J Mol Model (2013) 19:2091–2095
DOI 10.1007/s00894-012-1658-y

ORIGINAL PAPER

# Simulation of laser radiation effects on low dimensionality structures

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Received: 28 May 2012 / Accepted: 18 October 2012 / Published online: 15 November 2012


**Abstract** This paper presents a study on a system comprised of a low-dimensional structure ($Ga_{1-x}Al_xAs$ and GaAs quantum well wire), an intense laser field and an applied magnetic field in axial direction, resulting in a modified structure by interaction with the laser field. A variation of the concentration of aluminum is considered. So, the characteristics of the semiconductor such as the effective mass and width of the forbidden band vary due to the aluminum concentration. The electronic Landé factor control by changing of both intensity and frequency of a laser field on cylindrical quantum well wire was also reported. We use the laser dressed approximation for the treated "quantum wire + laser" system as quantum wire in the absence of radiation but with parameter (electronic barrier height and electronic effective mass) renormalized by laser effects. We consider a magnetic field applied in the parallel direction of symmetric axis of the quantum well wire. We take into account non-parabolicity and anisotropy effects on the conduction band by Ogg-McCombe Hamiltonian.

**Keywords** Landé Factor · Laser dressing · Magnetic field · Quantum well wire · Semiconductors

## Introduction

The effects produced by the application of external fields on low dimensional semiconductor systems provide a wide field of study. Research in this area is very active and fruitful because of possible technological applications that can be generated through the manipulation of optical properties, electronic or mechanical materials and the discovery of giant magnetoresistance and its applications in various electronic devices [1]. Previous works [2–5] have reported the changes in some semiconductor heterostructures under to the action of an intense laser field. These studies are important for understanding the behavior of some electronic properties such as the Landé factor, which is relevant in spintronics because it is related to the separation of the energies associated with the spin states [1]. The importance of this work lies in the direct relationship that has the Landé factor of the electron energy, and thus with the electronic properties such as electrical transport, optical properties, or information storage, which lead to a new variety of device development, such as laser diodes that are used in present compact disk systems and transmission lines with optical fiber, and high-speed devices such as high frequency and high-speed transistors [1, 6, 7]. The Landé factor provides information about the degrees of spin orientation and therefore its control involves the manipulation of these degrees of freedom. Different types of external fields have been used to control the Landé factor, electric and magnetic fields are the most used for this purpose [8].

In quantum wires that are influenced by an intense laser, some authors [8], have shown the variations on Landé factor depending on the radius of the wire, the change in the intensity and degree of tuning of the laser to a value of fixed magnetic field. However, these studies did not analyze the effects of laser on the Landé factor as a function of magnetic field [9].

The goal of this paper is to present a theoretical study of the effective Landé associated with a semiconductor quantum wire, subjected to the application of an intense laser and an applied magnetic field in the wire axial direction. This study is important in determining the energy changes of the system, considering an applied magnetic field that varies uniformly and also changes in the concentration of aluminum.

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## Theory

Landé factor in the absence of laser radiation

Consider a GaAs/(Ga, Al) As quantum well wire with cylindrical symmetry, with a finite potential barrier potential and a magnetic field applied in the axial direction. We take into account the effects of non-parabolicity and anisotropy in the conduction band by using the Ogg-McCombe Hamiltonian [10, 11].

$$\widehat{H}=\frac{\hbar^2}{2}\widehat{\overrightarrow{k}}\frac{1}{m(x,y)}\widehat{\overrightarrow{k}}+\frac{1}{2}g(x,y)\mu_B B\widehat{\sigma}_z+V(x,y)I+\widehat{\overrightarrow{W}} \tag{1}$$

In Eq. (1) we have $\widehat{\overrightarrow{k}}=-i\nabla+\frac{e}{mc}\widehat{\overrightarrow{A}}, \widehat{\overrightarrow{\sigma}}$ is a vector whose components are the Pauli matrices, $m(x,y)$ is the effective mass and $g(x,y)$ is the effective Landé factor, the last two terms depend on the position due to change in the interface between two materials that constitute the quantum wire. The height of the electronic confinement potential $V(x,y)$ was taken as 60 % of the difference between the energy gaps of $Ga_{1-x}Al_xAs$ and GaAs. The operator $\widehat{\overrightarrow{W}}$ expresses the anisotropy and non-parabolicity in electronic conduction band [5, 12] and depends on powers of $\widehat{\overrightarrow{k}}$ up to fourth order.

