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Quantum Advances
ISSN: 3143-0724 www.aristonpubs.com/journal/quantum-advances https://doi.org/10.69626/qa.2026.0069

RESEARCH ARTICLE

The effective g factor of anisotropic InAs quantum dot under the combined effects of the applied magnetic field, impurity, and spin–orbit coupling

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ABSTRACT: The effective Landé g-factor of an anisotropic Indium Arsenide (InAs) quantum dot (QD) is investigated under the combined influence of a magnetic field, an impurity, and Rashba (RSOI) and Dresselhaus (DSOI) spin-orbit interactions (SOI). This factor is crucial for spintronics. The results show that g is strongly tunable by the electric field (which mediates the SOI). Specifically, increasing the electric field enhances the RSOI and increases g, while DSOI tends to reduce g. In InAs, the RSOI dominates, leading to an overall enhancement of g with increasing electric field, emphasizing its potential for spin control in devices. Furthermore, g exhibits a peak value at a particular confinement strength due to a complex competition between energies. The anisotropy of the QD also provides a significant means for precisely controlling the effective g-factor.

Keywords: Anisotropy; Quantum Dot; Rashba and Dresselhaus; Gaussian Impurity; Landé g-Factor.

Received: 29 April 2026; Revised: 12 May 2026; Accepted: 25 May 2026; Published Online: 04 June 2026

1. INTRODUCTION

A quantum dot is a nanostructured material with numerous device applications, particularly in the field of spintronics. Due to its wide-ranging applications, it is regarded as one of the most promising areas of research in the field of nanotechnology. [1]. Anisotropic InAs quantum dots (QDs) represent an interesting class of nanoscale semiconductor structures that have gotten significant attention in the fields of nanotechnology and quantum optics [2]. Unlike isotropic quantum dots, which have a spherical shape, anisotropic InAs QDs possess an asymmetric geometry. One key feature of anisotropic InAs quantum dots is their highly tunable electronic energy levels. The anisotropic symmetry leads to the quantization of electronic states along different axes, enabling precise control over the energy spacing between quantum levels, making them particularly promising for various advanced applications [3, 4]. For example, these QDs' absorption and emission characteristics are direction-dependent which makes them suitable for advanced light-emitting diodes (LEDs) that can emit polarized light [5]. In anisotropic InAs QDs, spin-orbit interaction (SOI) plays an important role in precisely controlling their energy levels. Anisotropic QDs experience different degrees of SOI along distinct axes. This asymmetry results in the splitting and fine-tuning of electronic energy levels [6, 7]. By carefully manipulating external parameters, such as magnetic fields or electric fields, researchers can selectively influence the strength of the SOI, allowing for good control over the QD energy levels. These precisely controlled energy levels open the door for achieving specific functionalities and advancing the field of

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quantum computing and quantum technologies [8]. Researchers have shown a particular interest in QDs, and a considerable number of theoretical research has been carried out to investigate the impact of external effects on their properties [9–20]. It has been shown there is a correlation between the electronic properties of anisotropic InAs QDs and their size and shape. Hosseinpour provided a brief investigation of the influence of Rashba SOI and Gaussian impurity on the thermal properties of an asymmetric QD [9]. The absorption and emission spectra of QDs have been examined by various theoretical models [10–14]. These studies have revealed directional-dependent optical transitions due to the QDs anisotropy. Moreover, the impact of strain on the electronic and optical properties of anisotropic QDs made from InAs has been explored theoretically [15]. The Rashba SOI was considered when the researchers calculated the doped QDs' internal energy, heat capacity, and entropy. It has been shown that Rashba coupling, Gaussian impurity parameters, and applied fields may manipulate thermal properties and that increasing the electric field and Rashba coupling strength lowers the internal energy. Entropy (internal energy) drops due to changes in some factors, such as the magnetic field and intensity of the confinement potential [16–20].

