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Circularly polarized light in coupled quantum dots

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Abstract
Circular light polarization is studied in vertically self-assembled coupled quantum dots (QDs). We have calculated the emitted light polarization along the direction of spin-polarized states (considering 100% spin-polarized states). We have considered ellipsoidally shaped QDs made with InAs/GaAs. It has been shown that the interdot distance is a crucial parameter for circularly polarized light. For small, elongated QDs with small interdot distance the light polarization along the plane perpendicular to the growth direction is $P_{110} \sim 40\%$. In the case of large and elongated ($e \neq 1.0$) QDs with large interdot distance the light polarization is only $P_{110} \sim 5\%$. Comparison with experimental results has been highlighted for the case of large interdot distances (uncoupled QDs).

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In the last few decades, spin-based electronics (spintronics) has been used in research into and in applications of low dimensional structure (LDS), e.g. quantum wells (QWs) and quantum dots (QDs). Spintronics has been mainly used in quantum information technology [1–3]. A possible candidate structure for constructing quantum bits (qubits) is that of self-assembled coupled QDs (SACQDs), among others. In these structures, spin-polarized carriers can be electrically injected into SACQDs and recombine within the SACQDs [4]. In quantum computing architecture, the information concerning the carrier relaxation via the emission of phonons and the dipole recombination of spin-polarized states within QDs is of special importance (among other things). The carrier relaxation and the polarization efficiency of the emitted light in QDs have recently been the subject of theoretical and experimental research [4–8].

Circular polarization dependence of dipole recombination of spin-polarized states within a self-assembled quantum dot has been previously studied [8]. The numerical results in [8] were very close to the experimental reports [4]. In this paper, we have evaluated the circularly polarized light along the orientation direction of spin-polarized carriers in a system of two coupled SAQDs made with InAs/GaAs. For large interdot distances (uncoupled single QDs), our results are consistent with the polarization along to the direction [110] of the emitted light for the case of a single QD ($\sim$5%, [4, 8]) and for smaller distances the polarization increases, reaching maximum value for our typical geometry $\sim$40%. The dependence of the circularly polarized light on a large number of QD geometries is also explored. Circular polarization is also obtained along other polarization directions.

2. Theory

Our geometry consists of two ellipsoidal cap QDs made with InAs which are separated by a distance D, as illustrated in figure 1. The QDs are embedded in a wetting layer of InAs and are surrounded by GaAs. Single-electron and single-hole wavefunctions are calculated using the strain dependent $\mathbf{k}\cdot\mathbf{p}$ theory. In our calculations, we have fixed the height of the dots at $h = 2.1$ nm and varied the width-to-height ratio ($b = (d_{[110]} + d_{[1-10]})/h$) and elongation ($e = d_{[110]}/d_{[1-10]}$). The electron/hole wavefunctions were numerically computed on a real space grid with spacing equal to the wetting layer thickness 0.3 nm. Strain and carrier confinement split the heavy hole (HH) and light hole (LH) degeneracy and the states are doubly degenerate, denoted by $|\psi\rangle$ and $T|\psi\rangle$ (time reverses of each other). The energy gap (E_g) of the coupled SAQD structure strongly depends on the interdot distance as is shown in our investigation. All material parameters that have been used in the $\mathbf{k}\cdot\mathbf{p}$ simulations were obtained by [9, 10].

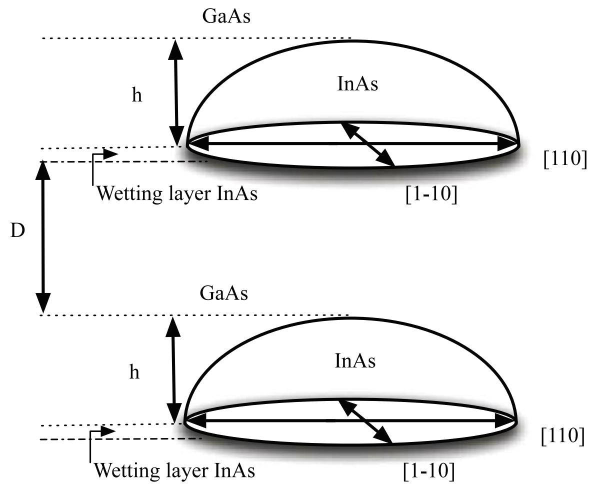

Figure 1. The geometry of the coupled quantum dot system made with InAs/GaAs and a wetting layer thickness fixed at 0.3 nm.