The wave functions of (1) can be chosen as:

$$\psi_j(\overrightarrow{r})=\begin{pmatrix}\varphi_{j,\uparrow}(\overrightarrow{\rho})\\ \varphi_{j,\downarrow}(\overrightarrow{\rho})\end{pmatrix}e^{ik_z z}, \tag{2}$$

where $\overrightarrow{\rho}$ indicates the spatial coordinates, $k_z$ is the magnitude of electronic wave vector along the axis of symmetry of the wire, $\varphi_{j,m_s}$ are the electron wave functions in a plane perpendicular to the symmetry axis for the two different electron spin projections ($m_s$=↑,↓) to the magnetic field direction. We consider low temperatures so that only the lowest electronic states are populated and $k_z$=0 can be taken. The Hamiltonian (1) turns diagonal and spin states ↑and ↓ are decoupled, so the Schrödinger equation has the form:

$$\begin{pmatrix}\widehat{H}_\uparrow & 0\\ 0 & \widehat{H}_\downarrow\end{pmatrix}\begin{pmatrix}\varphi_{j,\uparrow}(\overrightarrow{\rho})\\ \varphi_{j,\downarrow}(\overrightarrow{\rho})\end{pmatrix}=E\begin{pmatrix}\varphi_{j,\uparrow}(\overrightarrow{\rho})\\ \varphi_{j,\downarrow}(\overrightarrow{\rho})\end{pmatrix}, \tag{3}$$

where $\widehat{H}_\uparrow$ and $\widehat{H}_\downarrow$ correspond to the two electronic spin states (↑) and (↓), respectively. The vector potential can be chosen as $\overrightarrow{A}=\frac{1}{2}\overrightarrow{B}\times\overrightarrow{r}$ and wave functions $\varphi_{j,m_s}$ can be expanded in terms of eigenfunctions of two-dimensional harmonic oscillator:

$$\varphi_{j,m_s}(\overrightarrow{\rho})=\sum_k c_{jk}(m_s)\Phi_k(\overrightarrow{\rho}), \tag{4}$$

$$\varphi_{j,m_s}(\overrightarrow{\rho})=A_{n_k l_k}\left[\frac{\rho}{\sqrt{2}l_B}\right]^{|l_k|}L_{n_k}^{|l_k|}\left(\frac{\rho^2}{2l_B^2}\right)e^{-\frac{\rho^2}{4l_B^2}+i\theta l_k}, \tag{5}$$

where $A_{n_k l_k}=\left[\frac{n_k!}{2\pi l_B^2(n_k+|l_k|)!}\right]^{1/2}$ and $L_{n_k}^{|l_k|}$ are Laguerre associated polynomials. The expansion (4) can be used to write the Hamiltonian $\widehat{H}_{m_s}$ in terms of harmonic oscillator, with eigenvalues obtained by solving:

$$\sum_k\left[H_{m_s}^{j_k}-E_n(m_s)\delta_{jk}\right]c_{nk}(m_s)=0, \tag{6}$$

with $H_{m_s}^{j_k}=\left\langle\Phi_k(\overrightarrow{\rho})\middle|\widehat{H}_{m_s}\middle|\Phi_k(\overrightarrow{\rho})\right\rangle$ and $k$ corresponds to the pair of numbers $k\equiv(n_k,l_k)$ radial and magnetic, respectively. The g Landé factor associated with $E_0(\uparrow)$ and $E_0(\downarrow)$ states, is

$$g=\frac{E_0(\uparrow)-E_0(\downarrow)}{\mu_B B}. \tag{7}$$

In this expression is $\mu_B$ is Bohr magneton.

## Effects of the interaction of an intense laser on effective Landé factor in quantum wires

The model considered in this paper is an extension of the dressed states model, which is applied to electrons of the conduction band that interact with a laser field. That is to say, it is another approach which considers the radiation matter interaction and the influence of energy eigenvalues on degree tuning. The effect rests on the Landé factor of the electrons in the conduction band, which in turn are affected by two closest valence bands due to the variation of the width of the forbidden band.

