Propagation length of spin waves in a conducting system

J. Gómez¹, F. Perez¹, B. Jusserand¹, G. Karczewski² and T. Wojtowicz²

¹ Institut des Nanosciences de Paris, CNRS/Université Paris VI Campus Boucicaut, UMR 7588, 140 rue de Lourmel, 75015 Paris, France.
² Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, 02-668 Poland.
gomezj@cab.cnea.gov.ar

Abstract. We have studied propagating spin-flip waves excited in a two dimensional electron gas by angle resolved magneto-Raman spectroscopy. The damping rate of these excitations follows a quadratic law, as a function of \( q \), and the group velocity is linearly dependent with \( q \).
Consequently the propagation length presents a maximum for a given \( q \). We have estimated and analyzed the maximum propagation length showing that the spin waves are drastically attenuated in a microscopic distance, even in the intrinsic regime.

1. Introduction

Increasing interest is focused on propagating spin waves because of their potential ability to transport or modify logical information without involving charge current dissipation [1]. Obtaining the maximum coherence length of these waves is a challenge regarding this purpose.

Recent publications have highlighted the importance of the kinetic motion in the relaxation processes of the spin-flip waves (SFW) in a conducting system (see Ref. [2]). This damping mechanism is a consequence to the fact that the spin-flip single particle excitations are coupled to the SFW throughout the kinetic part of the Hamiltonian [2,3] and degrade the collective character of the spin waves.

In this work we have studied, by angle resolved electronic resonant Raman scattering (ERRS), SFW in a high mobility two-dimensional electron gas (2DEG) embedded in Cd\(_{1-x}\)Mn\(_x\)Te/Cd\(_{0.8}\)Mg\(_{0.2}\)Te quantum wells. Such systems have been recently introduced as a test-bed system for spin excitations of the spin-polarized 2DEG (SP2DEG). Indeed, the \( s-d \) exchange coupling of conduction electron with localized electrons of the Mn atoms provide a giant Zeeman energy to the 2DEG [4]

\[
Z(B,T) = x \times N_0 \alpha_e \times \langle S_z(B,T) \rangle - |g_e| \mu_B B
\]

where \( N_0 \) is the cation sites density, \( \alpha_e \) is the exchange coupling between the conduction electron of the well and the localized electrons on Mn impurities \( N_0 \alpha_e = -0.22 \text{ eV} \). \( \langle S_z(B,T) \rangle \) is the thermal average spin of a single Mn atom given by the modified Brillouin function, \( x \) is the effective Mn concentration, \( g_e \) is the normal electron \( g \) factor, and \( \mu_B \) is the Bohr magneton. In order to keep low alloy disorder and high electron mobility (\( \mu \sim 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)), \( x \) remained below 1.2% and the electron sheet density \( n_{2D} \) ranged in between 1.5 and 4\( \times 10^{11} \text{ cm}^{-2} \). Depending on the Mn nominal concentration \( xN_0 \) and \( n_{2D} \), the maximum spin-polarization degree \( \zeta = (n_{\uparrow} - n_{\downarrow})/n_{2D} \) can reach 80% for a magnetic field...
below 4 T, such that, when \( B \) is applied parallel to the quantum well plane, the Landau orbital quantization is kept negligible. Therefore, such SP2DEG is a conducting paramagnet having the spin-polarization degree of a conducting ferromagnet. Moreover, semiconductor quantum wells exhibit well-defined optical resonances which allow ERRS measurements to be performed. ERRS is a powerful tool to access to the wave-vector resolution of the spin excitation spectrum [4].

Particularly, we have studied two samples, named sample A and B respectively, with similar electron density \( n_{2D} \approx 3.6 \times 10^{11} \text{ cm}^{-2} \) and different manganese concentrations, \( x = 1.13\% \) for sample A and \( x = 0.22\% \) for sample B. In Fig 1a we show a typical SFW Raman spectra obtained in sample A for various Raman transferred wavevector \( q \), the inset shows the geometrical setup with the external magnetic field applied in the plane of the quantum well. In practice, to increase the transferred wavevector we must increase the angle, \( \theta \), of the incident laser beam with respect to the normal direction of the quantum well, as depicted in the inset.

The inset of Fig. 1b shows the evolution of the SFW energy \( \hbar \omega_{SFW} \) peak and the line width (\( \eta \)) as a function of \( q \). Both present a quadratic behavior as explained in Ref. [3] and [5] and can be modeled by Eqs (2) and (3) respectively.

\[
\hbar \omega_{SFW} = Z - \beta q^2 = Z - \frac{1}{\left| \zeta \right|} \frac{Z}{Z' - Z} \frac{h^2}{2m^*} q^2
\]

\[
\eta = \eta_0 + \eta_2 q^2 = \eta_0 + \frac{4E_F}{h} \frac{h^2}{2m^*} \frac{3\tau}{\omega_0^2} \left[ \frac{\omega_0^*}{\omega_0} \left( \frac{\omega_0^*}{\omega_0} \right)^2 + 1 \right] \left( \frac{\omega_0^*}{\omega_0} \left( \frac{\omega_0^*}{\omega_0} \right)^2 + 1 \right) q^2
\]