Spin-polarized ground states are constructed by taking a linear combination of the states comprising the doublet and adjusting the coefficient in order to maximize the expectation value of the pseudospin operator projected onto a direction l [8]. The required complex number α maximizes the following:

$$\frac{[\langle\psi| + \alpha^*\langle\psi|T]\hat{l}\cdot\mathbf{S}[|\psi\rangle + \alpha T|\psi\rangle]}{1+|\alpha|^2} \tag{1}$$

where $\mathbf{S}$ is the pseudospin operator [8] in the eight-band $\mathbf{k}\cdot\mathbf{p}$ theory and l the spin orientation.

Let us consider the situation in which the electron spin is polarized along the same direction l as the observed emitted light. The polarization which characterizes the emitted light is given by [11]

$$P_l = \frac{I_l^{(+)} - I_l^{(-)}}{I_l^{(+)} + I_l^{(-)}} \tag{2}$$

where $I_l^{(\pm)}$ is the light intensity with $\pm$ helicity. The intensity of emission of circularly polarized light for the case of spin-polarized electron and unpolarized holes is given by

$$I_l^{(\pm)} = |\langle\psi_\mathrm{h}|\hat{\epsilon}_l^{(\pm)}\cdot\mathbf{p}|\psi_\mathrm{e}\rangle|^2 + |\langle\psi_\mathrm{h}|T\hat{\epsilon}_l^{(\pm)}\cdot\mathbf{p}|\psi_\mathrm{e}\rangle|^2 \tag{3}$$

and for the case of spin-polarized holes and unpolarized electron the intensity of circularly polarized light is given by

$$I_l^{(\pm)} = |\langle\psi_\mathrm{h}|\hat{\epsilon}_l^{(\pm)}\cdot\mathbf{p}|\psi_\mathrm{e}\rangle|^2 + |\langle\psi_\mathrm{h}|\hat{\epsilon}_l^{(\pm)}\cdot\mathbf{p}T|\psi_\mathrm{e}\rangle|^2 \tag{4}$$

where the indices e and h correspond to electron and holes respectively, $\mathbf{p}$ is the momentum operator and $\hat{\epsilon}_l^{(\pm)}$ is the circular polarization vector with helicity $\pm$ (which denotes circularly polarized light that propagates along direction l). It is worth mentioning that the last two equations give identical results as a result of the anticommutation relations between $\mathbf{p}$ and T. As a result, the emitted light polarization is independent of whether the injected spin-polarized carriers are electrons or holes.

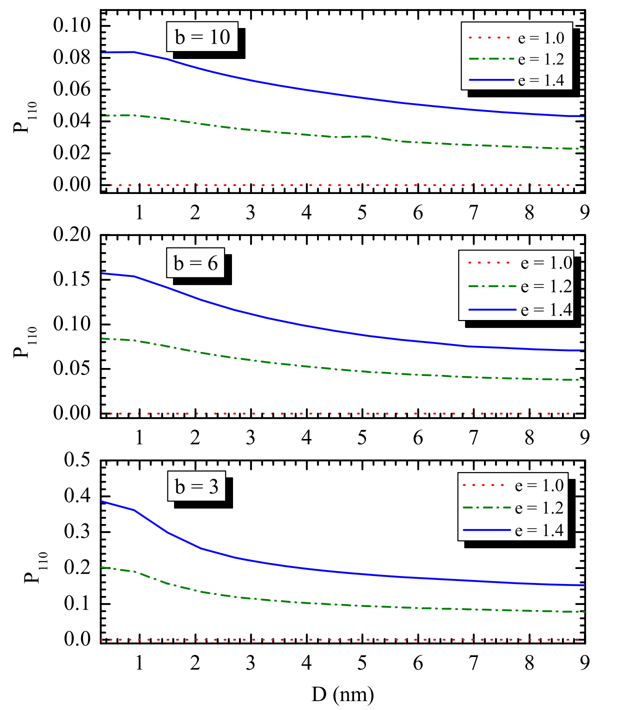

Figure 2. The polarization P_{110} as a function of the interdot distance for different elongations and width-to-height ratios with fixed dot height $h = 2.1$ nm.

3. Results

We are mainly focusing on the circular light polarization along the plane [110] which is perpendicular to the growth direction ([001]) for 100% spin-polarized carriers along [110].

