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Journal

Journal of Lightwave Technology, 32(3)

ISSN

0733-8724

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Publication Date

2014-02-01

DOI

10.1109/JLT.2013.2293345

Peer reviewed

0.2 V Drive Voltage Substrate Removed Electro-Optic Mach–Zehnder Modulators With MQW Cores at 1.55 μm

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Abstract—Novel electro-optic modulators in compound semiconductor epilayers using substrate removal techniques are reported. Epilayer consists of a p-i-n junction in which *i* layer is composed of an InGaAlAs/InAlAs MQW. This creates an optical mode with very strong vertical confinement and overlapping very well with the large electric field of the reverse biased p-i-n junction. This approach combined with the large quadratic electro-optic coefficient due to MQW improves efficiency of modulation significantly. Mach–Zehnder electro-optic modulators fabricated using this approach has 0.2 V (0.6 V) V_π for 3 (1) mm long electrodes at 1.55 μm under push pull drive corresponding to record modulation efficiency of 0.06 V·cm.

Index Terms—Compound semiconductor modulators, integrated optics, optical modulators.

I. INTRODUCTION

OPTICAL modulator is a key component for a wide range of applications requiring electrical to optical conversion. These include fiber optic communications, RF photonics, optical signal processing and instrumentation. Electro-optic modulators are among the most commonly used modulator types. One of the key metrics for an electro-optic modulator is the drive voltage needed to switch the modulator from on to off state or vice versa. This parameter is also known as V_π . Electrical power required to turn the modulator on and off is proportional to the square of this parameter. Clearly a low V_π modulator is needed to reduce electrical power consumption. Electro-optic modulators are fabricated in different material platforms such as LiNbO₃ [1], [2], polymer [3] and compound semiconductors [4]. Such modulators typically have V_π values of about a few volts and higher. Presently most commonly used electro-optic modulators are made in LiNbO₃. They have low frequency V_π of around 3 V with bandwidths around 20 GHz. This value increases with frequency and bandwidth. In an electro-optic modulator, there is a tradeoff between V_π and bandwidth. There are reports of very wide bandwidth LiNbO₃ modulators approaching 100 GHz [1]. But these devices have V_π of about 10 V. High V_π values

not only increase the power consumption but also require an external modulator driver to supply such V_π values at high frequencies. External driver adds to the power consumption and cost. In some cases, it is not even possible to use the modulator effectively even with a modulator driver. In such cases voltages less than V_π are applied and this creates performance degradation [5]. Therefore, there is significant advantage in reducing V_π of electro-optic modulators. We have been working on this issue for a while and our past work resulted in 0.3 V V_π Mach–Zehnder Modulators in bulk GaAs [6], [7] with 7 mm long electrodes at 1.55 μm corresponding to 0.21 V·cm modulation efficiency. We also made 2 V V_π modulators with 1.8 mm long electrodes at 1.55 μm in InP using multi quantum well (MQW) cores [8]. Recently, we also published modulator designs with traveling wave electrodes suitable for wide bandwidth operation [9], [10]. All of this study is based on substrate removal technology in compound semiconductors. This technology allows very compact optical waveguides and the ability to process both sides of an epilayer. This enables novel designs with superior properties. In this paper, we report a design with even lower V_π . We were able to reduce this value to 0.2 V for 3 mm long electrodes at 1.55 μm . This is not only important for further power reduction but makes it possible to make a very low drive voltage and a very wide bandwidth modulator by trading off V_π with bandwidth [10].

II. DEVICE DESCRIPTION

Fig. 1 shows the top schematic of the fabricated Mach–Zehnder intensity modulator along with cross sectional profile of one of the modulator arms. Epitaxial layer detail is also shown. Optical waveguides in the modulator arms are rib waveguides fabricated in an epitaxial layer removed from its growth substrate and glued onto a transfer substrate using the polymer benzocyclobutane (BCB) as glue. 1 μm wide rib is etched in the top InP layer. A p-i-n diode exists in the waveguide and *n* and *p* doped InP and In_{0.53}Ga_{0.39}Al_{0.08}As layers act as buried electrodes. Ohmic contacts are formed to these layers on the sides away from the optical mode. An alloyed *p* contact is made to *p* InP layer and a non-alloyed *n* contact is made to the *n* In_{0.53}Ga_{0.47}As layer. Epilayer exists only in areas where optical waveguiding is needed. Elsewhere it is removed. There is also an isolation implant on the y-branches. This isolates the arms electrically and they can be biased independently. In this design, very tight vertical confinement can be obtained due to very large index difference between the semiconductor epilayer

Manuscript received October 10, 2013; revised November 18, 2013; accepted November 25, 2013. Date of publication November 27, 2013; date of current version December 23, 2013. This work was supported by ONR grant N00014-13-1-0068.

