Theory of the Spin Relaxation of Photoexcited Carriers in Doped GaAs Quantum Wells

Marcelo Z. Maialle

Instituto de Física de São Carlos, Universidade de São Paulo

13560-970, São Carlos, SP, Brazil Departamento de Física Aplicada, Universidade São Francisco

13250-000, Itatiba, SP, Brazil

Received July 27, 1995

We calculated the effects of the electron-hole scattering via the exchange interaction on the spin relaxation times of photo-excited carriers in doped quantum wells. Even though we found this relaxation channel to be weaker than in bulk, it is still comparable with the spin-mixing channels due to the spin-orbit interaction. Therefore, they must be considered in equal footing to provide a complete picture of the spin relaxation in doped samples.

I. Introduction

Recent advances in time-resolved luminescence techniques have greatly stimulated the study of the exciton formation dynamics in a way which was not before accomplished by experiments in the continuous *cw* excitation regime. It has been now possible to investigate, on the time scale of picoseconds, different relaxation mechanisms among of which those causing relaxation of the spins of the photo-excited carriers. In this work, we studied doped quantum wells (QW), where the spin relaxation we considered is due to the electron-hole (e-h) scattering via the exchange interaction, also known as the Bir-Aronov-Pikus (BAP) mechanism[1].

The study of spin dynamics in semiconductors is of great interest because when an incident photon is absorbed in these materials to excite an e-h pair, the angular momentum conservation law dictates that only a pair with the same total spin as the photon angular momentum can be created. It is then possible to excite carriers with definite spins which, after relaxation and upon recombination, produce the polarized luminescence containing valuable information about the spinflip processes. For the IIIV compounds, such as GaAs, the spins of the electron in the conduction band at $\mathbf{k}$=0 are $\sigma_e = \pm 1/2$. For the valence band at $\mathbf{k}$=0, we have two degenerate bands, one with the hole total angular momenta $m_p = \pm 3/2$ (heavy holes) and the other with $m_p = \pm 1/2$ (light holes), assuming the quantization direction along the z axis. Therefore, a photon propagating along this direction with circular polarization must excite an e-h pair satisfying $\sigma_e + m_p = \pm 1$. In 2-D structures, due to subband formation, heavy and light holes at $\mathbf{k}$ =0 are no longer degenerate.

In this work, we consider doped QWs and for sake of clarity we shall treat only p-doped samples, such that a Fermi sea of holes exists due to the doping. Everything we shall say can be easily translated to the n-doped case, which has an electron degenerated population instead. Due to the exclusion principle, an incident pulse of polarized light excites e-h pairs in these p-doped samples only if it has energy high enough to create holes above their Fermi level. Therefore, an optical vertical transition produces electrons and holes with momenta greater than the Fermi momentum of the holes, p_F. The photo-excited carriers then relax their momenta and kinetic energies, such that electrons arriving at the conduction band edge recombine with any of the heavy-holes already existing on the top of the valence band to produce the luminescence signal. It is then clear that only the electron spin is important to determine the polarization of the luminescence, because the majority hole population can be considered completely spin depolarized if the optical excitation is low to prevent high concentration of excited holes in comparison with the doping-induced population. For bulk, Fishman and Lampel[2] have shown that the BAP process was the most effective mechanism in relaxing the electron spin in a doped sample. In what follows, we extend their work to consider the BAP process for 2-D semiconductor structures.

II. The BAP process

The exchange interaction between an electron and a hole can be separated into the short-range and the long-range exchange parts. We have shown[3] that the short-range contribution is not very effective in 2-D systems because it only mixes heavy- and light-hole spins, which are well separated in energy by the subband structure due to the confinement. The long-range contribution, on the other hand, gives rise to the longitudinal-transverse splitting of the exciton's kinetic-energy relation dispersion. Together with the scattering of the exciton's center-of-mass momentum, this produces a spin relaxation process of the type *motional narrowing*. In doped samples, the excitonic states are unlikely to happen due to the strong screening by the majority carrier population. However, a free electron can be scattered by the hole population via this long-range exchange, causing its spinflip. To calculate the electron spinflip rate we consider the process in which an electron with a momentum $\mathbf{k}$ and spin 1/2 ($\uparrow$) is scattered to a state with spin -1/2 ($\downarrow$). Using the Born approximation, we have:

