JOURNAL DE PHYSIQUE
Colloque C5, supplément au n°11, Tome 48, novembre 1987

PLASMONS AND SINGLE PARTICLE EXCITATIONS IN MODULATION DOPED QUANTUM WELLS

G. FASOL*, N. MESTRES, M. DOBERS, A. FISCHER and K. PLOOG

Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-7000 Stuttgart 80, F.R.G.
**Cavendish Laboratory, Madingley Road, GB-Cambridge CB3 OHE, Great-Britain*

Résumé. Le mouvement des électrons dans les différentes couches d'un système de N couches parallèles d'électrons est couplé par les forces Coulombiennes. Ainsi, dans le cas où $k_{||} < 1/d$, d étant la distance séparant les couches et $k_{||}$ le vecteur d'onde parallel au plan défini par ces couches, il y a N modes propres des plasmons. La différence d'énergie entre les modes propres des plasmons est une mesure de l'intéraction de Coulomb entre les couches. Nous mesurons la dispersion de ces modes discrets des plasmons à l'aide de la diffusion Raman en polarisation parallèle des photons incidents et des photons diffusés. En polarisation croisée, nous mesurons les spectres des fluctuations de la densité de spin. Dans une approximation simple, ces spectres sont proportionels aux spectres d'excitation des paires électron - trous. Nous pouvons bien expliquer ces spectres et leur changement avec la température par la partie imaginaire de la fonction Lindhard en deux dimension.

Abstract. In a layered electron gas with N layers the Coulomb interaction between layers correlates the motion of electrons on different layers. Thus for $k_{||} < 1/d$, where d is the interlayer separation and $k_{||}$ the in plane wavevector, the plasmon eigenmodes fan out into N discrete modes. With parallel polarisation of incident and scattered light, we measure the dispersion with $k_{||}$ of the discrete plasmon eigen modes with Raman scattering. In crossed polarisation the electronic Raman spectra are proportional to the 2D spin density fluctuation spectra. In a simple theory these spectra are proportional to the single particle excitation spectra. We find good agreement of the measured spectra and their temperature dependence with the imaginary part of the Lindhard dielectric response function.

Introduction. In a single sheet of carriers the plasmon dispersion is proportional to $k_{||}^{1/2}$, where $k_{||}$ is the in-plane wavevector, neglecting retardation. In a system of N parallel sheets of charges the Coulomb interaction between carriers on different sheets correlates their motion. As a result a system of N sheets of electrons, has N discrete layer plasmon eigenmodes which fan out into a band for $k_{||} < 1/d$, where d is the interlayer separation. In parallel polarisation of incident and scattered photons, we measure electronic Raman scattering from charge density fluctuations, yielding the dispersion of the discrete layer plasmon modes. In crossed polarisation we measure Raman spectra, which are proportional to the 2D in-plane spin density fluctuation spectra, which yield the single particle excitation spectra.

Raman measurements. We measure both the plasmon spectra and the in-plane single particle excitation spectra as a function of the in-plane wavevector component $k_{||}$. The technique to study plasmon spectra as a function of $k_{||}$ was introduced by Olego et al. [1]. Because of the relatively large refractive index, $\Delta k_{\perp}$ is almost constant in our experiments, while $\Delta k_{||}$ can be varied between 0 and about $1.5 \times 10^5 cm^{-1}$ by varying the angle between the light paths and the sample (see insert in Figure 3). For a sample with a large number of layers, $k_{\perp}$ is conserved during the scattering process, i.e. only modes for which the component of the wavevector transfer perpendicular to the layers is equal $k_{\perp}$ of the plasmon eigenmode will show up in the Raman spectra. For intermediate numbers of layers (around N = 15) a few modes, where $k_{\perp}$ is approximately conserved will appear in the Raman spectra [2]. In the case of a small number of layers (N = 5 or less) there is no $k_{\perp}$ conservation at all (although of course the actual wavevector transfer determined by the scattering geometry and the laser energy will influence the Raman intensity of the various plasmon eigenmodes). We have shown [3], that as a consequence all or almost all discrete layer plasmon eigenmodes can be observed in Raman scattering.

