Excitations of the Strongly Correlated Electron Liquid in Coupled Layers

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The low-lying excited states in a system of coupled layers of electrons in a gallium arsenide heterostructure are strongly affected by many-body correlations between the electrons for densities as high as $r_s = 5$. For a layer spacing of less than 100 nm the function $\mathrm{Im}\chi(\mathbf{q},\omega)$ near $q = 1.9k_F$ has a large peak at small ω which is apparently a soft-mode precursor to a charge density wave instability. This new peak should be observable with present experimental techniques in realistic samples. The linear gradient of the "acoustic" plasmon is depressed so much by many-body effects that for $r_s = 5$ it can become degenerate with the single-particle excitation spectrum for all $\mathbf{q}$.

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While the correlated electron liquid has been a major theoretical challenge for many years [1–8] it is a system that has proved extremely difficult to investigate experimentally. Electron layers in III-V semiconductor heterostructures should in principle be excellent systems for studying the strongly correlated two-dimensional electron liquid but unfortunately at the relatively high densities currently attainable experimentally the electrons are only weakly correlated and until now it is only when an external magnetic field is applied that the effect of strong correlations can be observed in such phenomena as, for example, the phase transition of the liquid to the incompressible fluid of the fractional quantum Hall ground state.

One can also have two or more layers of electrons confined in parallel planes. Within the random phase approximation (RPA) the dielectric function, electronic properties, and the collective excitations have been intensively studied for a finite number of layers [9–15] and also for a superlattice of layers [16–20]. In the study of light scattering the density-density correlations were calculated and optical properties investigated [21–23]. Correlations beyond the RPA have been included for the superlattice by Zhang and Tzoar [24] and by Lu and Golden [25, 26].

The effect of correlations on the nature of the ground state for the two-layer system and for superlattices has been investigated by Świerkowski *et al.* [27]. With more than one layer the Coulomb interactions between electrons in the different layers can significantly increase the strength of the correlations. The underlying reason is that even when the layers are far enough apart so there is no hopping, the electrons in different layers still couple through the Coulomb interaction and this causes electrons in one layer to act as a polarizable background for electrons in the other. This additional degree of freedom permits transitions from the electron liquid to inhomogeneous ground states to occur at relatively high electron densities [27]. In particular, transitions to charge density waves may occur at densities currently attainable experimentally. However, charge density waves are difficult to observe directly unless they are pinned to defects [28].

If the nature of the ground state can be so markedly affected by these correlations, one might expect the dynamic properties and the spectrum of low-lying excited states of the liquid phase to be dramatically affected near to the transition. In this paper we investigate the double-layer system in zero magnetic field at the relatively high densities $r_s \approx 5$ to 8, calculating the elementary excitation spectrum when the spacing between the layers takes the liquid phase close to the charge density wave instability. For a density of $r_s = 7$ the instability occurs when the layers are of the order of 25 nm apart which is still sufficiently large for hopping between layers to be neglected.

In the two-layer system there are two plasmon modes, an in-phase mode for which the oscillations in the two layers are in-phase and an out-of-phase mode for which they have opposite phases [10]. Of the two modes the in-phase mode has the higher energy. The acousticlike linear dispersion of the out-of-phase plasmon at small $\mathbf{q}$ is caused by the additional screening from adjacent layers which nullifies any long range electric field.

In Fig. 1 we show the dispersion curve at $r_s = 5$ of the lower lying collective excitation at zero temperature and in the absence of defect scattering when the spacing between the layers is $a = 25$ nm. Although within the pure RPA the plasmon has been shown to exist for small $\mathbf{q}$ at all densities [11], we find that the dispersion curve is sensitive to many-body correlations even at small $\mathbf{q}$. This is due to the linearity of the curve. For $a = 25$ nm and $r_s \gtrsim 5$, many-body correlations depress the curve so much compared with the RPA curve that it is degenerate with the single-particle excitation spectrum essentially for all nonzero $\mathbf{q}$. In this case strong correlations can completely destroy the acoustic plasmon as a separate mode even when there is no smearing of the single-particle boundary by defect scattering or thermal effects.

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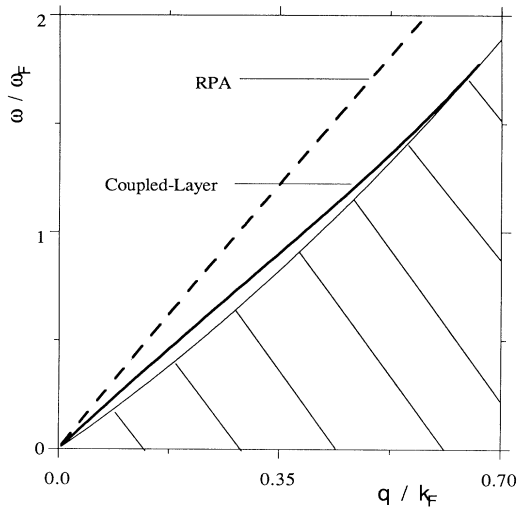

FIG. 1. The dispersion curve at $r_s = 5$ in the absence of defect scattering and at zero temperature for the lowest energy plasmon mode corresponding to $\chi_-(\mathbf{q},\omega)$ (solid line) compared with the RPA result (dashed line). The spacing between the layers is $a = 25$ nm.

At $a = 25$ nm tunneling between the layers is still negligible, and since for $r_s \lesssim 5$ the mode does exist the disappearance should be observable by applying a suitably varying gate voltage which sweeps the density through a small range centered on $r_s \approx 5$.