$$\frac{\hbar}{2\pi 2\tau_s(\mathbf{k})} = \sum_{\mathbf{p},\mathbf{p}',\mathbf{k}'} \sum_{m,m'} f_{p,m}(1-f_{p',m'}) \left| \left\langle \psi^{\downarrow}_{\mathbf{k}'} \phi^{m'}_{\mathbf{p}'} | V_{\rm exch} | \psi^{\uparrow}_{\mathbf{k}} \psi^{m}_{\mathbf{p}} \right\rangle \right|^2 \delta(E^e_{\mathbf{k}} + E^h_{\mathbf{p}} - E^e_{\mathbf{k}'} - E^h_{\mathbf{p}'}), \qquad (1)$$

where $E^h_{\mathbf{p}}(E^e_{\mathbf{k}'})$ is the energy of a hole (electron) with momentum $\mathbf{p}(k)$, and m and m' are the possible hole spins, $\pm 3/2$ and $\pm 1/2$. The hole distribution function is written as $f_{p,m}$, where care is taken for the hole not to be scattered into an occupied state. The exchange matrix elements that enter in this expression are given, for the bulk case, from the matrix:

$$\langle V_{\rm exch} \rangle_{(\sigma,m),(\sigma',)} = \delta_{\mathbf{K},\mathbf{K}''} \frac{3}{8} \frac{\Delta E_{LT}}{V|\phi_{3D}(0)|^2} [\mathbf{M}(\hat{\mathbf{K}})]_{(\sigma,m),(\sigma',m')} \ , \qquad (2)$$

where $\mathbf{K}=\mathbf{k}+\mathbf{p}$ is the e-h pair's center-of-mass momentum, ΔE_{LT} is the observed 3-D L-T splitting, $|\phi_{3D}(0)|^2 = (\pi a_0^3)^{-1}$, with a_0 as the Bohr radius, and $\mathbf{M}$ is an 8×8 matrix with the spin indices of the electron, σ, and hole, m, which depends only on the direction of $\mathbf{K}$ (see Ref.[3] for the explicit matrix form). In using this expression in Eq. (1), we must sum only over the terms that cause electron spinflip, which involve heavy- and light-hole states. For 2-D systems, this is simplified because in first order only the heavy-hole states participate. The exchange term in Eq. (1) is then, for the 2-D case (see also Ref. 3),

$$\langle V_{\rm exch} \rangle_{\uparrow,\downarrow} = \delta_{\mathbf{K},\mathbf{K}'} \frac{3}{16} \frac{\Delta E_{LT}}{S|\phi_{3D}(0)|^2} F(K)\ K \ , \qquad (3)$$

where $F(K)$ is a dimensionless form factor[3] due to the well confinement and S is the sample area. Note that in 3-D the exchange is finite as $\mathbf{K}$ vanishes, while in 2-D it goes linearly to zero.

We have calculated the relaxation rate Eq. (1) for the 2-D and 3-D cases. The integrals over the momentum spaces were in part calculated analytically, yielding for the 2-D case:

$$\frac{\hbar}{2\pi 2\tau_s(k)} = \frac{(N_{hh}a_0^2)^2}{4} \left(\frac{\hbar^2}{2\mu a_0^2}\right)^{-1} \left|\frac{3}{16}\Delta E_{LT}\right|^2 I_{k,p_F}, \qquad (4)$$

where N_{hh} is the heavy-hole 2-D density and μ the e-h reduced mass. We have arranged the integrals which were not evaluated into

$$I_{k,p_F} = \int_0^{2\pi} d\alpha' \int_0^{2\pi} d\alpha \int_0^1 dp\ p|F(K_{p_F})|^2 K^2 \Theta \left[2\mu \left(\frac{k\cos\alpha}{m_e} - \frac{p\cos\theta}{m_h} \right) + p\cos\theta - \sqrt{1-(p\sin\theta)^2} \right], \qquad (5)$$

where in this expression $p(k)$ is the hole (electron) momentum normalized by the hole Fermi momentum, $p_F = \sqrt{2\pi N_{hh}}$, which is also true for $K = |\mathbf{k}+\mathbf{p}|$. The step function is written as Θ, and $\theta = \alpha' - \alpha$.

