Effect of a high intensity laser beam on impurity binding energy in a nanocone

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Abstract. This paper presents theoretical results of a study that analyzed the effect of a high-frequency laser in the ground state binding energy of a hydrogenic donor impurity. For these results, the trigonometric sweep method and framework of the effective mass approximation is applied. The results showed that the binding energy changes depending on the laser intensity and the impurity position across of the nanocone axis. The results agree with previous results obtained in similar systems.

1. Introduction
There has been considerable interest in the study of the effect of an intense laser high frequency semiconductor devices, because it induces a nonlinear effect in the optical properties such as intersubband transitions, the peak refractive index change show a red shift [1], anisotropy in the absorption coefficients [2, 3] and capable of monitoring high-switching frequency optical signals [4].

A number of theoretical results on the study of the binding energy of a hydrogen-donor impurity in quantum well wires (QWWs) of GaAs-(Ga, Al)As under the laser-dressed effects both Coulomb potential and impurity confinement potential, respectively. Qu Fanyao et al. [5], their results show a rapid decrease of the ground-state binding energy for different values of the wire radius with increasing field intensity laser. E. C. Niculescu and A. M. Radu [6], they calculated the binding energy of an off-center donor impurity in a cylindrical QWW, in the presence of a static magnetic field, the position of the donor impurity and two directions of polarization of the laser field. The binding energy behavior is only slightly affected by the magnetic field, however the strong confinement and the presence of linearly polarized laser radiation, a significant change is observed in the binding energy for various directions of polarization and partially solve the degeneration of impurity states. The binding energy was studied for shallow-donor impurity located off-axis in GaAs coaxial cylindrical quantum wire under the action of an intense high-frequency laser field. The dependence of the binding energy as a function of the donor position along and perpendicular to the direction of polarization of the radiation and for different values thicknesses of barrier; in this results was observed that as parameter of the laser is increased binding energy also increases and in the absence of laser radiation the binding energy is degenerate for impurities located symmetrically in the QWW and the laser field effect partially breaks the degeneracy of ground state in the binding energy [7]. Recently, C. A. Duque et al. [8], a theoretical study the effect of an intense laser field on the states of a donor impurity in a GaAs-(Ga, Al)As QWW of rectangular cross section, under
the effect of a laser radiation field are applied independently oriented throughout horizontal and vertical directions in the \( xy \) plane. The application of the combined use of two fields of intense laser radiation oriented in different directions in the plane there are two effects induced by laser: i) two centers of Coulomb and ii) modifies the electron probability density due to the change of the confinement potential profile. Thus, the possibility of transition of one-dimensional electron coupled single, double and quadruple within the structure.

In particular, the research on solar cell in [9, 10] and photodetectors devices [4] as GaAs nanocone are important because they have an improved solar absorption, short-circuit current density and light-intense trapping. In this work was studied the effect of the intense high frequency laser on the ground-state binding energy of hydrogenic impurity located on the axis of a nanowire shape a nanocone of GaAs. The binding energy is determined according to the position of the impurities throughout the axis of the wire and the intensity of the laser field. This paper is organized as follows: in Section 2 we describe the theoretical framework. Section 3 contains the results and discussion, and finally, our conclusions appear in Section 4.

2. Theoretical model

A nanowire with cylindrical geometry and variable section was considered, the cylinder radii decrease with the nanowire height in agree with the next equation:

\[
R(z) = R_1 - \frac{R_2 - R_1}{H} z
\]

with \( R_1 \) and \( R_2 \) are the greater and lower radii, respectively, of the nanowire and \( H \) its height. \( z \) run between zero and \( H \). In Figure 1 is showing a schematic picture of the nanowire with an impurity localized on axis.

![Figure 1. Nanocone schematic figure, with the geometrical parameters.](image)

The impurity stationary schrödinger equation in arbitrary units (au), and considering the effective mass approximation framework, in cylindrical coordinates, is given by

\[
-\nabla^2 \Psi + \left( V(\rho, z) - \frac{2}{\sqrt{\rho^2 + (z - z_i)^2}} \right) \Psi = E \Psi
\]

In the above equation the \( V(\rho, z) \) term correspond to the geometrical confinement due to the structure, it is describe like infinite potential confinement give by,

\[
V(\rho, z) = \begin{cases} 
0 & \text{in of the nanocone} \\
\infty & \text{out of the nanocone}
\end{cases}
\]

And \( z_i \) is the impurity position, this potential is not modified by the laser. The Hamiltonian give by Equation 2 is modified when a laser beam is used. In order to include the effect of the laser we have consider that dimensions of the nanocone are in agree with the condition give by the Floquet method [11]. Under this method the Coulomb interaction is modified and new coulomb term, in au, is give by,
\[ V_c = -\frac{1}{|\vec{r} - \vec{r}_i + \vec{\alpha}|} - \frac{1}{|\vec{r} - \vec{r}_i - \vec{\alpha}|} \]  

(4)

Where \( \vec{r}_i \) is the impurity position, and \( \vec{\alpha} \) is a vector associated to laser dressing parameter \( (\alpha = |\vec{\alpha}|) \), this term is given by,

\[ \alpha = \left( \frac{8\pi e^2 I}{m_e^2 c^2 \omega^4} \right)^{1/2} \]  

(5)

