Time Dependent Luminescence Polarization of a GaAs Quantum Well

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The time dependent luminescence polarization of a GaAs quantum well is calculated from a phenomenological theory of the electron-heavy hole (e-hh) exciton spin dynamics. The electron spin relaxation is assumed to be dominated by the e-hh exchange interaction. The time development on the scale of picoseconds of both circularly polarized components is studied as a function of the exchange energy, recombination time and hole "spin" relaxation time. Some conclusions are drawn from a comparison with preliminary data.

1- INTRODUCTION

The spin dynamics of carriers in semiconductor quantum wells (QWs) can be examined by measuring the polarization of the electron-hole recombination radiation. The same technique has been used before in the bulk and consists of the analysis of the angular momentum transfer between light and semiconductor.[1] The number of works on QWs, both experimental and theoretical, has been growing very fast in the last years.[2-7]

Recent advances in ultrafast phenomena have permitted femtosecond time-resolved measurements which probe in real time the fast spin relaxations reflected on the luminescence polarisation. Freeman et al. [2] conducted such experiments with diluted-magnetic-QWs and arrived to a conclusion concerning the existence of a very fast spin relaxation mechanism in QWs connected with the confinement and enhanced electron-hole correlation in these systems.

A phenomenological model was developed in which the spin dynamics of excitons, with electron-heavy hole (e-hh) exchange interaction, determines the luminescence polarization.[3] The theory explains qualitatively various features of the experiment in ref. 2. Independently, Snelling et al. [4] concluded from their experiments with GaAs QWs that for low concentration of carriers the electron-hole exchange interaction plays a dominant role in the spin relaxation.

In this contribution we discuss the predictions of this same phenomenological model for the time development of the two circularly polarized σ^+ and σ^- components of the luminescence in the case of a QW in zero external magnetic field and resonantly excited with a σ^+ polarized light. Due to spin-flip scattering before recombination, the luminescence is not purely σ^+ polarized. One observes a decreasing degree of polarization $P = (I_+ - I_-)/(I_+ + I_-)$ of the luminescence with time, where I_i stands for the intensity of the polarized component i.

2- e-hh EXCITON SPIN DYNAMICS

Due to strong valence band mixing the hole "spin"-flip scattering time is assumed to be comparable to the momentum relaxation time of the order of picoseconds. The electron spin which has a much slower relaxation is assumed to relax only through the e-hh exchange interaction. Treating the hh spin states as a two state system, such interaction is described by:

$$H_{ex} = J\vec{L}\cdot\vec{S} \quad ; \quad \vec{S} = \frac{1}{2}\hbar\vec{\sigma}_e \;\; and \;\; \vec{L} = \frac{3}{2}\hbar\vec{\sigma}_h \;, \qquad (1)$$

where J is the exchange coupling constant and $\vec{\sigma}_e$ and $\vec{\sigma}_h$ are Pauli matrices vectors wich act over the electron and hole spinors, respectively.

We now consider the basis of product functions $|++>, |+->, |-+>$ and $|-->$, where the first sign corresponds to the electron and the second to the hole "spin" (it will be helpful later to refer to these states by the numbers 1,2,3 and 4 in that same order). The σ^+ excitation creates a $l_z = -3/2$ hh and $s_z = -1/2$ e pair corresponding to an initial condition when only state $|-->$ is occupied. The spin relaxations will correspond to transitions between these states. The σ^+ and σ^- intensities of the luminescence will be proportional to the population of the states $|--\rangle$ and $|++\rangle$, respectively. The evolution with time is obtained by first calculating the transition rates and then solving the system of coupled rate equations. According to our assumptions we have states $|+-\rangle$ and $|-+\rangle$ coupled by the exchange interaction which gives a transition rate $w_x = \Delta/h$, where $\Delta = 3J\hbar^2/2$ is the exchange energy splitting. The other transitions allowed in the model are between states $|++\rangle$ and $|+-\rangle$ and states $|-+\rangle$ and $|--\rangle$, corresponding to hole "spin" relaxation. The respective transition rates are given by a relaxation time t_s and obtained from the following relations:

$$\frac{w_{12}}{w_{21}} = \frac{w_{43}}{w_{34}} = e^{\Delta/kT} \tag{2}$$

and

$$t_s^{-1} = w_{12} + w_{21} = w_{34} + w_{43}. \tag{3}$$

If we use n_i for the population of state i, the system of rate equations is given by:

