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Many body effects on the spin relaxation of electrons in GaAs quantum wells

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Abstract

The dynamics and energy spectrum of spin-polarized electron gases are studied using time- and polarization-resolved interband luminescence experiments in p-type, modulation-doped quantum wells. A non-linear dependence of the electron spin relaxation versus excitation intensity is observed and attributed to a strong coupling of single electronic spin relaxation to the decay of the total polarization of the hole gas. The evolution of the luminescence spectra versus time and excitation power shows non-equilibrium distributions of the two components of the spin-unbalanced electron gas with similar temperatures but different Fermi energies. The spin-dependent band filling dominates over renormalization effects and leads to an appreciable shift between the emission spectra with different helicities of circular polarization.

Keywords: Spin dynamics; High density-effects; Time-resolved spectroscopy

A circularly polarized, near-band edge, excitation of a semiconductor structure permits the creation of a gas of photoexcited electrons with appreciable different populations of spin-up and spin-down components [1]. The dynamics and energy spectrum of this spin-unbalanced electron gas can be conveniently investigated in p-type structures by measuring the circularly polarized recombination between photocreated electrons and the non-polarized gas of holes, which mostly originates from doping. A variety of optical pumping experiments, including time-resolved spectroscopy, have been employed to determine the mechanisms of spin relaxation and its dependence on doping, temperature, dimensionality, etc. [2]. Only recent studies on excitons raised the problem of interactions within a gas of spin polarized carriers [3].

In this paper, the time evolution of the two spin components of a photocreated *electron gas* is investigated as a function of the density of carriers excited with a picosecond laser pulse. Exciting a p-type GaAs quantum well below the light-hole resonance, electrons with almost purely one spin component are photocreated. Filling of the conduction

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band is clearly different for both electron-spin components, leading to an appreciable shift between σ^+ and σ^- emission spectra. The effect of spin-dependent bandgap renormalization is relatively weak. The two spin components of the electron gas are characterized by Fermi distributions with very similar temperatures, but different Fermi levels. The decay of spin polarization of the electron gas is found to depend strongly on the excitation power: an usual monoexponential decay of spin polarization (with a characteristic time of 550 ps) is observed at low powers; whereas a fast depolarization process (characteristic time of 20 ps) turns on progressively when the density of photocreated carriers approaches the concentration of holes originating from doping. The observation of the fast component (typical for the relaxation of hole magnetic moment) in the electron-spin relaxation suggests that this is driven by the decay of the total polarization of the hole gas. Such a process may only be expected at sufficiently high excitation powers when concentration of photocreated, spin-polarized holes becomes comparable with the density of nonpolarized holes arising from doping.

We have studied four p-type modulation doped GaAs/GaAlAs quantum wells with hole sheet concentrations of $\sim 3\times10^{11}\,\mathrm{cm}^{-2}$, mobilities of $\sim 4000\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ and well widths from 30 to 80 Å. The quantum well structures were grown either on [3 1 1]-GaAs substrates and modulation doped with Silicon or on [1 0 0]-GaAs substrates and doped with Beryllium. These structures were initially extensively tested with conventional, low power, cw experiments [4]. We have measured luminescence and luminescence excitation spectra in different configurations of circular polarization of both the exciting and emitted light. Low temperature, magnetic field experiments in Faraday configuration were performed in order to determine the doping level and to estimate the effective masses. Polarization-resolved measurements in Voigt configuration (Hanle experiments) allowed us to estimate the spin relaxation time at very low excitation powers and investigate its changes as a function of temperature ($T = 2$–50 K).

