Vol. **106** (2004) *ACTA PHYSICA POLONICA A* No. 3

Proceedings of the International Workshop "Optical Properties of 2D Systems", Warsaw 2004

Single Particle and Collective Spin Excitations in Semimagnetic Quantum Wells

F. Perez, B. Jusserand

CNRS/LPN, Route de Nozay, 91460 Marcoussis, France

D. Richards

Dept. of Physics, Kings College London, Strand, London WC2R 2LS, UK

and G. Karczewski

Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, 02-668 Warszawa, Poland

Collective and single-particle spin-flip excitations of a two-dimensional electron gas in a semimagnetic $Cd_{1-x}Mn_xTe$ quantum well are observed by resonant Raman scattering. Application of a magnetic field splits the spin-subbands and a spin-polarization is induced in the electron gas. Above some critical field, a collective spin-flip mode, which disperses with in-plane wave vector, dominates the spectra. The energy of this mode is given by the bare Zeeman energy at vanishing wave vector as predicted by Larmor's theorem and its in-plane dispersion is well described by a model of the interacting polarizability of a spin polarized electron gas when both exchange and correlation are taken into account.

PACS numbers: 72.25.Dc, 73.21.–b, 75.70.–i, 78.30.–j

1. Introduction

High-mobility electron gases confined in semiconductor heterojunctions reveal new physics associated with electron–electron interactions in two dimensions. Spin-polarized electron gas systems are of particular interest, both because of the new information they are expected to provide about the respective contributions of the exchange and correlation parts in the Coulomb interaction, and also because of their importance for spin-based electronics. Under an external magnetic field B, a spin polarized two-dimensional electron gas (2DEG) can be achieved in which strong modifications of the exchange interactions are expected. However, most experimental investigations on 2DEG systems have been reported in the GaAs/GaAlAs system in which the g-factor, which governs the magnitude of the Zeeman spin splitting, is very small. Therefore in this system spin effects are only accessible with large external fields, at which point strong orbital quantization dominates the energy spectrum. Indeed, in the Raman scattering measurements of the electronic excitations of spin polarized electron gases confined in GaAs/GaAlAs heterostructures [1], both magnetoplasmons and spin-flip transitions appear simultaneously.

Semimagnetic quantum wells based on $Cd_{1-x}Mn_xTe$ materials allow a completely new approach to this problem. A giant Zeeman splitting Z is induced in these materials by exchange interactions between the conduction electrons and those localized on Mn ions [2]. Under the application of moderate magnetic fields spin effects dominate over orbital quantization and the reverse situation to that of GaAs becomes accessible, with large filling factors and significant spin polarization. Moreover, exchange-correlation interactions are expected to be more significant in $Cd_{1-x}Mn_xTe$ because of the smaller Bohr radius in this compound (6 nm in CdTe instead of 10 nm in GaAs). Due to exchange correlations, the spin subband separation is renormalized in the presence of carriers and the effective splitting Z^* becomes larger than the bare value Z. The aim of this lecture is to present a theoretical model corresponding to this new situation and to demonstrate that it provides an excellent description of spin-flip excitations under external magnetic field, which become accessible to the Raman scattering measurements thanks to the recent availability of high quality semimagnetic modulation doped quantum wells. In particular, we will show that the main features predicted within this model — coexistence of single particle and collective excitations, in-plane dispersion of spin-flip excitations and Larmor's theorem — are successfully demonstrated in our experiments.

Even though the electron mobility in semimagnetic quantum wells remains below that in GaAs systems, modulation doped quantum wells with a reasonable quality have been achieved in the past few years [3] and we have reported recently [4] the observation by electronic Raman scattering of the single-particle excitations (SPE) and collective charge excitations (plasmons) of 2DEGs in $Cd_{1-x}Mn_xTe$ modulation doped quantum wells, as reported previously in GaAs quantum wells [5]. This novel result demonstrated that degenerate electron gases exist at low temperature in semimagnetic quantum wells, despite the relatively large disorder induced, in particular, by alloy fluctuations. Raman scattering is a well-established method for the investigation of the elementary excitations of electron gases in semiconductors and their dispersion with the in-plane wave vector q [5]. The Raman scattering line shape associated with electronic transitions within the lowest conduction subband can be described by the imaginary part of the 2D polarizability. Assuming non-interacting electrons, the variations of the non-interacting polarizability $P(\omega, q, s)$ with B can be simply understood on the basis of the Zeeman splitting in the conduction band of the $Cd_{1-x}Mn_xTe$ quantum well. The quantity s is the effective polarization rate of the electron population in the presence of the effective splitting Z^*.