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Digital Object Identifier 10.1109/JLT.2013.2293345

Fig. 4. Current voltage characteristics of one arm of the modulator with 3 mm long electrode with and without 1.55 μm radiation. Insert shows PL spectra of the MQW.

Fig. 5. Normalized optical transmission of a Mach-Zehnder modulator with 3 mm long electrode under single arm and push pull drive at 1.55 μm . The two curves are shifted with respect to one another to approximately align extremes of the transfer functions.

IV. RESULTS AND DISCUSSION

For characterization, cleaved facets were formed and a DFB laser output at 1.55 μm is end fire coupled using a lensed fiber. Fig. 4 shows the current voltage (IV) characteristics of one of the modulator arms of a modulator with 3 mm long electrode. Insert shows the PL spectra of the MQW. PL peak is at 1.37 μm . IV with and without 1.55 μm radiation in the modulator is shown. Expected diode behavior is observed. Reverse leakage current up to 2 V reverse bias is less than 50 μA . This indicates that current related index changes do not contribute to modulation and voltages up to 1.5 V can be comfortably applied. The change in the current with 1.55 μm radiation is negligible up to -1.5 V and increases for higher reverse bias.

This shows photo detected current hence absorption is very low at moderate reverse biases but increases at higher reverse biases. Fig. 5 shows the transfer function of a modulator with 3 mm long electrode. Modulation as a function of applied reverse bias is clearly observed. Circles are the data points when only one of the arms is driven. Open squares show data when both arms are driven in push pull. In this case, the same reverse bias is applied to both arms, but the polarity of the ac modulating signal is reversed between arms. The two transfer functions are shifted with respect to one another to approximately align their extreme. Solid lines going through these data points is a curve fit to the well-known Mach-Zehnder modulator response. It is observed that under single arm drive and around 1.2 V reverse

bias, V_π is 0.4 V. For push pull drive, V_π goes down to 0.2 V around 0.8 V reverse bias. Over one maximum to minimum transition for the single arm drive two such transitions for the push pull drive are observed as expected. Measured V_π shows bias dependence and reduces as bias voltage increases. So it is not possible to curve fit the entire data to the expected Mach-Zehnder transfer function using a single V_π . For example V_π around 0.7 V reverse bias is about 0.25 V for the push pull drive. It gets even larger as reverse bias decreases. 0.2 V push pull and 0.4 V single arm drive V_π values for the curve fits shown correspond to a modulation efficiency of 0.06 V-cm, which is a record.

Transmission through the modulator also reduces slightly as reverse bias increases. The most likely cause of this decrease is the shift of the absorption of the MQW to longer wavelengths due to quantum confined stark effect (QCSE) as applied field increases. Even though the detuning between the PL peak and operating wavelength is about 180 nm, some absorption change is observed. For push pull drive, the change in normalized transmission is less than 5% around 0.8 V reverse bias which yields 0.2 V V_π . This corresponds to a maximum absorption change of 0.2 dB, which is tolerable. Such low absorption also agrees with very low photo detected current observed in the IV data. Photo detected current increase under increasing reverse bias again indicates increasing absorption due to QCSE. The main components of on chip propagation loss are scattering and free carrier (FC) absorption loss. By proper design, scattering loss can be reduced to 1–2 dB/cm level [12]. FC absorption loss mainly depends on the p doping level and can be at the order of several dB/cm. For these devices and other similar devices [7] the on chip propagation loss is less than 10 dB/cm. Another significant contributor to insertion loss is the coupling loss. Efficient coupling into such compact waveguides is challenging and can vary a fair amount from measurement to measurement. A significant amount of light also couples into the BCB layer and is transmitted fairly efficiently due to large reflection resulting from high index contrast between the BCB and semiconductor epilayer/transfer substrate. This light is not modulated and remains in the output even if all the light through the modulator is turned off. This stray light reduces the extinction ratio. This is experimentally observed and for both measurements extinction ratio is around 3 dB. In our recent work, we were able to improve the extinction ratio to about 15 dB by using a thin metal film on the surface of the transfer substrate [7]. This film absorbs the stray light going through the BCB which in turn improves the extinction ratio. It is also possible to improve coupling using novel mode transformers between very compact semiconductor waveguide and much bigger polymer waveguides. Studies in this direction on passive waveguides showed significant improvement in coupling efficiency [13]. This should also help to improve the extinction ratio since light trapped in the BCB layer will be significantly reduced. Fig. 6 shows the transfer function of another modulator with 1 mm long electrode. In this case modulation is again clearly observed and V_π changes a factor of two between single arm and push pull drives. It also increased a factor of 3 compared to the modulator with 3 mm long electrode as expected. Modulation efficiency is still 0.06 V-cm. Extinction

