

SINGLE PARTICLE EXCITATIONS AND PLASMONS IN A SINGLE ASYMMETRIC MODULATION-DOPED GaAs QUANTUM WELL

B. JUSSERAND ^{a,b}, D.R. RICHARDS ^a, G. FASOL ^a, G. WEIMANN ^c and W. SCHLAPP ^c

^a Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

^b CNET, Laboratoire de Bagneux, 196, Av. Henri Ravera, 92220 Bagneux, France

^c Forschungsinstitut der Deutschen Bundespost, 6100 Darmstadt, Fed. Rep. of Germany

Received 11 July 1989; accepted for publication 14 September 1989

We present and analyse electronic Raman scattering results on a single two-dimensional electron gas confined in a single quantum well, measured as a function of the scattering geometry and in the presence of additional illumination.

Electronic Raman scattering on single particle (SP) excitations and collective modes (plasmons) in two-dimensional electron gases (2DEG) have been extensively studied in the past years [1]. These experiments generally involved modulation-doped multi-quantum-well (MQW) samples in which there are a large number of adjacent electron sheets. Some scarce results have been also reported [2] on 2DEG located at heterojunctions where electronic Raman scattering seems to be hardly detectable. In this communication we present Raman spectra obtained on a one-side-doped 17 nm thick asymmetric *single quantum well*. The carrier density in the well was determined [3] from Shubnikov–de Haas measurements to amount to $4.5 \times 10^{11} \text{ cm}^{-2}$. This sample mainly differs from a classical heterojunction by the presence of an undoped GaAlAs barrier on the backside, a fact which results in an additional confinement for electrons and especially ensures the confinement of the photocreated holes in the same region. We obtained on this sample very intense and well defined signals corresponding to single particle and collective, interband and intraband excitations of the single electron gas present in the sample. Such an observation on a single quantum well appears as a crucial step in the investigation of external effects on the electron gas such as electric field induced confinement through a Schottky gate at the sample surface. In this communication, we will describe the electronic Raman spectra recorded on the sample at

liquid helium temperature and present the measured frequencies as well as their dispersion as a function of the in-plane wave vector. We will next analyse the effect of an additional illumination on the frequencies of the SP and collective interband excitations and thereby illustrate the possibility to externally adjust the electron density in the gas.

We show on fig. 1 Raman signals obtained in resonant conditions close to the $E_0 + \Delta_0$ gap and corresponding to the interband transitions between the lowest, occupied quantum level and the first excited one which is empty at this carrier concentration. As already well established on MQW samples [1], the SP spectrum is observed with perpendicular incident

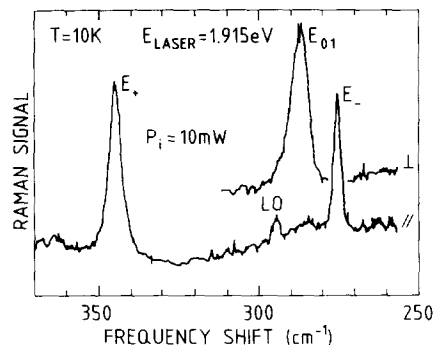


Fig. 1. Raman spectra of interband SP excitations ($\perp$) and plasmons ($\parallel$).

and scattered polarizations, directly reflecting the energy transition E_{01} between the two quantum levels. The associated collective excitation, predicted to appear at higher energy due to the Coulomb interaction, is coupled to the LO phonon via the associated electric field. In parallel configuration, two coupled modes therefore are observed, labelled E_+ and E_- , whose frequency directly reflects the carrier density in the gas when the bare energy transition E_{01} is known. All three lines observed on this sample are among the narrowest ever reported [4] on such systems, thus illustrating the high quality and homogeneity of the structure.

On fig. 2, we present Raman spectra obtained in resonant conditions close to the E_0 gap and corresponding to the intraband transitions across the Fermi energy inside the fundamental level. Both the

intraband SP excitations and plasmons display sharp incoming and outgoing resonances. This could suggest a scattering process involving intermediate exciton states, as introduced in ref. [4] for interband spectra. Such transitions in 2DEG are only observable at non-vanishing energies for a finite value of the in-plane wavevector $k_{||}$. They are moreover highly dispersive as a function of this quantity. We illustrate this dispersion, obtained by varying and carefully measuring the incidence angle on the sample, both for single particle (fig. 2a) and plasmon (fig. 2b) lines. The former contribution appears in perpendicular configuration as a band resulting from an integration of all possible transitions across the Fermi level displaying the same in-plane wave vector. Contrary to what happens in 3D systems, 2D SP bands display a well defined cut-off at higher energy which