2. Theoretical description

At vanishing magnetic field, the SPE line extends from 0 up to maximum energy $\hbar\omega$, which increases with increasing q ($\hbar\omega = \hbar v_{\rm F} q$ where $v_{\rm F}$ is the Fermi velocity of the 2D gas). Under magnetic field, the lowest conduction subband splits into two spin subbands. The single SPE spectrum observed at 0 T is thus expected to split at non-vanishing field into four new structures associated with spin conserving ($\uparrow\uparrow$ and $\downarrow\downarrow$) and spin flip ($\uparrow\downarrow$ and $\downarrow\uparrow$) transitions, which were degenerate at 0 T. Spin conserving transitions are expected to vary smoothly due to the increase in the Fermi velocity $v_{\rm F}^{\uparrow}$ of the majority spin subband, and decrease in $v_{\rm F}^{\downarrow}$ of the minority spin subband. On the contrary, spin flip transitions are expected to display large variations with the field. In particular, the SPE spectrum related to excitations from the majority to the minority spin subbands is a broad line centered at the effective Zeeman splitting Z^* and extending between

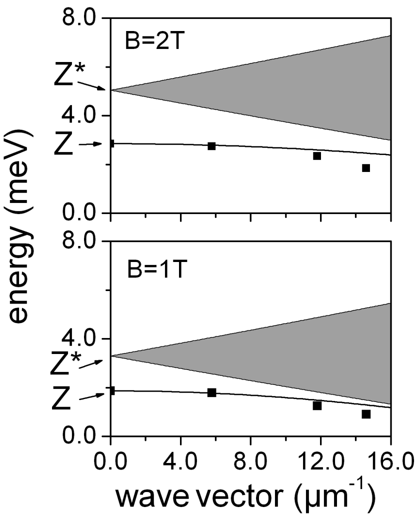

Fig. 1. In-plane dispersion of the SPE (hatched surfaces) and SF (thick line) excitations for two different values of the external field. For each field, experimental energies of the SF line (squares) are compared to the calculated energies in their wave vector range of existence.

$Z^* - \hbar v_F^\uparrow q$ and $Z^* + \hbar v_F^\uparrow q$; this energy range is shown in Fig. 1 for two different values of the Zeeman splitting.

This behavior is significantly modified when exchange-correlation interactions are taken into account. The interacting polarizability tensor $\Pi(\omega, q, s)$ under magnetic field can be deduced from extensions of the well-known random phase approximation, which applies to the collective charge excitation of spinless fermions. In the latter case, the polarizability tensor reduces to a scalar charge density polarizability $\Pi_{\text{ee}}(\omega, q, s)$ which reads

$$\Pi_{\text{ee}}(\omega, q, s = 0) = \frac{P(\omega, q, s = 0)}{1 - v(q)P(\omega, q, s = 0)},$$

where $v(q)$ is the Coulomb interaction.

For polarized electron gases, the polarizability tensor takes the following general form [6]:

$$\Pi(q, \omega, s) = \begin{pmatrix} \Pi_{\text{ee}}(q, \omega, s) & \Pi_{\text{em}} & 0 & 0 \\ \Pi_{\text{me}} & \Pi_{\text{mm}} & 0 & 0 \\ 0 & 0 & \Pi_+ & 0 \\ 0 & 0 & 0 & \Pi_- \end{pmatrix}$$

in which the spin flip components are decoupled and are written

$$\Pi_+ = \frac{P_{\uparrow\downarrow}}{1 - 2v(q)G^-_{\uparrow T}P_{\uparrow\downarrow}} \text{ and } \Pi_- = \frac{P_{\downarrow\uparrow}}{1 - 2v(q)G^-_{\downarrow T}P_{\downarrow\uparrow}} \tag{1}$$

while the charge density and spin density components become coupled together for non-vanishing polarization rate and are written

$$\Pi_{\text{ee}} = \left[P_{\uparrow\uparrow} + P_{\downarrow\downarrow} + 2v(q)(G^-_\uparrow + G^-_\downarrow)P_{\uparrow\uparrow} + P_{\downarrow\downarrow}\right]/D,$$

$$\Pi_{\text{mm}} = \left[P_{\uparrow\uparrow} + P_{\downarrow\downarrow} - 2v(q)(2 - G^+_\uparrow + G^+_\downarrow)P_{\uparrow\uparrow}P_{\downarrow\downarrow}\right]/D,$$

$$\Pi_{\text{em}} = -\left[P_{\uparrow\uparrow} - P_{\downarrow\downarrow} + 2v(q)P_{\uparrow\uparrow}P_{\downarrow\downarrow}(G^-_\downarrow - G^-_\uparrow)\right]/D,$$

