Measurement of heavy and light hole masses in InGaAs/InAlAs Quantum Wells

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Abstract

Photocurrent measurements at 10K with different biases on lattice matched InGaAs/InAlAs multiple quantum wells (MQW) with different well widths (w=70Å, 85Å and 100Å) have been performed to obtain accurate values of perpendicular heavy- and light-hole masses. The procedure suggested on this article uses transition energies from different electron-hole pairs at zero field to determine the masses. Since some of these transitions are forbidden for zero field, we extrapolate the bias dependent positions of all the observed transitions to obtain the zero field transition energies. By comparing these data with detailed numerical simulations we obtain values of the hole masses that fit the experimental data precisely.

Introduction

The prediction of optical transition energies with accuracy is of critical importance for the design of opto-electronic devices. For quantum wells using ternary and quaternary semiconductors this is severely hampered by large uncertainties in the anisotropic hole masses. The design of opto-eletronic devices with precision requires the knowledge of these masses with accuracy. This uncertainty may cause a totally erroneous prediction of the transition energies for InGaAs/InAlAs multiple quantum wells (MQW). As shown on table 1, the spread in the values found in the literature for the hole masses of the InAs can be as large as 40% and 28% for the m_{hh} and m_{lh}, respectively. The transition energy for a 100Å width quantum well (QW), for instance, can be off by 8 to 22meV, depending on the transition. From the analysis of table 1 it is obvious that the uncertainty of the heavy- and light-hole masses of InAs is the major problem. The masses on table 1 are perpendicular to the *xy* plane and are given by the equations:

$$\frac{m_{hh}}{m_0} = \frac{1}{g_1 - 2g_2} \qquad (1a)$$

$$\frac{m_{lh}}{m_0} = \frac{1}{g_1 + 2g_2} \qquad (1b)$$

where γ_1 and γ_2 are the Luttinger paramters[5].

We report a new experimental method to determine the hole mass which should greatly improve our ability to design opto-eletronic devices.

Experimental details

Lattice matched MQW structures were grown by molecular beam epitaxy (MBE), on a (100) n-type InP substrate. The *pin*-type structure is shown on figure 1. These structures were grown with 20 QW with nominal width of w=75Å, 85Å and 100Å. The barrier of the MQW structure is such that the total intrinsic width is always 0.5*m*m. Circular geometry mesa devices with 250*m*m optical windows were fabricated from these structures using conventional processing techniques.

Photocurrent experiments were performed at 10 K with conventional lock-in techniques, a tungsten lamp and a 270*mm* monocromator. The measurement system was fully computer controlled. The final spectra were obtained by taking the ratio of the photocurrent signal of the samples and the calibration spectra taken by a bulk InAs cooled photodiode to eliminate the system response. The resultant spectra for biases varying from 0V to 10V for the nominal 100Å thick MQW structure can be seen on figure 2. Note that for low bias voltage applied to the sample only transition with the same electron-hole wave function parity are observed. Increasing the electric field, the electron-hole wave functions are distorted and as a consequence several transitions are seen.

Data analysis

In order to obtain the heavy- and light-hole masses, we need to know the energy for several electron-hole transitions ($E_{e1\text{-}hh1}$, $E_{e1\text{-}lh1}$, $E_{e2\text{-}hh1}$,…) at zero field. As observed on figure 2 only some of these transitions are revealed at low bias. The extrapolation used to obtain these zero field transitions are described on the following.

The calculation of the eigenstates of an infinite quantum well subject to an electric field is, in principal, an exactly solvable problem for which the solutions are linear combinations of two independent Airy functions[6]. These solutions are, however, fairly complicated and it is sometimes desirable to use approximations. For small fields ($F \rightarrow 0$) this solution can be expanded in a Taylor series,

$$E_{ij} = E_{0ij} - A_{1ij}\,(V_x+V_i)^2 + A_{2ij}(V_x+V_i)^4 \qquad (2)$$

where E_{ij} are the transition energies between the i electron and the j hole states, E_{0ij} are the transition energies at zero field, V_i the built in voltage and V_x the bias voltage applied to the MQW. A_{1ij} and A_{2ij} are free fitting parameters. Using this approximation, the experimental transition energies, taken as the zeroes of the third derivative of each photocurrent spectra, can be fitted with equation 1 obtaining the extrapolated zero field transition energy E_0. For our structure we used V_i = 1.52V. Since the final value of E_0 does not depend strongly on V_i, its 5% uncertainty should not affect the final value of E_0. Figure 3 shows the transition energy as a function of applied electric field where the different symbols represent the different experimental transitions as described in the inset. The dashed lines are the result of the Taylor series approximation. The theoretical approach used to obtain the solid line will be explained below.