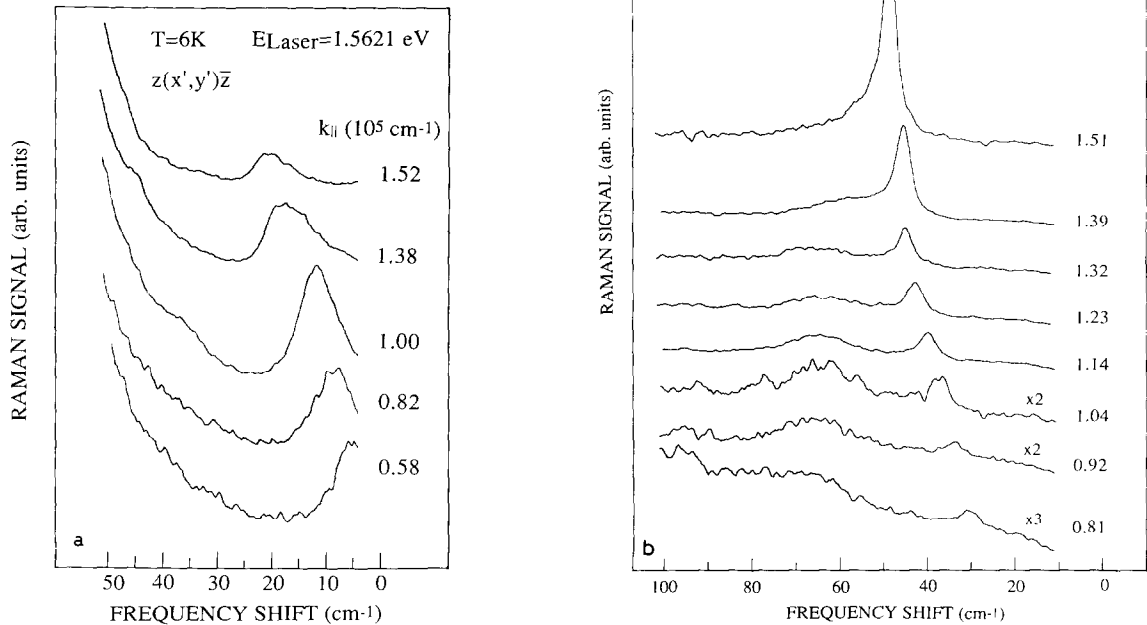


Fig. 2. Raman spectra of intraband SP excitations (a) and plasmons (b), both shown at different in-plane wavevector.

increases linearly both with the in-plane wavevector and the Fermi velocity. In the parallel configuration, we observed a single plasmon line as expected from a single sheet of electrons. Its frequency is predicted to exhibit a square root dependence on the product $nk_{\parallel}$. Such a square root dependence is specific to a single electron gas and was never observed on a modulation-doped GaAs/GaAlAs structure. When several different electron gases are present in the sample, they indeed interact together due to the electrostatic field and several coupled plasma lines are observed [5].

We show on fig. 3 the measured plasmon and SP dispersion curves on the whole range of in-plane wave vector we were able to probe. The linear dependence of the SP cut-off, which we measured, in agreement with the theory, provides a new determination of the electron density extracted from the Fermi velocity $v_F = 2.9 \times 10^7 \text{ cm s}^{-1}$. The plasmon branch is clearly highly dispersive and follows a square root dependence as a function of the in plane wave vector, but lies at significantly lower frequency than predicted using the full RPA expression for the dielectric constant.

Let us finally give some first results on external

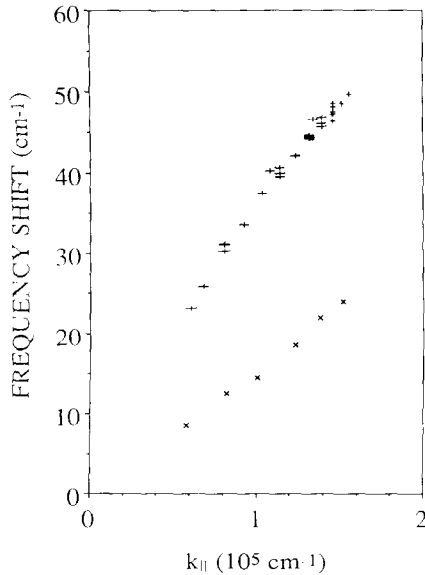


Fig. 3. Plasmon (+) and SP (x) dispersion curves. Error bars for in-plane wave vector are included for plasmon dispersion.

