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Electron spin-polarization in p-doped quantum wells

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Abstract: We study both theoretically and experimentally the luminescence in non-intentionally but heavily p-doped GaAs quantum wells of 55 and 150Å width. At $T=2\text{K}$ the PL spectra under cw excitation present an excitonic peak and a broad acceptor band. Time-resolved optical pumping of the acceptor line allows us to measure the free electron spin relaxation time. We have investigated its temperature dependence in the 4-40K range. The experimental findings are interpreted in the framework of the D'Yakonov-Perel' mechanism for the electron gas.

1. INTRODUCTION

The study of the optical response of semiconductors represents an important tool for the investigation of their electronic properties. Interband transitions near the fundamental band-gap (absorption, luminescence, ...) depend strongly on various external (e.g. excitation power, electric and magnetic fields and temperature) and intrinsic (sample quality and doping concentration) parameters. In intrinsic semiconductors the light absorption is followed by an electron-hole (band-to-band or exciton) radiative recombination. p-doped semiconductors present energy levels in the forbidden gap of the pure crystal and near the top of the valence band. At $T=0\text{K}$ these levels are empty for the electrons (no electron or one hole). Thus, an additional luminescence line (the acceptor-line) appears, associated to the new luminescence path for the photocreated electron-hole pair (via the hole bound to the acceptor).

In this paper we consider time-resolved optical pumping experiments performed on a set of non intentionally but heavily p-doped GaAs quantum wells. The advantage of dealing with p-doped samples is that the polarization is given by the minority photocreated carriers (electrons) which are in presence of a sea of majority carriers of opposite charge (holes) which can reasonably be considered as non polarized. We are then able to investigate the polarization properties of photocreated electrons.

We have studied experimentally and theoretically several aspects of the polarization response of a p-doped quantum well : the excitation power dependence of the spin relaxation time, its temperature dependence, and the influence of the doping level.

2. EXPERIMENTAL RESULTS

We have considered two samples with different doping concentrations. Each sample contains two quantum wells, 55 and 180Å thick, separated by a thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier. The doping level is not known precisely, but a rough estimate of the relative amount of dopants can be made when considering the intensities of the e-A° lines in the photoluminescence (PL) spectra of the quantum wells. In the following the sample with the higher (lower) doping level will be referred as sample 1 (sample 2).

Time-resolved PL spectra have been measured exciting the samples with a Nd:YAG synchronously pumped dye laser, which provides 5 ps pulses in the range 710-800 nm at a repetition rate of 76 MHz. The PL signal was dispersed through a 0.22 m double monochromator (1 meV resolution) and detected by a synchroscan streak camera with an overall time resolution of 20 ps. The sample was held in a variable temperature cryostat which allowed measurements between 4 and 40K.

Fig.1: Photoluminescence spectra at 4K of the 55Å (a) and 180Å (b) quantum wells of sample 1 (continuous lines) and sample 2 (dashed lines).

In Fig.1 are reported the cw PL spectra of the four QWs for an excitation power of 0.1mW corresponding to an average photogenerated carriers density of 5.10^6 cm^{-2} . Two features are observable: a narrow line, corresponding to the excitonic recombination (1.5315 and 1.594 eV for the 180 and 55Å QW, respectively) and a broad red-shifted band corresponding to the $e-A^\circ$ recombination. In the 55Å and 180Å quantum wells the acceptor binding energies are of the order of 20 and 15 meV, respectively, indicating that the acceptors are mainly located on the well edge [1].

Considering the relative intensities of the $e-A^\circ$ lines with respect to the excitonic ones, we estimate that the doping concentration is 3, 4 and 10 time larger in the 180Å QW of sample 2 (dotted line in Fig. 1b), 55Å (continuous line in Fig. 1a) and 180Å (continuous line in Fig. 1b) QWs of sample 1, respectively, than in the 55Å QW of sample 2 (dotted line in Fig. 1a) which is the less doped one.

Time-resolved PL measurements after circularly polarized excitation give access to the spin relaxation time τ_S and the PL decay time τ_R [2]. Due to the existence of numerous non

radiative channels the PL quantum yield is rather low in samples 1 and 2; we then had to use rather high excitation powers in order to achieve time-resolved measurements. In fact we were able to investigate the excitation power dependence of τ_S only in the purest quantum well (55Å QW of sample 2) where excitation powers of the order of 10 mW, corresponding for our experimental set up to $n_e=10^{10} \text{ cm}^{-2}$, could be sent to the sample. For the other QWs we had to use excitation powers of 40mW.

