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On the Spin-Flip Mechanisms of Electrons in Semiconductor Quantum Wells

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We have studied the temperature dependence of the spin-flip processes of electrons in p-type modulation-doped GaAs quantum wells. We have found that at low temperature ($T \leq 30$ K) the exchange interaction between electrons and holes is the main mechanism responsible for the spin-flip of the electrons, whereas at higher temperatures the so-called Dyakonov-Perel mechanism dominates. Furthermore, we have found that the recombination time increases considerably with increasing lattice temperature from a value of $\tau_r \approx 200$ ps at 5 K to $\tau_r \approx 400$ ps at 60 K.

Useful electronic devices rely on the precise control of electronic charge and, in general, the fact that the electrons also have a spin is ignored. However, the scattering processes for electrons depend on their spin state. Spin related effects of carriers are attracting a lot of attention in different fields of condensed matter physics. The interest in the spin mechanisms is due not only to fundamental curiosity but also to possible device applications: semiconductor-based spin-polarized sources have nowadays reached a state where electrons with polarizations of ≈90% can be obtained. These sources are made out of III–V compounds grown epitaxially, lifting the degeneracy of the holes at the top of the valence band either by quantum confinement effects and/or by strains due to lattice mismatch effects [1, 2]. In bulk materials, high doping reduces the spin relaxation time and therefore the electron polarization. However, the use of modulation doping in two-dimensional structures allows the achievement of long spin-flip times for electrons [3, 4]. Optical pumping and optical orientation experiments have been traditionally used in semiconductors to investigate the spin properties of carriers and excitons [5]. In bulk semiconductors, the spin relaxation of excitons and free carriers has been extensively studied in the past. The dependence of the various spin-relaxation mechanisms on temperature and doping has been used to distinguish between them [6, 7]. Two main processes, exchange (BAP) [8] and the Dyakonov-Perel (DP) mechanism [9], have been identified as responsible for the spin flip[2]). The DP mechanism is due to cubic terms in the dispersion relation of the conduction band (linear terms, in

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[2]) An additional mechanism, due to coupling between conduction- and valence-band states has to be considered for small gap semiconductors.

the case of two-dimensional systems), and the spin-flip time due to this mechanism is inversely proportional to the electron scattering time. The relative importance of these mechanisms is modified in doped semiconductor quantum wells (QWs) due mainly to the new electronic bandstructure, which affects the hole spin-relaxation, and to the higher carrier mobility, which is important for mechanisms sensitive to carrier momentum relaxation, such as the DP one. Spin relaxation of free carriers has been studied in doped QWs and an increase (decrease) of the spin-flip time, τ_{sf}, of holes (electrons) as compared with bulk values has been found [10, 11].

In this work, we have investigated the temperature dependence of the polarization- and time-resolved emission of several p-doped QWs with different well widths 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 $\approx 3 \times 10^{11}$ cm^{-2}. The samples, mounted in a cold-finger cryostat, are optically excited 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 $\approx$5 ps. The sample temperature was varied between 5 and 80 K, and the excitation power between 1 and 40 mW.

Fig. 1a depicts the photoluminescence excitation spectra at $T = 2$ K of one of the samples used in the experiments, grown in the [100] direction and with a QW width of 30 Å. Due to the Moss-Burstein shift, the PL (not shown) lies $\approx$20 meV below the hh transitions. Exciting the p-type GaAs QWs below the lh resonance, electrons with almost purely one spin component are photocreated. The time evolution of the unpolarized PL at 8 K for an electron density of 5.3×10^9 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 three levels, which obtains rise and decay times of $\tau_r = (65 \pm 7)$ ps and $\tau_d = (225 \pm 15)$ ps, respectively.