This work aims to compute and investigate the dependence of energy spectra and effective Landé factor of anisotropic InAs-QD on the Hamiltonian physical parameters such as magnetic field strength, Dresselhaus spin-orbit interaction strengths, and anisotropic confinement effects. Impurities, such as dopants can be strategically or unintentionally introduced during the growth of anisotropic InAs QDs. These impurities can modify the local electronic environment and, consequently, influence the energy levels of the quantum dots. Numerous theoretical studies have been devoted to solving the Schrodinger equation for the QD system using various approaches, such as the variational approach [21, 22], the 1/N expansion method [23, 24], and the exact diagonalization method [25–29]. Previously, it has been found the presence of impurities has a significant influence on system modification [30–33]. In this study, we also investigate the influence of impurity on and off positions on the energy spectrum and the g factor. The paper is organized as follows; in section 2 we have presented the Hamiltonian model and formulation. We have also shown the obtained results of the energy spectra and the effective Landé factor g in section 3. The conclusion is given in section 4.

2. THEORETICAL MODEL

The total Hamiltonian describing an electron confined within an anisotropic doped quantum dot composed of InAs, while subject to external magnetic and electric fields, can be expressed as follows:

$$\hat{H} = \frac{(\mathbf{p} - e\mathbf{A})^2}{2m^*} + V_{\text{conf}}(x,y) + V_{\text{imp}}(x,y) + \hat{H}_{\text{SO}} + \hat{H}_{\text{Zeeman}} \tag{1}$$

The initial term represents the Hamiltonian of an electron in the presence of a magnetic field. Here, m^* signifies the effective mass of the electron within the InAs material, and e corresponds to the elementary electric charge.

The isotropic QD Hamiltonian in the presence of a magnetic field is a well-known problem. The analytic expression for the eigenenergy levels is given by

$$E = (2n + |m_l| + 1)\,\hbar\Omega - \frac{1}{2}\hbar m_l \omega_c \tag{2}$$

where

$$\omega_c = \frac{eB}{m^*}, \qquad \Omega = \sqrt{\omega_0^2 + \frac{\omega_c^2}{4}}$$

and

$$n = 0, 1, 2, \ldots, \qquad m_l = 0, \pm 1, \pm 2, \ldots$$

Here, n and m_l represent the radial and azimuthal quantum numbers, respectively.

To mimic a practical application, we introduce the asymmetric harmonic oscillator confinement potential, often referred to as "heterostructure confinement". This potential characterizes the confinement of charge carriers by imposing restrictions on their motion. This potential is expressed as follows[9]:

$$V_{\text{conf}}(x,y) = \frac{1}{2} m^* \left(\omega_x^2 x^2 + \omega_y^2 y^2\right) \tag{3}$$

where

$$\omega_x \neq \omega_y.$$

The presence of the impurity (donor or acceptor) plays an essential role by changing the potential shape. The third term is the Gaussian impurity model[9]:

$$V_{\text{imp}}(x,y) = V_0 \exp\left[-\frac{(x-x_0)^2 + (y-y_0)^2}{d^2}\right] \tag{4}$$

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where (x_0, y_0) denotes the impurity position. Positive values of V_0 represent the strength of the acceptor impurity potential, while negative values of V_0 correspond to the donor impurity potential strength. The parameter V_0 is adjustable and can influence the strength of these impurities.

The fourth term in the Hamiltonian is due to the interaction between orbital angular and spin momenta. This term includes the effects of Rashba and Dresselhaus spin--orbit interaction; the SOI Hamiltonian can be written as

$$\hat{H}_{\mathrm{SO}} = \hat{H}_R + \hat{H}_D = \frac{\alpha_R}{\hbar}\left[\sigma \times (p - eA)\right]_z + \frac{\alpha_D}{\hbar}\left[\sigma \cdot (p - eA)\right]_z \tag{5}$$