The presence of the laser field in the system, requires a renormalization of the effective mass and the energy gap. The extended dress laser approach considers some restrictions, that is to say, the model represents the heterostructure + laser + magnetic field as a system formed by the modified heterostructure due to laser field + magnetic field [8]. In this approach the characteristic parameters of each material, effective mass, energy gap and Landé factor, are renormalized using the following expressions:

$$\frac{1}{m}=\frac{1}{2M}\left[1+\frac{M}{\mu_{68}}\left(\frac{\Lambda_0^2\beta_\gamma}{3\delta'}+\prod\right)\right], \tag{8}$$

and

$$\varepsilon=\varepsilon_0-\delta+\sqrt{\frac{8\Lambda_0^2}{3}+\left(\delta+\frac{\Lambda_0^2}{3\delta'}+\frac{4\Lambda_0^2}{3\Lambda_1}\right)^2}, \tag{9}$$

where

$$\Pi = \frac{\left(1+\frac{\Lambda_0^2\beta_\gamma}{3\delta'}+\frac{4\Lambda_0^2\beta_{\gamma'}}{3\Lambda_1}\right)\left(\delta+\frac{\Lambda_0^2}{3\delta'}+\frac{4\Lambda_0^2}{3\Lambda_1}\right)+\frac{4\Lambda_0^2\beta_{\gamma''}}{3}}{\sqrt{\frac{8\Lambda_0^2}{3}+\left(\delta+\frac{\Lambda_0^2}{3\delta'}+\frac{4\Lambda_0^2}{3\Lambda_1}\right)^2}} \tag{10}$$

$$\beta_\gamma = -\frac{\mu_{68}}{\mu_{67}}\frac{1}{\delta'}+\frac{8\mathrm{E_p}}{3}\frac{\mu_{68}}{\mathrm{m_0}}\left(\frac{1}{\varepsilon_0^2}+\frac{2}{\varepsilon_0'^2}+\frac{2}{\varepsilon_0\varepsilon_0'}\right) \tag{11}$$

$$\beta_{\gamma'} = -\frac{1}{\Lambda_1}+\beta_{\gamma''} \tag{12}$$

$$\beta_{\gamma''} = -\frac{4E_p}{3}\frac{\mu_{68}}{\mathrm{m_0}}\left(\frac{8}{\varepsilon_0^2}+\frac{1}{\varepsilon_0'^2}+\frac{2}{\varepsilon_0\varepsilon_0'}\right). \tag{13}$$

In Eqs. (8)–(13) we have the following terms: $\frac{1}{M}=\frac{1}{m_{\gamma6}}+\frac{1}{m_{\gamma8}}$, $\Lambda_0=\frac{\varepsilon A_0|p|}{2m_0c}$, $A_0$ is the classical amplitude of vector potential of the photon, which is related to the field amplitude in vacuum $A_\omega=\sqrt{\frac{2\pi\hbar c^2}{\omega\,\Omega}}$ within a volume $\Omega$, via $A_0=2\sqrt{N_0}A_\omega$ where $N_0>>1$ is the average number of photons in the field. In addition $\varepsilon_0=E(\Gamma_6^c)-(\Gamma_8^v)$ is the fundamental energy gap fundamental in the semiconductor, $\varepsilon$ is the renormalized energy gap of the semiconductor by the effects of laser, $\varepsilon_0'=\varepsilon_0+\Delta$, $\Delta=E(\Gamma_8^v)-E(\Gamma_7^v)$, is the energy gap by spin orbit splitting in the valence band, $\delta=\varepsilon_0-\hbar\omega$ is the degree of tuning of the laser, $\delta'=\delta+\Delta$, $\Lambda_1=\varepsilon_0+\hbar\omega$, $E_p=\frac{p^2}{2m_0}$, $p$ is the conduction interband matrix element with the corresponding states of the valence band $\Gamma_8^v$ and $\Gamma_7^v$, $m_0$is the mass of free electron $\frac{1}{\mu_{67(8)}}=\frac{1}{m_{\gamma6}}-\frac{1}{m_{\gamma7(8)}}$, where $m_{\gamma6}$,$m_{\gamma7}$ and $m_{\gamma8}$ are effective masses associated to conduction electrons in $\Gamma_6^c$ heavy holes in $\Gamma_8^v$ and holes in $\Gamma_7^v$. The field effects of laser radiation and aluminum concentration on the effective Landé factor $Ga_{1-x}Al_xAs$ can be evaluated by the expression (14)

$$g=g_0-g_0\frac{4E_p}{3}\frac{\Delta}{\varepsilon(\varepsilon+\Delta)}+g_0\delta_g, \tag{14}$$

where $g_0$ is Landé factor of free electron and $\delta_g=-0.056-0.276x+0.276x^2$ denotes a variation of Landé factor respect to aluminum concentration.

