Electronic Raman Scattering on Modulation Doped GaAs Quantum Wells: Conduction Band Structure and Collective Effects *

Bernard Jusserand

CNET, Laboratoire de Bagneux

196 Avenue Henri Ravera, 92220 Bagneux, France

We report on a detailerl analysis of electroiiic Raman scattering results in modulation doped siiigle quantum mells. We illustrate thereby the great power of this technique to get a detailed characterization of the electron density distribution and the band structure in doped heterostructures. We report in particular on a. recent observaton, for first time directly by spectroscopy, of the spin splitting of the conduction band of GaAs due to the lack of inversion symmetry.

I. Introduction

Modulation doped structures are of great interest for tlie study of the quasi-two-dimensional electron gas (2DEG), in botli transport and optical experiments because of the high mobility achieved by separating the electroiis from the ionized donors. Among these studies, a large amount of work has been devoted to oiie side modulation doped single quantum wells. Tliis system appeais very promising for spectroscopic probes of the integer and fractional quantum Hall effects by optical measurements under quantizing magnetic field[1-3]. On the otlier hand, electronic Raman scattering is a powerful tcol to probe electronic excitations, both collective and single-particle, occuring in a 2DEG. This was first suggested by Burstein et al.[4] and has since been extensively demonstrated[5]. Moreover, in the backscattering set-up, we can change the wavevector in tlie plane of the 2DEG by simply rotating the sample relative to tlie fixed incident light wave vector. This provides a unique possibility to determine the dispersion of these excitations and to extract the subband structure ar: well as the electron density in modulation doped structures[6-11]. More recently, the observation, ill tliffererit polarization configurations, of distinct spin-density anc single-particle excitations, in addition to charge-density waves, opened the way to an independeiit measure of both direct and exchange-correlation

Coulomb interactions of the electron gas[12-14].

In this communication, we will illustrate these possibilities through tl-ie presentation of a whole set of electronic Raman scattering results on 180 Å thick GaAs single quantum wells claded between GaAlAs barriers. Modulation doping is obtained from a Si localized doping iii tlie upper barrier only. This results ill an asymmetric potential profile due to the self-consistent electric field. Moreover, due to the thin spacer (100Å), tlie typical electron density lies above $1.0 \times 10^{12} cm^{-2}$ but tlic Fermi energy remains below the bottom E_2 of tlie second subband. We will present Raman scattering results oii intersubband and intrasubband transitions both with single particle and collective character on the same sample. From their in-plane dispersion and line-shape, we extract determinations of tl-ie electron density, tlie band structure and the lifetime of the involved states[9,11]. We will ill particular report on our recent first spectroscopic observation of tlie spin splitting of tlie GaAs conduction band because of the lack of inversion symmetry[10]. All Raman scattering experiments are done at liquid Helium temperature (1.8 K) aiid under close energy resonance with the fundamental energy gap.

Fig. 1 shows electronic intersubband Raman spectra in parallel (polarized spectra) and crossed (depolarized spectra) polarizations respectively, for several different Raman in-plane rvave vectors q. Due to the sym-
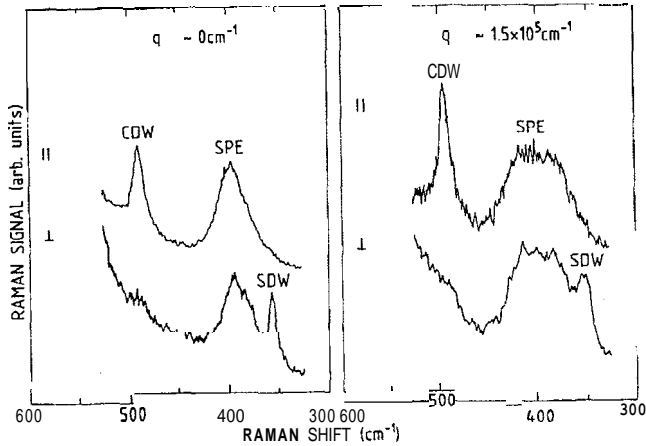
Figure 1: Electronic Raman scattering spectra obtained with a resonance laser energy of 1.64 eV and at pumped liquid He temperature (1.8K). Tlie left side of tlie figure shows collective (CDW and SDW) and individual (SPE) intersubband excitations of the 2DEG for a very small Raman in-plane wavevector, while the right side exhibits tlie same excitations at larger q.