According to the infinite well zero-field solutions $E_n = (\hbar/2m^*)(n\pi/w)^2$, it is clear that the electron and hole quantum states of the well depend basically on the width w and the effective mass. The procedure that enable us to, with the experimental transition energy ($E_{e1\text{-}hh1}$, $E_{e1\text{-}lh1}$, $E_{e2\text{-}hh1}$,…), provide the hole masses is based on this relationship, and is described in the following. With the transition energies obtained from the extrapolation described in the previous paragraph, it is possible to have the difference between the first two states of the electron, heavy and light holes, E_{e2}-E_{e1}, E_{hh2}-E_{hh1} and E_{lh2}-E_{lh1}, respectively (i.e., $E_{e2}-E_{e1} = E_{e2\text{-}hh1} - E_{e1\text{-}hh1}$, etc.…). These differences depend also on the width w and the effective mass of the corresponding particle ($E_{e2} - E_{e1} = (3\hbar/2m_e^*)(\pi/w)^2$). Since the electron effective mass, m_e^*, is well known[4], the energy difference E_{e2}-E_{e1} should depend only on the width w. Thus, this is used to verify the nominal values of the quantum well width (table 2). Knowing the actual width of the well, the differences E_{hh2}-E_{hh1} and E_{lh2}-E_{lh1} will depend only on the heavy and light hole effective mass. However, the finite well solution should not be a good approximation.

But, the finite quantum well is a good approach. Solving numerically the finite quantum well, the same procedure described above is used to obtain the well width, and the hole masses m_{hh} and m_{lh}. Table 2 exhibits the best w, m_{hh} and m_{lh} for the InAs material that, when used in conjunction with known parameters for GaAs and AlAs satisfies the energy differences E_{e2}-E_{e1}, E_{hh2}-E_{hh1} and E_{lh2}-E_{lh1}, respectively.

The experimental procedure described above gives the quantum well material hole mass (i.e. InGaAs). However, as discussed previously, the major uncertainty of the literature resides on the value of the InAs hole mass. So the masses that should be fitted are the InAs and not the InGaAs masses. To be able to do that the InAs Luttinger parameters (γ_{1InAs} and γ_{2InAs}) are found by inverting equations 1 and the InGaAs Luttinger parameters ($\gamma_{1InGaAs}$ and $\gamma_{2InGaAs}$) are found by the linear approximation:

$$g_{1InGaAs} = (g_{1GaAs} - g_{1InAs})x + g_{1InAs} \qquad (3a)$$

$$g_{2InGaAs} = (g_{2GaAs} - g_{2InAs})x + g_{2InAs} \qquad (3b)$$

where the gallium percentage x is *0.468* and γ_{1GaAs} and γ_{2GaAs} are given by the GaAs masses of table 1. Then, equation 1 is used to obtain the InGaAs hole masses.

Using the values of table 2, the finite quantum well in a uniform electric field is now solved for different biases and the transition energies are depicted as functions of the electric field (solid line on figure 3). The energy gap for the InGaAs and InAlAs materials at 10K used are 0.814eV and 1.520eV respectively. For the conduction- and valence-band offset ratio (DE_C/DE_V) we assume 0.723.

Comparing tables 1 and 2 it is possible to verify the large difference between the literature and our experimental values for the InAs heavy and light hole masses. The different values for the hole masses for different samples on the tables are due to the fact that our calculation does not include the exciton binding energy which should be larger for smaller wells[7]. For the 74Å and 85Å QW, even though one is able to obtain the values for the masses, it is not possible to fit accurately the transitions energies under bias. This implies that the values for the hole masses should have a larger error for smaller QWs. As the well width increases the exciton binding energy diminishes and should not significantly affect our results for a 95Å QW width. Figure 4 depicts the expected transition energies using the values of the hole masses of table 1 and the experimental data. On this graph, especially for the curves of the light hole states, the theoretical curves are totally different from the experimental data. Comparing the graphs of figures 3 and 4 it becomes clear that the heavy and light hole masses found by our procedure fits much more precisely the experimental data than the set of values from the literature.