$\hat{H}_{\mathrm{SO}}$ consists of the Rashba interaction, whose strength is characterized by the parameter α_R, and the Dresselhaus interaction with a strength characterized by α_D. The electric field E of the quantum well-confining potential affects these coupling characteristics (i.e., $E_z = -\partial V/\partial z$) along the z direction at the interface in a heterojunction as

$$\alpha_R = \gamma_R e E,$$

$$\alpha_D = 0.78\,\gamma_D \left(\frac{2m^* e}{\hbar^2}\right)^{2/3} E^{2/3}$$

where the Dresselhaus coefficient is

$$\gamma_D = 130 \text{ eV Å}^3,$$

the Rashba coefficient is

$$\gamma_R = 110 \text{ Å}^2,$$

and the effective mass

$$m^* = 0.0239\, m_0$$

is considered for the InAs quantum dot, where m_0 is the free-electron mass.

$\hat{H}_{\mathrm{Zeeman}}$ indicates the normal Zeeman effect, defined as

$$\hat{H}_{\mathrm{Zeeman}} = \frac{1}{2} g_0 \mu_B B \sigma_z \tag{6}$$

where g_0, μ_B, and σ_z are the material Landé g factor, Bohr magneton, and Pauli spin matrix, respectively.

In addition to the previous quantities, the effective Landé g-factor, g_{eff}, is computed for the low-lying state using the relation

$$g_{\mathrm{eff}} = \frac{E^{(\uparrow)}_{\mathrm{G.S.}} - E^{(\downarrow)}_{\mathrm{G.S.}}}{\mu_B B} \tag{7}$$

3. RESULTS AND DISCUSSION

The investigation of the effective Landé g-factor in anisotropic InAs quantum dots (QDs) has been conducted in the presence of a fixed magnetic field while maintaining a constant electric field. In Figure 1, the effective Landé g-factor has been plotted as a function of the magnetic field at a fixed value of the electric field for different spin-orbit interaction (SOI) cases. For the $\alpha_R = 0$ case (solid line), even when $\alpha_D \neq 0$, the curves show a constant value of the Landé g-factor, which matches that of bulk InAs material, since the Dresselhaus SOI has only a minor contribution in small band-gap semiconductors. For the dashed line, the presence of Rashba spin-orbit interaction (RSOI) enhances the value of the g-factor due to the larger separation between the states with different spin orientations, $\Delta E = E_\uparrow - E_\downarrow$.

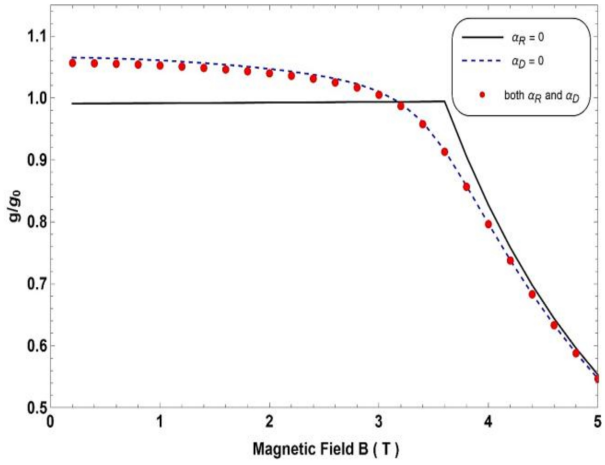


Fig. 1. Effective Landé g factor vs. magnetic field for isotropic confinement $\hbar\omega_0 = 8$ meV and $E = 3 \times 10^5$ V/cm.

For the fixed parameters $B = 1\,\mathrm{T}$ and $\omega_x = \omega_y = 8\,\mathrm{meV}$, the two types of spin-orbit interaction (SOI) can be manipulated by changing the electric field strength. The effect of SOI strength

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on the effective Landé g-factor has been investigated in Figure 2. In the first case, the Dresselhaus effect was neglected ($\alpha_D = 0$). The Rashba spin-orbit interaction (RSOI) enhances the g-factor as the electric field increases, which is clearly shown by the dashed line in the figure. This result demonstrates the significant role of Rashba SOI in spintronic devices. On the other hand, by neglecting the Rashba effect ($\alpha_R = 0$), the Dresselhaus SOI slightly reduces the absolute value of the g-factor as the electric field increases, as shown by the solid line in the figure. The combined effect, represented by the dotted points, shows the dominance of the Rashba SOI over the Dresselhaus SOI.

