Journal of the Optical Society of Korea, Vol. 11, No. 3, September 2007, pp. 133-137

Comparison of Quantum Wells based on InGaAs(P)/InP and InGa(Al)As/InAlAs Material Systems in View of Carrier Escape Times for High-Saturation-Optical-Power Electroabsorption Modulators

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(Received August 27, 2007 : revised September 15, 2007)

We compare electroabsorption modulators (EAMs) with multiple quantum wells (MQWs) based on InGaAs(P)/InP and InGa(Al)As/InAlAs material systems. We carefully choose the quantum-well structures so that the structures based on different material systems have similar band-offset energies and excition-peak wavelengths. Assuming the same light wavelength of 1.55 μm, we show the transfer functions of EAMs with each quantum-well structure and calculate the escape times of photogenerated charge carriers. As the heavy-hole escape time of the quantum well based on InGaAs(P)/InP is much longer than those of photogenerated charge carriers of InGa(Al)As/InAlAs, the EAM based on the InGa(Al)As/InAlAs material seems to be more suitable for high-optical-power operation.

OCIS codes : 230.0230, 230.5590, 250.7360

I. INTRODUCTION

Multiple quantum wells (MQWs) realized with very thin (a few nm) alternating semiconductor layers are widely utilized in modern technologies these days. The reduced density of state due to the quantum confinement has enabled the low threshold current, making possible very efficient diode lasers used in many applications [1]. In optical intensity modulators for optical fiber communications, the MQWs are used to induce very large change in absorption coefficient via the quantum-confined Stark effect (QCSE) with the applied electric field, enabling efficient intensity modulation of the incident continuous-wave (CW) light [2].

The optical intensity modulator that utilizes this electroabsorption effect - absorption-coefficient change via electric field - is called the electroabsorption modulator (EAM). The EAMs have many advantages including high modulation speed and efficiency, possible polarization independence, and ease of integration with the laser diode. For these advantages, they are widely used in optical fiber communications [3-6].

At EAMs, photocurrent is generated in the active electroabsorption layer due to the absorption of the incident light. As high optical power is used to improve the link efficiency [7], the generated photocurrent may cause electroabsorption saturation unless electrons and holes generated due to light absorption are quickly removed from the active electroabsorption layer. Therefore, the issue of optical saturation is very important in the EAM research.

Two different kinds of material systems are typically used in fabricating the EAMs. One is based on the InGaAs(P)/InP material system and the other is based on the InGa(Al)As/InAlAs. Of all the material parameters, the band-offset splitting ratio is the most important one that causes the difference between these two material systems in handling the optical power. This is because the band-offset energy works as the barrier height for the quantum well (QW) and the barrier height determines the escape times of the charge carriers (electron or hole). For the InGaAs(P)/InP material system, the band-offset splitting ratio between the conduction and the valence band is 40:60, while for InGa(Al)As/InAlAs, it is 70:30.

There has been an inconsistency in the literature as to which material system is more beneficial for EAMs in handling high optical power. For example, Moss *et al.* presented a work concluding that InGaAs/InGaAsP quantum well is more suitable for the high-power MQW EAM [8]. On the contrary, Hawdon *et al.* concluded that a MQW EAM based on InGaAs/InGaAlAs is better [9]. In this paper, we aim to clarify this issue and point out that the confusion has arisen from different criteria in comparing two material systems. We carefully choose QW structures in order to compare the two material systems. By doing so, we try to draw a conclusion as to which material system is more beneficial for high-optical-power EAMs for 1.55-μm operation.

In Section II, we first discuss the prior works and compare these approaches. In Section III, QW structures we select to compare different material systems are introduced and explained. After selecting the structure, in Section IV, we show the results of transition energy shifts vs. the electric field, and calculate the carrier escape times. In Section V, we summarize the results and conclude.

II. PRIOR WORKS

Moss *et al.* compared two material systems with equal valance-band barrier heights to calculate the electron sweep-out time [8]. In this approach, due to the different band-offset splitting ratio, the barrier height for the conduction band in the InGaAs/InGaAlAs QW became much higher than that of the InGaAs/InGaAsP QW. Thus, the electron-sweep-out time for the InGaAs/InGaAlAs QW became longer than that of the InGaAs/InGaAsP QW.

