Physica E 57 (2014) 138–144

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

# Magnetic field effect on the third harmonic generation in quantum well wires with triangular cross-section

E.C. Niculescu, M. Cristea, A. Radu *

*Department of Physics, "Politehnica" University of Bucharest, 313 Splaiul Independenţei, Bucharest RO-060042, Romania*

## HIGHLIGHTS

- The 3rd-order nonlinear susceptibility in triangular cross-section QWWs is studied.
- Electronic states strongly depend on the magnetic field strength and orientation.
- An axial orientation of the magnetic field allows the third harmonic generation.
- The triple cvasi-resonance may be achieved for a *y*-polarized pump radiation.

## ARTICLE INFO

*Article history:*
Received 22 August 2013
Received in revised form
22 September 2013
Accepted 29 October 2013
Available online 11 November 2013

*Keywords:*
Quantum well wire
Magnetic field
Intersubband transitions
Third harmonic generation

## ABSTRACT

The conduction subband structure of a triangular cross-section GaAs/AlGaAs quantum well wire under magnetic field is theoretically investigated by taking into account a finite confining potential and two orientations of the field relative to the wire axis. The calculation of the subband energy levels is based on a two-dimensional finite element method within the effective mass approximation. It is shown that the magnetic field could be used for tuning the intersubband transitions: in the transverse field there is an obvious augment of the energy levels, whereas an axial field induces blueshifts/redshifts on the subband energies, depending on the azimuthal quantum number. We found that an axial orientation of the field allows the third harmonic generation and this process is enhanced for a particular polarization of the incident light and a proper field strength. A third-order nonlinear susceptibility with a peak value of $10^{-13}\ (m/V)^2$ is predicted when the triple resonance condition is achieved.



## 1. Introduction

In the last decades the development of new techniques for growing quantum well wires (QWWs) has allowed obtaining novel one-dimensional structures of various compositions, sizes, and shapes [1–10]. The theoretical study of the external field effects on the electronic structure and optical properties of these systems is one of great relevance for potential technological applications. In particular, it is proved that for an electron subjected simultaneously to the potential of the QWW and to a static magnetic field, the energy spectrum and wave functions are significantly altered due to the competition between the magnetic confinement and spatial quantum confinement [11–15]. Since it can be applied experimentally in a well controlled way, the magnetic field becomes an interesting tool to control and modulate the intensity output of the optoelectronic devices. These aspects have motivated the realization of many studies focused on the subband structure and the electronic properties of one-dimensional systems under applied magnetic fields, as well as on the linear and nonlinear optical absorption in QWWs.

Photoluminescence studies of Bayer et al. [16] revealed a size dependence of the changeover from geometric to magnetic confinement in $In_{0.53}Ga_{0.47}As/InP$ QWWs when the magnetic field is perpendicular to the wire axis. There are also reports on the photoluminescence spectra and anisotropic energy shift of GaAs quantum wires in high magnetic fields [17] and on the magnetic field effects on the binding energy of shallow donors in GaAs QWWs [18]. By using the finite difference method Bilekkaya et al. [19] have calculated the ground state energies of an electron in QWWs with different shapes in the presence of applied electric and magnetic fields. The optical intersubband transitions in QWWs subjected to magnetic fields [20,21] as well as the simultaneous effects of external electric and magnetic fields on the optical absorption coefficients and refractive index changes of a hydrogenic impurity confined in a cylindrical quantum wire with convex bottom [22] have also been investigated. Polaron effects on third-harmonic generation (THG) in cylindrical quantum wires with a finite [23] and infinite [24] confining potential have been

* Corresponding author. Tel.: +40 723514439.
*E-mail addresses:* radu@physics.pub.ro, treizone@yahoo.com (A. Radu).

1386-9477/$ - see front matter 
http://dx.doi.org/10.1016/j.physe.2013.10.036

studied by Yu et al. They found that the THG coefficient is greatly enhanced and its peak shifts to the higher photon energy when the influence of electron–phonon interaction is taken into account. The THG in cylindrical parabolic quantum wires with applied electric [25] and magnetic [26] fields have been also theoretically investigated.

Recently, the study of optical properties has been extended to QWWs with particular geometries. There are - for instance - reports on the influence of the electron-hole interaction on the electro-optical properties of hyperbolic QWWs [27], the hydrostatic pressure effect on the intersubband optical absorption and refractive index changes in V-groove QWWs [28] and the optical absorption in asymmetric graded ridge QWWs [29]. Using the infinite confining potential model, Khordad et al. have investigated the optical properties of the QWW with equilateral triangle cross section [30] and the second- and third-harmonic generation (THG) in GaAs QWWs with triangular cross-section [31]. They found that, by optimizing the confinement potential, a maximum THG can be obtained and the corresponding resonant peaks shift towards lower energies by increasing the size of the triangle side. Very recently, Duque and collaborators [32] presented the results of the calculation of the linear and nonlinear optical absorption and relative change of the refractive index associated with 1s→2p transitions between donor states in a QWW of triangular cross-section. However, because of the increased complexity of the numerical calculations, these studies treat particular cases of structures without applied external fields and/or in the infinite confining potential approximation.

