Enhanced electro-optic effect in GaInAsP–InP three-step quantum wells

H. Mohseni,[a)] H. An, Z. A. Shellenbarger, M. H. Kwakernaak, and J. H. Abeles
Sarnoff Corporation, Princeton, New Jersey 08543-5300

(Received 3 November 2003; accepted 21 January 2004)

We report on the enhanced electro-optic coefficient of GaInAsP three-step quantum wells (3SQW) for high power electrorefraction modulator applications. Measured electro-optic coefficient of the 3SQW is nearly three times higher than the conventional rectangular quantum well (RQW) at $\lambda = 1.55\ \mu m$. The enhanced electro-optic effect, combined with a low optical absorption coefficient $\alpha < 1\ cm^{-1}$ in the 3SQW increases a modulator figure of merit by nearly 36 times, and decreases the power consumption by nearly one order of magnitude compared with a conventional RQW design. [DOI: 10.1063/1.1682699]

InP-based electrorefraction modulators are attractive for analog rf applications such as photonic fiber optic links, because of their high saturation power and suitability to monolithic integration. A material with simultaneously high electro-optic coefficient and low optical absorption is desirable for modulators with low switching voltage and low optical insertion loss. In particular, the gain of an analog rf-photonic link is proportional to the square of the electro-optic coefficient and inversely proportional to the optical absorption coefficient.

There have been extensive efforts to enhance the electro-optic coefficient with a low optical absorption in the III–V material. The most promising structures are symmetric[1] and asymmetric[2] coupled quantum wells, with theoretical enhancements approaching a factor of 10.[2] Experimentally, a factor of 5 higher electrorefraction has been obtained in an AlGaAs/GaAs asymmetric coupled quantum well.[3] However, similar improvements have not been demonstrated in the InP-based materials.

This letter reports phase modulators employing InGaAsP/InP three-step quantum wells (3SQW) exhibiting nearly three times higher electro-optic coefficient compared to conventional rectangular quantum wells (RQW) at very low optical loss values. Stepped quantum wells, unlike coupled quantum wells, do not require very thin epitaxial layers or large change of material composition. Recent data[4] indicate that even at the conventional growth temperature and duration, material interdiffusion can severely deform thin potential barriers. A high degree of interdiffusion in the GaInAsP material system may complicate the attainment of enhanced electrorefraction in the coupled quantum well approach.

An enhanced change of index in stepped quantum wells has been predicted theoretically,[5] and measured experimentally.[6] However, optical absorption, and hence modulator performance, of these structures was not demonstrated. Later detailed experimental studies on GaAs/AlGaAs stepped quantum wells revealed negligible improvement of modulation performance due to the enhanced optical absorption.[7]

We calculated optical absorption spectrum of the quantum wells using an effective mass approach. The excitonic effect was calculated based on a variational method,[2] and change of index was calculated from the Kramers–Kronig relationship. The electric field inside the active region was calculated using diffusion-drift and Poisson's equation. We optimized the thickness and composition of the layers of the quantum well to maximize change of index per change of voltage $\Delta n/\Delta V$, while keeping the absorption coefficient below $\alpha = 1\ cm^{-1}$ at $\lambda \sim 1550$ nm. Figure 1 shows the conduction and valence bands of an optimized 3SQW under an external electric field of $E = 40$ kV/cm. The barrier layers are InP and the composition and thickness of the layers in the quantum well from left to right are $In_{0.54}Ga_{0.46}As$ (21 Å), $In_{0.59}Ga_{0.41}As_{0.89}P_{0.11}$ (21 Å), and $In_{0.70}Ga_{0.30}As_{0.64}P_{0.36}$ (38 Å). Energy level of the first and second electronic states E_{e1} and E_{e2}, as well as first heavy- and light-hole states E_{hh1} and E_{lh1} with their corresponding squared wave functions are overlapped with the band structures.

Optimized quantum well structures were then grown by low-pressure metalorganic vapor phase epitaxy on n-type InP substrates. The thickness of the active region in all of the designs is kept at ~0.4 μm by adjusting the number of quantum wells. This region is sandwiched between 1.5-μm-thick n- and p-type InP cladding layers, and the device is terminated with a 50-nm-thick, highly doped InGaAs cap layer. Structural and optical properties of the epitaxial layers were characterized with high-resolution x-ray diffraction and pho-

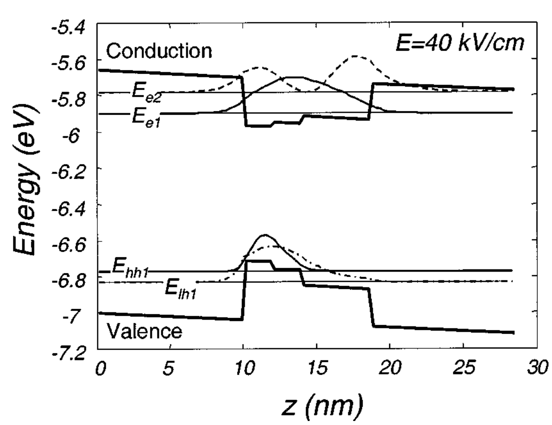

FIG. 1. Energy band structure of an optimized 3SQW at an external electric field of 40 kV/cm. Calculated first and second electron wave functions as well as the heavy- and light-hole wave functions are shown.