In this work, we concentrate on the results obtained in time resolved experiments in the absence of magnetic fields. These experiments have been

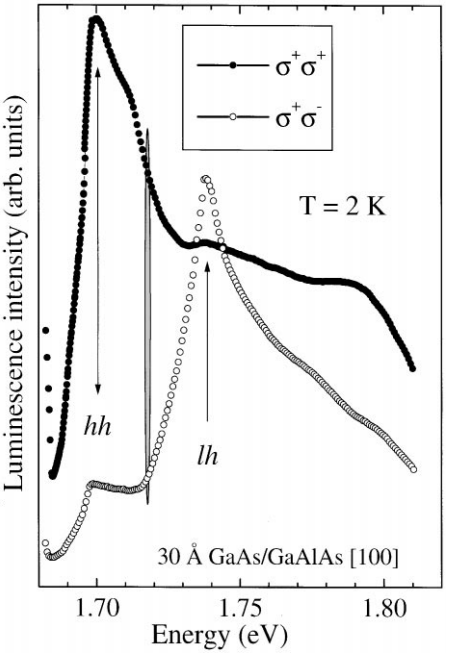

Fig. 1. Photoluminescence excitation spectra of a 30 Å-thick p-type modulation doped ($p = 3\times10^{11}\,\mathrm{cm}^{-2}$) quantum well measured in the configuration of aligned (σ^+/σ^+) and crossed (σ^+/σ^-) polarizations of the excited/emitted light. The shaded area indicates the energy used for excitation in the time-resolved experiments.

carried out with a standard up-conversion setup (time resolution of 5 ps), using a double monochromator to disperse the up-converted signal. The exciting light, obtained from a Pyridine 1 dye laser, synchronously pumped by the 532 nm line of a mode-locked Nd : YAG laser, was circularly polarized and the luminescence intensity was analyzed into its σ^+ and σ^- components. We have measured luminescence spectra at fixed times, as well as the luminescence decay at fixed emission energies, both as a function of temperature ($T =$ 10–50 K) and as a function of the laser power, giving concentrations of excess carriers in the range between $\sim10^{10}\,\mathrm{cm}^{-2}$ and $\sim10^{11}\,\mathrm{cm}^{-2}$. Representative experimental results are discussed here for a 30 Å thick quantum well modulation doped with Beryllium.

Fig. 1 depicts photoluminescence excitation (PLE) spectra of the 30 Å, [1 0 0]-oriented sample

at low temperature, excited with a σ^+-polarized light, recorded at the tail of the emission (not shown), and which peaks 12 meV below the first structure of the PLE spectra. The solid (open) points correspond to the emission of σ^+ (σ^-) light. The onset of the absorption due to the heavy-hole transition is clearly seen as a peak in the $\sigma^+\sigma^+$ spectrum at 1.7 eV, while the one corresponding to the light-hole transition is dominant in the $\sigma^+\sigma^-$ spectrum at 1.738 eV. As can be deduced from this figure, the sample shows a relatively high degree of optical alignment, indicating a long spin-flip relaxation time for the photoexcited electrons. In the following, we fix the excitation energy below the light-hole transition where, as expected, the highest degree of luminescence polarization is observed. Using p-type samples we can easily investigate spin alignment effects in the conduction band: electrons with an unbalanced population of the two spin components, created under circularly polarized excitation, recombine with non polarized holes which mostly originate from doping. Therefore, the spin relaxation of the electrons can be obtained from the difference of the time evolution of the two orthogonally polarized emissions. In an ideal sample, using the estimated hole Fermi energy of 2 meV, and assuming a ratio of six between the hole and electron effective masses, the circularly polarized luminescence spectra are expected to directly reflect the distributions of electrons with different spin components in an energy range up to $\sim$12 meV above the conduction-band edge. However, as shown in Fig. 2, the spectra measured at 26 ps after a 40 mW excitation, which is the highest used in our experiments, cover a somehow wider spectral range. We assume that even these spectra, probe only the properties of the electron gas since the investigated sample shows an appreciable spectral broadening already under low-power cw excitation (half width of the luminescence $\sim$10 meV).

Fig. 2 represents the σ^+ and σ^- components of the luminescence spectra excited with σ^+ pulses at 1.717 eV at two different delay times after the laser excitation. The spectra obtained at short times clearly show the difference in the occupation of electronic states with opposite spins. This difference in occupation vanishes at longer delay times as can be recognized in the spectra measured at 422 ps.