Fig. 2 shows the PL dynamics for different lattice temperatures at a photocreated electron density of 2.6×10^9 cm^{-2}. Increasing T a large increase of τ_d is observed from 215 ps at 5 K to 475 ps at 60 K. The inset in the figure compiles the temperature dependence of the PL decay time. The triangles are obtained from fits of time traces as those shown in the figure, corresponding to detection energy at

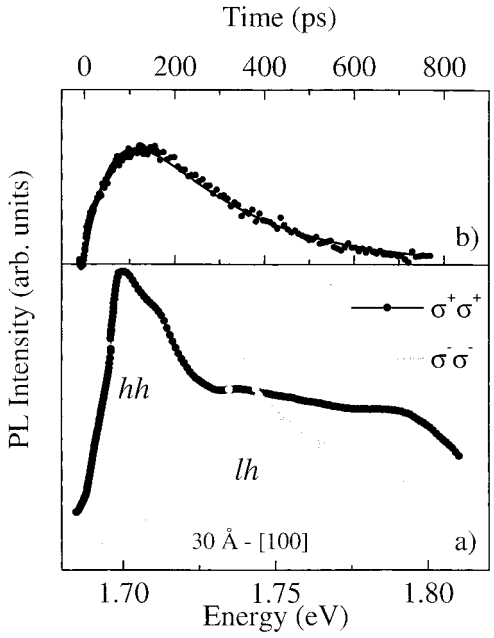

Fig. 1. a) Photoluminescence excitation spectra for the 30 Å thick QW grown on a [100] GaAs substrate under σ^+ excitation: σ^+ (black dots) and σ^- (gray dots) polarized emission. b) Time evolution of the unpolarized photoluminescence exciting at 1.717 eV and detecting at the PL peak; the line is the best fit to a three level model (see text)

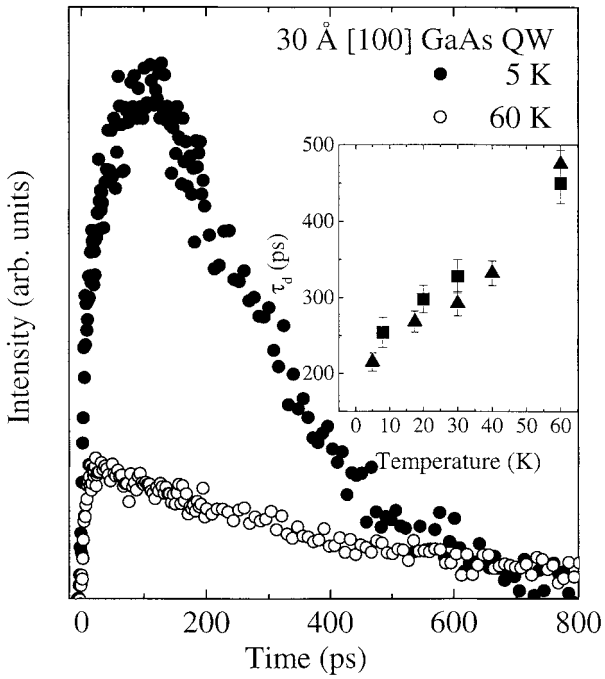

Fig. 2. Time evolution of the PL for two different temperatures: 5 K (solid circles) and 60 K (open circles). The inset shows the temperature dependence of the decay time obtained from time traces (triangles), and from fits of decay of the integrated emission band (squares)

the maximum of the PL emission, while the squares result from fits of the decay of the integrated emission band. The good agreement between both sets of data excludes any wavelength dependence of τ_d as the origin of its temperature dependence. Therefore, the rise of τ_d is attributed to heating of the carriers due to electron–phonon scattering, which moves the electrons out of the 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 80 Å. Furthermore, with increasing lattice temperature, 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.

Let us concentrate now on the spin dynamics. Fig. 3a depicts the time dependence of the polarization-resolved emission of the same sample as in Fig. 2, exciting with σ^+ polarized light with an excitation power of 1 mW at 5 K. It is clearly seen that the emission co-polarized with the excitation ($\sigma^+\sigma^+$) overcomes the counter-polarized ($\sigma^+\sigma^-$) up to very long times after the pulsed excitation. This implies that the PL polarization degree, defined as $\mathcal{P} = (I^{++} - I^{+-})/(I^{++} + I^{+-})$, where $I^{++(+-)}$ is the PL intensity exciting with σ^+ pulses and detecting the $\sigma^+(\sigma^-)$ emission, reaches high values and lasts even longer than the PL emission, as shown in Fig. 3b. The decay time of $\mathcal{P}$ represents an effective spin-relaxation time, τ_{sf}. It is clearly seen that the decay is not monoexponential, indicating the presence of different spin-flip mechanisms. The fast time, τ_1, is attributed to the nondegenerate character of the holes almost immediately after the laser pulse. This carrier distribution favors the efficiency of spin-flip electron scattering via the exchange interaction with holes [12]. 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