To compare different material systems, it would be better to use the approach used by Hawdon *et al.*, which compared structures with the same barrier bandgap energies [9]. In [9], either InGaAsP or InGaAlAs was used as barriers for the same InGaAs well. In doing so, however, Hawdon *et al.* did not take the exciton-peak wavelength into account. As a consequence, structures they compared had different exciton-peak wavelengths. Since a wavelength of 1.55 μm is commonly used for optical fiber communications, it is more appropriate to compare different materials with the same exciton-peak wavelength, so that different structures may have the same detuning for 1.55 μm.

III. QW STRUCTURES CONSIDERED IN THIS WORK

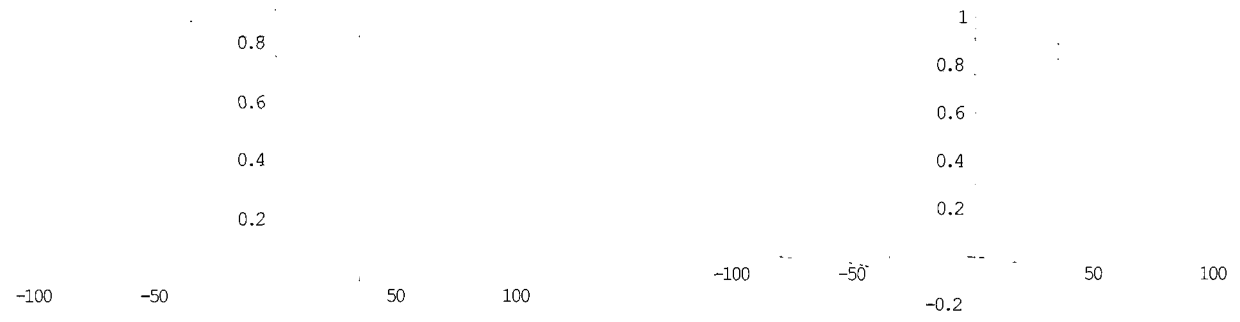
For comparison, we select the QW structures based on two material systems as follows. For the InGaAs(P)/InP material system, we choose the QW with an $In_{0.55}Ga_{0.45}As_{0.96}P_{0.04}$ (E_g = 0.769 eV) well, $In_{0.81}Ga_{0.19}As_{0.41}P_{0.59}$ (E_g = 1.078 eV) barrier. For the InGa(Al)As/InAlAs material system, the QW is composed of an $In_{0.53}Ga_{0.47}As$ (E_g = 0.75 eV) well and an $In_{0.53}Ga_{0.20}Al_{0.27}As$ (E_g = 1.16 eV) barrier. Both structures are assumed to be lattice matched to InP.

Although the ground-state energies of two QW structures considered are not the same due to the different effective masses and band splitting ratios of two material systems, the structures we choose have the same exciton wavelength at ~1.50 μm with the same well thickness (7 nm). As a consequence, unlike the previous studies, we can use the same light wavelength (1.55 μm) with the same thickness for each layer for fair comparison.

Figure 1 (a) and (b) show energy band diagrams and ground-state energy levels and envelope wavefunctions of the electron and the heavy hole for InGaAsP/InGaAsP QW under electric field of (a) 0 and (b) 120 kV/cm. The energy levels and envelope wavefunctions are calculated from the finite difference method [10]. Fig. 2 (a) and (b) show the case of InGaAs/InGaAlAs QWs under electric field of (a) 0 and (b) 120 kV/cm. Figs. 1 and 2 show different band splitting ratio of each structure and demonstrate how they respond to the applied electric field.