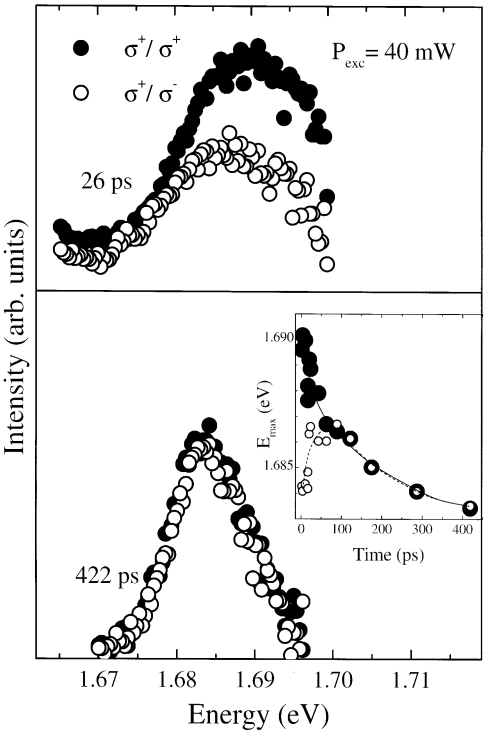

Fig. 2. σ^+ and σ^- components of the photoluminescence spectra measured 26 and 422 ps after a σ^+-polarized pulse excitation with mean laser power of 40 mW and excitation energy of 1.717 eV. The inset shows the time evolution of the energy positions corresponding to the intensity maxima in the respective luminescence spectra.

The difference in the occupation of electronic states with opposite spin components leads to the energy difference between the positions of the maxima in the σ^+ and σ^- luminescence spectra. These maxima positions are plotted versus the delay time in the inset to Fig. 2. It can be seen that the concentration of electrons with minority spins (open circles) initially increases as a function of time. This increase is correlated with the red shift of the σ^+ emission (solid points) and it occurs at the expense of the decrease of the electron concentration with majority spins. It originates from the fast spin depolarization observed under these particular excitation conditions, as will be shown below. After the spin polarization vanishes, the σ^+ and σ^- luminescence spectra overlap and both show the same effect of

further emptying of the conduction band. Excluding very short delay times after excitation, i.e., already after a few picoseconds, each spin component of the electron gas can be qualitatively characterized by its own Fermi distribution, each one with different chemical potential but both with very similar temperatures.

It could be argued that due to differences in the exchange interaction, the unbalanced populations of the two spin components could also induce a difference in the many-body renormalization between occupied electronic states with opposite spins. We have systematically observed that the low-frequency onset of the emission associated with the majority spins sets out always below the corresponding onset of the minority-spin luminescence. This effect is, however, rather weak as can be seen from the spectra shown in the upper part of Fig. 2.

Our most intriguing experimental finding is illustrated in Fig. 3. We have found that the decay of spin polarization of the electron gas depends very much on the intensity of the laser excitation. The decay of the degree of luminescence polarization, $(I^{\sigma^+} - I^{\sigma^-})/(I^{\sigma^+} + I^{\sigma^-})$, measured at $T = 10\,\mathrm{K}$ can be well reproduced by a sum of two exponential decays with two distinct characteristic times of 20 and 550 ps. The amplitude of the fast component vanishes at low excitation power, whereas this fast process almost completely determines the electron spin depolarization at the highest level of laser excitation. It is well known that for any mechanism of electron spin relaxation [5], the probability of spin flip transitions increases as a function of the electron k-vector. Therefore, the increase in the rate of spin relaxation as a function of the laser power may result partially from a larger electron kinetic energy caused either by an increase of the effective electron temperature or of the initial electron concentration. However, this simple reasoning hardly explains our data. From an analysis of the time evolution of the luminescence spectra, we have estimated an increase in the mean kinetic energy of the electron gas of only 4 meV at the highest laser power. This amount is not sufficient to reduce the spin relaxation time down to 20 ps, since at low excitation powers but high lattice temperatures ($kT \sim 3.44$ meV) we still observe a relatively long spin relaxation time ($\sim$80 ps). We have obtained