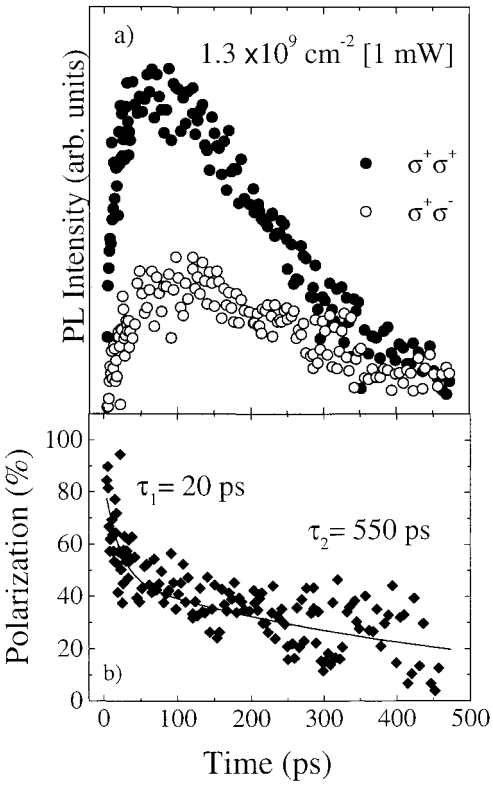

Fig. 3. a) Time evolution of the PL exciting with σ^+ polarized pulses at 1.717 eV: σ^+ (solid circles) and σ^- (open circles) polarized emission. b) Time evolution of the polarization degree; the line is the best fit to a double-exponential decay

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. A fit of the decay of $\mathcal{P}$ at 40 K obtains values of 10 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 by solid circles in Fig. 4. From the different spin-flip mechanisms, in bulk semiconductors BAP dominates at low T, while DP is the most important at high temperatures [13]. The T dependence of τ_{sf} allows the identification of the spin-flip mechanisms: for BAP a $T^{1/2}$ one is expected [8], while DP predicts a T^{α} dependence (the exponent α is determined by the temperature dependence of the scattering time of the electrons) [8, 14]. The best fit of our experimental data to those laws obtains $\alpha = 2.6 \pm 0.3$ (dashed line in Fig. 4), and proves 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

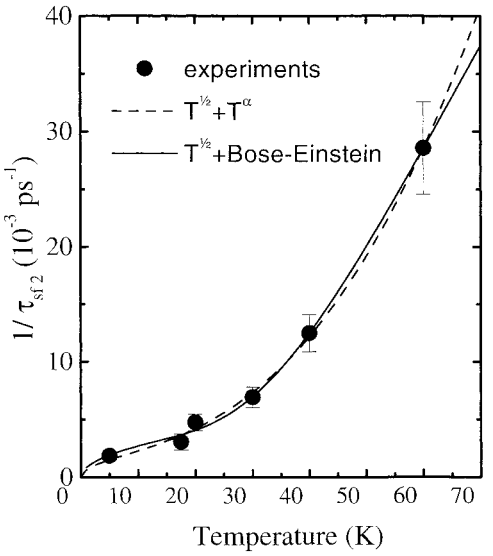

Fig. 4. Temperature dependence of the "electron" spin-flip rate. The lines represent the best fit to the predictions of Dyakonov-Perel and exchange mechanisms (dashed) or Dyakonov-Perel and scattering by phonons (solid)

over at higher temperatures. An alternative model to fit the DP contribution would be to consider the spin-flip rate proportional to Bose-Einstein statistical factors for phonon emission plus absorption [15]:

$$\tau_{\mathrm{sf}}^{-1} = \tau_0^{-1}[1 + 2/(\mathrm{e}^{\theta/T} - 1)] .$$

Using this alternative model the BAP contribution is similar to that obtained with the previous one. This second procedure has more physical meaning, since it gives an estimation of the phonons involved in the electron scattering. The best fit (solid line in Fig. 4) obtains θ = 135 K, which indicates that the mean energy of the acoustic phonons taking part in the scattering process is $\approx$11 meV.

In conclusion, we have shown that the spin-flip of electrons in two-dimensional semiconductors is driven by the BAP and DP 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. The mean energy of the acoustic phonons contributing to the scattering processes in the DP mechanism amounts to 11 meV.

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