$$\Pi_{\text{me}} = -\left[P_{\uparrow\uparrow} - P_{\downarrow\downarrow} + 2v(q)P_{\uparrow\uparrow}P_{\downarrow\downarrow}(G^+_\downarrow - G^+_\uparrow)\right]/D,$$

in which $G^+_\uparrow$, $G^-_\uparrow$, $G^+_\downarrow$, $G^-_\downarrow$, $G^-_{\uparrow T}$, and $G^-_{\downarrow T}$, are different exchange-correlation matrix elements, $P_{\uparrow\uparrow}$, $P_{\downarrow\downarrow}$, $P_{\uparrow\downarrow}$, and $P_{\downarrow\uparrow}$ the non-interacting polarizability for the four possible transitions.

We will focus our discussion in this paper on the spin-flip interacting polarizability Π_+ given in Eq. (1). Due to exchange correlations, a new pole appears in the polarizability when the denominator vanishes. This is the collective spin-flip (SF) excitation which, because the interaction potential is negative, is expected to lie below the single particle energies by an “excitonic correction”, as illustrated in Fig. 1. The SPE becomes strongly screened and the Raman spectra are dominated by the collective mode. Moreover, the spin-flip collective line displays downward energy dispersion when the in-plane wave vector is increased. At some finite value of q it enters the energy range for SPE and becomes strongly damped, at which point one then recovers a broad Raman response similar to the SPE line, but with a line shape modified by exchange-correlation interactions. According to Larmor's theorem, one should expect that the SF energy coincides with the bare Zeeman splitting Z at $q = 0$.

3. Experiment and discussion

We demonstrated recently [7] the validity of the above model based on the Raman spectra on a 10 nm thick $Cd_{1-x}Mn_xTe$ quantum well with a Mn concentration $x = 1.65\%$. The barriers were made of $Cd_{1-x}Mg_xTe$ with 15% of Mg and modulation doping is achieved by introducing iodine within the top barrier only. The spacer thickness was 40 nm and the electron density $n = 2.25 \times 10^{11}$ cm^{-2}. We report here new Raman results on a sample with less manganese and more carriers. Due to the smaller Mn concentration, full polarization of the electron gas cannot be achieved contrary to the first sample, but the lower alloy disorder allows us to obtain a much more detailed determination of the excitations. The Raman spectra were measured from a sample immersed in superfluid helium using a Ti-sapphire laser with a power density below 1 W/cm^2 to avoid heating the Mn^{2+} system. With a laser energy close to 1.65 eV, a strong resonance was achieved with the E_1H_2 absorption edge [5]. The sample was mounted in the bore of a superconducting solenoid providing a magnetic field in the plane of the quantum well up to 4.5 T. The resonance position does not move significantly over this magnetic field range. To measure the dispersion of the excitations, we have performed measurements at four different angles of incidence on the sample surface.

In Fig. 2, we show the Raman spectra obtained at different applied magnetic fields for a given finite $q = 11.8$ μm^{-1}. At zero field, the spectra display a single line close to the laser energy, assigned to the SPE. At very small field, the SPE line splits into two components, one increasing and decreasing in energy. When the energy of the lower line vanishes, a narrow peak emerges. For larger fields the narrow peak completely dominates the spectra. At other values of q, the same field variation is observed, the transition between the low field SPE and the large field SF taking place at different magnetic fields, increasing with q.

In Fig. 3, we show the field dependence of the measured SF energies at the four different wave vectors considered. In excellent agreement with Larmor's theorem, the variation at $q = 0$ is well reproduced with a Brillouin function assuming $x = 0.75\%$ and $T_{\text{eff}} = 2.7$ K. Based on this fit, we have calculated, using the spin-flip interacting polarizability, the effective Zeeman energy Z^* as well as the SF energies at different q as a function of B. We show the measured SF energies as a function of q in Fig. 1, for $B = 1$ and 2 T respectively, which we compare

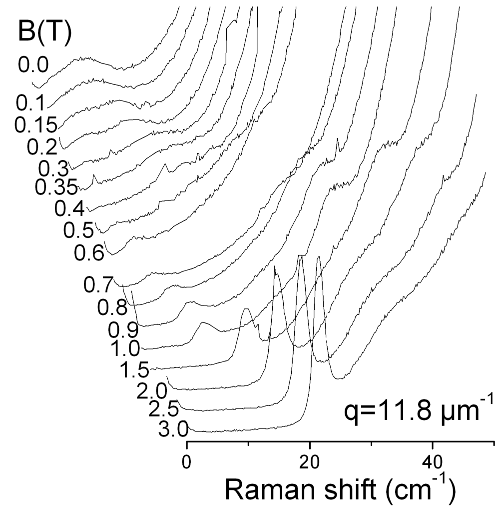

Fig. 2. Raman spectra as a function of the external magnetic field at $q = 11.8\ \mu\text{m}^{-1}$.