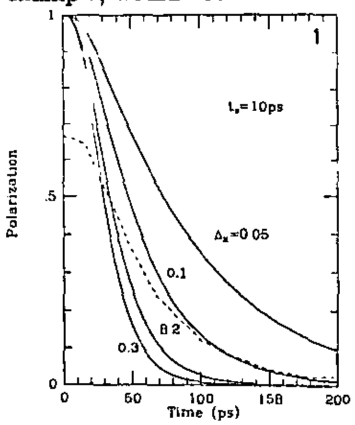
$$\frac{d}{dt}\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{pmatrix} = \begin{pmatrix} -w_{12} - t_r^{-1} & w_{21} & 0 & 0 \\ w_{12} & -w_{21} - w_x & w_x & 0 \\ 0 & w_x & -w_{34} - w_x & w_{43} \\ 0 & 0 & w_{34} & -w_{43} - t_r^{-1} \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{pmatrix} \tag{4}$$

where we added the recombination time t_r. Note that we are considering the luminescence to be dominated by direct radiative recombination.

Besides t_r, whose effects are easy to keep track of and do not influence the degree of polarization, the model is characterized by two parameters: Δ and t_s; both not well known. t_s is usually estimated indirectly from the experiment with some assumptions regarding the spin relaxation and there exists no agreement yet between theory [8,9] and experiment [10,11] regarding the value of the exchange energy splitting Δ in QWs. The theory relies on the value for the bulk which is also not well known. The time evolution of the luminescence polarization as described by the present model is quite sensible to both parameters in an independent way. Even though the model is a highly simplified representation of the situation, we believe that a qualitative comparison with the experiment can help in the estimates of both Δ and t_s. In view of the lack of published data, we use here a preliminary unpublished data on GaAs QW [12] to guide our calculations and to draw some preliminary conclusions.

3- RESULTS AND DISCUSSION

We first fixed t_s at different values and changed Δ. It was found then that only $t_s \sim 1ps$ is able to describe the observed degree of polarization decay and with three different values of Δ. Figure 1 shows that a $t_s = 10ps$, for example, would not be able to do so.



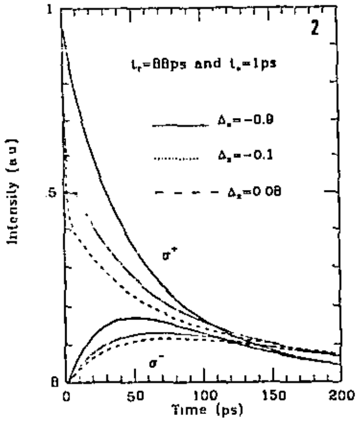


FIGURE 1- Degree of polarization P of the luminescence as a function of time delay with parameter $t_s = 10ps$ and different values of the exchange energy splitting Δ in units of meV. The dashed line gives the observed polarization decay which is well fitted with a $t_s = 1ps$. Temperature is 4k.
FIGURE 2- Time evolution of the two circularly polarized components of the luminescence. The experimental data show the exact same qualitative behaviour. A better comparison is obtained with $\Delta = -0.9meV$.

In figure 2 we show the results for the time development of each component for the three values of Δ obtained above. The maximum in the σ^- intensity, wich is also observed experimentaly, is shown to have its position in time increasing with Δ. Our calculations show also that, as expected, a larger t_r just pushes this maximum to later times and slows down the decay of both polarizations.

In conclusion, we have seen that this simple model presents specific features in the time dependent luminescence polarization, what makes it useful in the development of this largely unexplored area of spin dynamics in QWs. We have also given another indication that the e-hh exchange interaction is an important spin relaxation mechanism in QWs.

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