To simplify the 3-D result[1], we have used the fact that in bulk $m_e \approx m_{lh} \ll m_{hh}$, such that we only considered holes being scattered from the heavy-hole band and to heavy- and light-hole bands. This simplifies Eq. (1) for the bulk as:

$$\frac{\hbar}{2\pi 2\tau_s(k)} = \frac{3}{16\pi} k a_0 (N_{hh} a_0^3) \left(\frac{\hbar^2}{2m_e a_0^2}\right)^{-1} \left|\frac{3}{8}\Delta E_{LT}\right|^2 I_k^{3D} \ , \tag{6}$$

where now N_{hh} is the volumetric density, and the remaining integrals are written as

$$I_k^{3D} = \sum_{j=l,h} \int_0^{2\pi} d\alpha \int_{-1}^{1} dy \int_0^1 dx \int_0^1 dz x z^2 \Theta(f_j) M_j \ , \tag{7}$$

with

$$M_h = \sin^4\phi, \quad M_l = \frac{1}{3}[\sin^4\phi + \sin^2(2\phi)] \ , \tag{8}$$

$$f_j = (2kx)^2 + z^2 + 4kxz\cos\beta - \delta_{h,j} \ , \tag{9}$$

$$\tan\phi = \frac{\sqrt{1-y^2}}{k/z+y} \ , \tag{10}$$

and

$$\cos\beta = xy + \sqrt{(1-x^2)(1-y^2)}\cos\alpha \ . \tag{11}$$

III. Results and discussion

In order to obtain the bulk and the confined electron spinflip rates, $1/\tau_s$, we have calculated the integrals in Eqs. (5) and (7) numerically using the Monte Carlo's method. We have used the following parameters for GaAs: $a_0 = 146.1$Å, $m_e = 0.067$, m_{hh}=0.62 (3D), 0.112 (2D), $m_{lh} = 0.087$ (3D), $\Delta E_{LT} = 0.08$ meV. The distribution functions $f_{p,m}$ were taken at zero temperature, and for the 2-D case we considered only infinity-barrier QWs. In Fig. 1, it is shown in full lines the result for the electron spin-relaxation times as a function of the electron momentum normalized by the hole Fermi momentum. We considered an 100 Å -wide QW with a heavy-hole density $N_{hh} = 10^{12}$ cm^{-2} ($E_F = 21.4$ meV), which simulates a bulk density of $N_h = 10^{18}$ cm^{-3} ($E_F = 5.7$ meV) used for the 3-D case. We notice from this figure that right after excitation ($k/p_F \approx 1$), bulk and confined electrons have the same order of magnitude for their spin-relaxation times, about 100 ps, but as k decreases the increase in the relaxation time for the confined electrons is much stronger. The bulk τ_s behaves like $1/k$ for small k [cf. Eq. (6), and Ref. [2]], and it tends to saturate for $k > p_F$ because, for large k, the exclusion principle no longer plays an important role. The slight increase observed for τ_s^{3D} in this region is due to the fact that, for large k, the e-h pair's c.m. momentum $\mathbf{K}$ approaches k, causing the exchange matrix elements for heavy-hole spins to vanishes [cf. Eq. (8), ϕ is the angle between $\mathbf{K}$ and $\mathbf{k}$]. The only non-vanishing matrix elements left are for light-hole states, which have an occupation number much smaller than the heavy-hole states. The decrease observed for τ_s^{2D} as function of k is mostly due to the increase in the phase space available for scattering, which also saturates for $k > p_F$. For larger k, the 2-D results shown here should be interpreted with caution, because inter-subband scattering and valence-band spin mixing become important factors, both not considered in our calculation.

The carriers' wave functions we have used to calculate the exchange matrix elements were plane waves, but including the e-h Coulomb attraction we expect a greater probability of finding the electron and the hole at same position, therefore increasing the exchange strength. Neglecting screening, we can make use of the Sommerfeld factors [i.e., $|\psi_k(0)|^2$, see Ref. [4]] to obtain an upper bound for this enhancement. This is shown in Fig. 1 (lines with the S index), where we used a *pure* 2-D Sommerfeld factor [4] to simulate that of our *quasi-*

2-D system. We note that the bulk electron relaxation time is the one mostly affected. Of course, screening will weaken considerably this effect.

