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TEMPERATURE DEPENDENCE OF CARRIER RECOMBINATION AND SPIN-FLIP PROCESSES IN P-DOPED GAAS QUANTUM WELLS

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We have studied the temperature (T) dependence of the spin-flip processes of electrons in p-type modulation-doped GaAs quantum wells. We have found that at low T, ≤30K, the exchange interaction between electrons and holes is the main mechanism responsible for the spin-flip of the electrons, whereas at higher T the so-called D'yakonov-Perel'(odd terms in the dispersion relation of the conduction band) mechanism dominates. Furthermore, we have found that the recombination time increases considerably with increasing lattice T from a value of τ_r~ 200ps at 5K to τ_r~ 800ps at 80K.

The spin properties of carriers in semiconductors can be conveniently studied by means of pumping with circularly polarized. near-band edge, light, which creates a gas of carriers with appreciable different populations of spin-up and spin-down components. Spin relaxation of excitons and free carriers in bulk materials has been extensively investigated in the past.[1,2]. Temperature (T) and carrier density dependence of the spin times (τ_{sf}) have been used to establish the different mechanisms responsible for the spin-flip processes. Spin relaxation of free carriers has been studied in doped QW's and an increase (decrease) of τ_{sf} of holes (electrons) as compared with bulk values has been found[3]. However, it is the general opinion that further experimental and theoretical work are needed to reach a full comprehension of spin relaxation in semiconductor QW's.

In this work, we have investigated several p-doped QW's with different well widths (30Å to 80Å) and fabricated under different conditions (i.e., grown on [311]-GaAs substrates and modulation doped with Si or on [100] substrates and doped with Be), all of them however showing similar hole concentrations of ~$3x10^{11}cm^{-2}$. The samples, mounted in a cold-finger cryostat, are optically excited

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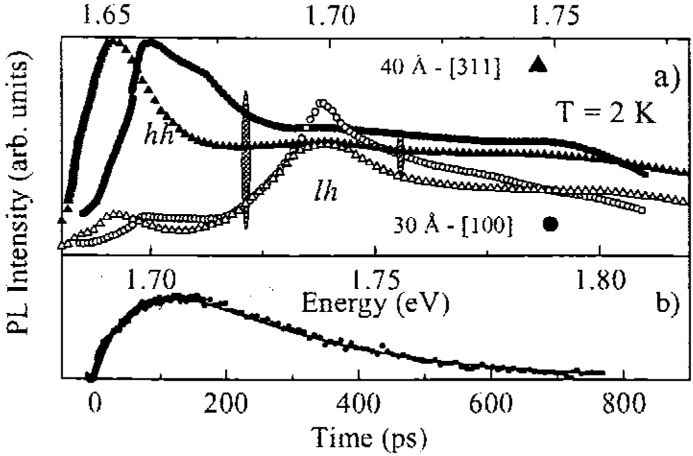

Fig.1: a) PLE spectra of two GaAs QW's at 2K. Closed (open) points: σ^+ for excitation and σ^+ (σ^-) emission. b) Time-resolved emission of [100]-sample at 8K detecting at PL (1.681eV).

with pulses from a dye-laser pumped with a mode-locked Nd-YAG laser. The photoluminescence (PL) was time resolved with an up-conversion spectrometer with a time resolution of 5 ps. The exciting light was circularly polarized by means of a $\lambda/4$ plate, and the PL was analyzed into its σ^+ and σ^- components as a function of time delay after the excitation pulse. The sample temperature was varied between 5K and 80K.

Figure 1a depicts the PLE spectra of two of the samples used in the experiments, the bottom (top) axis corresponds to a QW grown in the [100] ([311]) direction, the scales have been shifted to bring to energies of the light-hole (*lh*) transitions at the same position. Due to the Moss-Burstein shift, the PL (not shown) lies ~20 meV below the *hh* transitions. The shaded areas indicate the energies used to optically pump the samples. Exciting the p-type GaAs QW's below the *lh* resonance, electrons with almost purely one spin component are photocreated. We will restrict our discussion to the [100] sample. The time evolution of the unpolarized PL at 8K for an electron density of $5.3\text{x}10^9$ cm^{-2}, exciting at 1.717 eV and detecting at the PL peak, is shown in Fig.1b. The line is the best fit using a simplified model with 3 levels, which obtains rise and decay times of τ_r=65 ps and τ_d=225 ps, respectively. These times depend strongly on the excitation density and the temperature, we will concentrate in the following on the T dependence.

