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Terahertz fields and the dynamical control of spin in quantum dot molecules

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Abstract

We study the time evolution of electronic spin in a double quantum dot system (quantum dot molecule, QDM) under strong harmonic fields in the terahertz region. The dynamics of the wavefunction for a single electron includes the spin–orbit (SO) effects of both Rashba and Dresselhaus types and is obtained in terms of Floquet states and the quasienergy spectrum. A low magnetic field applied perpendicular to the plane of the QDM provides additional flexibility. We find that it is possible to control the electronic spin from a given initial state by proper choice of applied fields. The electron can be either dynamical localized or allowed to oscillate between the dots, with or without SO-induced spin flip.

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Keywords: Spintronics; Spin orbit effects; Quantum dot molecules

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1. Introduction

Control of spin states for applications in quantum computation and spintronics has recently attracted a great deal of attention [1]. Different mechanisms have been suggested to perform this control. Quantum dot molecules (QDMs), potential candidates to implement quantum qubits and gates, have been studied experimentally under microwave radiation [2]. Theoretical studies of electronic states have been reported [3], including spin–orbit (SO) and perpendicular magnetic fields in GaAs [4] and harmonic electric fields [5,6]. Here we analyze the possibility of controlling the spin by applying both perpendicular magnetic and harmonic electric fields. Moreover, we study InSb molecules, where SO effects are very important.

2. Theory

An electron of charge $-e$ and effective mass m^* is confined to the xy plane, while laterally in double quantum dots by electrostatic potentials applied to the gates. A perpendicular magnetic field $\mathbf{B} = B\hat{z}$ is applied. The lateral confinement is modelled by Gaussian functions, as suggested in Ref. [3], with similar parameters but fixing the coupling between the dots by setting the barrier height parameter to 10 meV. The line joining the centers of the dots coincides with the x-axis. Thus, the Hamiltonian H_o in absence of electric field includes magnetic terms, the Zeeman splitting and the SO effects with both SIA (Rashba) and BIA (Dresselhaus) terms, see details and material parameters in Ref. [7]. The level structure for this system as a function of B is similar to the single-dot spectrum [8], namely SO decreases the energy and turns energy crossings to anticrossings; the wave functions $\Phi_i(\mathbf{r}, \sigma)$ become admixtures of spin states [7]. When the electron is harmonically driven by an electric field $\mathbf{F} = F \sin \omega t\, \hat{\mathbf{x}}$, the dynamics of the system is governed by the

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time-dependent Schrödinger equation with Hamiltonian $H = H_o - exF \sin \omega t$, which we solve using the Floquet formalism [9]. Thus, the wave function $\psi(\mathbf{r}, t, \sigma) = \exp(-\mathrm{i}\varepsilon t/\hbar)\varphi(\mathbf{r}, t, \sigma)$. Here, ε is the Floquet exponent or the quasienergy, and φ must fulfill a periodic condition in time. Additional solutions, a consequence of the time periodicity, have been called "replicas" or "sidebands". We Fourier-expand the wave functions φ, with weights Φ_i for the corresponding replicas. In all our calculations, four zero-field states ($i = 1, \ldots, 4$) and their 99 replicas are included in the expansion. For a given initial condition, the time evolution of the wave function $\Psi(\mathbf{r}, t, \sigma)$ can be followed expanding it in terms of functions ψ. We will consider that the system is prepared at $t = 0$ such that the initial wave function is a linear combination of two static states, α and β, chosen to locate the electron primordially at the left dot with net spin up. The function $\Psi(\mathbf{r}, t, \sigma)$ can be separated into its spin components up (↑) and down (↓). Integrating a component over a given region, $x<0 (x>0)$, the probability of finding the electron at the left L (right R) dot, with that particular z-projection of spin at any t, can be determined.

3. Results

Typically, the quasienergy spectrum shows crossings and anticrossings (AC), which can be explained in terms of the dynamical symmetry of the system, see, for example, Ref. [10,11]. For a two-level system, the field intensities at which quasienergy bands cross can be related to zeros of Bessel functions and scale with frequency [10]. Moreover, it has been shown that dynamical localization (suppression of tunneling) appears at the crossings, when electric and/or magnetic fields are applied to a double-well system [10,12]. In what follows the frequency is fixed to $\hbar\omega = 10\,\mathrm{meV}$. Quasienergy spectra for smaller frequencies scale as expected, showing a more complex pattern. In Fig. 1 quasienergy spectra are shown as a function of the field intensity for different magnetic fields.

At $B = 0$ the quasienergy bands are doubly degenerate, having the same spatial symmetry but different net spin at zero electric field. The first quasienergy crossing appears at $F \approx 3.6\,\mathrm{kV/cm}$. For low magnetic field, the SO interaction lifts degeneracy, yielding two crossings at $F \simeq 3.5$ and $3.2\,\mathrm{kV/cm}$. The static level structure shows an AC around $B = 1\mathrm{T}$ and the character of the third and fourth wave functions changes [8], such that the quasienergy AC appears at lower field intensity, while the crossings remain at approximately the same fields.

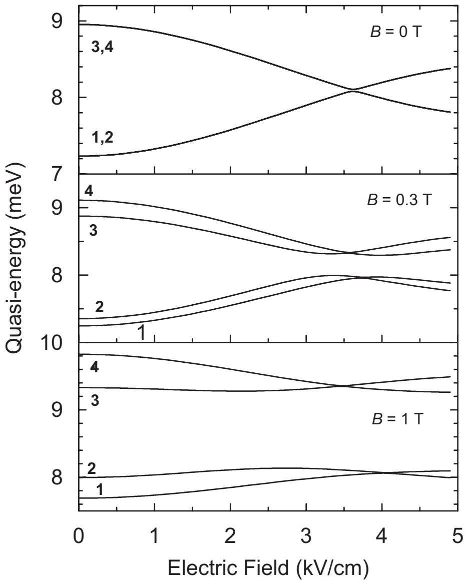

Fig. 1. Quasienergies for different values of the magnetic field as function of the electric field intensity. The electric field frequency is $\hbar\omega = 10\,\mathrm{meV}$. Labels at left refer to the zero-field levels. Splitting of the quasienergies due to SO at $B \neq 0$ is evident.