For a n-doped QW, it is shown in Fig. 1 (dotted line) the result for the hole spin-relaxation time without the Sommerfeld enhancement and with the same carrier concentration as before (therefore, the same E_F). The behavior observed is similar to the electron τ_s, but shifted for larger k, which in this case represents the hole momentum.

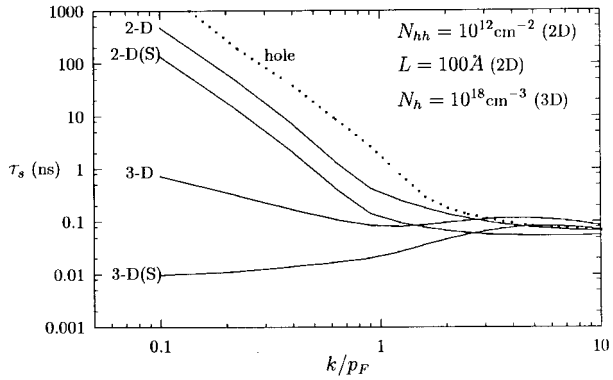

Figure 1. Spin-relaxation times for bulk and confined electrons, solid lines. The lines with the S index are for the relaxation times when the Sommerfeld enhancement is included. The dotted line is the hole spin-relaxation time in a n-doped QW. See text for details.

In conclusion, we have calculated the spin-relaxation times for carriers excited in doped QW samples which have their spins relaxed via the BAP process. We have shown that in bulk this relaxation channel is stronger than in confined systems, despite the fact that the exchange strength to be enhanced by the 2-D confinement. For momentum closer to the band edge, the relaxation rates we found are very weak compared with the recombination rate of the excited carriers, therefore they must not play any major role in relaxing the spin of thermalized carriers. On the other hand, right after excitation, when the carriers momenta are close to p_F, τ_s was found to be of the same order of magnitude as those obtained from other spin-relaxing mechanisms, e.g., the valence-band spin mixing[5] and the D'yakonov-Perel' process[6] (which also have similar limitations with weaker relaxation rates for carriers close to the band edge). These other spin-relaxation rates, as well as the one calculated here, are still weak when compared with the experimental results for τ_s for electrons and holes excited in doped QWs, which are mostly in the range of few hundreds of picoseconds[7,8]. This shows that, despite the recent efforts, further experimental and theoretical studies are still needed to understand the processes causing spin relaxation in doped semiconductor structures.

Acknowledgments

The author would like to thank Prof. L.J. Sham for introducing him to this problem, Prof. O. Hipólito for the hospitality of his group, and CNPq-Brazil for financial support.

References

1. G.L. Bir, A.G. Aronov and G.E. Pikus, Sov. Phys. -JETP **42**, 705 (1976) [Zh. Eksp. Teor. Fiz. **69**, 1382 (1975)].
2. G. Fishman and G. Lampel, Phys. Rev. B**16**, 820 (1977).
3. M.Z. Maialle, E. A. de Andrada e Silva, L.J. Sham, Phys. Rev. B**47**, 15776 (1993).
4. M. Shinada and S. Sugano, J. Phys. Soc. Japan **21**, 1936 (1966).
5. T. Uenoyama and L.J. Sham, Phys. Rev. B **42**, 11 (1990). Ph. Roussignol, R. Ferreira, C. Delalande, G. Bastard, A. Vinattieri, J. Martnez-Pastor, L. Carraresi, M. Colocci, J.F. Palmier, B. Etienne, Surf. Sci. **305**, 263 (1994).
6. M.I. D'yakonov and V. Yu. Kachorovskii, Sov. Phys. Semicond. **20**, 110 (1986) [Fiz. Tekh. Poluprovodn. **20**, 178 (1986).].
7. T.C. Damen, L. Vina, J.E. Cunningham, J. Shah, L.J. Sham, Phys. Rev. Lett., **67**, 3432 (1991).
8. B. Baylac, T. Amand, X. Marie, B. Dareys, M. Brousseau, G. Bacquet, V. Thierry-Mieg, Solid State Comm. **93**, 57 (1994).