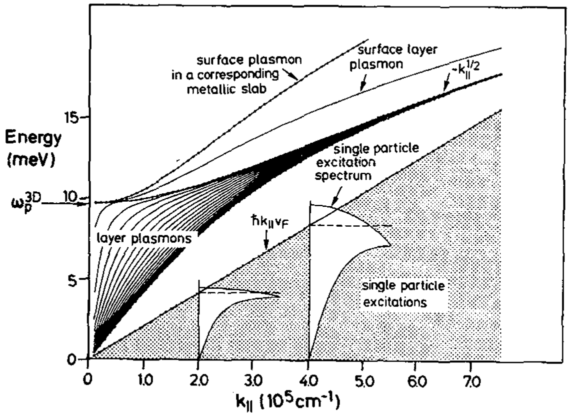

Figure 1. Dispersion of the elementary excitations (single particle excitations and collective modes = plasmons) of a layered electron gas (here with N=20 layers).

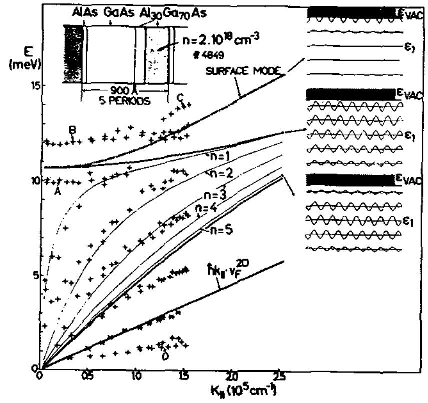

Figure 2. Measured dispersion of coupled layer plasmon modes (labelled n=1 to 5), coupled intersubband and plasmon excitations (A,B,C). The measured dispersion of the plasmon eigenmodes is compared with calculation [4] containing no fit parameters. Inserts show schematic of the sample structure and of the charge density oscillations associated with the plasmon eigenmodes.

Figure 1 shows a schematic view of the dispersion of the single particle excitation spectra and of the coupled layer plasmon eigenmodes for a layered electron gas sample with N layers. Also shown are the single particle excitation spectra for two different values of $k_{||}$, as well as possible surface layer plasmon modes. The latter have not been observed yet. We study n-type modulation doped quantum wells with n = 2 to n = 20 parallel wells. The basic period of each of these wells is shown in the upper left hand corner of Figure 2. The Raman measurements are done with a Krypton ion laser pumped dye laser, a 2m double monochromator and photon counting. The samples were mounted on the cold finger of a flowing Helium cryostat. Figure 2 shows the experimental points (crosses) for the dispersion of the coupled layer plasmon modes of a sample structure (No. 4849) with five layers. The plasmon eigenmodes are labelled n = 1 to n = 5, and are compared with the calculated dispersion using a theory by Jain and Allen [4]. Also seen are modes attributed to coupled intersubband and plasmon modes (A, B, C) and a mode attributed to electrons in a higher subband (0). The dispersion shown in Figure 2 is extracted from Raman spectra such as those shown in Figure 3. In parallel polarisation we measure the plasmon modes and in crossed polarisation we measure the spin density fluctuation spectra. In a simple picture the spin density fluctuation spectra are proportional to the single particle (= electron hole pair) excitation spectra.

In Figure 4 we show the single particle excitation spectra measured at different temperatures with Raman scattering. The spectra are very well explained by the Lindhard Mermin response function, which includes the effects of finite temperature and a phenomenological scattering time. We have calculated the Lindhard Mermin function numerically using the phenomenological scattering time as a fit parameter. The best such fits are shown in Figure 4 as the solid curves. The agreement is really very good, taking account of the simplicity of this picture. Figure 5 shows that the single particle excitations correspond to creation of an electron above the Fermi circle and a whole below the Fermi circle.

Since the range of single particle excitations is below 5 meV in our case, accurate control of the temperature is essential. We measure the coldfinger temperature with a calibrated Ge resistor, and we determine the temperature of the electron gas using the exponential high energy tail of the bandgap luminescence, as shown in Figure 6. The good agreement of calculated and measured Stokes and Antistokes sides of the Raman spectra confirm our determination of the temperature of the electron gas.