By the analysis of photocurrent measurements at 10K on InGaAs/InAlAs MQW we obtain values of heavy- and light-hole mass. Using these masses instead of the values obtained on the literature we are able to fit precisely numerical simulations with the experimental data. The procedure suggested to acquire the new masses includes an extrapolation to obtain the zero field transitions and a detailed numerical simulation. For the design of opto-eletronic devices witch strongly depend on the correct prediction of the transition energies on QWs, the obtained values for the hole masses has proved to be more appropriate.

	InAs		GaAs		InGaAs	
	m_{hh}	m_{lh}	m_{hh}	m_{lh}	m_{hh}	m_{lh}
Set 1	0.435 [1]	0.038 [1]	0.327 [2]	0.090 [2]	0.384 [3]	0.052 [3]
Set 2 [4]	0.263	0.027	0.377	0.091	0.307	0.040

Table 1

Values from the literature for the heavy- and light-hole mass (m_{hh} and m_{lh}) for different materials.

Nominal w	*w*	m_{hhInAs}	m_{lhInAs}
70 Å	74 Å	0,150	0,040
85 Å	85 Å	0,173	0,049
100 Å	95 Å	0,234	0,080

Table 2

Best *w*, m_{hh} and m_{hh} for the InAs materiel that satisfies the experimental data.

	74Å	$Ga_{0.468}In_{0.532}As$	Be:5E18
	36Å	$Ga_{0.588}In_{0.412}As$	Be:5E18
	60Å	$Al_{0.180}Ga_{0.291}In_{0.529}As$	Be:5E18
	72Å	$Al_{0.364}In_{0.636}As$	Be:5E18
	36Å	$Al_{0.371}Ga_{0.223}In_{0.409}As$	Be:5E18
	1200Å	$Al_{0.477}In_{0.523}As$	Be:5E18
	180Å	$Al_{0.477}In_{0.523}As$	Be:2.5E18
	720Å	$Al_{0.477}In_{0.523}As$	Be:2.5E18
	400Å	$Al_{0.477}In_{0.523}As$	UD
20x	w	$Ga_{0.468}In_{0.532}As$	UD
	210Å - w	$Al_{0.477}In_{0.523}As$	UD
	400Å	$Al_{0.477}In_{0.523}As$	UD
	1500Å	$Al_{0.477}In_{0.523}As$	Be:2.5E18
	59Å	$Al_{0.371}Ga_{0.223}In_{0.409}As$	Be:2.5E18
	61Å	$Al_{0.364}In_{0.636}As$	Be:2.5E18
	60Å	$Al_{0.180}Ga_{0.291}In_{0.529}As$	Be:2.5E18
		InP Substrate	

Figure 1
Detailed *pin*-type structure used in the photocurrent experiment.

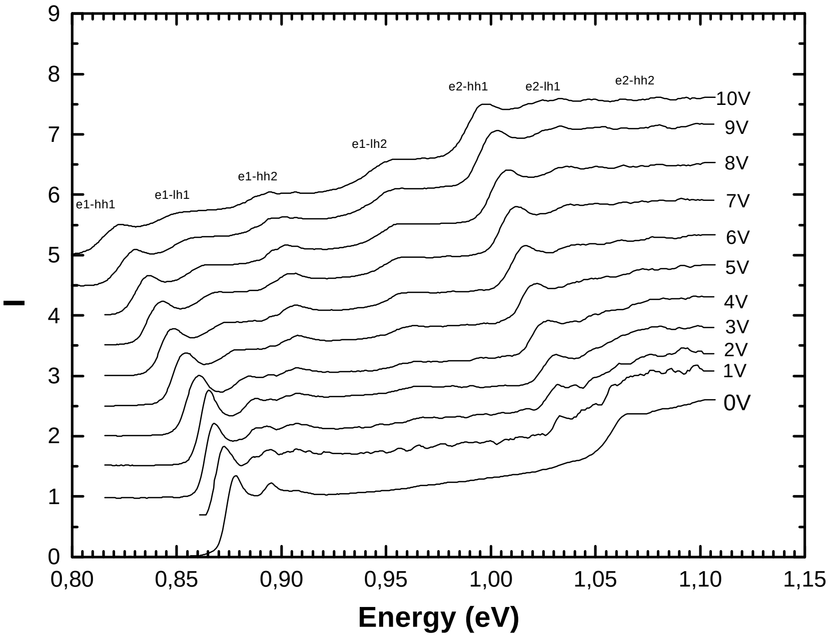

Figure 2
Photocurrent spectra taken at 10K from a nominal 100Å MQW as a function of the reverse bias.