All the QWs were excited at their E_1-H_1 excitonic transition and the detection was set at the peak of the $e-A^\circ$ line. After a right circularly polarized excitation, the time dependences of the PL signals $I^+(t)$ and $I^-(t)$ are recorded by rotating the quarterwave plate located before the detection system (analyser, spectrometer and streak camera). The time dependence of the polarization, $P(t)$, is then calculated [3].

Fig.2: Temperature dependence of the electronic spin relaxation time:

(a) for the 180Å quantum wells of sample 1 (empty squares) and 2 (circles).

(b) for the 55Å quantum well of sample 1; the photogenerated electron density is $n_e=4.10^{10} \text{ cm}^{-2}$. The continuous line corresponds to calculations with $n_e=2.10^{10} \text{ cm}^{-2}$ and $N_{\text{imp}}=7.10^{11} \text{ cm}^{-2}$.

(c) for the 55Å quantum well of sample 2 for two values of n_e , 10^{10} cm^{-2} (rhomb) and $4.10^{10} \text{ cm}^{-2}$ (circle). Continuous lines are calculated assuming $N_{\text{imp}} = 3.10^{11} \text{ cm}^{-2}$ and $n_e=0.5 \cdot 10^{10} \text{ cm}^{-2}$ (upper curve) and $n_e=2.5 \cdot 10^{10} \text{ cm}^{-2}$ (lower curve).

The lifetimes of the four e-A° lines are of the order of 1ns at 4K and decrease with temperature. Typical values of the order of 300ps are reached at 30K. On the contrary, as shown in Fig. 2, the temperature dependence of the electron spin relaxation time differs significantly for the two well widths we have considered. In sample 1 and 2, for the thinner well, τ_S decreases with temperature (Fig. 2b and 2c). At 4K typical values of 2-3 ns are measured, which decrease down to 200-300 ps for a temperature of 30K. But for the 180Å QWs no clear dependence of τ_S with temperature is observed (Fig. 2a). τ_S remains of the order of 2-3 ns in the temperature range investigated.

In Fig. 2c we have plotted the electron spin relaxation times measured for the 55Å QW of sample 2 for two excitation powers (10 and 40mW). At all temperatures τ_S is shorter for a higher photocreated electron density (at 10K, 1.6 and 4ns for $n_e = 4 \cdot 10^{10}$ and 10^{10} cm^{-2} , respectively).

Let us finally point out that for the same excitation power (40mW) and for the 55Å QWs, the shortest of the two measured spin relaxation times belongs to the sample with lower doping level. The same trend, although less pronounced, is observed for the larger QWs (Fig.2a).

3. THEORETICAL CONSIDERATIONS

We consider in the following the temperature dependence of the polarization decay time of the e-A° line. Free electrons and free holes are photocreated at $t=0$ and (almost) instantaneously thermalize with a given polarization. Electrons recombine preferably with bound holes (for weak laser intensities and/or for large times), and simultaneously loose their polarization via a D'Yakonov and Perel' like mechanism [4]. We suppose that the bound holes are completely non polarized (note that the repetition rate of the excitation laser is $\approx 10\text{ns}$), and thus that the observed polarization decay should be assigned to the electron gas. The spin-flip probability for the electron gas is then given by [5, 6] :

$$1/\tau_{sf}(N_s, T) = \int d\epsilon \left[-\partial F(\epsilon, N_s, T)/\partial \epsilon \right] \tau^*(\epsilon, N_s, T) [\Omega(\epsilon)]^2 / \int d\epsilon \left[-\partial F(\epsilon, N_s, T)/\partial \epsilon \right] \quad (10)$$