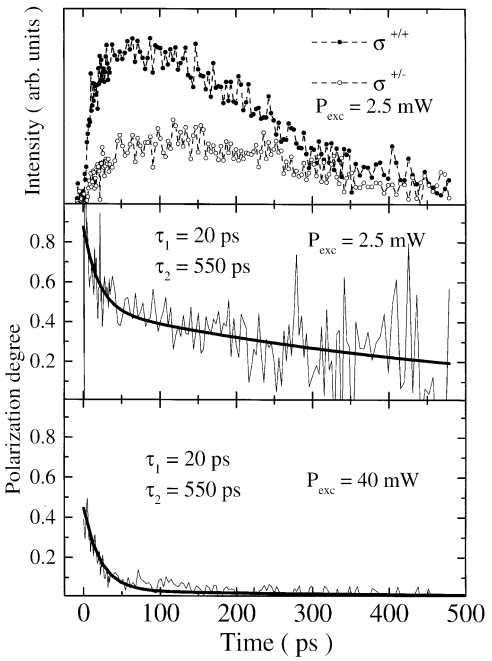

Fig. 3. From the top: decay of σ^+ and σ^- luminescence signals detected at $E_{em} = 1.684$ eV under pulsed, σ^+ excitation with mean laser power of 2.5 mW; time evolution of the polarization degree $(I^{\sigma^+} - I^{\sigma^-})/(I^{\sigma^+} + I^{\sigma^-})$ of the luminescence signal detected at 1.684 eV for two different (2.5 and 40 mW) mean laser powers. The solid lines represents the best fit according to the sum of two exponential decays: $A\exp(-t/\tau_1) + B\exp(-t/\tau_2)$.

that at $T = 40\,\mathrm{K}$ and high excitation powers (> 2.5 mW), the spin decay is also described by two exponentials. The characteristic decay times are, however, considerably reduced compared to those observed at 10 K and they amount to 10 and 80 ps, respectively. At a fixed temperature, the dynamics of the luminescence polarization is very well reproduced by the sum of two exponential functions, whose amplitudes depend on the excitation power whereas the corresponding decay times are power and excitation-energy independent.

The observed relaxation times of 10–20 ps lay in the middle of the range between typical spin relaxation times in the valence band ($\sim$5 ps) [6] and the characteristic decay time of exciton magnetic moments ($\sim$40 ps) [3,6]. Hence, we speculate that the relaxation of the electron spin is driven by the depolarization of the hole magnetic moments. We

have estimated that the fast process in the decay of the electron spin polarization becomes important when the concentration of photocreated holes is similar to the doping level. In order to account for the power dependence, we assume that an electron spin-flip transition is driven by the spin depolarization of the total hole gas and not simply by a spin-flip transition of a single hole. The number of photocreated, both spin-polarized, electrons and holes is equal at any excitation power. However, a finite total polarization of the hole gas occurs only at a high excitation power, when the concentration of optically created carriers becomes comparable to the concentration of holes arising from doping. It is worth noticing that signatures of a long spin relaxation time, characteristic for electrons, have been also reported in the studies of spin depolarization of holes in n-type samples [6].

In summary, the electron spin dynamics in p-type quantum well structures is found to be strongly dependent on the excitation power. An extremely fast process dominates the dynamics of the electron spin flip at high excitation, when the concentration of photocreated carriers becomes comparable to the doping level. This process is interpreted as arising from electron spin-flip transitions driven by the fast depolarization of the hole gas. Polarization- and time-resolved luminescence spectra reveal the existence of different quasi-Fermi distributions for two spin components of the electron gas. The energy shift observed between differently polarized luminescence spectra reflects the spin-unbalanced population of one-particle electronic states and indicates that the effects of many-body renormalization are relatively small in the range of the investigated carrier densities.

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