The change of the effective mass between GaAs and $Ga_{1-x}Al_xAs$ is negligible for $x\leq0.40$ and the effective mass is considered the same for the two materials.

## Procedures

The effective mass and the energy gap of the semiconductor material GaAs/b(Ga, Al) As in the presence of an intense laser field was calculated, and thus the behavior of these variables with respect to the intensity and frequency of the laser were obtained.

A numerical diagonalization of the Hamiltonian associated with the two possible electron spin states in a Landau level basis of 700 states with a degree of accuracy in the convergence of eigenenergies for each of the spin states was performed. Therefore the Landé factor associated with a quantum wire as a function of various parameters was calculated. In this work, a variation of the concentration of aluminum also was considered.

## Results and discussion

Obtained data consider a $GaAs/Ga_{0.70}Al_{0.30}As$ quantum wire with cylindrical geometry and a radius of 50 Å. Also considered is a homogeneous magnetic field which varies between 5 and 20 T applied in the direction parallel to the axis of the wire. Due to laser radiation and changes in the concentration of aluminum, semiconductor characteristics such as the effective mass and energy gap vary depending on the aluminum concentration, the intensity and frequency of the laser field. Figures 1 and 2 show the behavior of the effective mass and energy gap as a function of the laser field strength for two values of the concentration of aluminum at a fixed tuning degree $\delta=0.05\varepsilon_0$, $\varepsilon_0=1.52\,eV$, respectively.

Figure 3 shows the effective Landé Factor as a function of applied magnetic field for two different values of laser intensity, $I=0.02\times10^{-4}I_0$ and $I=0.03\times10^{-4}I_0$,

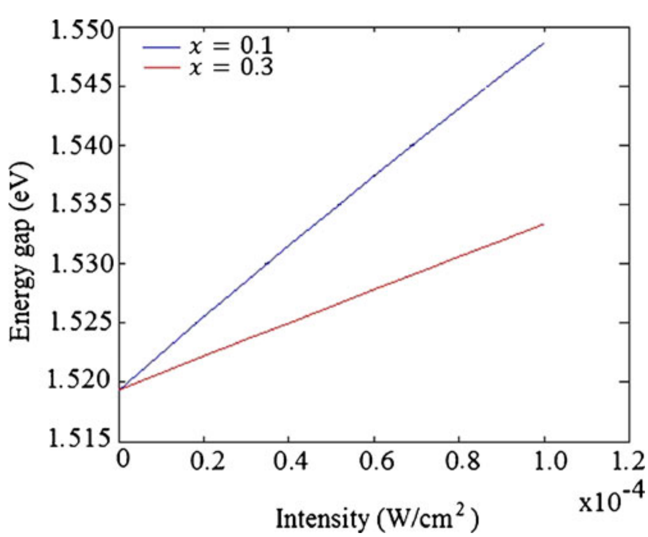


**Fig. 1** Energy gap as a function of the intensity of the laser field for two concentration values

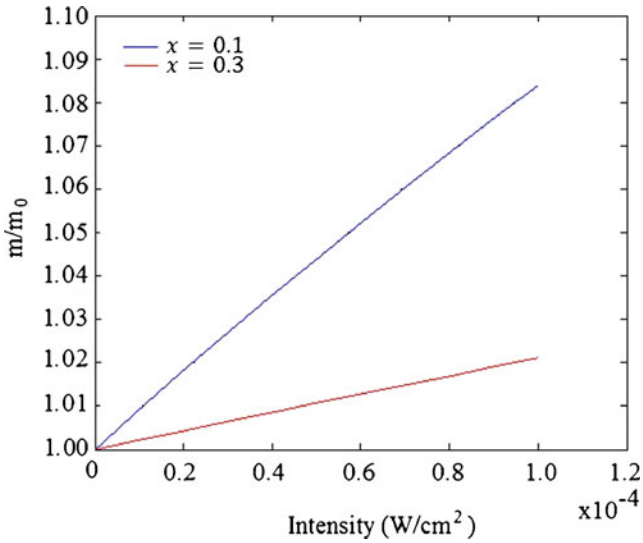


**Fig. 2** Effective mass as a function of the intensity of the laser field for two concentration values

keeping the tuning degree, δ, fixed at 0.05 and using $I_0=5\times10^{13}\,Wcm^{-2}$. This figure shows that increases in the laser intensity can lead negative values of the effective Landé factor to positive values in the range 5–20 T. Hence, there is a change in the energies associated with the electronic conduction states with a different spin, in other words, the electronic state of lowest energy is $E_0(\uparrow)$, but as the laser intensity increases the electronic state of lowest energy is replaced by $E_0(\downarrow)$. On the other hand, increases in the magnetic field from 17 to 19 T when the laser field intensity and the degree of tuning are fixed at $I=0.02\times10^{-4}I_0$ and $\delta=0.05\varepsilon_0$, respectively, the sign of the Landé effective factor can be modified, which switches the conditions associated with the electron spin.