modulation effects on the 2DEG electron gas. As already shown by luminescence and luminescence excitation [3] on the same sample, asymmetric quantum wells display the unique property to have a variable carrier density under an illumination at energies close to or higher than the band gap of the GaAlAs barrier. The effective density surprisingly decreases with increasing illumination. The most probable explanation [6] to this phenomenon involves the self-consistent electrostatic potential due to the one-side modulation doping. It results in a large energy barrier which hinders the electrons photo-created in the upper GaAlAs barrier, but not the corresponding holes, from relaxing into the quantum well. The holes then easily recombine with the electrons existing in the well due the modulation doping and, in a steady state regime, the electron concentration decreases with increasing illumination. We show on fig. 4a the variation of E_{01} (horizontal axis) and $E_{+,-}$ (vertical axis) as a function of the illumination intensity. As we quoted previously, the E_{+} frequency strongly decreases under illumination, thus reflecting the decrease in the electron density. More surprisingly the interband transition displays a *very small and non-monotonic* change in the same time. To understand this feature, we calculated, on the basis of a simple model [3], the change in the position of the two involved quantum levels as a function of

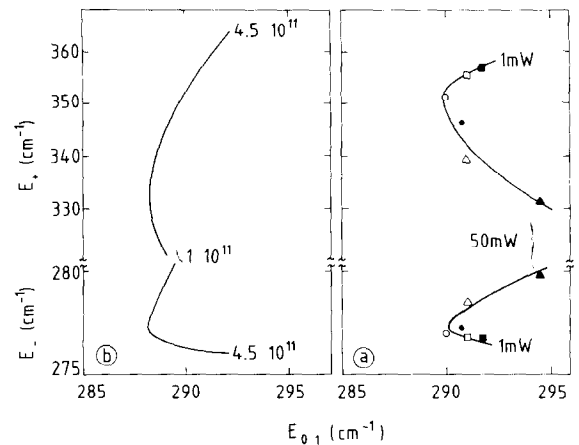


Fig. 4. Variation of the interband SP excitations and plasmons measured as a function of the intensity (a) and calculated as a function of the electron density (b).

the electron density. This calculation takes into account the change in the self-consistent electrostatic potential but not the, eventually different, corrections to both frequencies due to many body effects. The results are shown on fig. 4b in the same presentation as used in fig. 4a, the free parameter being now the electron density. The non-monotonic variation is well reproduced and can be qualitatively described when comparing the variation of each quantized level frequency (not shown on the figure) when the electron density is increased: the second level becomes sensitive to the change in the quantum well shape due to the electrostatic potential at higher densities than the fundamental one but afterwards varies more rapidly with the density. As a result the interband energy first decreases and then turns to increase as observed in the experiment. Let us finally note that this variation is well reproduced taking into account only the change in the electrostatic potential, a fact which suggests a rigid shift of the two levels due to many body effects in our experimental conditions.

In summary, we report the first observation of both

intraband and interband electronic Raman spectra on a single electron gas confined in a single GaAs quantum well. The interband and SP intraband transitions are well described on the basis of the state-of-art dielectric response theories [5], while the low value of the measured intraband plasma frequency is not yet understood.

References

- [1] For a recent review see: A Pinczuk and G. Abstreiter, in: *Light Scattering in Solids V*, Eds. M. Cardona and G. Güntherodt (Springer, Heidelberg, 1989) p. 153.
- [2] G. Abstreiter and K. Ploog, *Phys. Rev. Lett.* 42 (1979) 1308.
- [3] M.H. Meynadier, J. Orgonasi, C. Delalande, J.A. Brum, G. Bastard, M. Voos, G. Weimann and W. Schlapp, *Phys. Rev. B* 34 (1986) 2482.
- [4] For recent comparable interband spectra on comparable samples, see: G. Danan, A. Pinczuk, J.P. Valladares, L.N. Pfeiffer, K.W. West and C.W. Tu, *Phys. Rev. B* 39 (1989) 5512.
- [5] G. Fasol, R.D. King-Smith, D. Richards, U. Ekenberg, N. Mestres and K. Ploog, *Phys. Rev. B* 39 (1989) 12695.
- [6] A.S. Chaves, A.F.S. Penna, J.M. Worlock, G. Weimann and W. Schlapp, *Surf. Sci.* 170 (1986) 618.