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AN EVALUATION OF CYCLOTRON EFFECTIVE MASS AND ELECTRON G-FACTOR IN SEMICONDUCTOR QUANTUM WELL

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Abstract: Using the theoretical formalism of M. De Dios-Leyva etal (2006), we have evaluated the cyclotron effective mass, 2D cyclotron effective mass and g_{11}-factor for GaAs-$Ga_{0.65}Al_{0.35}As$ quantum well both as a function of magnetic field B (T) and also as a function of well width. Our theoretically evaluated results are in good agreement with the experimental data and also with other theoretical workers.

Keywords: Cyclotron effective mass $g_{\parallel}$-factor, Semiconductor quantum well, effective mass approximation, Landau states, quantum well wires (QWWs), quantum Dots (QDs), super lattices (SLs)

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INTRODUCTION

The understanding of the physics of wells (QWs), and quantum well wires (QWWs), Quantum dots (QDs) and superlattices (SLs) has been a great interest to solid state physics, several studies have been performed to evaluate the physical properties of these systems[1-6]. The possible use of electron spins in the architecture of solid state based quantum computer has raised special attention in the study of the behaviour of the electron spin coupled with the external magnetic field. In such type of studies the fundamental importance has been given that no loss can occur when the spins transport information. This goal may be achieved by manipulating the electron g-factor in semiconductor hetrostructure and designing appropriate external gate control devices. The cyclotron effective mass and electronic g-factor have possible application and also in the interpretation of experimental date in this research. These factors play an important role in the magneto-optical and magneto-transport studies optically detected nuclear response experiments, spin electronic and quantum beats measurements. These are also applied the integer quantum Hall Effect.

For the calculation of electron g-factor and cyclotron effective mass one needs the detailed understanding of the interaction between the external applied magnetic field and the electronic state of semiconductor hetrostructure. One new technique like electron spin resonance, spin quantum beats, spin Raman scattering experiments and capacitance and energy spectroscopic. Lattice effects on the orbital contribution, quantum confinement and applications of hydrostatic pressure and external electric/magnetic field may considerably modify conduction electron g-factor both in magnitude and sign in different semiconductor hetrostructure. Theoretical point of view both electron g-factor and cyclotron effective mass provide an excellent tool for testing the band structure electronic calculation in the dimensional semiconductor hetrostructure.

In this paper, we have evaluated cyclotron effective mass (Mc/Mo) and 2D cyclotron effective mass (M_{2D}/Mo) as a function of magnetic field B (T). We have also evaluated (mc/mo) and g_{11} factor as a function of well width (A^0) for GaAs and $Ga_{0.65}Al_{0.35}As$ QW keeping (L=50A^0). Our theoretical evaluated results are in good agreement with the experimental data.

MATERIALS AND METHODS

One uses Ogg-McCombe Hamiltonian [11-18] within the effective mass approximation and in the forth order of $\bar{k}.\bar{p}$ perturbation theory. This Hamiltonian acts on the two fold Γ_6 spin degenerate conduction band of the bulk materials of the GaAs-Ga_{1-x}Al As quantum well under an applied magnetic field parallel in the growth z-direction. This is written as

$$H = \frac{\hbar^2}{2m^*}\overline{K}\vec{I} + \frac{1}{2}g\mu_B B\sigma_z + \Gamma\sigma.\tau + a_1\overline{K^4}\vec{I} + \quad (1)$$

$$\frac{a_2}{l^4_B}\vec{I} + a_3[\{k^2{}_x, k_y{}^2\} + \{k^2{}_y, k^2{}_z\}]\vec{I} + a_4 B\sigma_z + a_5\{\sigma.K, k_z B\vec{I}\} + a_6 B\sigma_z k^2{}_z + V(z)\vec{I}$$

Where $\vec{I}$ is the 2x2 unit matrix

$$\hat{\vec{K}} = \hat{\vec{k}} + e\hat{\vec{A}}/\hbar c$$

$$\hat{\vec{K}} = -i\nabla$$

Landau gauge is used for the vector potential

$$\hat{\vec{A}} = -yB\hat{\vec{x}}$$

a_i = 1-6 are constants taken from ref. 14 for equal values for the well and barrier materials.

V(z) is square well confining potential taken from Ga_{1-x} Al_xAs and GaAs band gap offset.[19]

m* and g are the z-growth direction position dependent conduction electron effective mass and Landu g-factor.