Figure 2 illustrates the polarization P_{110} as a function of the interdot distance for different width-to-height ratios and elongations. Although the carriers are 100% polarized, the emitted light is less than 100% polarized. For axially symmetric QDs ($e = 1.0$) the polarization is zero because the intensities with different helicities are equal (see equation (2)). Circular light polarization increases as the QDs become more elongated because of the azimuthal symmetry breaking (see the dependence of $I_l^{(\pm)}$ on the circular polarization vector).

Increasing the interdot distance, the electron energies in the two lowest conduction bands converge towards that of an electron in a single QD. These two states approximately correspond to even and odd parity of a symmetric double well. The energy difference between the ground state and first excited state decreases as the distance increases. On the other hand, in the valence band the energy splitting decreases as the separation distance increases. Both conduction and valence band ground energies increase on increasing the separation distance. As a result the energy gap increases on increasing the interdot distance. Furthermore, the energy gap takes on large values for small QDs (small width-to-height ratio) and small values for large QDs (large width-to-height ratio) due to large ground state conduction band energy for the case of small QDs and small ground state conduction band energy for the case of large QDs.

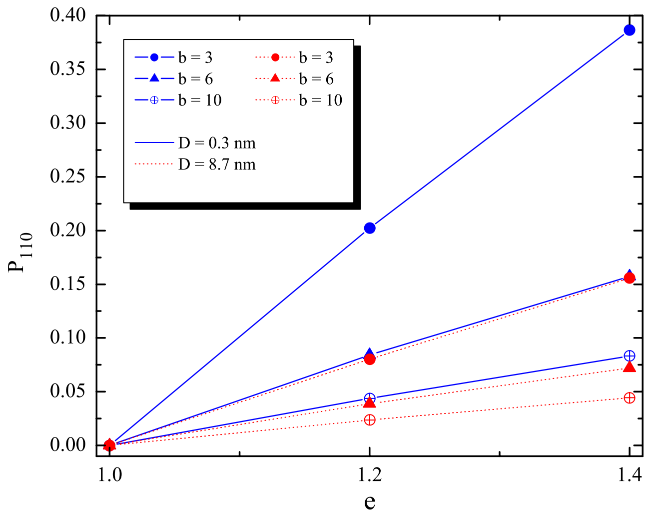

Figure 3. The polarization P_{110} as a function of the elongation for different interdot distances and width-to-height ratios, and fixed dot height $h = 2.1$ nm.

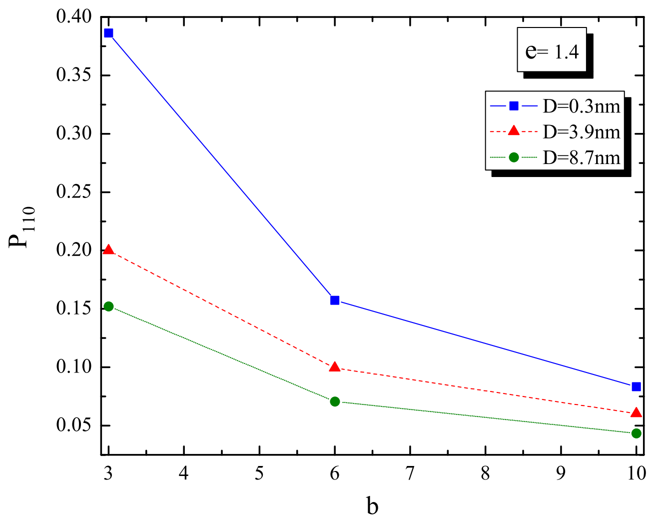

Figure 4. The polarization P_{110} as a function of width-to-height ratio with fixed elongation ($e = 1.4$) and different interdot distances with fixed dot height $h = 2.1$ nm.

In the case of large separation distance, the carrier wavefunctions corresponding to each QD do not overlap. On the other hand, when the QDs are brought together, the wavefunctions strongly overlap. As a result the intensities $I_l^{(\pm)}$ for small separation have larger values than for the case of large interdot distance. As a consequence, for small interdot distance, the numerator in equation (2) takes a larger value than for the case of large separation distance. Therefore, as the interdot distance takes smaller values, the polarization increases, and it decreases as the interdot distance increases due to equation (2). Furthermore, the carrier wavefunctions depend on the size of the QD. In the case of small QDs (small width-to-height ratio), the wavefunctions are larger than the wavefunctions corresponding to large QDs due to the strong carrier confinement. As a result, for small QDs, the light polarization is larger than for the case of large QDs. It is worth mentioning that for axially symmetric QDs the intensities $I_l^{(\pm)}$ have the same value for large and small interdot distances (are independent of the interdot distance) and as a result the light polarization vanishes. In the limit of large interdot distance (uncoupled QDs) and elongation $e = 1.4$ the results are consistent with the numerical calculations previously reported [8] and the experimental results [4] (∼5% circularly polarized light for 100% polarized carriers). The thickness of the wetting layer must be included in the height of the QDs in order to achieve the above mentioned comparison.