where ϵ is the in-plane electron kinetic energy ; T the temperature ; N_s the areal density of the gas ; F the electron distribution (Fermi-Dirac) ; τ^* the velocity relaxation time and $(\hbar/2)\Omega \cdot \sigma$ the (anisotropic, linear upon the in-plane wavevector) spin-splitting hamiltonian for the conduction band of a thin quantum well established by D'Yakonov and Kachorovskii [5]. We suppose that the electron velocity relaxation is due to elastic scatterings by the (screened) ionised impurities sitting near one of the quantum well interfaces. We use a RPA-like screening for the degenerate electrons [7] and neglect the screening effects of holes. In the following we discuss the variation of τ_{sf} with the temperature, ionised impurities areal concentration N_{imp} , well width and electron gas density N_s . (i) We note that for a non-degenerate gas τ_{sf} varies like T^{-1} if τ^* is T -independent. For a degenerate gas, however, the T -dependence of τ_{sf} is more complicated. For instance, at very low temperatures ($\epsilon_F \gg K_B T$, where ϵ_F is the Fermi energy) we can expand the integrals in eq.(10) to obtain $1/\tau_{sf} \approx C \{ \epsilon_F \tau^*(\epsilon_F) + (\pi^2/6)(K_B T)^2 \partial^2 [\epsilon_F \tau^*(\epsilon_F)] / \partial \epsilon_F^2 \}$, where C is a material constant for a fixed well width and barrier height. Thus τ_{sf} does not diverge as $T \rightarrow 0$. Moreover, we find numerically that the second derivative changes sign and becomes negative as T decreases to 0, so that τ_{sf} initially increases with decreasing temperature, reaches a maximum value at a critical temperature T_c [with $K_B T_c \approx \epsilon_F \propto N_s$] and decreases to a finite value at $T=0$. We can track this behaviour (presence of a maximum for τ_{sf}) back to the accident at $q=2K_F$ of the Lindhardt screening. Although it will be hardly observable at low electron densities ($T_c < 4K$ if $N_s < 10^{10} \text{ cm}^{-2}$), nevertheless it must attenuate the $1/T$ increase of τ_{sf} with decreasing temperature at low temperatures. (ii) As a general rule, the D'Yakonov and Perel' mechanism predicts that the spin-flip depolarization time for the electron gas should increase with decreasing velocity relaxation time. For the ionised impurity scatterings we consider in this work, τ^* has been evaluated within the first Born approximation, for which $\tau^* \propto N_{imp}^{-1}$. Consequently, $\tau_{sf} \propto N_{imp}$ follows from eq.(10). N_{imp} must be a fraction of N_{acc} . We suppose that this fraction is essentially the same for the two wells of same width at a given temperature. Thus, even if the acceptor doping is not known, a rough relative (from sample to sample) evaluation can be extracted from the experiments, and can provide a strong test for the D'Yakonov and Perel' mechanism. (iii) A well width dependence comes from both τ^* and $|\Omega|$. The last one dominates and gives for the spin-flip probability $1/\tau_{sf} \propto E_1^2$ (see ref. [5]), where E_1 is the energy of the first electron bound level ($E_1 \approx 66 \text{ meV}$ and $\approx 12 \text{ meV}$ for the 55Å and 180Å wells respectively). Thus, τ_{sf} should increase with increasing well thickness (roughly like $1/L^4$ for wide wells or an infinite barrier

height). (iv) Finally, we consider the N_S dependence of τ_{sf} . In a simple view, decreasing N_S : weakens the static screening and rises the scattering probability ; decreases ϵ_F and then also $|\Omega(\epsilon_F)|$. Thus τ_{sf} should increase with decreasing N_S .

Finally, we remark that increasing the temperature enhances the scatterings by acoustical phonons. Thus, for high temperature (roughly greater than 20K) the steep (roughly $1/T$ -like) decrease of τ_{sf} due to the ionised impurities should be smoothed by considering these inelastic processes.

4. CONCLUSION

In bulk semiconductors the D'Yakonov-Perel' mechanism is only valid at high temperatures [8] when enough thermally activated carriers can feel the non parabolicity of the conduction band. For a thin quantum well, due to the quantum confinement, this limit should be reached more easily. In the 4-40K temperature range that we have investigated, as shown in Fig. 2a we are still in the bulk limit for a 180Å well, where no clear dependence of τ_s with temperature is observed. But the main point is that for a 55Å well the D'Yakonov-Perel' mechanism dominates for temperatures as low as 7K. Moreover, for this well size the calculated laser intensity (or N_S) dependence of the electronic spin relaxation time is in very good quantitative agreement with the experimental datas (Fig. 2c). The influence of the doping level can only be analysed qualitatively due to a lack of precise measurement of this latter parameter. From the cw PL spectra we estimate a variation of an order of magnitude of the doping level for the 55Å QWs of sample 1 and 2. In the calculations only a factor 2 was introduced. The expected dependence from the D'Yakonov-Perel mechanism (an increase of τ_s with the doping level) is observed but with a mediocre quantitative agreement. This can be due to our estimate of the doping level which assumes (in particular) that all the characteristic times involved in the photoluminescence process are the same in the two samples, which most likely is not the case.

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