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The linear and circular polarizations of exciton luminescence in GaAs/AlGaAs quantum wells

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Abstract: We report on the low temperature linearly and circularly polarized photoluminescence excitation spectra, and on the temporal dependence of the polarized PL in undoped GaAs/Al_xGa_{1-x}As quantum wells (QW). The polarization excitation spectra $P_{lin}(E_L)$ and $P_{cir}(E_L)$, E_L is the exciting (laser) energy, monitored at the upper energy part of the photoluminescence (PL) band show two bands that are attributed to the (e1:hh1)1S and (e1:hh1)2S exciton states. $P_{lin}(t)$ and $P_{cir}(t)$ decay much faster than PL(t). These observations are explained by the recombination of delocalized excitons in the high energy side of the PL band. These excitons can move over large "islands" in the QW plane and have a defined $\vec{K}_{||}$. They scatter between the islands and relax by emitting acoustic phonons within the islands where they recombine. The spectral shape of P_{lin} and P_{cir} is thus determined by the exciton - LA phonon scattering rate and the polarization relaxation time dependences on $\vec{K}_{||}$.

1. Introduction

The degree of linear and circular polarization (P_{lin} and P_{cir}), observed in the photoluminescence spectrum of semiconductors under optical pumping, is determined by the dynamic processes of the photoexcited e-h pairs [1-3]. The temporal dependence of $P_{cir}(t)$, monitored in the spectral range of the (e1:hh1)1S excitons in undoped GaAs/AlGaAs QWs was analyzed in terms of the electron and hole spin relaxation and the e-h exchange interaction [4-7]. The relaxation of excitons moving in the plane of the QW was shown to affect the decay of $P_{lin}(t)$ and was used to describe this motion as that of an almost free particle [8].

In this work we compare the spectra of P_{lin} and P_{cir} under selective excitation in the (e1:hh1) band of GaAs/AlGaAs QW's. We also studied the decay of $P_{cir}(t)$ and $P_{lin}(t)$. This allows us to explain the spectral and dynamic features of delocalized excitons in terms of polarization preserving elastic scattering between interfacial islands (in the QW plane) and inelastic exciton-LA phonon scattering processes. The depolarization of the exciton occurs while it is in a $\vec{K}_{||} \neq 0$ state. It is due to depolarizing elastic scattering from static scatterers in the course of its in-plane motion.

2. Experiment

The GaAs/Al_xGa_{1-x}As multiple QW's studied here were all grown by molecular beam epitaxy on

(001)-oriented GaAs substrates. All samples showed similar results. Here we report on the results obtained for a MQW with $x = 0.33$, a well width of $50\text{\AA}$, barrier width of $200\text{\AA}$ and 50 periods. It was placed in an immersion type dewar and pumped by either cw or pulsed dye lasers (6 psec pulse width). The spectral resolution of the spectrometer was 0.05meV and the temporal resolution of the time correlated photon counting system was about 60 psec.

Fig.1a shows the PL spectrum of the MQW under study. The main band (centered at 1.629eV) is the (el:hh1)1S exciton and the weaker band (at 1.640eV) is the 2S exciton. Figs.1b and 1c show $P_{lin}(E_t)$ and $P_{cir}(E_t)$, monitored at the energy marked with an arrow. All these spectra were obtained under cw excitation. When the monitored energy is tuned throughout the high energy part of the PL band, the $P_{lin}(E_t)$ and $P_{cir}(E_t)$ are similar to those shown in Figs.1b and 1c, respectively. Fig.2 shows typical decay curves of the $PL(t)$, $P_{lin}(t)$ and $P_{cir}(t)$. All the decay curves shown were monitored at the peak of the PL band (1.629 eV , cf. Fig.1a), and excited 2.7meV above it, namely, within the (el:hh1)1S band.