The dependence of the polarization on the elongation is shown in figure 3 for different geometric parameters. For axially symmetric dots, the polarization along the direction [110] vanishes for all the geometries that we have used. In the case of large elongation ($e = 1.4$), small dot size ($b = 3$) and interdot distance ($D = 0.3$ nm) the polarization has the largest value ($P_{110} = 0.38$, the emitted light is 38% polarized). Polarization has the smallest values for large dots for all the interdot distances which have been used in our investigation. It is worth mentioning that for the case of small interdot distance the emitted light polarization (38% polarized) becomes almost

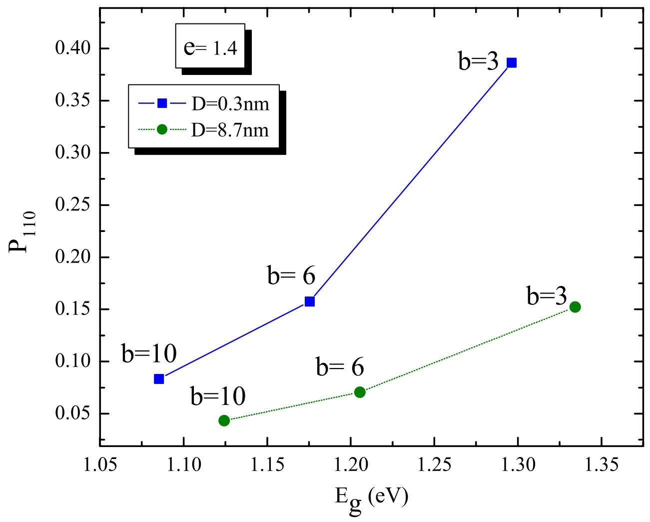

Figure 5. The polarization P_{110} as a function of the energy gap for different interdot distances and width-to-height ratios with fixed dot height $h = 2.1$ nm.

eight times larger than for the case of large interdot distance (almost uncoupled single QDs, ∼5% polarized).

The polarization as a function of the width-to-height ratio is shown in figure 4 for different interdot distances and fixed elongation. It is obvious that for the smallest interdot distance the light polarization becomes large, and as the interdot distance increases the light polarization decreases. On increasing the width-to-height ratio the dot energy gap (E_g) decreases and the light polarization decays due to the change of the carrier wavefunctions which are involved in equation (2).

Figure 5 presents the light polarization P_{110} as a function of the energy gap (E_g) of the dots for fixed elongation. Although the width-to-height ratios are the same for the two different interdot distances, the energy gaps have different values. The value of b influences the carrier wavefunctions and the energy difference between the lowest electron energy at the conduction band and the top hole energy at the valence band due to the change of the structure geometry. The emitted light polarization along the direction [110] increases as the energy gap increases or as the width-to-height ratio decreases.

For other polarization directions like [001] the polarization efficiency it found to be very close to 1 ($P_{001} = 0.99$) and almost independent on the interdot distance. So ($P_{001} = 0.99$) is the best choice if one is interested in the light polarization along the growth direction. Along the directions [100] and [010] the circular polarization vanishes, $P_{100} = P_{010} = 0$, for any of our QD geometries.

Overall, we have studied a system made with two SAQDs which could ideally describe a spin qubit for quantum computer architecture. Although the carriers are 100% polarized, the emitted light is less than 100% polarized. Small photon polarization does not mean that the spin polarization within the coupled QDs is small. In the case of large interdot distance, the limit of insulated QDs (figure 3, $b = 10$ and $e = 1.4$), the light polarization is 4.6%. Therefore, we can conclude that the observed 1% polarization [4] was generated by carriers that were $1/0.046 \sim 21.7\%$ polarized. Lastly, the polarization efficiency along the direction [110] strongly depends on the interdot distance, and the size and the elongation of the QD. In the other directions like [100] and [001], the polarization is independent of the dot geometry. To the best of the author's knowledge there has been no experimental report on circularly polarized light produced by a system of two coupled SAQDs, for direct comparison to our theoretical results.

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