Some Key Issues on the Optimization of Multiple Quantum Well Structures for Amplitude Modulation

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Main parameters of InGaAs/InAlAs multiple quantum well amplitude modulators, such as contrast ratio, insertion loss and chirp parameter, were calculated in order to find a quantum well structure which optimizes them. The parameters were estimated from the theoretical absorption curves, which were calculated for different values of applied reverse bias and were compared with experimental data. A study of the device parameters as a function of the Ga content and operation voltage was performed. The study showed that optimum values for the modulator parameters cannot be obtained simultaneously. The influence of the residual doping level and the applied pre-bias are emphasized.

1 Introduction

Much attention has been driven to the InGaAs/InAlAs multiple quantum well (MQW) system due to its suitable properties for the development of amplitude modulators to be used in telecommunication [1-4]. This system can produce structures that operate at 1.55 μm and it can be grown on InP substrates for optoelectronic integration. Another characteristic is the lower valence band offset compared to that of the InGaAs/InP system, which is desirable to avoid saturation effects due to a long hole escape time from the quantum wells (QWs). Nevertheless, if the InGaAs/InAlAs system is expected to be used in the next multigigabit long haul fiber transmission systems, the MQW structure containing these materials should be further optimized.

Strained InGaAs layers are necessary in order to obtain a large Stark shift while keeping a satisfactory overlap between electron and hole wavefunctions. With such strained structures, it is possible to maximize the change in the absorption coefficient ($\Delta\alpha$). But the optimization of this parameter alone may not be enough. In parallel one should achieve degeneracy of the heavy and light hole energies, minimized residual absorption and refractive index independent of applied voltage. To try to optimize all these parameters, as a function of the structural ones, a theoretical prediction is desirable.

In this communication device parameters such as contrast ratio (*CR*) and chirp parameter (α_L) were calculated as a function of the Ga content (x) and operation voltage (ΔV) in order to find a quantum well structure which optimizes them. A comparison with the available experimental data was performed.

2 Calculations

The modulator parameters *CR*, I_L and α_L are estimated from the calculated absorption curves for different applied reverse voltages. The electronic structure is calculated self-consistently through a 4 X 4 Luttinger-Kohn Hamiltonian. The QWs are considered uncoupled. The optical matrix elements are polarization dependent and from this fact the absorption curves could be calculated for both TE and TM polarizations. The strain was introduced through a deformation potential. Excitonic interaction was taken into account. The contributions for the broadening factor were homogeneous broadening, temperature dependent broadening, charge density dependent broadening and fluctuations in the QWs thickness and electric field. To calculate the electrostatic potential of the whole *pin* diode structure, Poisson and continuity equations were solved selfconsistently. The change in the refractive index (Δn) was obtained from the theoretical absorption variation with applied reverse bias, using the Kramers-Krönig relation.

3 Experimental details

For the comparison with theoretical data, samples were grown by MOVPE at 100 mbar and at 635^0C on InP substrates. The active region consists of an intrinsic 20 period MQW structure with tensile strained InGaAs QWs with different thicknesses (t_{QW}) and Ga content in the QW alloy, x. The InAlAs barriers are 65 Å thick and they are tensile strained between 0.05 and 0.1%. The MQW structure is inserted between n and p layers, forming a *pin* diode. The samples were processed as photodiodes and were characterized by photocurrent (PC) at different reverse bias voltages.

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The propagation of the light was along the growth axis. Absorption measurements were performed only at zero reverse bias. Both PC and absorption measurements were carried out at 300 K. The absorption spectra was used to quantify the PC curves in units of cm^{-1}.

t_{QW} and x were experimentally determined by X-ray diffractometry after a simulation of the X-ray spectrum and they are respectively equal to 76.5 Å and 0.475 for sample A, 103 Å and 0.49 for sample B and 99 Å and 0.5 for sample C. Measurements were carried out in a double crystal diffractometer, using the k_α radiation of a Cu tube.

4 Results and Discussion

The theoretical $\Delta\alpha$ as a function of applied electric field was obtained from the calculated absorption curves for different values of the applied reverse bias by subtracting its values for different reverse voltages from that for the lowest non zero reverse voltage (pre-bias). Since the PC spectra qualitatively reveal the absorption characteristics of the sample [2], one could obtain experimental values for $\Delta\alpha$. To achieve that, the PC spectra were calibrated by performing absorption measurements at zero bias, as described elsewhere [2]. Calculated absorption curves reproduce very well the PC measured ones, as is shown in Fig. 1 for sample B. This fact leads to an excellent agreement between $\Delta\alpha$ taken from the calculated absorption curves and those taken from the calibrated PC measurements.

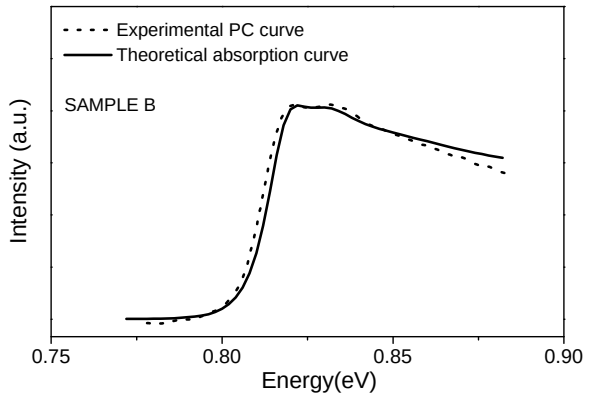

Figure 1. Measured PC curve (dotted line) of sample B. The theoretical absorption curve is represented by the solid line.