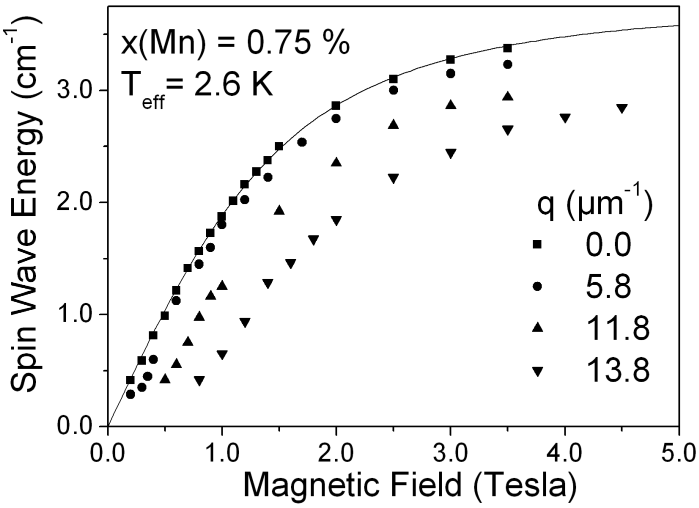

Fig. 3. Variation with the applied magnetic field of the measured SF excitation energies at four different wave vectors (symbols). The thick full line represents a Brillouin function fit of the SF line measured at $q = 0$.

with the calculated dispersions of both the SPE and the SF energies. This figure further illustrates the good description of the Raman data provided by the spin-flip interacting polarizability. In particular, the critical wave vector at which the SF enters the SPE band and becomes overdamped compares well with the experimental observations.

4. Conclusions

In conclusion, our Raman scattering investigation of 2D electron gases in semimagnetic quantum wells provided a detailed picture of the emergence of collective spin-flip excitations from the continuum of single particle transitions with increasing magnetic field. We have clearly demonstrated the collective nature of the narrow Raman line, which dominates the Raman response at finite B, and have been able to describe well its in-plane dispersion. Though restricted to a paramagnetic quantum well, our study provides a powerful indication that collective spin-flip excitations should be the dominant excitation mechanism in both paramagnetic and ferromagnetic low-dimensional semiconductors.

Acknowledgments

We thank C. Gourdon (Groupe de Physique des Solides, Paris) for the loan of a superconducting magnet and J. Cibert, A. Lemaitre, M. Potemski, C. Testelin, and D. Wolverson for valuable discussions.

References

[1] A. Pinczuk, B.S. Dennis, D. Heiman, C. Kallin, L. Brey, C. Tejedor, S. Schmitt-Rink, L.N. Pfeiffer, K.W. West, *Phys. Rev. Lett.* **68**, 3623 (1992); H.D.M. Davies, J.C. Harris, J.F. Ryan, A.J. Turberfield, *Phys. Rev. Lett.* **78**, 4095 (1997).

[2] J.A. Gaj, R. Planel, G. Fishman, *Solid State Commun.* **29**, 435 (1979).

[3] G. Karczewski, J. Jaroszyński, A. Barcz, M. Kutrowski, T. Wojtowicz, J. Kossut, *J. Cryst. Growth* **184/185**, 814 (1998).

[4] B. Jusserand, G. Karczewski, G. Cywinski, T. Wojtowicz, A. Lemaître, C. Testelin, C. Rigaux, *Phys. Rev. B* **63**, 161302 (2001).

[5] B. Jusserand, M.N. Vijayaraghavan, F. Laruelle, A. Cavanna, B. Etienne, *Phys. Rev. Lett.* **85**, 5400 (2000) and references therein.

[6] A.K. Rajagopal, *Phys. Rev. B* **17**, 2980 (1978); J.C. Ryan, *Phys. Rev. B* **43**, 4499 (1991); K.S. Yi, J.J. Quinn, *Phys. Rev. B* **54**, 13398 (1996); J. Moreno, D.C. Marinescu, *Phys. Rev. B* **68**, 195210 (2003); P. Gori-Giorgi, J.P. Perdew, *Phys. Rev. B* **69**, 041103 (2004).

[7] B. Jusserand, F. Perez, D. Richards, G. Karczewski, T. Wojtowicz, C. Testelin, D. Wolverson, J.J. Davies, *Phys. Rev. Lett.* **91**, 086802 (2003).