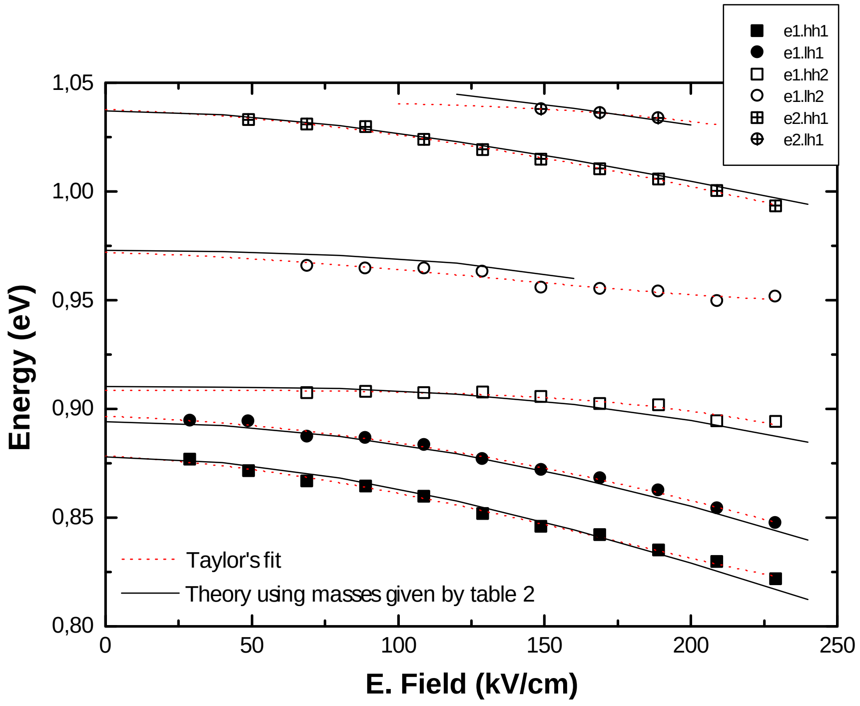

Figure 3
Change of the transition energy as a function of the applied electric field. The symbols corresponds to different experimental transition energies for the nominal 100Å thick MQW. The dashed line is the fitted Taylor's series and the solid line the finite QW simulation for a 95Å thick MQW, m_{hhInAs}=0.234 and m_{lhInAs}=0.080.

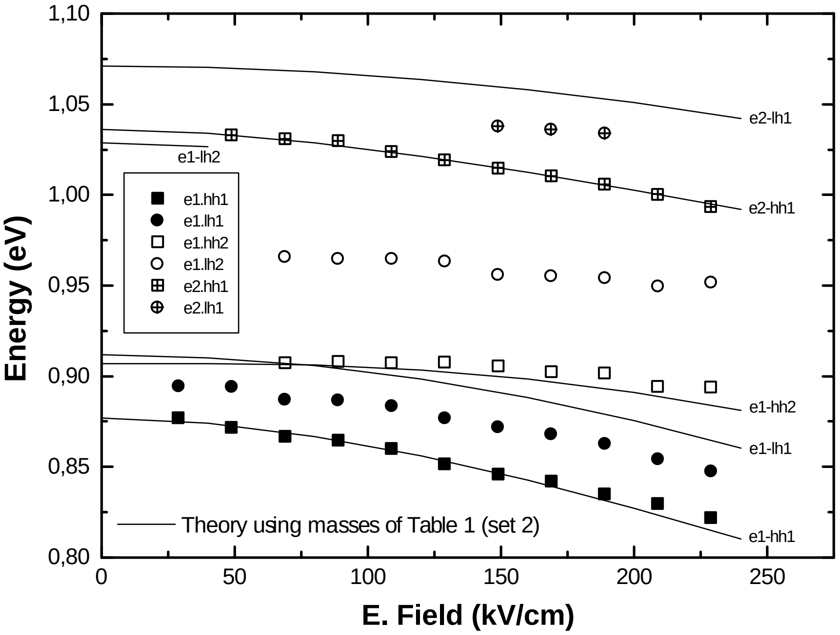

Figure 4
Experimental (symbols) and calculated (solid line) transition energies as a funtion of the electric field. Here the calculated curve was obtained using the masses from the literature (Table1).

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