The good theoretical reproduction of the experimental data offers a reliable way to predict structures with optimized performance. Therefore a study of the variation of the modulation parameters such as *CR*, I_L and α_L, as a function of x, was performed. The Ga content was varied from 0.475 to 0.53. The thickness of the QWs were such so as to keep the fundamental transition at 1.49 μm for operation at 1.55 μm. We have found that a minimum value of ΔV, for a given CR, is obtained for a Ga content of 0.512. For the same Ga content one finds that the absorption energy for TE and TM polarization is essentially the same. In other words, it is possible to find an optimized structure for both minimized operation voltage and polarization independence.

Once $\Delta\alpha$ is known, the change in the refractive index Δn is obtained and the chirp parameter is calculated. In order to obtain α_L the relation [5]:

$$\alpha_L = \frac{4\pi\Delta n}{\lambda\Delta\alpha} \tag{1}$$

was used. The α_L values, calculated through the theoretical absorption curves, which are represented by solid lines in Fig. 2, well reproduce the experimental data represented by symbols. A –2V pre-bias and a detuning of 30 meV were used for both experimental and theoretical data.

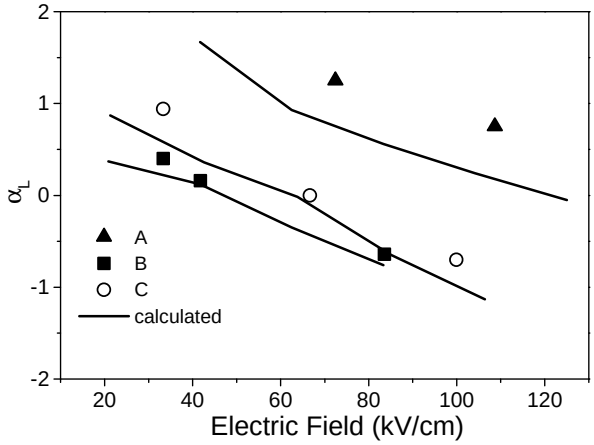

Figure 2. α_L as a function of the externally applied electric field. Solid lines and symbols are α_L calculated from the theoretical absorption curves and from the calibrated PC measurements, respectively.

The chirp parameter, for a QW alloy composition in the range from 0.494 to 0.502 and from 0.509 to 0.51, remains between 0 and –1 for applied reverse voltages between –1 and –5 V. These results are shown in Fig. 3.

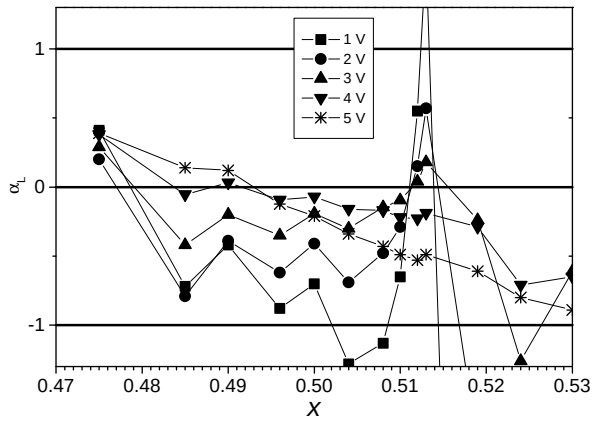

Figure 3. Chirp parameter as a function of the Ga content for different applied reverse bias.

With the presented results it is possible to understand the modulator parameters as a function of the Ga content. But one should emphasize that these parameters can also show a dependence on the residual doping level (RDL) and the applied pre-bias. As expected, one observes that the ΔV

which gives 10 dB of contrast ratio (ΔV_{10dB}), increases from 4.8 V to 5.6 V resulting from an increase of the RDL from 1 to 3x10^{16} cm^{-3}. The value of 4.8 V can be recovered if instead of a pre-bias equal to –1V, a pre-bias of –2V is applied. Another result is that for low pre-bias, α_L depends very strongly on the RDL as shown in Fig. 4. This effect arises because since charge from background impurities may affect the excitonic peak of the absorption curve, it may also affect α_L. Such effect takes place for low pre-bias because the MQW is not completely depleted. Suitable values of α_L for all applied voltages can be achieved only if the value of the pre-bias is such that depletes the entire MQW region.

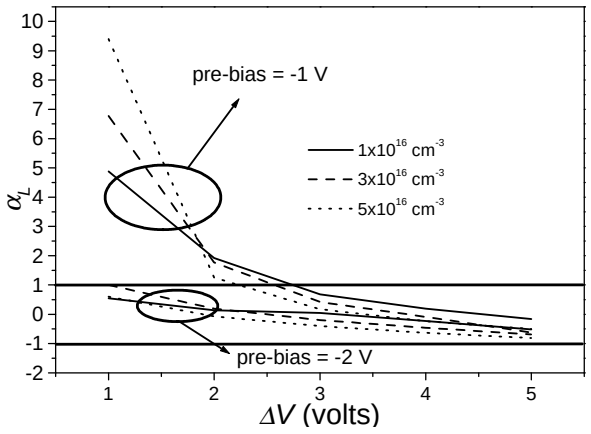

Figure 4. α_L as a function of the applied reverse voltage for three different values of the RDL. The first and the second sets of data were calculated respectively for –1V and –2V applied pre-bias. They are indicated by the circles and arrows.

5 Conclusion

Amplitude modulator parameters such as contrast ratio, chirp parameter and polarization sensitivity were considered theoretically. A good agreement between theoretical and experimental values for the different parameters was obtained.

The study of device parameters as a function of the MQW structure has shown that although minimum operation voltage and polarization independence can be simultaneously obtained, the correspondent α_L is not optimized. The influence of both RDL and applied pre-bias in the device parameter was addressed.

Acknowledgement

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