

Spin Relaxation Time in InAlAs/AlGaAs Quantum Dots

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Received: 23 November 2013 /Accepted: 12 January 2014 /Published: 2014

Abstract: We report systematic temperature dependent measurements of spin relaxation time in self-assembled $\text{In}_{0.72}\text{Al}_{0.28}\text{As}/\text{Al}_{0.28}\text{Ga}_{0.72}\text{As}$ quantum dots by continuous-wave photoluminescence. The degree of circular polarization decreases as a function of temperature. The spin relaxation time τ_s is deduced from the circular polarization degree using a three dimensional pseudo-spin precession model. The spin relaxation time decreases rapidly from few hundred picoseconds at 10 K to few tens picoseconds at 85 K. This large change of the spin relaxation time is explained in terms of acoustic phonon emission mechanism. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Semiconductors, Quantum dots, Spin relaxation, Photoluminescence, Circular polarization.

1. Introduction

During the past decade, self-assembled semiconductor quantum dots have attracted considerable interest thanks to their fundamental physics and various potential applications [1, 2]. For the application of these quantum dots to quantum information processing and to the development of quantum dot lasers and single-photon sources, it is very important to study the polarization of the emitted photons associated with exciton annihilation [3]. Spin relaxation measurements through various techniques have been performed with bulk semiconductors, quantum wells and quantum dots. In quantum dots, for example, the spin relaxation measurements using optical orientation in steady-state and time-resolved photoluminescence have been reported [4-6]. For isotropic quantum dots, the relevant eigenstates are bright excitons formed by circularly polarized photons with the angular momentum of ± 1 , and the emission is found to be

circularly polarized (σ^+ or σ^-) via the selection rule of optical transitions. However, the symmetry of the quantum dots is lowered because their formation process and the exchange interaction are thus no longer isotropic [7, 8]. Correspondingly, the anisotropic exchange interaction splits the $|\pm 1\rangle$ radiative doublet into two eigenstates

$$|X\rangle = (|1\rangle + |-1\rangle)/\sqrt{2}, \quad (1)$$

and

$$|X\rangle = (|1\rangle - |-1\rangle)/i\sqrt{2}, \quad (2)$$

linearly polarized respectively along the $[110]$ and $[\bar{1}\bar{1}0]$ directions. Moreover, a part of polarization becomes linear. As a result, the optical orientation and optical alignment are interconnected, which can be treated as “polarization conversion” [9, 10].

In this paper, we will study the circular polarization of the emitted photons of self-assembled InAlAs/AlGaAs. The spin relaxation time (τ_s) is deduced from the circular polarization degree (P_c) using a three-dimensional pseudo-spin precession model proposed by Kaji et al to explain the “polarization conversion” phenomenon [10].

2. Sample Growth and Experiments Details

The experiment was carried out on a sample containing In_{0.72}Al_{0.28}As/Al_{0.28}Ga_{0.72}As Stransky-Krastanov quantum dots. The structure of the sample consists of GaAs (001) substrate, on which the self-organized coherent InAlAs islands are formed by the depositing of nominally 4.8 monolayer of InAlAs between 500 Å thick layers of Al_{0.28}Ga_{0.72}As. The dot density in the sample is about 10¹⁰ cm⁻². The resultant photoluminescence PL is dispersed by a monochromator blazed at 0.6 μm and detected by a silicon avalanche photodiode. The samples were held in a closed cycle He cryostat and excited by a He-Ne laser ($\lambda = 633$ nm) and the Vd: Vanadet laser ($\lambda = 320$ nm). The polarization was analyzed by quarter-wave-plates and linear polarizer. In a previous work [11] we have determined the degree of linear polarization. We have found a value on the order of 20 %.

3. Results and Discussion

The luminescence circular polarization degree is defined as:

$$P_c = (I^+ - I^-)/(I^+ + I^-), \quad (3)$$

Here, I^+ and I^- denote the circularly polarized luminescence components. I^+ has the same circularly polarization than the excitation light. The detection energy dependence of the polarization resolved photoluminescence spectra and of the circular polarization degree is displayed in Fig. 1.

