k-Dependence of the Electron Spin-Flip Time in GaAs

A. Amo, L. Viña, P. Lugli, A. I. Toropov and K. S. Zhuravlev

1 SEMICUAM Dpto. de Física de Materiales, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
2 Lehrstuhl für Nanoelektronik, TU München, Arcistrasse 21, D-80333 München, Germany
3 Institute of Semiconductor Physics, Pr. Lavrentieva, 13, 630090 Novosibirsk, Russia

Abstract. The k-dependence of the electron spin flip time \( T^\perp \) in undoped GaAs is experimentally determined for the first time. Time-resolved optical orientation under strong optical injection is used to directly obtain \( T^\perp \), which monotonically decreases by more than one order of magnitude when the electron k-vector varies from 0 to 2.5 \( \times 10^6 \) cm\(^{-1}\). Our results are well reproduced by a Monte-Carlo simulation of the electron-hole scattering and demonstrate that, at low lattice temperatures, the main spin flip mechanism of conduction band electrons is the Bir-Aronov-Pikus, i.e. a spin relaxation mechanism based in the exchange of spins between electrons and depolarized holes. We also show with the simulations that many body effects, such as phase space filling, result in an increase of \( T^\perp \) with excitation density.

Keywords: Electron spin flip, Pauli blockade, time-resolved polarization.

PACS: 72.25.Rb, 72.25.Fe, 71.35.Ee, 78.47.+p

The electron spin-relaxation processes in direct gap semiconductors have attracted the attention of the solid-state physics community for the past three decades. Optical orientation has proven to be an extremely powerful tool for the manipulation and study of the electron-spin degree of freedom in direct gap semiconductors: in particular, the spin relaxation mechanisms have been thoroughly studied in III-V materials, such as GaAs, both bulk\(^1\) and low-dimensional. Surprisingly, despite the enormous body of experimental and theoretical results in this field, some fundamental aspects of the physics of electron spin relaxation in semiconductors have been neglected. One of these issues is the electron-momentum (k) dependence of the spin-flip processes, which is of great importance both from a fundamental point of view and in the design of applications that rely on the transport and injection of electrons with a preserved spin state. Another fundamental issue that has not been explored until very recently, is the physics of spin-dependent electron many-body processes\(^2,3\) and phase-space filling effects.\(^4\) In this communication we will present experimental results that shed some light on the two aforementioned issues.

We used a time- and energy- resolved photoluminescence (PL) setup (spectrograph + streak camera) in order to investigate the circularly polarized emission (\( \sigma^- \) and \( \sigma^+ \)) of a nominally undoped 2.5 \( \mu \)m thick GaAs epilayer of highest purity, after a non-resonant \( \sigma^- \) pulsed excitation (1.5 ps duration). At low excitation densities, the PL intensity is circularly polarized. When the excitation density is increased, the PL light becomes linearly polarized. To study this transition, we used a photoionization scheme (\( \sigma^- \) excitation, \( \sigma^+ \) detection) and a time-resolved PL setup to measure the decay of the PL intensity at a fixed emission energy. The results are shown in Fig. 1.

FIGURE 1. (a) PL spectra (left scale) and \( \varphi \) (right scale) for a delay of 150 ps and excitation density \( n_0 \) of 3.9 \( \times 10^{17} \) cm\(^{-3}\). (b) Upper panel: time evolution of the \( \sigma^- \) and \( \sigma^+ \) PL intensity for the excitation conditions of (a) at an emission energy of 1.514 eV \( (E_{\text{ex}} = 5 \text{ meV}) \); the lower panel shows the corresponding \( \varphi \) (dashed line is a fit to an exponential decay function).
temperatures and low excitation densities the PL is dominated by excitonic features. However, at high excitation densities (>1.2×10^17 cm^{-3}) the screening of the carriers leads to the formation of an electron-hole plasma [see Fig. 1(a)], characterized by quasi-degenerate Fermi-Dirac distributions of spin-up and spin-down electrons, as well as holes (holes are unpolarized after the first 100 fs). The imbalance between the electron spin-up and spin-down populations is evidenced through the spectral dependence of the degree of circular polarization [φ; Fig. 1(a)]. The spin-flip dynamics of the electrons with a given electron kinetic energy in the conduction band (E_{k_e}) can be accessed by monitoring the time evolution of φ at a given emission energy [Fig. 1(b)]. The electron spin-flip time (τ_{sf}) for each E_{k_e}, which is twice the decay time of φ(E_{k_e}), can be measured in this way.

Under our conditions of strong optical pumping in an undoped system (i.e., equal number of injected electrons and holes) the dominant electron spin relaxation mechanism is expected to be the so called Bir-Aronov-Pikus (BAP), which relies on the exchange interaction between the electrons and a population of depolarized holes.\(^5\)

Figure 2 shows τ_{sf} for different E_{k_e}, and three different initial photo injected carrier densities (n_0). τ_{sf} increases with increasing n_0 and decreases with increasing E_{k_e}. In order to investigate the effect of the degeneracy of the electron and hole populations on τ_{sf}(E_{k_e}) we introduce a phenomenological, BAP-based model of the spin-flip time given by:

\[ \tau_{sf}^s(E_{k_e}) = \tau_{sa} (E_{k_e}) \times P_{\text{spin-flip}}(E_{k_e}), \]

where \( \tau_{sa} (E_{k_e}) \) is the electron-hole scattering time, and \( P_{\text{spin-flip}}(E_{k_e}) = \left( \frac{P_{\text{a}}}{P_{\text{e}}} E_{k_e} \right)^a \) is the probability for an electron to flip its spin when it scatters with a hole. We have calculated τ_{sf} (E_{k_e}) for our experimental conditions by means of a Monte-Carlo simulation (see inset of Fig. 2). The solid lines in Fig. 2 show the result of a fitting of the experimental τ_{sf} points to the phenomenological expression of \( \tau_{sf}^s(E_{k_e}) \) with the simulated τ_{sa} (E_{k_e}). The fit was performed simultaneously for the three considered excitation densities in order to obtain universal values of the fitting parameters, \( P_a \) and \( \alpha \), which yield \( P_a = 3.38 \times 10^{-2} \) meV\(^a\) and \( \alpha = 0.65 \).

The model very well explains the freezing of the electron spin-flip as the excitation density is increased: the higher the population, the lower the electron-hole scattering rate (and also spin-flip rate) due to the occupation of final states after the scattering events (inset of Fig. 2).\(^6\) Thus, phase-space filling plays a major role in the spin-flip mechanisms of electrons under strong excitation, and should be taken into account in the design of spintronic devices.

**REFERENCES**