Fig. 6. Normalized optical transmission as a function of applied voltage for modulator with 1 mm long electrode at $1.55 \mu\text{m}$ under single arm and push pull drive conditions. The two curves are shifted with respect to one another to approximately align extremes of the transfer functions.

ratio is again low due to unmodulated light trapped in BCB. Bias dependence of V_π is again observed and V_π reduces to 0.5 V for operation around 1.2 V reverse bias under push pull drive.

These results can be explained by considering the different physical effects contributing to index change. Applied electric field generates index changes through linear electro-optic (LEO), quadratic electro-optic (QEO) and FC effects. The resultant differential phase shift between the arms of the interferometer is proportional to the difference of the index changes in each arm. A fixed bias voltage as well as a time varying modulating voltage is applied to each arm. Resulting bias and AC fields are $E_{\text{Bias}} = V_{\text{Bias}}/t$ and $E_{\text{AC}} = V_{\text{AC}}/t$, where t is the electrode gap or thickness of the i -region. In operation, both arms are biased with the same voltage polarity or both p-i-n diodes are reverse biased in each arm. For push pull drive, polarity of the modulating voltage is reversed between the arms changing the direction of E_{AC} in each arm. Then it can be shown that

$$\Delta n_{\text{LEO}} = \frac{n_m^4}{n_e} r_{41} \Gamma_{\text{LEO}} E_{\text{AC}},$$

$$\Delta n_{\text{QEO}} = \frac{n_m^4}{n_e} 2R (E_{\text{Bias}} + E_b) \Gamma_{\text{QEO}} E_{\text{AC}},$$

$$\text{and } \Delta n_{\text{FC}} = 2C_n \Delta N_{\text{AC}}^x \Gamma_{\text{FC}n} + 2C_p \Delta P_{\text{AC}}^y \Gamma_{\text{FC}p}$$

where E_b is the built in field, n_m is the material index, n_e is the effective index of the mode, r_{41} is the LEO coefficient, R is the QEO coefficient, Γ_{LEO} and Γ_{QEO} are the overlap factors of the optical mode with the AC electric field appropriate for the LEO and QEO effects, $\Gamma_{\text{FC}n}$ and $\Gamma_{\text{FC}p}$ are the overlap factors of the optical mode with the depleted n and p layers, ΔN_{AC} and ΔP_{AC} electron and hole concentration changes in response to AC voltage and C_n, C_p, x and y are the appropriate parameters for FC effects. Contribution of the QEO effect appears as a linearly proportional term to the AC field or voltage [14]. As a matter of fact, we can describe this term with an effective LEO coefficient r_{41}^{eff} where $r_{41}^{\text{eff}} = 2R (E_{\text{Bias}} + E_b)$. A worst case estimate would be $r_{41}^{\text{eff}} \approx 2RE_{\text{Bias}}$. R shows strong wavelength dependence and increases significantly as the operating wavelength gets closer to the PL peak of the MQW. But then MQW absorption also increases significantly and the insertion