Figure 2 shows the PL dynamics for different lattice temperatures at a photocreated electron density of $2.6\text{x}10^9$ cm^{-2}. Increasing T a large increase of τ_d is observed from 195 ps at 5 K to 475 ps at 60 K. This rise is attributed to heating of the carriers due to electron-phonon scattering, which moves the electrons out of the

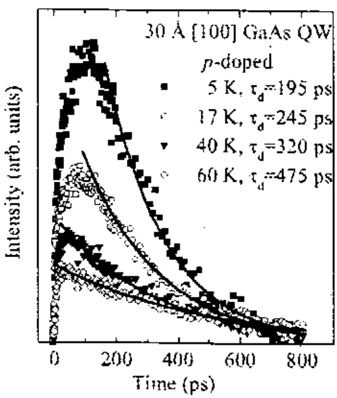

Fig.2: PL time evolutions for different lattice temperatures. Lines are best fits to mono-exponential decays.

emission region, therefore competing with the radiative recombination processes. The rate of increase of τ_d is independent of growth direction but it doubles when the well width is enlarged from 30 to 80Å. Furthermore, with increasing lattice T, the electron and hole distribution functions broaden yielding a smaller density of occupation and thus decreasing the PL intensity as can be readily seen in Fig.2. The rate of increase of τ_d is independent of the growth direction, but increases considerably with increasing QW width; for 80Å QW attaining τ_d=780 ps at 60 K.

Let us now discuss the spin properties of our system. The decay time of the polarization degree, defined as $\rho = (I^{++} - I^{+-})/(I^{++} + I^{+-})$, where $I^{++(-)}$ is the PL intensity exciting with σ^+ pulses and detecting the σ^+ (σ^-) emission, represents an effective spin-relaxation time, τ_{sf}. The time evolution of ρ for the [100] QW, exciting at 1.717 eV and detecting at the PL peak, is shown in Fig. 3a for tow different temperatures with a photocreated electron density of $5.3x10^9 cm^{-2}$. It is clearly seen that the decay is not monoexponential, indicating the presence of different spin-flip mechanisms. A fit with the sum of two exponential decays (lines in Fig. 3a) obtains spin-flip times of τ_1=20 ps and τ_2=550 ps. The fast time, τ_1, is attributed to the nondegenarate character of the holes almost immediately after the laser pulse. This carrier distributions favor the efficiency of spin-flip electron scattering via the exchange interaction with holes[4]. The slow time, τ_2, corresponds to the spin flip of electrons in the presence of a degenerate hole gas; it is important to note that τ_2 is a factor of two longer than the PL decay time, τ_d. Both times are independent of the excitation power, but the contribution to the spin relaxation of the fast mechanism increases with power. Increasing T, both spin-flip mechanisms speed up considerably. The fit at 40 K obtains values of 10 ps and 80 ps for τ_1 and τ_2, respectively. We will concentrate in the following on τ_2, which we identify as the intrinsic spin-flip of electrons, τ_{sf}. The T dependence of the spin-rate, $1/\tau_{sf}$, is depicted with solid points in Fig.3b. Two mechanisms are commonly considered for electron spin relaxation in intrinsic semiconductors: the Elliot-Yafet mechanism[5], only important in narrow gap semiconductors, and the D'yakonov-Perel' (DP) arising from the linear in **k** term of the conduction band dispersion in QW's[6]. An additional mechanism has to be considered in the presence of holes: the so-called Bir-Aronov-Pikus (BAP) due to the exchange interaction between electrons and holes[7]. In bulk semiconductors BAP dominates at low T, while DP is the most

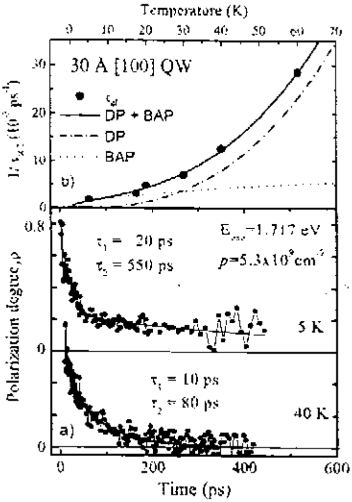

Fig.3: a) Time evolution of polarization degree at different temperatures. b) Temperature dependence of spin-flip rate, lines: fit to different mechanisms.

important at high temperatures[8]. The T dependence of τ_{sf} allows the identification of the spin-flip mechanisms: for BAP a $T^{1/2}$ is expected[7], while DP predicts a T^{α} dependence[6]. The best fit of our data to those laws obtains α=2.6±0.3, and proofs that, similarly to electrons in bulk, the spin-flip processes of two-dimensional electrons are governed by the exchange mechanism at low temperatures, while the DP mechanism takes over at higher temperatures.

Summarizing, we have shown that the spin-flip of electrons in two dimensional semiconductors is driven by the DP and BAP mechanisms at low and high temperatures, respectively; and that the decay time of the PL increases with T due to heating of the carriers through electron-phonon scattering.

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