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Rashba induced spin multistability of the intersubband optical absorption in asymmetric coupled quantum wells

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We study the multistable behavior of the intersubband optical absorption for *InSb*-based tunnel-coupled quantum wells. We consider four sublevels coming from the splitting of the two deepest levels due to the inversion asymmetry of the structure (Rashba effect), and a weak external in-plane magnetic field (Zeeman effect). Photoexcitation with an intense terahertz pump produces the redistribution of nonequilibrium electrons among the four spin sublevels. The redistribution produces a photoinduced self-consistent potential, giving rise to the renormalization of energy distance between sublevels. Depending on total electron concentration, magnetic field intensity, and pumping efficiency, we find different multistable behaviors in the intersubband optical absorption spectrum. Based on the matrix density, we describe the electron redistribution by means of a system of balance equations for electron concentrations.

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1. Introduction

Optical multistability (OM) is a fairly common phenomenon in nonlinear optical systems consisting in the existence of more than two states for the output optical signal corresponding to a single input signal. The simplest cases correspond to the bistability (OB) and tristability (OT), where only two or three output states occur [1–7].

Semiconductor nanostructures are among the most promising nonlinear media for devices based on the OM, since they require very low energy to work as electronic gadgets. These structures present dynamical nonlinearities, which arise from the behavior of the absorption through the excitation of resonant transitions between bound states. Recently, after the success in the study of OB in semiconductor heterostructures [8–14], there have been several works on OM for these structures [15–21]. The importance of these works lies in the potential applicability of the phenomenon for ultra-fast optical switches, memories, transistors, logic circuits, and other optoelectronic devices. Such devices offer many advantages with respect to the well known atomic gas-cavity systems. Among them, dipole moments are much larger due to the small effective mass of the electrons. Also, the versatility of the material choice and structure settings which allow a specific design for predetermined purposes.

In the present work we show how the Rashba effect can cause a strong non-linearity of the intersubband absorption in inversion asymmetric structures. Moreover, Rashba effect will favor the spin-flipping transitions and these transitions can

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become dominant after far-infrared excitation [22]. Both phenomena may induce OM of the spin intersubband optical absorption in tunneling coupled semiconductor heterostructures.

In addition, when any structure is subjected to an in-plane magnetic field, the Zeeman spin splitting also occurs, breaking the electronic degeneracy. Thus, as a result of Rashba and Zeeman effects, we have four coupled sublevels instead of two tunnel coupled levels. Such sublevels can be partially filled with electrons coming from a doped region. Depending on the doping concentration and, therefore, on the Fermi level, we can find different possibilities for the occupation of electronic sublevels. The resonant intersubband pumping changes the electronic density of sublevels. Thus, the resonant intersubband photoexcitation leads to a non-equilibrium distribution of electrons over tunnel-coupled sublevels and their subsequent dynamic redistribution to reach equilibrium. This redistribution produces the Coulomb renormalization of the sublevels through the photoinduced self-consistent potential. To say, we have an initial energy separation between sublevels before pumping and a renormalized sublevels splitting after pumping. Therefore, electronic redistribution and subsequent level splitting renormalization are the main cause of the intersubband optical absorption multistability. To show this multistable spin behavior we have chosen an *InSb*-based heterostructure since the large Landé factor of this material allows an appreciable Zeeman splitting for weak magnetic fields.

We will analyze three scenarios depending on the initial occupation of the sublevels: a low density case, with only the two Zeeman split sublevels of the ground state occupied; an intermediate density case, with three occupied sublevels; and a high doping concentration case, when the four states are partially filled before photoexcitation. One must be careful with the intensity of photoexcitation because a very strong terahertz photoexcitation would lead to saturation.

2. Model and dynamic equations

2.1. Eigenstates

First we consider the asymmetric coupled double quantum well (ADQW) before photoexcitation, but subjected to transverse electric and in-plane magnetic fields. Although the procedure to obtain eigenstates is fully explained elsewhere [23], we briefly summarize it here. In the parabolic approximation, the one-electron Schrödinger equation for ADQW can be written as [24,25]:

$$\left(\varepsilon(\mathbf{p}) + \frac{\hat{p}_z^2}{2m_z} + U(z) + \widehat{W}(\mathbf{p},z)\right)\Psi(\mathbf{p},z) = E(\mathbf{p})\Psi(\mathbf{p},z), \tag{1}$$

for 2D momentum $\mathbf{p} = (p_x, p_y)$, where $\Psi(\mathbf{p},z)$ and $E(\mathbf{p})$ are the eigenfunctions and eigenvalues, respectively. And $\varepsilon(\mathbf{p})$ is the kinetic energy in the in-plane direction. $U(z) \simeq U_{0z} + eF_\perp z$ is the potential energy with $U_{0z} = \Delta E_c$ in the barriers and $U_{0z} = 0$ in the wells, being $F_\perp$ the uniform transverse electric field. Band diagram for the ADQW is shown in Fig. 1. Wavefunctions $\Psi^\alpha(\mathbf{0},z)$ are depicted over the structure potential.

For weak in-plane magnetic fields $\mathbf{H} \parallel OY$, the magnetic energy is defined as $\widehat{W}(\mathbf{p},z) = \bar{v}^z[\hat{\boldsymbol{\sigma}} \times \mathbf{p}]_z + w_H^z\hat{\sigma}_y$, where the first term is directly related to Rashba effect through $\bar{v}^z = eF_\perp\hbar/4m_z\varepsilon_g^z$, named as characteristic spin velocity, with ε_g^z the gap energy [26]. Finally, $w_H^z = (\bar{g}^z/2)\mu_B H$ is the Zeeman splitting with $\bar{g}^z$ the effective Landé factor, and μ_B the Bohr magneton.

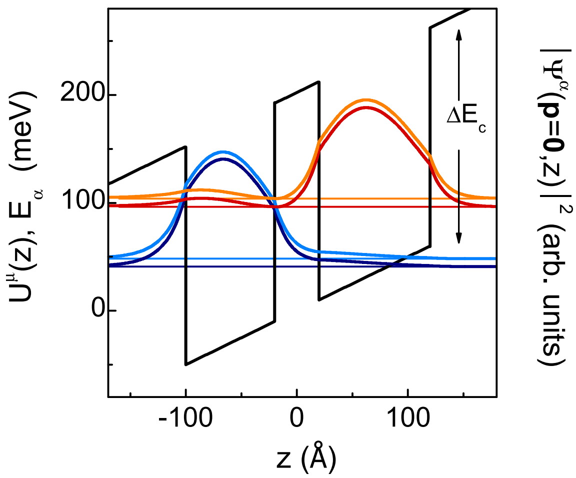

Fig. 1. Scheme of the double quantum well with the two deepest tunnel-coupled levels and their corresponding spin splitting sublevels. Wave functions are included.

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