tag{1}$$

where r_{ex} is the extinction ratio $(P_{\text{min}}/P_{\text{max}})$ and δ is an arbitrary phase shift due to path length difference between the arms. We use this function to curve fit the measured data. The fits to this equation are shown as continuous curves in Fig. 2. Based on this fitting, the drive voltage under single arm drive and quasi-push-pull drive were found as 0.6 ± 0.1 V and 0.3 ± 0.05 V, respectively. These are the lowest drive voltages reported for any kind of modulator. This corresponds to a drive voltage length products of 0.42 ± 0.07 V cm and 0.21 ± 0.03 V cm for single arm and quasi-push-pull drives, respectively. Propagation loss were independently measured using Fabry–Perot resonators, using same waveguides was 8 dB/cm. 3 dB/cm of the loss was due to free carrier absorption. Coupling loss is about 5 dB/facets mainly due to lack of mode transformers. In this technology, it is possible to make efficient mode transformers from the semiconductor waveguide to a large polymer waveguide since substrate is removed. Such mode transformers will significantly reduce coupling loss. The phase shift experienced by the optical mode is $\Delta\phi = \Delta\beta l = (2\pi/\lambda)\Delta n_{\text{eff}} l$, where l is the electrode length, λ is the free space operating wavelength, and Δn_{eff} is the change in the effective index of the mode. $\Delta n_{\text{eff}} = \Delta n \Gamma$, where Δn is the index change of the material and Γ is the overlap of the material experiencing index change with the optical mode. In compound semiconductors, LEO, QEO, PL, BF, and thermo-optic (TO) effects contribute to index change. The maximum current injected to a 7 mm long arm was less than 1 μA. This corresponds to a very low power dissipation and rules out the TO effect. QEO has very strong wavelength dependence and is most effective near the bandgap of the material. Since the experiment is carried out at 1.55 μm, far away from the bandgap of the material, this effect is negligible.[3] The magnitude of LEO contribution can be either positive or negative, depending on the direction of the optical waveguides with respect to the crystal orientation.[3] PL and BF effects contribute due to depletion of the charge in QWs. Measured capacitance of each arm as a function of applied reverse bias is shown in Fig. 3(a). These data show that QWs deplete almost linearly up to 2 V reverse bias. Capacitance drops sharply at higher reverse bias due to complete depletion of the QWs. Once the QWs deplete, there is no longer a strong vertical field across the *i*-region and LEO contribution disappears. Furthermore, since all charge overlapping with the optical mode is depleted, PL and BF contributions also disappear. Hence, modulation becomes inefficient, as observed in Fig. 2(b). The magnitudes of the LEO, QEO, PL, and BF effects are calculated as a function of applied voltage for a 1 cm long electrode and are shown in Fig. 3(b). In the calculation, commercial semiconductor device and optical mode solvers are used. The calculated phase shift is with respect to the phase at 0 V. At first, it could be surprising that PL and BF effects are almost as strong as the LEO contribution given that there is charge depletion only in QWs. The magnitude of LEO, PL, and BF effects can be compared using a straightforward calculation as follows: Depleting 10^{18} cm^{-3} doped GaAs creates a combined PL and BF index change of $\Delta n \approx 9.6 \times 10^{-3}$.[3,4]

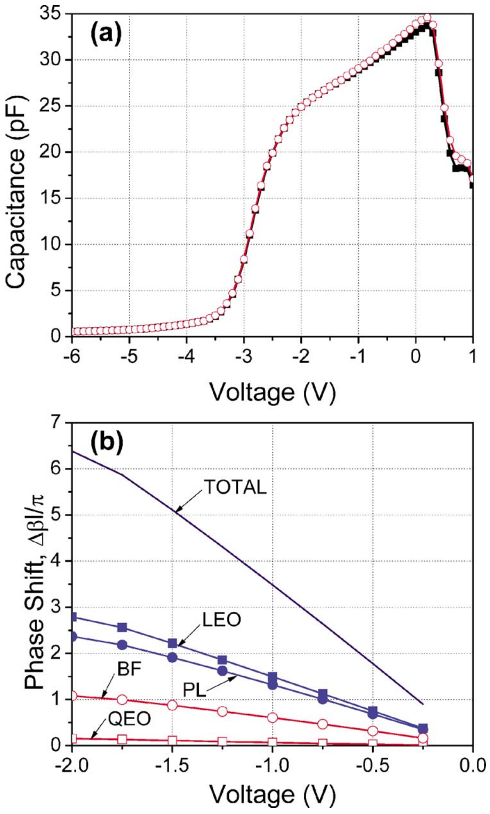

FIG. 3. (Color online) (a) Measured capacitance of 7 mm long interferometer arms and (b) magnitude of the calculated phase shift due to LEO, QEO, PL, and BF effects for 1 cm long electrode.

Hence, for completely depleted QWs, $\Delta n_{\mathrm{eff}}=\Delta n\Gamma=9.6\times10^{-3}\times0.05=4.8\times10^{-4}$. The corresponding phase shift is $\Delta\phi=\Delta\beta l=(2\pi/\lambda)\Delta n_{\mathrm{eff}}l=4.3\pi$. If we assume that the quantum wells deplete completely at −2 V, the phase shift per applied volt is then $4.3\pi/2\ \mathrm{V}=2.1\pi/\mathrm{V}$. Similarly, phase change due to LEO could be estimated using the well known expression, $\Delta n_{\mathrm{eff}}=(1/2)r_{41}n^3(V/d)\Gamma$ with $r_{41}=1.6\ \mathrm{pm/V}$, $n=3.4$, $d=0.15\,\mu\mathrm{m}$, and calculated $\Gamma=0.45$. Then, a phase shift of 1.2π is obtained per volt. These simple estimations agree well with the full numerical calculation values of $1.8\pi/\mathrm{V}$ and $1.5\pi/\mathrm{V}$ for BF+PL and LEO effects, respectively. In this work, optical guides were fabricated such that all effects add up. If the orientation of the waveguides is rotated 90°, LEO effect changes sign and the modulation becomes far less efficient. According to the calculation, a π phase shift should be possible with an applied voltage of 0.3 V to an arm with 1 cm long electrodes. This is about 25% less than what is observed and is possibly due deviation of the doping level in QWs from the one used in the calculations. In this paper, Mach–Zehnder modulators with drive voltage of 0.3 V were presented. These modulators use substrate removed very compact GaAs/AlGaAs optical waveguides for tight optical confinement and buried doped QWs as electrodes. Separation between the doped QW electrodes is only 0.15 μm. This allows the creation of very large modulating electric fields with low voltages. Such large fields create large index changes due to LEO effect and carrier depletion. Furthermore, very strong optical confinement improves the optical overlap, hence, large material index changes can be utilized very efficiently.

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