Γ is constant associated with spin orbit term (due to the fact that GaAs has no. inversion symmetry), $l_B = \sqrt{\frac{\hbar c}{eB}}$ is the Landau length, μ_β is the Bohr magnetron $\hat{\sigma} = (\hat{\sigma}_x, \hat{\sigma}_y, \hat{\sigma}_z)$ is the Pauli matrices and $\hat{\tau}$ is a vector operator with components such as $\hat{\tau}_x = \hat{k}_y\hat{k}_x\hat{k}_y - \hat{k}_z\hat{k}_x\hat{k}_z$ and corresponding cyclic permutation. The above Hamiltonian is a 2 x 2 conduction band effective Hamiltonian.[13-15] This Hamiltonian includes effects of non-parabolicity by taking into account the coupling between the lowest Γ_{6c} conduction band, Γ_{7v} and Γ_{8v} valance bands and the Γ_{7c} and Γ_{8c} p - anti bonding conduction bands.

The 2nd.term in RHS of eqn. (1) is the Zeeman contribution, the second order in $\vec{k}$ spin dependent term (with the factor a_4, a_5, and a_6) together with the third one is spin orbit interaction). The third order ***k*** contributes the changes in the hetrostructure effective g-factor.

The terms in a_1 and a_3 govern the energy dependence of the Cyclotron effective mass where as term with a_2 gives the diamagnetic shift of the Landau electronic length.

Let the Eigen function of H be

$$\psi(r) = \phi(y,z)\frac{e^{ikx}}{\sqrt{L_x}} \tag{2}$$

Here k_x is good quantum number as $\hat{H}$ does not depend on x explicitly. L_x is QW length along x direction. $\psi(\vec{x})$ and $\phi(y,z)$ are two component wave function.

Now we write the Hamiltonian[20,21]

$$\hat{H} = \hat{H}_0 + \hat{W} \tag{3}$$

where $\hat{W}$ is the perturbed Hamiltonian and may be neglected. This only contributes small correction to the energy levels.[22] The Eigen function of $\hat{H}(or\hat{H}_0)$ may be written as

$$\psi_+(r) = \frac{1}{\sqrt{L_x}} e^{iK_x x}\left(\phi_n(y) f^+{}_{n,m}(z)\right) \tag{4}$$

and

$$\psi_-(\bar{r}) = \frac{1}{\sqrt{L_x}} e^{iK_x x}\begin{pmatrix} 0 \\ \phi_n(y) f_n, \bar{m}(z) \end{pmatrix} \tag{5}$$

Where the symbols ± corresponds to (↑) spin up and (↓) spin down states respectively. Eigen functions $\phi_n(y)$ is 1D harmonic oscillator is given by

$$\phi_n(y) = \frac{1}{[n!2^n l_B \pi^{\frac{1}{2}}]^{\frac{1}{2}}} e^{\frac{-(y-y_0)^2}{2l^2{}_B}} H_n\left(\frac{y-y_0}{l_B}\right) \tag{6}$$

Where H_n are the Hermite polynomials, y_o=$K_x l$ is the orbit centre position and E_n=ħω_c(n+1/2) with n=0, 1, 2, ... and ω_c=eB/m*c are the 1D energies. The sub-index m = 1, 2, 3, ... in both fn,m$^{\pm}$ (z) and is associated with the electronic levels $E^{\pm}_{n,m}$. This indicates $E^{\pm}_{n,m}$ m-th QW confined energy and n=0, 1, 2, ... for given m represents the corresponding sub bands energy level.[24]

The Cyclotron effective mass is given by

$$m_c^{\uparrow\downarrow} = \frac{\hbar eB/c}{[E^{\uparrow,\downarrow}{}_{n+1}(B) - E_n^{\uparrow,\downarrow}(B)]} \quad (7)$$

The two-dimensional (2D) Cyclotron effective mass is given as

$$m_{2D}^{\uparrow\downarrow} = \frac{(\hbar eB/c)(n+1/2)}{[E^{\uparrow,\downarrow}{}_n(B) - E_n^{\uparrow,\downarrow}(B=0)]} \quad (8)$$

The parallel g-factor is

$$g_{\parallel} = \frac{[E^{\uparrow}{}_n(B) - E^{\downarrow}{}_n(B)]}{\mu_B B} \quad (9)$$

RESULTS AND DISCUSSIONS

In this paper, using the theoretical formalism developed by M. De. Dios-Leyva etal, [25] we have theoretically evaluated electronic Landau level energy, Cyclotron effective mass (M_c/m_o), 2D Cyclotron effective mass (m_{2D}/m_o) and g_{11}-factor for L=50A^o GaAs-$Ga_{0.65}Al_{0.35}$As QW as a function of as a function of the growth direction applied magnetic field. The results are shown in table T_1, T_2, T_3 and T_4 respectively. We have also evaluated cyclotron effective mass (m_c/m_o) for GaAs-$Ga_{0.65}Al_{0.35}$As QW as a function of well width. The theoretical results were compared with experimental data I[25] and II[26]. The results are shown in table T_5. In another evaluation, we have obtained the theoretical result of g_{11}-factor for GaAs-$Ga_{0.65}Al_{0.35}$As QW as a function of well width (A$^{\circ}$). The results are compared with another two experimental data I[27] and II which is shown in table T_6[28].