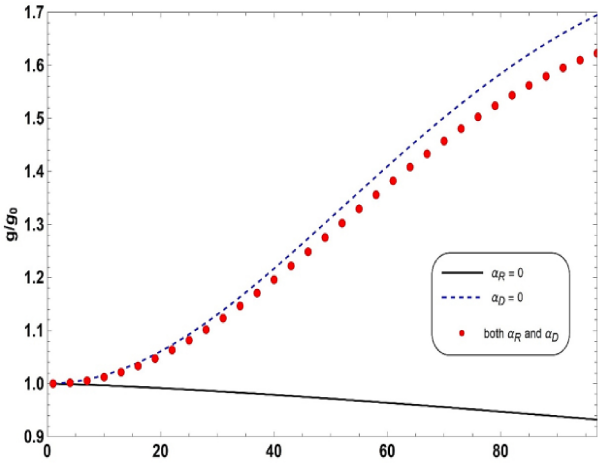


Fig. 2. Effective Landé g factor vs. electric field for quantum dots.

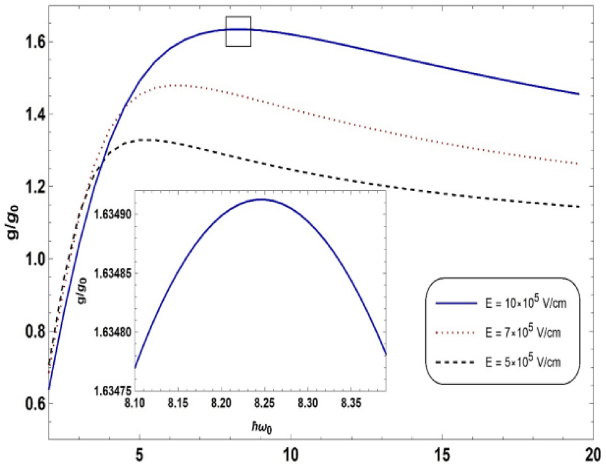


Fig. 3. Effective Landé g factor vs. isotropic quantum dot confinement potential for different electric field values.

The size of the symmetric quantum dot ($\omega_x = \omega_y = \omega_0$) significantly affects the value of the Landé g-factor at a fixed electric field, as shown in Figure 3. At a particular value of the confinement strength (which is inversely proportional to the quantum dot size), the g-factor curve reaches its maximum value. For example, at $E = 10\times10^5\,\mathrm{V/cm}$, the g-factor attains a peak value of $g \approx 1.6g_0$ for $\omega_0 = 8.25\,\mathrm{meV}$. This peak value decreases and shifts toward lower confinement strengths as the electric field is reduced.

In Figure 4 and 5, the effect of quantum dot anisotropy has been investigated. For a fixed confinement product ($\omega_x\omega_y$), the g-factor is plotted as a function of the ratio of the confinement strengths in the y- and x-directions, ω_y/ω_x. The figures reveal an interesting dependence on the confinement strength along the x-direction. As shown in Figure 4, anisotropy initially enhances the absolute value of the g-factor. However, with further increase in anisotropy, the g-factor decreases as the quantum dot gradually assumes an elliptical shape.

To demonstrate the geometric symmetry of the confinement ratio, the g-factor is plotted in Figure 4b as a function of $\log(\omega_y/\omega_x)$. The figure exhibits the expected symmetry about $\omega_x = \omega_y$, which corresponds to $\log\left(\frac{\omega_y}{\omega_x}\right) = 0$.