loss of the device becomes excessive. In this study, the separation between the operating wavelength of $1.55 \mu\text{m}$ and MQW PL peak of $1.37 \mu\text{m}$ is large enough to minimize MQW absorption. We compensate the corresponding decrease in R using a sufficiently high E_{Bias} . For example in our earlier work [8], we found $R = 4.1 \times 10^{-19} (\text{m/V})^2$. If $E_{\text{Bias}} = 10^7 \text{ V/m}$ and we obtain $r_{41}^{\text{eff}} = 2 \times 10^7 \times 4.1 \times 10^{-19} = 8.2 \times 10^{-12} \text{ m/V}$. This value is almost 6 times the bulk electro-optic coefficient value of $r_{41} = 1.4 \times 10^{-12} \text{ m/V}$. Therefore significant drive voltage reduction is possible. Based on numerical calculation, we obtain $\Gamma_{\text{LEO}} = 0.58$ and $\Gamma_{\text{QEO}} = 0.49$. Using these numbers at around 1.1 V reverse bias and under push pull operation, we estimate $\Delta n_{\text{LEO}} = 4.7 \times 10^{-5}$ and $\Delta n_{\text{QEO}} = 1.61 \times 10^{-4}$. Carrier depletion and related index change also take place in $1.5 \times 10^{18} \text{ cm}^{-3}$ doped $n\text{-In}_{0.53}\text{Ga}_{0.39}\text{Al}_{0.08}\text{As}$ and $3.6 \times 10^{18} \text{ cm}^{-3}$ doped $p\text{-In}_{0.53}\text{Ga}_{0.39}\text{Al}_{0.08}\text{As}$. Index change in these layers is estimated using the published numbers for InP. FC induced index changes scale inversely with electron and hole effective masses [15]. Since electron and hole effective masses for $\text{In}_{0.53}\text{Ga}_{0.39}\text{Al}_{0.08}\text{As}$ are smaller than InP, expected carrier index change for InP will be lower than $\text{In}_{0.53}\text{Ga}_{0.39}\text{Al}_{0.08}\text{As}$. As a result, it is possible to use expected index change due to carrier depletion of InP as a lower bound for $\text{In}_{0.53}\text{Ga}_{0.39}\text{Al}_{0.08}\text{As}$. Depletion of $1.5 \times 10^{18} \text{ cm}^{-3}$ doped $n\text{-InP}$ gives an index change of about [15] 4.1×10^{-3} . Hence $2C_n \Delta N_{\text{AC}}^x \approx 4.1 \times 10^{-3}$ for $\Delta N_{\text{AC}} \approx 1.5 \times 10^{18} \text{ cm}^{-3}$. Based on numerical calculation, the overlap of the depleted $n\text{-In}_{0.53}\text{Ga}_{0.39}\text{Al}_{0.08}\text{As}$ layer with the optical field is about 1 percent. As a result, carrier depletion induced index change due to n region is at the order of 4.1×10^{-5} . Similarly using the appropriate numbers for the p layer [15], we expect an index change around 7.3×10^{-6} . Hence total FC depletion induced index change is 4.83×10^{-5} . This is consistent with our earlier work which showed almost equal contribution from LEO and FC effects [7]. These effects are about 3.5 times smaller than the QEO due to MQW. Based on these index changes, we estimate V_π as 0.2 V for 3 mm electrode device which is in very good agreement with the measured value.

V. CONCLUSION

We fabricated novel electro-optic modulators in compound semiconductor epilayers using substrate removal techniques. This approach creates very strong vertical confinement. Using a p-i-n junction in the epilayer, a very strong electric field overlapping very well with the optical mode is generated. Thickness of the i -region becomes the gap of the modulator electrode. This gap can be made submicron and very uniform over large areas. Efficiency of modulation is further increased using a MQW core with large QEO coefficient. The separation between the PL peak of MQW and operating wavelength was increased to 180 nm to reduce the MQW absorption. Corresponding reduction in the QEO coefficient was compensated using a large bias field. Under push pull drive, V_π of 0.2 V at 0.8 V bias was obtained for 3 mm long electrode at $1.55 \mu\text{m}$. V_π becomes 0.6 V for 1 mm long electrode as expected. These values double under single arm drive. Corresponding modulation efficiency under push pull drive is 0.06 V-cm, which is a record. This is a factor of 3.5 better than

modulators fabricated using the same approach with bulk material in the waveguide core [6], [7]. V_{π} shows bias dependence and reduces as reverse bias increases. Modeling supports these observations and shows that QEO is the most significant effect. MQW absorption at moderate bias is found to be negligible. At increased reverse bias, absorption increases due to QCSE as evidenced in the reverse leakage current of the device. Such low voltage modulators could be the basic technology for very wide bandwidth traveling wave electro-optic modulators using the tradeoff between V_{π} and bandwidth.

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