Figure 2: Schematic geometrical determination of the SPE Raman signal for three different band filling situations.

metry of the valence band states in GaAs, Raman cross-sections, due to virtual interband processes, in crossed (respectively parallel) polarization have been shown[15] to be related to spin-density (respectively charge density) mechanisms. One thus observes in parallel (respectively crossed) polarization collective charge density waves (CDW) and spin density waves (SDW) occuring in tlie 2DEG. In strong resonance conditions, one also observes, in both polarizations, a. broader band of single particle excitations (SPE), with an intensity comparable to the collective ones, contrary to tlie tlieoretical prediction of complete screening. Though the origin of this observation is not yet fully understood, it appears to be very uscful: the SPE band indeed peaks at the bare intersubband energy $E_2 - E_1$ of the doped structure (this is only strictly true when assuming tlie same parabolic dispersion for both subbands). On our sample we can thereby extract an accurate determination of tlie subband separation (49meV) in good agreement with the estimation deduced from luminescence[11] (48meV). Moreover this band displays a specific behavior as a function of q. Unlike the CDW and SDW, wliicli remain approximatively unchanged, the SPE band is strongly broadened with increasing Raman in-plane wave vector according to tlie clensity of intersubband transitions.
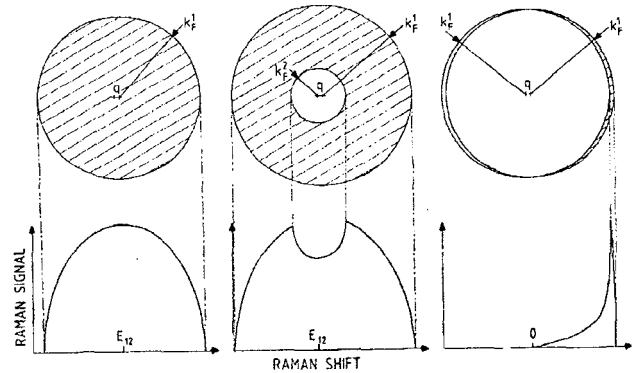
This is schematized on Fig. 2 in which wc show tlie

2D Fermi disk associated to tlie initial and final bands respectively for three different cases: a) the second subband is empty as in the sample discussed in this communication, b) it is partially filled and c) the density is tlie same in both subbands, a situation which applies to intrasubband transitions. Tlie final state Fermi disk lias been shifted by $-\vec{q}$ to account for tlie Raman wavevector transfer. As the Raman shift amounts to approximately $\hbar^2 \vec{q} \cdot \vec{k}/m^*$ when assuming $q \ll k$, tlic horizontal scale of the figure can be directly transformed irito an energy scale. Tlie Raman signal for eacli case is tlien grapliically deduced from tlie length of the equi-energy lines inside tlie initial and outside the final Fermi disks. In case a, thc SPE signal appears as a. broad band extending between two cut-off frequencies, shifted by $-\hbar q v_F$ and $+\hbar q v_F$ from the $E_2 - E_1$ energy respectively. Tlie corresponding dispersion curve is shown in Fig.3 and compared to tlie experimental dispersion. The slope of the SPE dispersion reflects the electron density in E_1. However the accuracy of this determination is limited due to the intrinsic broadening of tlie transitions (2meV). This quantity reflects the lifetime of both initial and final states. Energy-dependent values are needed to correctly fit tlie SPE lineshape at every in-plane wavevector[11].