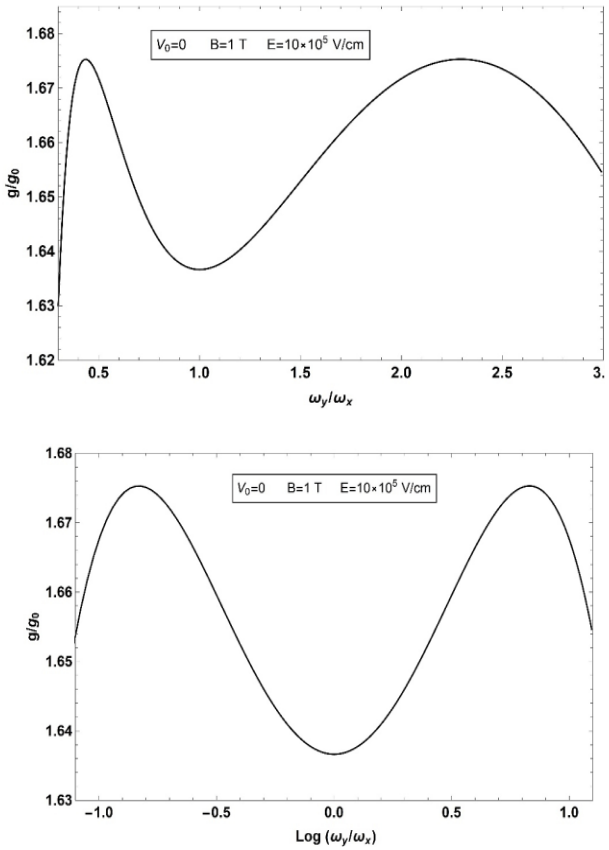


Fig. 4. Effective Landé g factor vs. anisotropy of the quantum dot confinement potential: (a) g as a function of ω_y/ω_x; (b) g as a function of $\log(\omega_y/\omega_x)$, at $\sqrt{\omega_x\omega_y} = 8.25$ meV.

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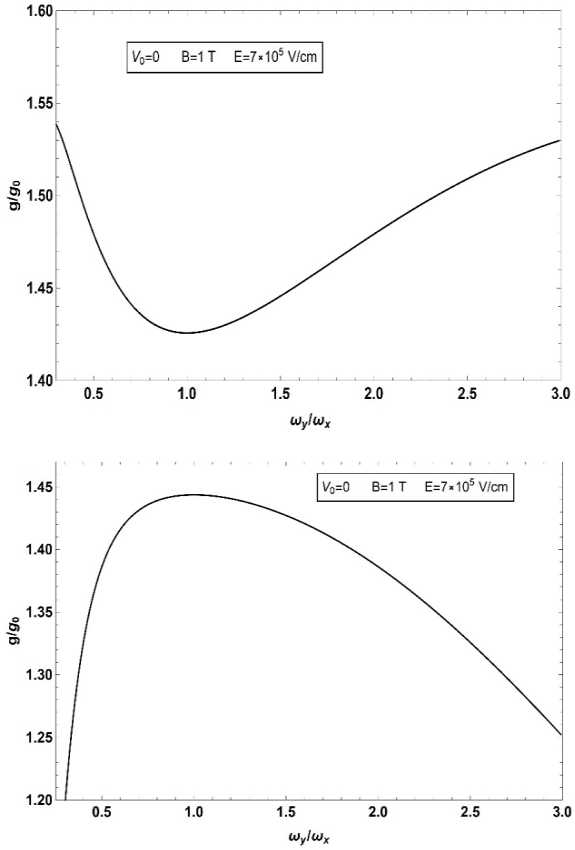


Fig. 5. Landé g factor vs. anisotropy of the potential: (a) for $\sqrt{\omega_x\omega_y} = 8.25$ meV; (b) for $\sqrt{\omega_x\omega_y} = 5$ meV.

In Figure 5, the g-factor exhibits different behavior with respect to the anisotropy of the quantum dot (QD). As shown in Figure 5a, for $E = 7\times10^5$ V/cm and $\sqrt{\omega_x\omega_y} = 8.25$ meV, the anisotropy enhances the g-factor as $|\log(\omega_y/\omega_x)|$ increases. In contrast, for $E = 7\times10^5$ V/cm and $\sqrt{\omega_x\omega_y} = 5$ meV, the anisotropy reduces the g-factor as $|\log(\omega_y/\omega_x)|$ increases, as shown in Figure 5b.