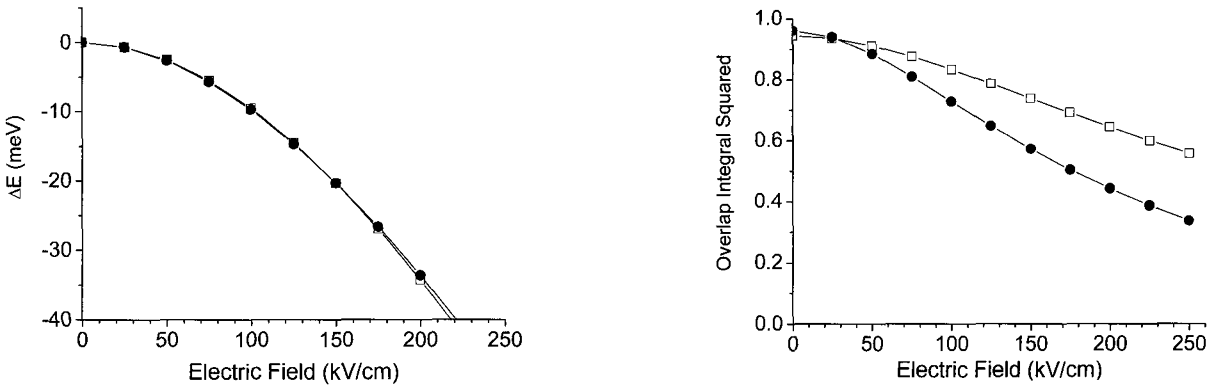
(a) (b)

FIG. 1. Energy band diagrams with ground-state energies and envelope wavefunctions of the InGaAsP/InGaAsP QW under electric field of (a) 0 and (b) 120 kV/cm. The numbers on the vertical axis are shown in eV.



(a) (b)

FIG. 2 Energy band diagrams with ground-state energies and envelope wavefunctions of the InGaAs/InGaAlAs QW under electric field of (a) 0 and (b) 120 kV/cm. The numbers on the vertical axis are shown in eV and the ones on the horizontal axis are in Å.



(a) (b)

FIG. 3. (a) ΔE and (b) overlap integral squared for InGaAsP/InGaAsP (□) and InGaAs/ InGaAlAs (●) QWs.

IV. COMPARISON OF QWs BASED ON DIFFERENT MATERIAL SYSTEMS

In this section, we investigate differences between InGaAsP/InGaAsP and InGaAs/InGaAlAs QWs, and show calculated carrier escape times. In Fig. 3 (a), the ground transition energy (ΔE) as a function of the applied electric field is presented for both QWs. Open squares (□) are for InGaAsP/InGaAsP QW and filled circles (●) are for InGaAs/InGaAlAs QW. The overlap integral squared also changes with the electric field as the electron and heavy-hole wavefunctions are pulled in opposite directions by the electric field. Fig. 3 (b) shows the overlap integral squared as a function of the electric field. Same symbols are used in Fig. 3 (b) as in Fig. 3 (a).

With these results, the transfer functions are calculated for MQW EAMs composed of each type of QW. When calculating the absorption coefficient from the transition energy and the overlap integral squared, a simple Gaussian broadening function is used [11]. Shown in Fig. 4 are the calculated normalized transfer functions for the EAMs with different QWs. An intrinsic-layer thickness of 0.2 μm, a waveguide length of 200 μm, an optical confinement factor of 0.20, a built-in potential of 0.8 V, and incident light of 1.55 μm are assumed for the calculation. Fig. 4 demonstrates that there is not much difference in transfer function for