3. Analysis

Consider first the spectral features of $P_{cir}(E_t)$ and $P_{lin}(E_t)$ shown in Figs.1b and 1c. The 2S band always appears at about 10meV above the monitored energy, E_m , when this is tuned in the upper part of the PL band. The similar shape of the 1S and 2S polarization bands lead us to conclude that the exciton depolarizes while in its intermediate $\vec{K}_{||} \neq 0$ state, either in the 1S or in the 2S dispersion curves. The exciton is in such an intermediate state in between its optically active states of $\vec{K}_{||} = 0$ at E_t and E_m . We explain the dynamics of polarized excitons by the model described in Fig.3a: The QW plane is considered to have interfacial islands in which the exciton can move with a well-defined $\vec{K}$. In each such island, the exciton translational motion is then described by a set of free particle dispersion curves, $E_{1S}(\vec{K}_{||})$, $E_{2S}(\vec{K}_{||})$, etc. Two such curves are shown in Fig.3a. Excitons are created in 1S states with $\vec{K}_{||} \sim 0$ (process I). Then they scatter into other islands, where they are in a state with $\vec{K}_{||} > 0$, in either 1S (process II) or 2S. The next process (III) is an acoustic phonon-assisted relaxation into the lowest translational state in the island where it recombines (process IV). Since the two polarization bands show a decrease in polarization with the increase in the in-plane wavevector $\vec{K}_{||}$ of the intermediate excitonic state we conclude that the excitonic depolarization occurs in this $\vec{K}_{||} \neq 0$ state due to elastic scattering processes that occur while the exciton moves over large scale interface islands. Two effects, both depending on $\vec{K}_{||}$ determine the depolarization: a. The exciton-LA phonon energy relaxation time [9]. b. The polarization relaxation time. This model can be used to calculate the temporal dependence of $P_{cir}(t)$ and it is described in Fig.3b. (A similar description is used for $P_{lin}(t)$). The exciton $|+1\rangle$ and $|-1\rangle$ spin populations in the island where they are created and in the one where they recombine ($A_t^\pm$ and $A_m^\pm$) and the appropriate decay times are used in order to set the rate equations:

$$\frac{dA_t^+}{dt} = -\frac{A_t^+}{\tau_a} - \frac{A_t^+}{\tau_{cir}} + \frac{A_t^-}{\tau_{cir}} + G_0\delta(t) \quad (1)$$

$$\frac{dA_t^-}{dt} = -\frac{A_t^-}{\tau_a} - \frac{A_t^-}{\tau_{cir}} + \frac{A_t^+}{\tau_{cir}} \quad (2)$$

$$\frac{dA_m^+}{dt} = -\frac{A_m^+}{\tau_r} + \frac{A_t^+}{\tau_a} - \frac{A_m^+}{\tau_{cir}^0} + \frac{A_m^-}{\tau_{cir}^0} \quad (3)$$

$$\frac{dA_m^-}{dt} = -\frac{A_m^-}{\tau_r} + \frac{A_t^-}{\tau_a} - \frac{A_m^-}{\tau_{cir}^0} + \frac{A_m^+}{\tau_{cir}^0} \quad (4)$$

Fig.1: The cw PL and polarized PL excitation of a GaAs/Al_{0.33}Ga_{0.67}As MQW observed at T=2K. (a) PL. (b) Circular polarization. (c) Linear polarization.

Fig.2: The time dependence of the PL and polarized PL of same MQW as in Fig.1 monitored at $E_m = 1.6292\text{eV}$ and excited at $E_L = 1.6319\text{eV}$. (a) PL(t) (b) $P_{\text{cir}}(t)$ (c) $P_{\text{lin}}(t)$. The solid curves are the model fit.

Fig.3: (a) A schematic description of the model used to interpret the polarization spectra. (I) - (IV) present the various excitonic processes, see text. (b) Schematic energy level diagram for the model assumed for the spin-relaxation dynamics.

The equations are solved and the fit to the experimental curves is shown (by solid lines) in Fig.2. The time constants obtained are $\tau_r = 230\text{psec}$, $\tau_{\text{cir}}^0 \approx \tau_{\text{cir}}^0 \approx 600\text{psec}$. τ_a , τ_{cir} and τ_{lin} depend on the $(E_l - E_m)$ energy separation and were determined for several E_l energies within the (e1:hh1)1S band. We find τ_a in the range of 120-220 psec τ_{cir} in the range of 30-50 psec, and τ_{lin} in the range of 5-15 psec. Finally we use the fitted $\tau_{\text{cir}}(\vec{K}_{\parallel})$ and $\tau_{\text{lin}}(\vec{K}_{\parallel})$ and the relations between the exciton $\vec{K}_{\parallel}$ to that of its electron and hole components in order to determine the spin relaxation k dependence of the electron part and hole part of the excitonic wavefunction. The hole spin relaxation time dependence on the holes k_h is found to be in agreement with calculations based on impurity assisted spin flip scattering [10]. The electron spin relaxation times however are surprisingly short taking into account the relative small k_e involved. We attribute that to a strong e-h exchange interaction between the two components of the exciton which decreases the electron spin relaxation time as compared to that of free electrons [7].

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