Here \( E_F \) is the Fermi energy, \( Z = \hbar \omega_0 \) the bare Zeeman energy, \( Z' = \hbar \omega_0^* \) the Coulomb enhanced Zeeman energy, \( m^* \) the effective electron mass, \( \tau \) is the life time of the single particle excitation and \( \eta_0 \) is the line width at \( q = 0 \). Fig. 1b shows the experimental and modeled evolution of the curvature parameter, \( \eta_2 \), as a function of the Zeeman frequency for the studied samples. To model \( \eta_2 \) we have used \( \tau = 1.1\text{ps} \), as discussed in Ref. [3], this value is dominated by the disorder scattering time (\( \tau_{dis} \)), with respect to the intrinsic Coulomb scattering time (\( \tau_{e-e} \)) contribution, \( \tau^{-1} = \tau_{dis}^{-1} + \tau_{e-e}^{-1} \).
2. Propagation length of the collective SFW

To calculate the propagation length ($l_{\text{prop}}$) of the SFW we must use Eq. (4)

$$l_{\text{prop}} = v_g T_2$$  \hspace{1cm} (4)

where $v_g = d\omega/dq$ is the group velocity and $T_2$ is the life time of the spin wave with wavevector $q$. By using Eq. (2) and (3) we obtain the analytical expression for $l_{\text{prop}}$, see Eq. (5).

$$l_{\text{prop}} = 4\beta \frac{q}{\eta_0 + \eta_2 q^2}$$ \hspace{1cm} (5)

Parameters $\beta$ and $\eta_2$ in Eq. (5) are modeled by the theory described in Ref. [3] and [5] and estimated by our experimental results. For fully evaluate Eq. (5) we have used the experimental value of $\eta_0$ (line width at $q=0$) because at the moment there is not a complete theory to describe its behavior as a function of the parameters of the sample. A representative behavior of the $l_{\text{prop}}$ as a function of $q$ is showed in Fig. 2a.

Contrary to the intuition, the propagation length decreases for high enough value of $q$, this result is related to the fact that the attenuation processes become more and more important when increasing $q$. Such behavior, gives a particular maximum $l_{\text{max}}$ in the curve for a given $q = q_c$, that indicates the existence of a maximum propagation length for a given spin wave with an associated wave vector $q_c$.

By analyzing the extremal properties of Eq. (5) we obtain the expressions for $q_c$ and $l_{\text{max}}$, given by the Eqs. (6) and (7) respectively.

$$q_c = \sqrt{\frac{\eta_0}{\eta_2}}$$  \hspace{1cm} (6)

$$l_{\text{max}} = \frac{2\beta}{\sqrt{\eta_0 \eta_2}}$$ \hspace{1cm} (7)

Inset of Fig. 2a shows the evolution of $q_c$ as a function of the bare Zeeman energy. In Fig 2b we

Figure 2. a) Typical propagation length as a function of $q$. the relaxation processes become important for high value of $q$ limiting the propagation length of the SFW. The inset shows the evolution of the $q_c$ as a function of the Zeeman energy. b) Maximum attainable propagation length as a function of $Z$. In all cases continuous lines correspond to the model.
present the maximum attainable propagation length as a function of $Z$. Both, modelled and experimental values show an almost constant behaviour (at least in the accessible experimental range) and $l_{\text{max}}$ does not exceed 1.5 $\mu$m. Even, if the disorder scattering contribution is suppressed and we consider only the intrinsic Coulomb scattering time ($\tau_{\text{e-e}}$), the expected $l_{\text{max}}$ is about of 15 $\mu$m, such a result evidences the effectiveness of this relaxation processes which prevents having a macroscopic propagation length.

In summary, we have estimated the propagation length of spin waves which are drastically limited by the relaxation processes originated in the delocalized character of the spin carriers. This is true even if the disorder contribution is suppressed, that means the intrinsic contribution is strong enough to damp the SFW in a short distance. We came also to the conclusion that, to make the spin wave propagate further, it needs to loose the memory of the individual electrons, say, it needs to be fully collective. Such a feature has been predicted by quantum mechanics when electrons propagate in a one dimensional channel. In such a channel, the spin is separated from the charge, it should propagate alone as a full collective mode where the individual character of electrons is lost, and therefore, no damping by the kinetic motion is expected to appear.

References

[1] V. V. Kruglyak and R. J. Hicken, J. Magn. Magn. Mater. 306, 191 (2006).
[2] E. M. Hankiewicz, G. Vignale, and Y. Tserkovnyak, Phys. Rev. B 78, 020404(R) (2008).
[3] J. Gómez, F. Perez, E. M. Hankiewicz, B. Jusserand, G. Karczewski, and T. Wojtowicz, Phys. Rev. B 81, 100403(R) (2010).
[4] Cynthia Aku-Leh et. al. Phys. Rev. B 76, 155416 (2007).
[5] F. Perez, Phys. Rev. B 79, 045306 (2009).