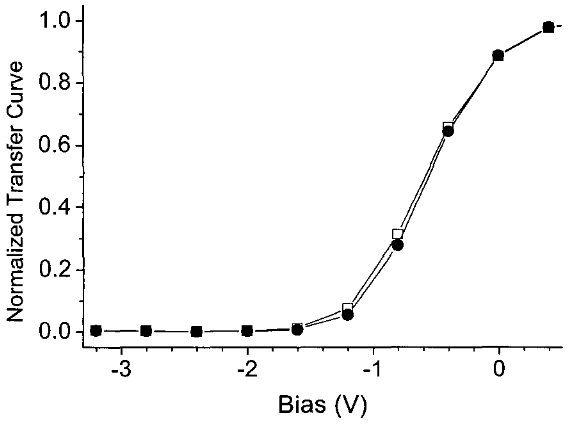
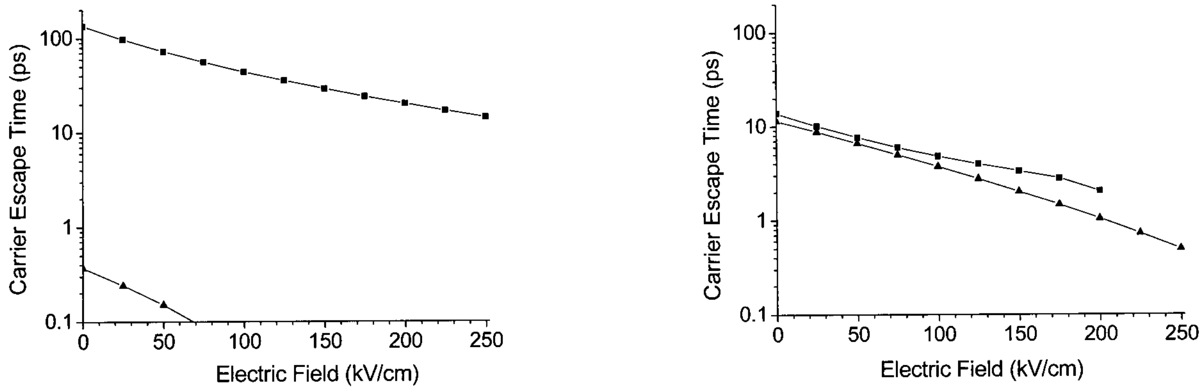


FIG. 4. Estimated normalized transfer curves for the EAMs with InGaAsP/InGaAsP (□) and InGaAs/ InGaAlAs (●) QWs.



(a) (b)

FIG. 5. Electrons (▲) and heavy holes (■) escape times of the QW for (a) InGaAsP/InGaAsP and (b) InGaAs/InGaAlAs QWs.

EAMs with different QWs.

Three physical mechanisms contribute to the field dependence of the lifetime of photogenerated carrier in a QW in an electric field: recombination, thermionic emission, and tunneling [12]. Because the carrier recombination rate is usually negligible in comparison to the faster tunneling and thermionic emission rates, here we only consider thermionic emission and tunneling.

Figure 5 shows calculated electron (▲) and heavy-hole (■) escape times for each QW. The calculation methods are given in detail in [12,13]. The barrier thickness in calculating the escape times is assumed to be 6 nm. In case of InGaAsP/InGaAsP QW, despite the very fast escape time (<1 ps) of the electron, the escape time of the heavy hole is so long that the remaining heavy holes would screen the external electric field, causing the saturation in the EAM. For the InGaAs/InGaAlAs QW, however, both the electron and the heavy hole show rather short escape times. Hence, the field screening effect due to the charge carriers remaining in the QW is lessened. As a consequence, the saturation intensity can increase [12].

In [9], it is claimed experimentally that the short-pulse saturation intensity for InGaAs/InGaAlAs QW is at least a factor of 10 greater than that for InGaAs/InGaAsP QW. However, the EAMs are not typically operated in the short-pulse mode. They are operated rather in the CW mode for analog fiber link or in the on-off mode for digital fiber link. It remains to be seen experimentally how much the improvement factor with the InGaAs/InGaAlAs QW will be for the saturation optical power defined, for example, by the value that gives a degradation of the link RF gain by 3 dB.

V. CONCLUSION

We have examined the transition energies, envelope wavefunctions under electric field for InGaAsP/InGaAsP and InGaAs/InGaAlAs QWs. The QW structures selected for comparison were optimized for operation at 1.55 μm. They also had similar band-offset energies with the same well thickness for fair comparison. From the calculated escape times for both QW structures, it has been shown that the EAM with the InGaAs/InGaAlAs QW seems to be more suitable for the high-optical-power operation due to smaller charge carrier escape times.

ACKNOWLEDGEMENT

This work was supported by the research fund of Hanyang University (HY-2006-S).

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