Figure 4 shows the Landé effective factor as a function of applied magnetic field for two different values of the degree of tuning, $\delta=0.05\varepsilon_0$ and $\delta=0.1\varepsilon_0$, and keeping the intensity fixed at $I=0.03\times10^{-4}I_0$. It can be noticed that increases in the degree of laser tuning produces a decrease in the value of the Landé effective factor, from positive values to negative values, in contrast, an opposite behavior to the previous case can be seen.

It can be seen that an increase in the magnetic field increases Landé effective factor, therefore, at fixed values of tuning degree and intensity the increase in the magnetic field produces an increase in the Landé factor due to exerted confinement by the magnetic field on the electron wave function.

## Conclusions

For the lowest concentration of aluminum increases in the forbidden band width are more pronounced with increases in the intensity of the laser field, compared to increases at higher concentrations. In the same way changes in the effective mass are most noticeable with the laser intensity increases.

Effective electronic Landé factor in $GaAs/Ga_{0.70}Al_{0.30}$ quantum wires was studied in the presence of an intense laser field as a function of applied magnetic field in the axial direction to the wire. It was shown that Landé factor can be controlled through variation of the laser, in other words, the

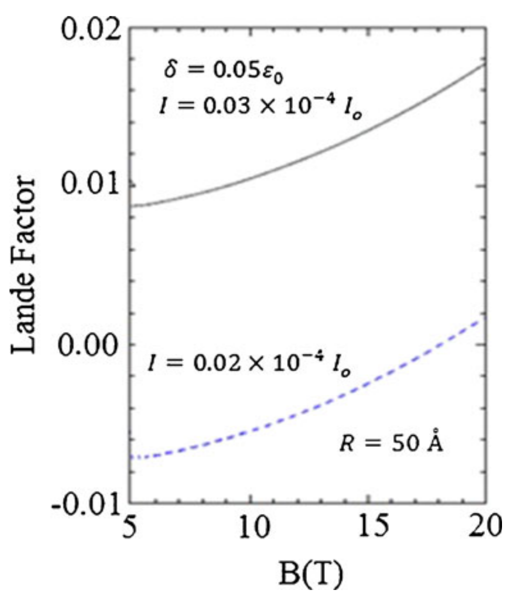


**Fig. 3** Landé factor as a function of magnetic field according to two different values of laser intensity and a fixed tuning degree

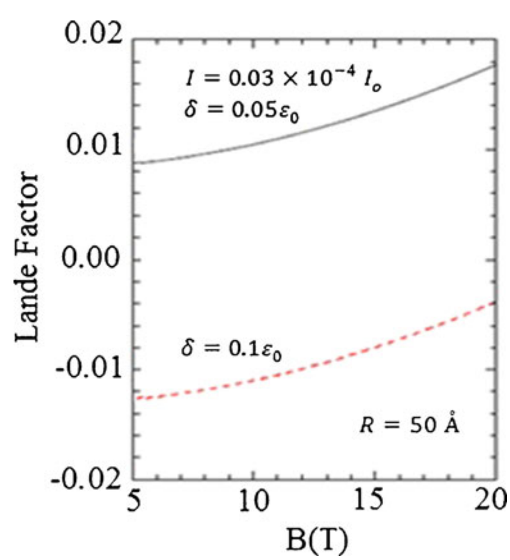


**Fig. 4** Landé factor as a function of magnetic field for two values of tuning laser degree and a fixed intensity

behavior of the mathematical function that describes it varies, but its forms does not.

Landé factor increases with laser intensity increases and decreases with degree of laser tuning decreases. So it can be shown that Landé factor can be controlled by the degree of laser tuning.

Increases in magnetic field produce an increase in the value of the effective Landé factor. This result has been reported in previous works without considering the laser radiation. The laser effects are more prominent when the applied magnetic field is enhanced.

In this work the functional dependence between the Landé factor and the intensity or degree of tuning of the laser cannot be established, but the region with significant changes can be seen.

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