The main objective of this work is the theoretical study of the magnetic field effects on the THG in GaAs/$Al_{0.3}Ga_{0.7}As$ QWWs with equilateral triangle cross section. The calculations are based on the finite element method within the effective mass approximation. We discuss the possibility of the THG associated to the intersubband transitions when the magnetic field is applied along or perpendicular to the wire axis. The paper also presents a field-induced case of triple resonance of the THG for which a peak value as high as $10^{-13}\ (m/V)^2$ can be achieved.

The structure of the work is as follows: Section 2 briefly presents the theoretical model. The corresponding results and discussion are given in Section 3. Finally, Section 4 contains the main conclusions of the study.

## 2. Theory

The system consists of a GaAs wire embedded in an $Al_{0.3}Ga_{0.7}As$ matrix. The transverse cross section of the QWW is an equilateral triangle with a side $L$ (Fig. 1(A)). We assume that the electrons confined in the QWW interact with a static magnetic field $\vec{B}$ which could be oriented along the wire (on the $z$-axis) or in the transverse plane (Fig. 1(B)).

The appropriate Hamiltonian for the electron in the effective mass approximation may be written as

$$H=\frac{1}{2m^*}(\vec{p}+e\vec{A})^2+V(x,y) \tag{1}$$

Here $m^*$ and $e$ are the effective mass and the elementary charge, respectively, $\vec{p}=-i\hbar\nabla$ is the momentum, $\vec{A}$ is the vector potential of the magnetic field, and $V(x,y)$ is the confinement potential due to the band discontinuity (Fig. 1(B)):

$$V(x,y)=\begin{cases}0, & \text{if } (x,y) \text{ is inside the wire;}\\ V_0, & \text{if } (x,y) \text{ is outside the wire.}\end{cases} \tag{2}$$

As in Ref. [33] when the magnetic field is applied along the wire axis, i.e. $\vec{B}=B\hat{z}$, we chose the symmetric gauge $\vec{A}=-(B/2)(-y\hat{x}+x\hat{y})$. The Hamiltonian of the system can be rewritten as

$$H=\frac{p_x^2+p_y^2+p_z^2}{2m^*}+\frac{qB}{2m^*}(yp_x-xp_y)+\frac{q^2B^2}{8m^*}(x^2+y^2)+V(x,y) \tag{3}$$

We note the appearance of two different kinds of magnetic field related terms in the Hamiltonian operator: the derivative terms that couple the motions along directions perpendicular to the magnetic field (i.e. $x$ and $y$), which are reminiscent of the Lorentz force [34], and a parabolic magnetic potential, which enhances the confinement of the electronic wave functions in the transverse plane. As the vector potential associated with this field does not depend on $z$, $H$ commutes with $p_z$ and therefore the electron wave function can be written as

$$\Psi(x,y,z)=e^{ik_zz}\ \Phi(x,y) \tag{4}$$

Here $k_z$ is the wave number corresponding to a free motion in the $z$-direction and the function $\Phi(x,y)$ is a two-dimensional eigenfunction corresponding to the bottom of the subband ($k_z=0$). One may observe that, in the absence of the quantum confinement potential $V(x,y)$, the resulting two-dimensional Schrödinger equation can be separated into two differential equations, describing the motion along the $x$- and $y$-axis. Each equation is identical to that of a 1D harmonic oscillator so that the magnetic field contribution to the energy consists in the formation of discrete Landau levels [35]. In the QWW structure, the energy levels are expected to be quantized by the combination of spatial ($V(x,y)$ potential) and magnetic confinements (Landau levels).

In the case of a magnetic field parallel with the $x$ direction, $\vec{B}=B\hat{x}$, a non-symmetric gauge is used [33] $\vec{A}=By\hat{z}$. The Hamiltonian

$$H=\frac{p_x^2+p_y^2+p_z^2}{2m^*}+\frac{qByp_z}{2m^*}+\frac{q^2B^2y^2}{2m^*}+V(x,y) \tag{5}$$

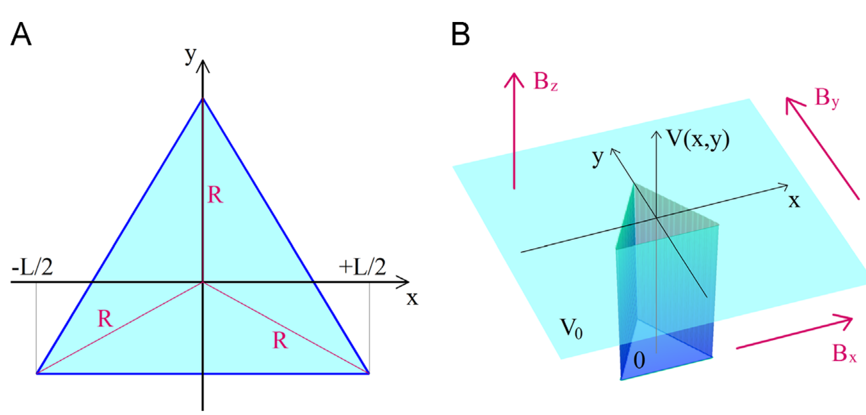


**Fig. 1.** (A) Cross section of the QWW; (B) Confinement potential of the QWW.