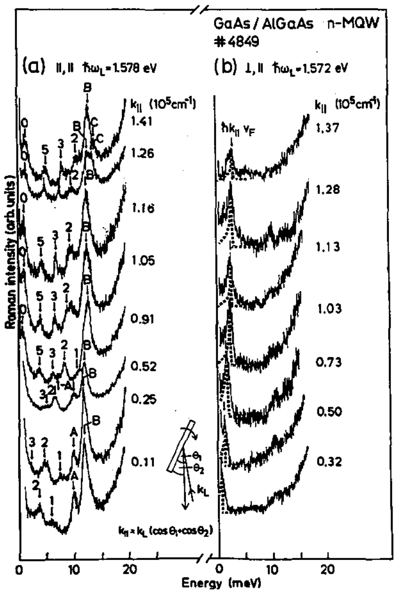

Figure 3. Measurements of a) the collective modes (discrete layer plasmon eigenmodes) and b) spin density fluctuation spectra (single particle excitation spectra) for a sample structure with five modulation doped quantum wells.

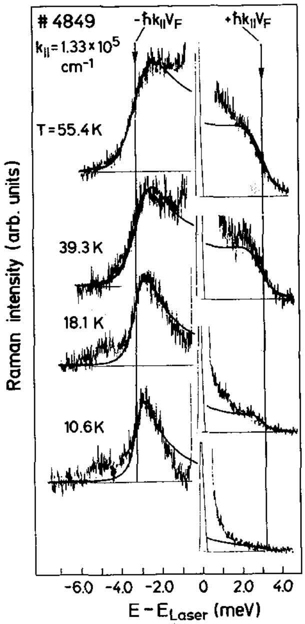

Figure 4. Single particle excitation spectra measured at different electron gas temperatures. Spectra are well explained by simple Lindhard-Mermin dielectric function using a phenomenological scattering time as fit parameter (solid curves).

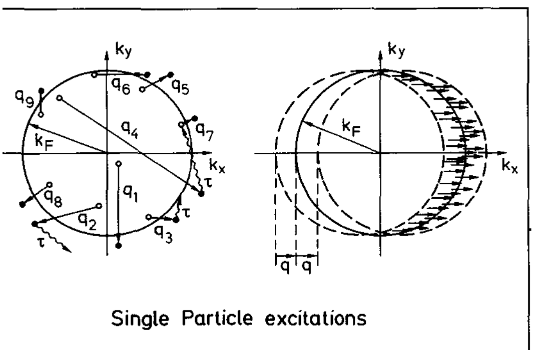

Figure 5. Schematic diagram of single particle excitations, used in a simple picture here to explain the spin density fluctuation spectra.

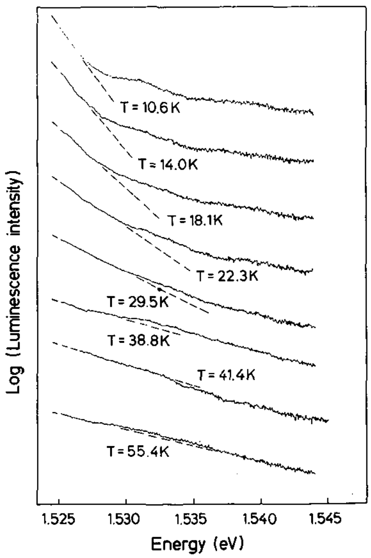

Figure 6. To determine the temperature of the electron gas, we measured the exponential high energy tail of the bandgap luminescence

Conclusions. In conclusion, we have measured the dispersion of the discrete coupled layer plasmon modes in the layered electron gas using resonant Raman scattering. We find good agreement of the plasmon dispersion with a recent theory by Jain and Allen [4]. We measure the spin fluctuation spectra as a function of temperature, which we interpret in terms of the single particle excitation spectra. The shape of the spectra and their temperature dependence can be well explained by the imaginary part of the simple Lindhard-Mermin response function using a phenomenological scattering time as fit parameter.

Acknowledgments. The authors would like to acknowledge with gratitude the help and support of M. Cardona. They are very grateful to D. Heitmann, K. von Klitzing, G. Lonzarich and D. King-Smith for many helpful discussions and to H. Hirt, M. Siemers and P. Wurster for expert technical support.

References.

1. D. Olego, A. Pinczuk, A. C. Gossard and W. Wiegmann, Phys. Rev. B25, 7867 (1982)
2. A. Pinczuk, M. G. Lamont and A. C. Gossard, Phys. Rev. Lett. 26, 2092 (1986)
3. G. Fasol, N. Mestres, H. P. Hughes, A. Fischer and K. Ploog, Phys. Rev. Lett. 56, 2517 (1986)
4. J. K. Allen and P. B. Allen, Phys. Rev. Lett. 54, 2437 (1985)