Where \( e \) is the electron charge, \( I \) is the laser intensity, \( m_e \) is the electron mass, \( c \) light velocity and \( \omega \) is the frequency. Again it was considered that the impurity is localized on the nanocone axis and the laser has a polarization in \( z \), under above condition the coulomb term is writing, in cylindrical coordinates, as:

\[ V_0 = -\frac{1}{\sqrt{\rho^2 + (z - z_i + \alpha)^2}} - \frac{1}{\sqrt{\rho^2 + (z - z_i - \alpha)^2}} \]  

(6)

In agree with the above conditions the Equation 2 can be written as:

\[ -\nabla^2 \Psi + (V_0 + V_\alpha) \Psi = E \Psi \]  

(7)

The shape of nanocone permit us considerate the adiabatic approximation [12] for to separate the particle axial and radial motion. By mean of this approximation, and considering the axial symmetry, the Schrödinger equation can be reduce from 3 to 1 dimension problem, and it can be written as:

\[ -\frac{\partial^2 F(z)}{\partial z^2} + V_{eff}(z)F(z) = EF(z) \]  

(8)

Where the effective potential \( V_{eff} \) is given by,

\[ V_{eff}(z) = E_p(z) + \int_0^{R(z)} \rho \Phi^2(\rho) \, d\rho \]  

(9)

\( \Phi(\rho) \) is the solution to the nanocone radial Schrödinger equation and \( E_p(z) \) the ground state energy for the radial equation, \( F(z) \) is the eigenfunction for \( z \) direction. The Equation 8 is solve numerically. The binding energy(\( E_b \)) for the impurity is obtained by the expression:

\[ E_b = E_0 - E \]  

(10)

The \( E_0 \) term correspond to the energy of a particle in the nanocone, without impurity.

3. Results and discussion

The theoretical calculation was realized considering the values for \( R_1 = 15 \)nm, \( R_2 = 10 \)nm, \( H = 300 \)nm, for a GaAs structure.

In Figure 2 is showing the effective potential \( V_{eff} \), for a impurity localized in a \( \frac{H}{2} \) and \( \frac{H}{3} \) from the bottom of the structure, as a \( z \) function and different values of the \( \alpha \) parameter. In this figure is observe that for \( \alpha = 0 \) there is a single well in \( V_{eff} \) caused by the coulomb interaction, and when the laser beam was considered \((\alpha \neq 0)\) the single well is splitting in a double quantum well.

The \( V_{eff} \) in the double well structure has lower deep that the well in the case \( \alpha = 0 \). In Figure 2(a) it is observed that the barrier between wells are increasing when \( \alpha \) is increasing. Also, in Figure 2(a) and (b), it is possible to observe that for a some value of \( \alpha \neq 0 \) the bottom
of the left well is more deeper that the bottom right well, in Figure 2(a) it is observed that the
left well for $\alpha = 50\text{nm}$ is slightly deeper that in the case for $\alpha = 30\text{nm}$.

![Graph](image_url)

**Figure 2.** Effective potential for an impurity localized at (a) $z_i = H/2$ and (b) $z_i = H/3$ from the nanocone base, as a function of $z$, for different values of the $\alpha$ parameter.

In Figure 3(a) the binding energy is shown as a function of the impurity position and some values of $\alpha$ parameter. In all cases showed it can be observe a diminishing in the binding energy when the impurity from away of the wider region ($R_1$) to the narrow region ($R_2$). Additionally for the impurity localized in narrow region the binding energy is no modified by the laser intensity, in this case the geometrical confinement is greater than the laser effect.

In Figure 3(b), is showing the binding energy as a function of the $\alpha$ parameter and some values of the impurity position. In this figure is observed a diminishing in the energy for some values of $\alpha$ parameter and later the energy is increasing with $\alpha$ value. This behaviour can be understand with help of the $V_{eff}$ Figure. For $z_i = H/2$ the electron is confined in the left well and if the $\alpha$ value is continued increasing the energy began to diminish, because the left well become deeper, and if we continued increasing the $\alpha$ value, the left well it get closer to the bottom of the structure and the electron is repel from the barrier, approaching it to impurity and the energy is increasing. For $z_i = H/3$ the electron has a higher energy that $z_i = H/2$ because the electron is localized in the wider region and more closer to the impurity, in this case the lateral confinement is lower that the case with $z_i = H/2$, but when $\alpha$ is increasing the energy has the same behaviour that in the case with $z_i = H/2$. When $z_i = 2H/3$ the impurity is far away from the impurity causing a lower energy that in $z_i = H/2$ case. In this last case the effect of the structural confinement is lower that the other cases and the variation in the energy is more slight that the other case when the electron is confined in the left well of the effective potential.

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The increasing the binding energy with the laser field have been report by others author in similar system [6]. Radu [13] shown the effect upon impurity binding energy as a function of parameter and different impurity positions, for a cylindrical wire. Ungan et al. [14] studied the effect the laser in a quantum well for different position of the impurity, in this work the binding energy show a similar behavior that we report. Duque et al. [8] considered a wire with rectangular section and different laser beam polarizations to calculate the binding energy for a impurity in the wire. All these work show that the energy values have a high dependence with the impurity position and the parameter, and the values ranges for the binding energy are similar for all them.

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4. Concluding remarks
Theoretical results obtained for an impurity in a GaAs nanocone with infinity confinement was presented in the effective mass frame work. It was found that the binding energy is diminishing when the impurity is localized from the wider region to narrow region, for the same impurity position the effect of a laser beam is increase the energy for some values of the parameter. The competition between geometrical confinement and laser beam effect cause a diminishing and later increasing in the binding energy, for different values of the parameter. The high dependence of the binding energy with the impurity position and the parameter associated with the laser beam has been observed in similar systems by others authors.

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