a)Electronic mail: hmohseni@sarnoff.com

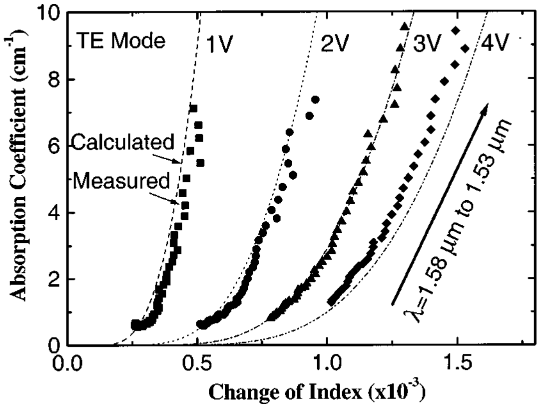

FIG. 2. Measured and calculated optical absorption coefficient vs change of index for a 3SQW modulator over λ=1530–1580 nm and bias values of V=1, 2, 3, and 4 V.

toluminescence techniques. The material is then processed into single mode ridge waveguides through standard photolithography and CH_4/H_2 based reactive ion etching. We measured optical absorption coefficient and change of index of the modulators by measuring Fabry–Perot oscillation,[8] optical transmission, and the modulator photoresponse. Leakage currents were significantly lower than values that could cause heat-induced change of index. Figure 2 compares the measured and calculated optical absorption coefficient versus change of index for a modulator with 3SQW active region. The data points are collected from λ=1.53 to 1.58 μm with 10 nm increments, and for bias values of 1–4 V. Calculated change of index and optical absorption coefficient show good agreement to the measured data for bias values up to nearly 3 V. We believe that field-dependent excitonic broadening is the main reason for the gradual deviation between the measured and modeled data at higher bias values. We compared the performance of 3SQW and RQW systematically. Since the detuning from the energy gap of the devices has a significant effect on the measurement, we only compared devices with similar band gap energies. Also, plotting α versus $\Delta n/\Delta V$, and eliminating their wavelength dependency reduced the detuning effect in our comparison. Figure 3 compares the performance of a modulator with 3SQW active region to a modulator with a conventional RQW at λ=1.550 μm and TE polarization. The layer thickness and composition of the RQW were optimized for maximum $\Delta n/\Delta V$ using our modeling approach. The barrier of the RQW is InP (85 Å) and the quantum well is $In_{0.58}Ga_{0.42}As_{0.90}P_{0.10}$ (85 Å). The peak photoluminescence energies of the 3SQW and RQW were 0.877 and 0.875 eV, respectively. Variation in the growth quality was negligible, since the samples were a few growth runs apart. The measured change of index of the RQW at $\alpha \sim 1\ \text{cm}^{-1}$ is about 1×10^{-4}/V, similar to the reported values in the literature,[9] while it is about 2.8×10^{-4}/V for 3SQW. Also, note that both α and $\Delta\alpha/\Delta V$ are smaller in the 3SQW for bias values below ~4 V. The importance of a low optical loss can be better understood by considering the gain of an impedance matched analog rf photonic link:[10]

$$G=\left(\frac{e^{-\alpha L}}{V_\pi}\,\frac{\pi 10^{-l/10}Rr_dP}{4}\right)^2, \tag{1}$$

where α is the optical absorption coefficient, L is the length of the modulator, and V_π is the voltage required for a π phase shift, R is the detector responsivity, r_d is the detector resistance, P is the laser power, and l is the total loss from the interconnects and fiber optics in decibels. Retaining the relevant parameter to the modulator, one can define modulator figure of merit as $M=(\exp(-\alpha L)/V_\pi)^2$. Assuming a small change of index, the value of V_π can be calculated as $V_\pi=\lambda/[2L(\Delta n/\Delta V)]$. Here λ is the laser wavelength and $\Delta n/\Delta V$ is the change of index versus change of bias in the modulator. Therefore, the optimum length of the modulator required to maximize M can be calculated as $L_{\text{opt}}=1/\alpha$ and the figure of merit of a modulator with the optimum length becomes

$$M_{\text{opt}}=4e^{-2}\left(\frac{\Delta n/\Delta V}{\alpha\lambda}\right)^2. \tag{2}$$