Tlie CDW and SDW lines are not strongly dispersive and, due to the large electron density, they are well separated from the SPE band (see Fig. 1 and 3). Thus one is able to accurately determine their energies, and to deduce the electron density. Using a RPA calculation based on self-consistently determined wavefunctions[6,13], we deduce from the CDW energy an electron density of $1.3 \times 10^{12}cm^{-2}$. With this value,
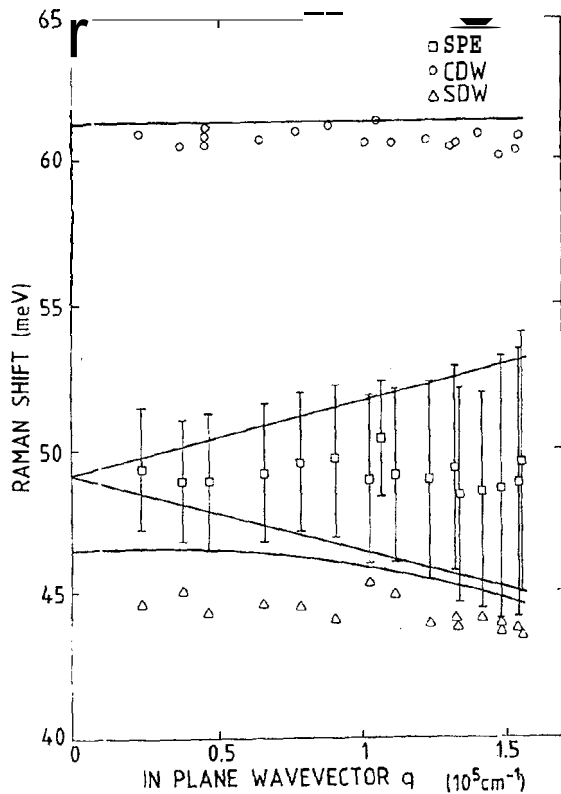
Figure 3: Dispersion curve of the collective (CDW and SDW) and individual (SPE) intersubband excitations of tlie 2DEG, deduced from Raman scattering experiments as a function of q The vertical lines are the width at half maximum of the SPE line and tlie solid lines calculatetl dispersion curves.

one may ex.ract from self-consistent subbands calculations tlie potential profile of tlie structure and tlie subbands energies. The calculated value of tlie E_1 to E_2 intersubband energy obtained by this procedure is in very good agreement with experimental values provided by PL and Faman measurements. Moreover, from the experimental SPE, CDW and SDW lines, one may extract an experimental determination of the direct and exchange-correlation Coulomb interaction in quasi-two-dimensional electron gases and compare them to different models of these quantities[12−14].

Let us now turn to the analysis of the intrasubband electronic transitions. Tlie corresponding Raman spectra are shown on Fig. 4 for several in-plane wavevectors in both polarization configurations. As we already explained for tle intersubband ones, SPE and collective excitations can he observed simultaneously at strong resonance. Tlie low energy part of the spectra in both polarizations is attributed to SPE band. It extends from zero to a maximum energy $+\hbar q v_F$. However, con-
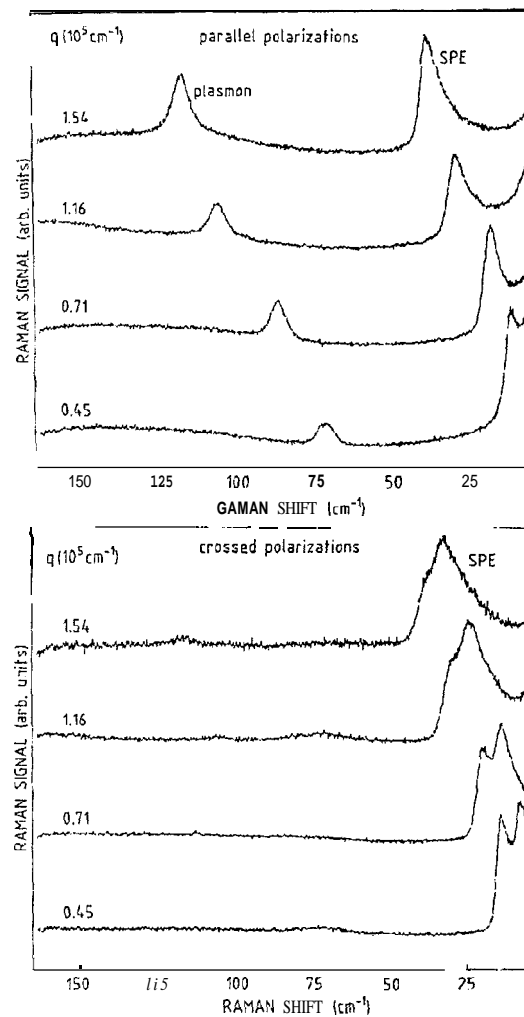

Figure 4: Electronic Raman scattering spectra on intrasubband excitations in parallel (left-side) and crossed (right side) polarizations for several in-plane wavevector.
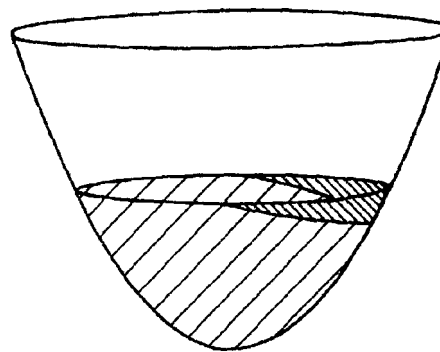