In table T_1, we have shown the electronic levels of the first m=1 sub bands of Landau levels. The non-linear behaviour of the $E^{\pm}_{n,m}$=1 Landau electronic levels is due to the presence of non-parabolic terms in the Hamiltonian. Our theoretical result shows that the effects of nonlinearity are stronger for the highest Landau levels and also for large values of the applied magnetic field as compared with the effects on the lowest Landau states. The above mentioned properties of the Landau energy levels lead to the behaviour of the Cyclotron masses as shown in table T_2

and T_3. We have evaluated Cyclotron mass (m_c/m_o) for GaAs-$Ga_{0.65}Al_{0.35}$As QW (L=50A^o) for n=0, 1, 2, 3 and 4 keeping m=1. Our evaluated results of (m_c/m_o) increases as a function of ?(T) for all n. The increase is linear for two values of n and nonlinear for large value of n. Similar behaviour is also observed for 2D cyclotron mass as a function of ?(T) shown in table T_3. The first dependent g_{11}-factor is shown in table T_4. In this case also our evaluated results increases as a function of ?(T) for all values of n. It appears that field depends on g_{11} factor is due to the magnetic field effect on the electronic Landau states as well as to the confinement or barrier penetration of the electron wave function due to the presence of $Ga_{0.65}Al_{0.35}$As barrier. We have also calculated Cyclotron effective mass (m_c/m_o) and g_{11} factor both as a function of well width (A^o) for GaAs-$Ga_{0.65}Al_{0.35}$As QW. The calculated result were compared with the experimental data I[26] and II[27] for (m_c/m_o) shown in table T_5 and another experimental data I[28] and II[29] for $g_{\|}$ factor shown in table T_6. Our evaluate results of (m_c/m_o) is larger in magnitude for experimental data I and small for experimental data II as a function of well width. The evaluated results of (m_c/m_o) decrease as a function of well width as per experimental observation. Similar trend is also obtained for $g_{\|}$ factor. There is some recent results[30-36] which also reveal the similar behaviour.

CONCLUSION:

In this paper, we have evaluated cyclotron effective mass (m_C/m_0) and g_{11} factor both as a function of well width for GaAs-$Ga_{0.65}Al_{0.35}$As QW. We observe that both (m_C/m_0) and g_{11} decreases as a function of well width. Our evaluated results are larger in magnitude with experimental results but trends are same with expt.

Table T_1

An evaluated results of electronic Landau levels as a function of the growth direction applied magnetic field for L=50A^o, GaAs-$Ga_{0.65}Al_{0.35}$As Quantum Well for m=1 sub-bands of Landau states.

Magnetic field B (T)	n=0	n=1	n=2	n=3	n=4	n=5
0	72.3	77.8	86.5	90.5	95.6	98.2
5	74.6	80.5	97.5	98.4	105.4	110.4
10	78.5	85.8	108.5	110.2	119.2	121.8

12	81.2	92.5	112.3	115.8	125.4	132.6
14	83.0	98.8	125.6	130.6	136.8	140.8
15	85.8	106.5	132.3	138.6	144.3	152.6
16	87.2	118.2	139.7	145.3	155.5	162.4
18	89.0	123.6	147.5	154.2	161.7	172.5
20	91.5	135.5	153.6	160.5	172.8	181.6
22	93.2	140.8	159.2	169.8	182.5	190.5
24	95.5	144.6	164.2	175.2	194.3	198.2
25	97.8	155.3	173.6	185.3	199.5	205.3

Table T_2

An evaluated results of Cyclotron effective mass (m_c/m_o) for GaAs-$Ga_{0.65}Al_{0.35}As$ QW as a function of growth direction magnetic field (m=1), L=50A°.