Inserting the measured values of optical absorption coefficient and change of index for bias values of 2 V into Eq. (2), one obtains $M_{\text{opt}}\sim 0.10\ \text{V}^{-2}$ for the RQW and $M_{\text{opt}}\sim 3.60\ \text{V}^{-2}$ for 3SQW. This means that replacing the conventional RQW with the 3SQW can improve the gain of an analog rf link by 15.5 dB. Low electroabsorption is also crucial for other applications such as resonant-enhanced micro-ring modulators,[11] where the ring quality factor Q is inversely proportional to the absorption coefficient α. Another important parameter for an electrorefractive modulator

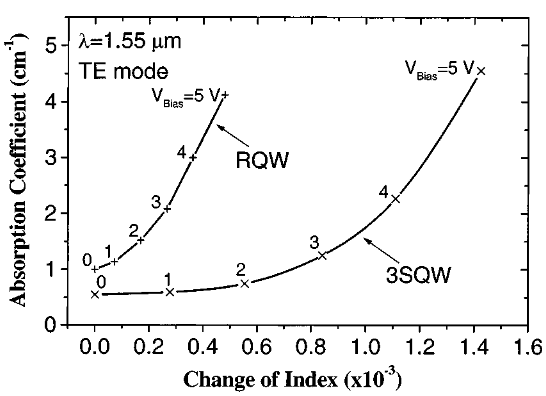

FIG. 3. Performance of a modulator with 3SQW active region compared to a modulator with a conventional RQW active region at λ=1.550 μm and TE polarization. 3SQW shows nearly three times higher change of index per voltage and lower optical loss compared to the RQW.

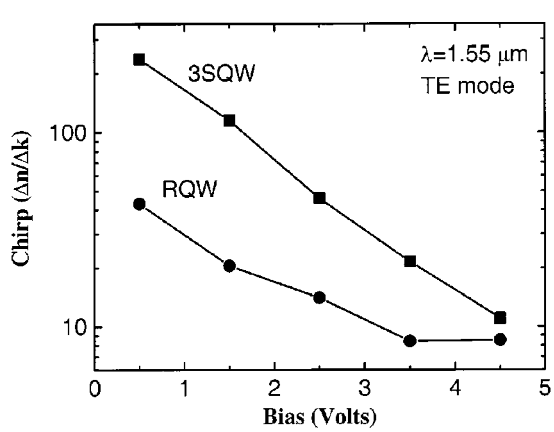

FIG. 4. Chirp factor of modulators with 3SQW and RQW at different bias values.

is a high chirp factor $\Delta n/\Delta k = (4\pi/\lambda)(\Delta n/\Delta\alpha)$, since it ensures a high contrast ratio in Mach–Zehnder (MZ) modulators.[12] Figure 4 illustrates the measured chirp factor of modulators with 3SQW and RQW active regions at different bias values. The higher value of chirp in the 3SQW is due to both a higher change of index and lower change of absorption.

In conclusion, we demonstrated InP-based phase modulators based on 3SQW with nearly three times higher $\Delta n/\Delta V$ compared with conventional RQW. Enhanced $\Delta n/\Delta V$ combined with an optical absorption coefficient below 1 cm^{-1} lead to ~36 times higher figure of merit, and nearly one order of magnitude lower power consumption in the modulator. These properties make 3SQW an excellent candidate for high-power, low-drive voltage MZ modulators required for high performance analog rf link applications.

[1] Y. Chan and K. Tada, IEEE J. Quantum Electron. **27**, 702 (1991).
[2] C. Thirstrup, IEEE J. Quantum Electron. **31**, 988 (1995).
[3] H. Feng, J. Pang, M. Sugiyama, K. Tada, and Y. Nakano, IEEE J. Quantum Electron. **34**, 1197 (1998).
[4] J. Bursik, D. Malakhov, Y. Wang, G. Weatherly, and G. Purdy, J. Appl. Phys. **91**, 9613 (2002).
[5] D. Dave, J. Appl. Phys. **74**, 6872 (1993).
[6] Y. Suzaki, S. Arai, S. Baba, and M. Kohtoka, IEEE Photonics Technol. Lett. **3**, 1110 (1991).
[7] T. Woodward, J. Cunningham, and W. Jan, J. Appl. Phys. **78**, 1411 (1995).
[8] T. R. Walker, Electron. Lett. **21**, 581 (1985).
[9] J. Zucker, K. Jones, B. Miller, and U. Koren, IEEE Photonics Technol. Lett. **2**, 32 (1990).
[10] See, for example, S. Hamilton, D. Yankelevich, A. Knoesen, R. Weverka, and R. Hill, IEEE Trans. Microwave Theory Tech. **47**, 1184 (1999).
[11] M. Kwakernaak, A. Lepore, H. Mohseni, H. An, Z. Shellenbarger, and J. Abeles, presented at Conference on Lasers and Electro Optics, Baltimore, MD, 2003 (unpublished).
[12] M. K. Chin, IEEE Photonics Technol. Lett. **4**, 583 (1992).