Figure 5: Schematic representation of the states participating to the intrasubband Raman process (thick hatched surface) among the occupied ones in the Fermi sea (thin hatched).
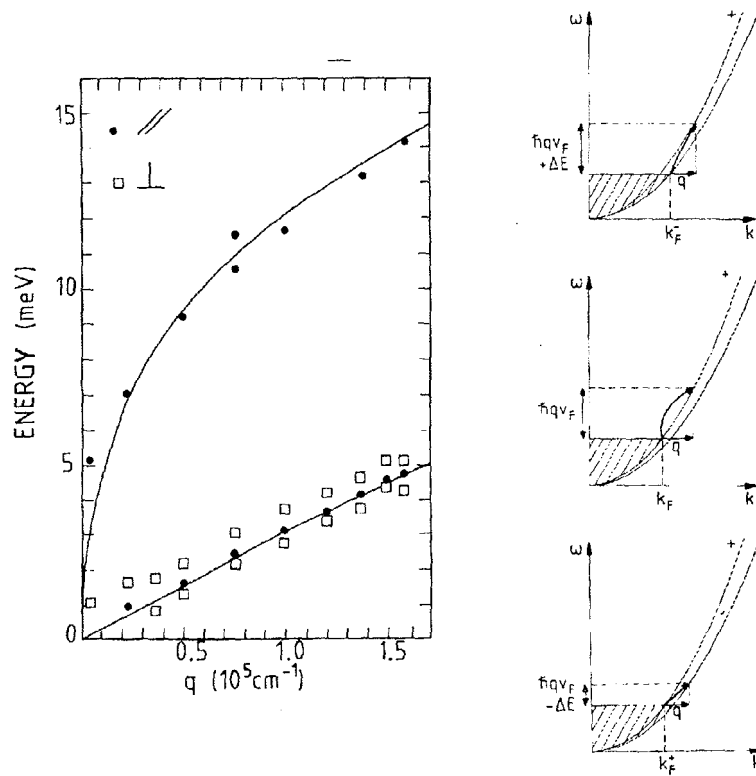
Figure 6: Schematic representation of tlie different possible intrasubband transitions and tlie correspoiiding calculated dispersion curves, also including the plasmon one. A comparison is made with the experimental dispersions.

trary to the intersubband case: it reflects the density of transitions between two occupied subbands: E_1 and E_1. Due to tlie final state occupation, and because the Raman wavevector is usually much smaller than k_F, the only initial states which can participate in the Raman process (see Fig.2c and 5) are very close to the Fermi level and their in-plane wavevector is oriented along q. Due to this restriction, the Raman line shape is well peaked around $+\hbar q v_F$. Moreover, the lifetime broadening is very small for these transitions ($< 0.2 meV$) i.e. ten times less than for intersubband transitions. This is a further indication that this broadening indeed significantly depends oii tlie energy of the involved states. Thanks to these features, the determination of the intrasubband SPE dispersion provides an accurate test of the 2D character of the involved states (linear dispersion) and an accurate determination of the electron density. h value of 1.3×10^{12} cm^2 is deduced from the parallel spectra.

Moreover the Raman line shape is particularly sensitive to tlie detail of the band structure around $k_F \frac{\vec{q}}{|\vec{q}|}$, which was up to now assumed parabolic and doubly spin-degenerate. This appears in our spectra through a splitting of the SPE band in crossed polarization. This splitting reflects a very small, generally neglected effect in the band structure of GaAs: tlie additionnal spin splitting due to spin-orbit interaction in crystals without inversion symmetry[10]. Taking into account this splitting and tlie Raman selection rule, we indeed predict (see Fig. 6) the observation of a single SPE band in parallel polarization, with a cut-off energy $\hbar q v_F$, and two SPE bands in crossed polarization with the same wavevector dependence but shifted from tlie previous one by respectively $+\Delta E$ and $-\Delta E$, where ΔE is the splitting at the Fermi wavevector in the direction of $\vec{q}$.