From Figure 3 to 5, one can observe the combined effects of the electric field, confinement strength, and quantum dot anisotropy on the absolute value of the effective Landé g-factor. In practice, the value of the g-factor is an important parameter for controlling the spin relaxation time in quantum computing applications. Therefore, further investigations aimed at enhancing or reducing the g-factor through external parameters remain an active area of research and may be explored in future work.

The influence of an acceptor impurity in the quantum dot has been investigated and is presented in Figure 6. As shown in Figure 6a, an on-center impurity slightly increases the g-factor of a symmetric quantum dot with a low confinement potential. However, as the confinement potential becomes stronger, the g-factor decreases.

For a symmetric quantum dot, the effects of the impurity profile (strength and spatial extent) are illustrated in Figure 6b as a function of the magnetic field. For a fixed value of d, the g-factor increases with increasing impurity strength at low magnetic fields, before the crossing or anti-crossing of the energy levels occurs. Similarly, a larger value of d produces a comparable enhancement of the g-factor.

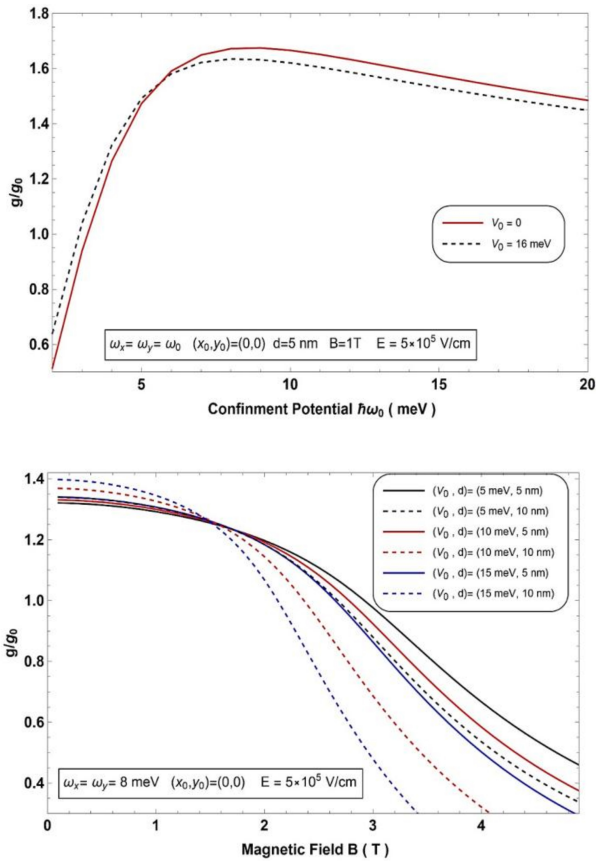


Fig. 6. Landé g factor vs. a) confinement strength for isotropic quantum dot b) magnetic field for different impurity profiles (position and strength).

4. CONCLUSION

In this work, the anisotropic quantum dot Hamiltonian has been solved using the diagonalization method in the presence of a perpendicular magnetic field and Gaussian impurity, considering both types of spin-orbit interaction: Rashba and Dresselhaus spin-orbit interaction. The diagonalization process has been carried out using the one-dimensional harmonic oscillator basis to find the eigen solutions of the InAs QD for different cases. In the computational process, the issue of convergence has been ensured, and the obtained numerical results have been tested. The effective Landé g factor of the system has been studied. The result shows the strong dependence of g^* on the SOI interaction, the quantum dot confinement strength, and the anisotropy of the quantum dot in addition

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to the magnetic field.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Funding

Funding not available

Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

A. Shaer : Writing – original draft, Visualization, Software, Investigation; **M.K. Elsaid**: Writing – original draft, Investigation, Methodology, Supervision.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Acknowledgment

Not applicable.

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