The photoluminescence spectra are obtained at 9 K with excitation energy exceeding the energy of wetting layer. We notice that the photoluminescence is centred at 1.63 eV and its full-width at half-maximum is 114 meV. We measure a circular polarization degree of 20 %.

Fig. 2 shows the temperature dependence of the circular polarization degree P_c (T) obtained with an excitation density about 9 W. cm⁻².

The circular polarization degree P_c decreases slowly in the range between 10 K and 40 K. Then, it decreases rapidly from 20 % at 40 K to 2 % at 85 K.

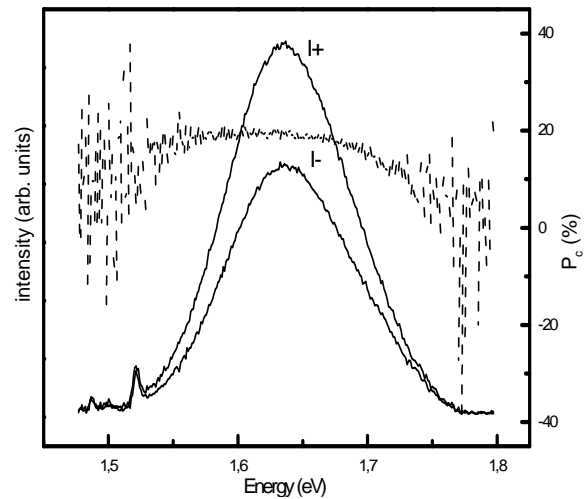


Fig. 1. Polarization resolved photoluminescence spectra at 9 K (solid line) and circular polarization degree (dashed line).

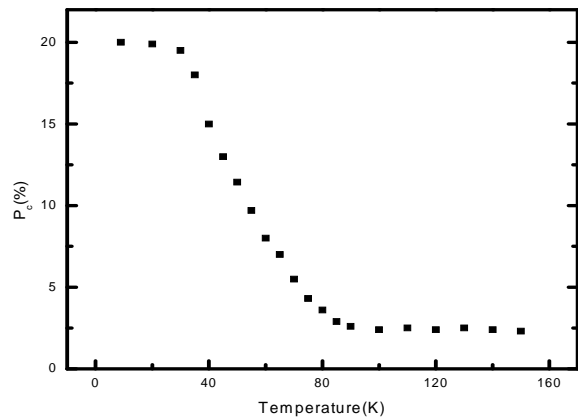


Fig. 2. Temperature dependence of circularly polarization degree (P_c).

From 85 K, P_c remains constant. Spin relaxation in a zinc blend semiconductor can be achieved by interband absorption of circularly polarized light. Spin polarization of the excited free electrons manifests itself in a circular polarization of the photoluminescence light. It is well known that in InAlAs/AlGaAs QDs [9], CdSe/ZnSe QDs [12], and InAs/GaAs QDs [13], LO phonon-assisted excitation causes the fast energy relaxation of photogenerated excitons while preserving the degree of spin polarization. Correspondingly, this excitation energy can be used for effective injection of excitons with high spin polarization. Kaji et al [10] have studied the polarization conversion, considering bright excitons generated and injected into their ground states (quasiresonant excitation). They proposed a three dimensional pseudo-spin precession model to explain this phenomenon. In order to evaluate the exciton spin relaxation time τ_s we have used this model. Indeed, despite our QDs were excited under non resonant excitation, the spin polarization degree is

almost preserved during the fast energy relaxation [14]. According to this model the circular polarization degree is given by:

$$P_c = \frac{T_S}{\tau_R} \left[\frac{P_0}{1 + (\Omega_{exc} T_S)^2} \right], \quad (4)$$

where P_0 is a sample constant, T_S is the exciton spin lifetime and is defined as

$$\frac{1}{T_S} = \frac{1}{\tau_S} + \frac{1}{\tau_R}, \quad (5)$$

τ_R is the recombination time which is almost constant for an excitation density up to 9 W. cm^{-2} and at a temperature lower than 100 K. The experimental value of τ_R is on the order of 630 ps.

The precession frequency is defined as:

$$\Omega_{exc} = \delta / \hbar, \quad (6)$$

where δ denotes the exciton fine structure and \hbar is the Planck constant.