□(T)	←-----------(m_c/m_o)--------------→ (m=1)				
	n=0	n=1	n=2	n=3	n=4
0	0.082	0.084	0.092	0.096	0.104
5	0.084	0.088	0.098	0.102	0.108
10	0.086	0.090	0.104	0.108	0.112
15	0.089	0.094	0.105	0.114	0.115
18	0.090	0.098	0.110	0.118	0.120
20	0.092	0.102	0.114	0.122	0.125
22	0.094	0.106	0.118	0.126	0.130

24	0.096	0.109	0.122	0.130	0.132
25	0.098	0.112	0.126	0.134	0.136
28	0.102	0.114	0.129	0.138	0.140
30	0.104	0.118	0.130	0.142	0.145

Table T_3

An evaluated results of 2D Cyclotron effective mass (m_{2D}/m_o) for GaAs-$Ga_{0.65}Al_{0.35}$As QW for L=50A^o as a function of growth direction magnetic field □(T).

B (T)	←-----------(m_{2D}/m_o)--------------→ (m=1)				
	n=0	n=1	n=2	n=3	n=4
0	0.080	0.082	0.084	0.089	0.092
5	0.081	0.086	0.088	0.092	0.099
7	0.083	0.089	0.090	0.096	0.106
9	0.085	0.092	0.096	0.099	0.112
10	0.088	0.095	0.099	0.103	0.118
12	0.091	0.099	0.102	0.109	0.122
14	0.094	0.105	0.107	0.112	0.125
15	0.097	0.108	0.115	0.118	0.129
18	0.099	0.112	0.120	0.125	0.135
20	0.102	0.115	0.126	0.130	0.138
22	0.106	0.118	0.129	0.135	0.142
24	0.109	0.120	0.132	0.138	0.143

25	0.112	0.124	0.136	0.142	0.146
28	0.115	0.128	0.139	0.144	0.150
30	0.118	0.130	0.142	0.147	0.152

Table T_4

An evaluated results of g_{11} factor for L=50A^o GaAs-$Ga_{0.65}Al_{0.35}$ QW as a function of the growth dimension applied magnetic field.

B (T)	←-----------(g_{11}-factor)--------------→ (m=1)				
	n=0	n=1	n=2	n=3	n=4
0	0.122	0.124	0.132	0.204	0.217
5	0.124	0.128	0.206	0.247	0.268
7	0.126	0.132	0.258	0.268	0.305
9	0.128	0.136	0.297	0.358	0.362
10	0.130	0.139	0.325	0.392	0.428
12	0.134	0.143	0.367	0.435	0.495
14	0.136	0.146	0.405	0.495	0.573
15	0.138	0.149	0.435	0.558	0.645
17	0.140	0.156	0.468	0.592	0.708
19	0.144	0.159	0.506	0.675	0.786
20	0.148	0.163	0.558	0.706	0.825
22	0.152	0.168	0.605	0.768	0.889
24	0.156	0.172	0.674	0.804	0.922

26	0.159	0.178	0.703	0.855	0.962
28	0.163	0.184	0.768	0.903	1.032
30	0.165	0.190	0.804	0.947	1.057

TableT_5

An evaluated result of Cyclotron effective mass for GaAs-$Ga_{0.65}Al_{0.35}$ QW as a function of well width (A^o) Theoretical results were compared with expt. I and expt. II

Well width (A^o)	Cyclotron Effective Mass (m_c/m_o)		
	Theoretical	Expt. I[25]	Expt. II[26]
5	0.115	0.109	0.118
10	0.108	0.104	0.114
15	0.102	0.100	0.109
20	0.097	0.093	0.107
30	0.092	0.089	0.103
40	0.086	0.085	0.092
50	0.084	0.080	0.087
60	0.080	0.076	0.083
70	0.076	0.072	0.080
80	0.073	0.069	0.076
90	0.070	0.066	0.072
100	0.069	0.062	0.069
110	0.067	0.060	0.065

120	0.065	0.058	0.062
130	0.062	0.056	0.060
150	0.060	0.054	0.058

Table T_6

An evaluated result of g_{11}-factor for GaAs-$Ga_{0.65}Al_{0.35}As$ QW as a function of well width The theoretical results were compared with the experimental result I and II.

Well width (A°)	g_{11}-factor		
	Theoretical result	Expt. I[27]	Expt. II[28]
5	0.546	0.584	0.687
10	0.538	0.468	0.562
20	0.512	0.402	0.485
30	0.504	0.352	0.395
40	0.497	0.306	0.324
50	0.482	0.205	0.267
60	0.465	0.186	0.205
70	0.247	0.105	0.125
80	0.134	0.032	0.062
90	0.076	-0.007	-0.004
100	0.065	-0.058	-0.096
120	-0.067	-0.126	-0.146
140	-0.125	-0.148	-0.205

150	-0.246	-0.257	-0.269
160	-0.324	-0.305	-0.325
180	-0.364	-0.348	-0.355
200	-0.405	-0.386	-0.402

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