These predictions are in perfect qualitative agreement with tlie experimental dispersion (see Fig. 6) and provide the first direct measure of the spin splitting (0.38 meV). This contrasts with tlie previous indirect determinations deduced from polarization measurements[16]: in these experiments, the splitting was assumed to be negligible with respect to level broadening and the adclitional spin orbit effect was estimated from the induced precession of the electron spin in tlie conclution band. The same mechanism was also involved in tlie recent spin-splitting determination from
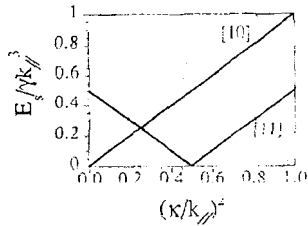
Figure 7: Spin-splitting calculated along [10] aiid [11] directions as a function of the sample parameter $\kappa/k_{\parallel}$.

Figure 8: Depolarized intrasubband Raman spectra for the same in-plane wavevector oriented along three different directions in the layer plane.

anti-weak-localization studies in magnetoconductance experiments[17]. In our Raman experiment, we are able to measure the splitting because of the specific features of Raman scattering by intra-subband SPE excitations which we previously emphasized and because we are studying modulation doped heterostructures. This indeed allows to ohtaiii large doping concentrations, and thus large splittings ($\Delta E \propto k_F^3$), with high mobilities at low temperature, and thus weak liiie broadening of the transitions. We compare this accurate determination with models of the spin splitting in heterostructures[18]. Our experimental value is in good agreement with the predicted one averaged over the in-plane directions, thus providing a further support to the description of this splitting in bulk GaAs in terms of an additional *spin-orbit coupling of the conduction band with the higher energy anti-bonding p-states*[19]. However 2D models predict a large anisotropy of the spin splitting:

$$\Delta E = \gamma(\kappa^4 k_{\parallel}^2) - (4\kappa^2 - k_{\parallel}^2)k_x^2 k_y^2)^{1/2}$$

which moreover strongly depends on the confinement wavevector $\kappa^2 = < k_z^2 >$ [20]. This is illustrated on Fig.7 where we show the dependence of the splitting onto the ratio $\kappa/k_{\parallel}$. The splitting continuously evolves from a 3D situation for vanishing values of the ratio towards a 2D one at large κ. In the formei' case the splitting moreover is proportionnal to $k_{\parallel}$ while it varies linearly with $k_{\parallel}$ in the 2D limit. Ia between, various situations appear with a splitting along [10] either smaller or larger than along [11]. A systematic study as a function of $\kappa/k_{\parallel}$ and of the wavevector orientation is therefore of great interest to probe the 2D models of this effect.

The dependence on the wavevector magnitude can be probed by Raman scattering either on different samples with the same parameters except the electron density or, more accurately, by the application of an elec-
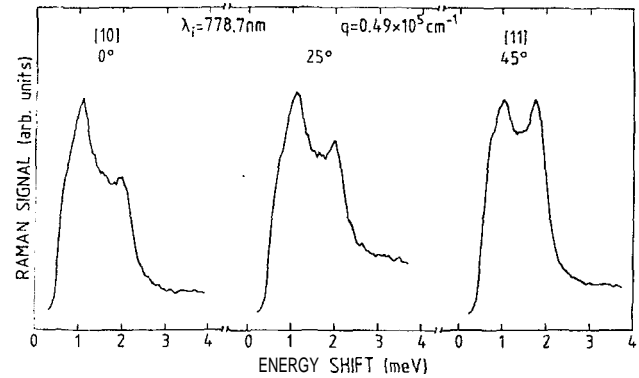
tric field onto the electron gas using a Schottky contact to deplete the electron channel. The effect of the wavevector orientation can he more easily investigated by turning the sample with respect to the scattering wavevector direction. This allows to select a given direction to be probed in the Fermi sea as shown on Fig. 2 and 5. Some preliminary results on the saine sample are shown on Fig.8 [20]. Contrary to the predictions illustrated on Fig.7, we observe a moderate anisotropy which makes us supect some deficiency in the 2D extension. Further experiments on the angular and density dependence of the splitting are in progress and should bring some new light oiito this problem.

In conclusion, we illustrated the great power of electronic Raman scattering to probe modulation doped quantum wells aiid to obtain thereby novel information about the band structure of GaAs and about many body effects at low dimension. The work reported in this communication lias greatly benefited from the collaboration for sample preparation and characterization, optical experiments, theoretical analysis and discussions of B. Etienne, V. Thierry-Mieg, A. Izrael, H. Peric, D. Richards, J. Y. Marzin and J. M. Gerard.

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