Since the anisotropic exchange interaction caused by the symmetry reduction works as in-plane magnetic field effectively, the precession of exciton spin with the frequency Ω_{exc} can occur even in a zero magnetic field. The study of quantum dots fine structure by using the longitudinal magnetic field dependence of the circular polarization allows us to measure δ (14 μeV) and thereby, the precession frequency Ω_{exc} [15]. We have estimated the values of τ_S using equation (1), the experimental values of Ω_{exc} and τ_R , and considering several values of P_0 . We have summarized the results in the Table 1.

Table 1. Values of τ_S at 10 K and 85 K for different values of P_0 .

P_0 (%)	τ_S (ps) at 10 K	τ_S (ps) at 85 K
100	150	20
90	180	20
80	220	20
70	300	25
60	450	25

In Fig. 3, we have presented the estimated values of τ_S considering that $P_0 = 80\%$. We remark that the exciton spin relaxation time depends significantly on the temperature. The measured spin relaxation time decreases from few hundreds of picosecond to few tens of picosecond in the range between 10 K and

85 K. The activation energy given by the Arrhenius plot of τ_S is on the order of 5 meV (Fig. 4). Correspondingly, at a temperature ranging from 30 to 85 K, the acoustic phonon emission process between the exciton ground state and the excited exciton states seems to be a dominant spin relaxation mechanism. A similar dependence was reported in highly uniform InAs/GaAs QDs by Tackeuchi et al [14]. The spin relaxation time decreases rapidly from 1.1 ns at 10 K to 200 ps at 130 K. This decrease has been explained in terms of acoustic phonon emission mechanism. We remark that τ_S is weaker in InAlAs/AlGaAs QDs than in InAs/GaAs QDs.

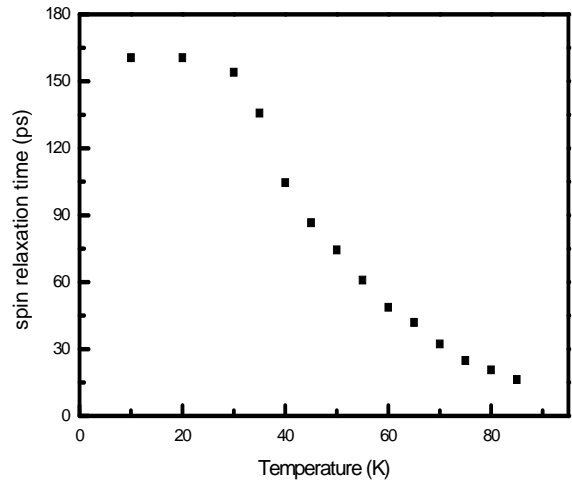


Fig. 3. Temperature dependence of the spin relaxation time in quantum dots. The solid line is the Arrhenius fit.

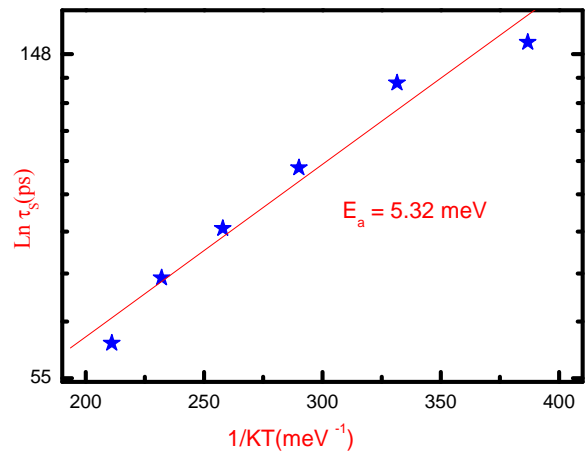


Fig. 4. The Arrhenius plot of the spin relaxation time.

4. Conclusion

To conclude, we have studied the temperature dependence of the photoluminescence polarization of self-assembled $\text{In}_{0.72}\text{Al}_{0.28}\text{As}/\text{Al}_{0.28}\text{Ga}_{0.72}\text{As}$

quantum dots. We have estimated the spin relaxation time from the circular polarization degree using a three-dimensional pseudo-spin precession model. We have found that it decreases rapidly from few hundreds of picosecond to few tens of picosecond in the range between 10K and 85K. This great change has been attributed to acoustic phonon emission mechanism.

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