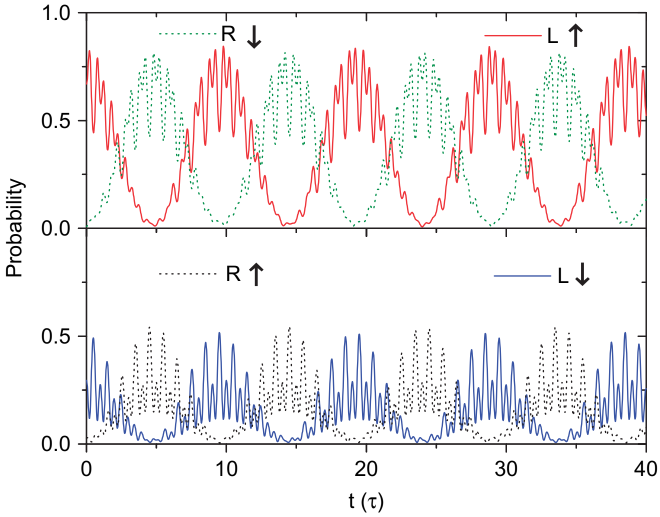

Fig. 2. Probability of finding the electron at the left L (right R) dot with a given spin. $F = 2\,\mathrm{kV/cm}$, $\hbar\omega = 10\,\mathrm{meV}$ and $B = 0\,\mathrm{T}$. The initial state is a linear combination of static states $\alpha = 1$ and $\beta = 4$. As the electron moves between dots, it flips its spin due to SO.

Figs. 2 and 3 show the probability of finding the electron in the dots with a given spin as a function of time (in units of the field period $\tau = 0.41\,\mathrm{ps}$), for $B = 0$ at different field intensities. The continuous (red) line on the top panel shows the probability of finding the electron in the left dot with spin ↑, while in the bottom panel (blue) with spin ↓. On the other hand, dotted lines (green and black, respectively) show the probability of finding it in the right dot. Fig. 2 shows results for $F = 2\,\mathrm{kV/cm}$, i.e., away from the AC. It is clear that the electron tunnels between the dots while flipping its spin, as the maxima and minima of the $L\uparrow$ and $R\downarrow$ probabilities alternate. The bottom panel shows the same oscillatory behavior for the other spin components in each dot. In contrast, at the quasienergy crossing, $F = 3.6\,\mathrm{kV/cm}$, shown in Fig. 3, we observe that the probabilities remain approximately constant, clearly indicating dynamical localization for both spin components.

It is important to mention that for $B \neq 0$, building up the initial state of zero-field states with a given spin also results in spin flipping while the electron jumps from dot to dot.

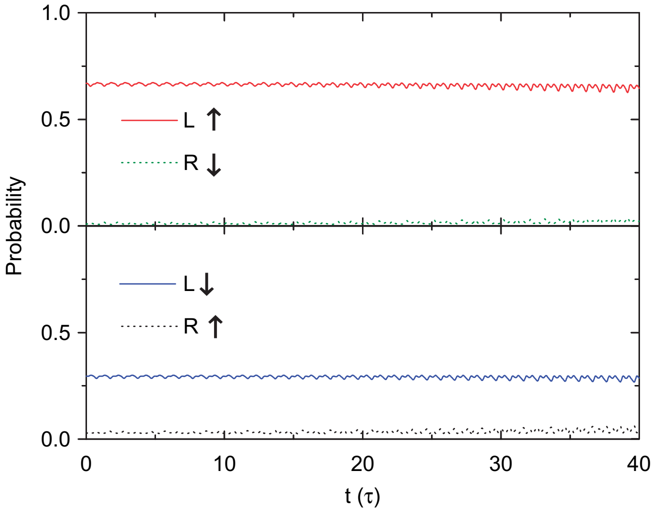

Fig. 3. Probability of finding the electron at the left L (right R) dot with a given spin. $F = 3.6\,\mathrm{kV/cm}$ (ac-field value at the crossing of quasienergies in Fig. 1); $\hbar\omega = 10\,\mathrm{meV}$, $B = 0\,\mathrm{T}$, $\alpha = 1$ and $\beta = 4$. Dynamical localization is observed for both spin components.

However, it is also possible to observe cases where the tunneling occurs without spin flipping. This behavior is a consequence of the symmetry changes induced by the magnetic field [4].

4. Conclusions

A single electron in a InSb QDM has been studied using the Floquet formalism within a four-level approximation. We include SO effects, a perpendicular magnetic field and a harmonic electric field along the line joining the dots. The quasienergy spectrum as a function of the field intensity strongly depends on the magnetic field, showing crossings and anticrossings. The time evolution of the electron is fully described. A proper selection of magnetic and harmonic fields, as defined from the crossings in the quasienergy spectrum, as well as the initial state allow one to control the electron spin in time. At $B = 0$, we observe dynamical localization at electric fields where a quasienergy crossing occurs, while tunneling between dots accompanied by electron spin flips is seen otherwise. For non-zero magnetic fields, at (away from) crossings the electron tunnels with (without) changing spin. The SO effect is crucial for the occurrence of spin flip.

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