The most notable result from our calculations is the prediction of a strong renormalization of the liquid elementary excitation spectrum into a new soft quasimode. Figure 2 provides a view of the overall spectral strength of the elementary excitations in the system for a layer spacing $a = 25$ nm and density $r_s = 7.35$. The temperature here is taken to be $T = 0.5$ K with a defect scattering time τ corresponding to an electron mobility of $\mu = 10^5$ Vcm^{-2}. By $r_s = 7.35$ the acoustic plasmon has already merged with the single-particle excitation region. Around $\mathbf{q} = 1.9k_F$ there is a strong shift of single-particle spectral strength towards zero energy. This indicates a concentration of low-lying excited states with a density modulation period close to that of the incipient charge density wave instability [27]. The appearance of this mode indicates that it costs relatively little energy to excite the system into a state with a periodic modulation of the density. The closer the soft mode is to zero energy the longer spontaneous fluctuations into a density modulated excited state can remain and there would be a tendency for the system to be unstable to a periodic charge density wave ground state.

As the precursor of the charge density wave ground state in the liquid phase the soft mode could be used to experimentally confirm the existence of charge density waves. A sizable new peak appearing in the imaginary part of the liquid dielectric response function at

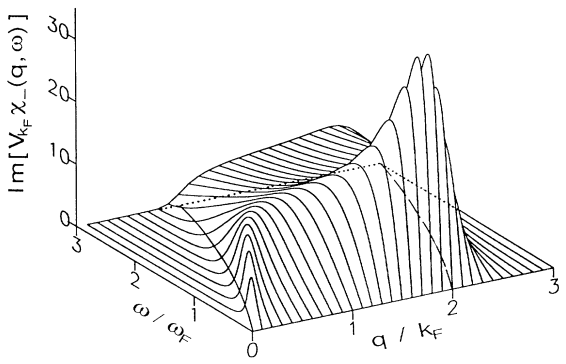

FIG. 2. $\mathrm{Im}\chi_-(\mathbf{q},\omega)$ for $r_s = 7.3$. There is no plasmon collective mode. Note the large peak near $\mathbf{q} = 1.9k_F$ for small ω. $v_{k_F} = 2\pi e^2/k_F$ where k_F is the Fermi momentum. The spacing between the layers is $a = 25$ nm, the sample temperature is $T = 500$ mK, and the mobility of the sample is $\mu = 10^5$ V cm^{-2}.

$\mathbf{q} \approx 1.9k_F$ and small ω would be observable using standard Raman scattering techniques.

We can follow the position of the charge density wave precursor peak as a function of density for fixed values of the layer spacing, temperature, and defect scattering rate. Figure 3 shows the imaginary part of the total response function as a function of ω at fixed $\mathbf{q} = 1.9k_F$. For $a = 25$ nm the actual instability occurs at $r_s = 7.63$, and as the density is lowered towards this value the peak grows sharper and moves towards zero ω in a manner analogous to the paramagnon peak in spin systems. The sharpness of the peak very close to the transition is lim-

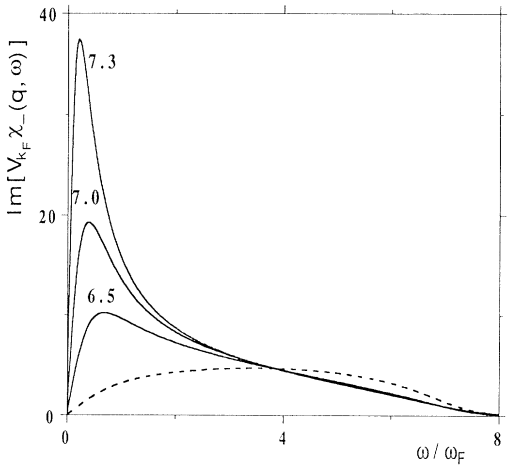

FIG. 3. $\mathrm{Im}\chi_-(\mathbf{q},\omega)$ at $\mathbf{q} = 1.9k_F$ as a function of layer density. The actual instability occurs at $r_s = 7.63$. The labels on the curves refer to the r_s values. The dotted line shows $\mathrm{Im}\chi_0(\mathbf{q},\omega)$ which for these axes is r_s independent. The spacing between the layers, the sample temperature, and mobility are as in Fig. 2.

ited primarily by defect scattering. For electrons in gallium arsenide at density $r_s = 5$ the momentum transfer $\mathbf{q} = 1.9k_F$ corresponds to 5×10^5 cm^{-1} which is within the current observing range for Raman scattering [29].

The calculation is unchanged if there are two layers of holes rather than electrons. Recently Santos *et al.* [30], taking advantage of the larger effective mass of holes in gallium arsenide, have reported the fabrication of high mobility single layers of holes at densities much lower than $r_s = 5$.

The above results have been deduced from the dielectric response function $\chi_{ll'}(\mathbf{q},\omega)$ where $l, l' = 1, 2$ number the layers and $\mathbf{q}$ is the wave vector within the plane of the layer. The response function has two eigenvalues

$$\chi_{\pm}(\mathbf{q},\omega) = \frac{\chi^s(\mathbf{q},\omega)}{1 + \{V_{11}(\mathbf{q})\ [1 - G(\mathbf{q})] \pm V_{12}(\mathbf{q})\}\chi^s(\mathbf{q},\omega)}\ , \tag{1}$$

corresponding to the two density eigenvectors $\delta n_{\pm}(\mathbf{q})$. The + and − label density modulations in the two layers that are in phase (+) and opposite in phase (−). $\chi^s(\mathbf{q},\omega)$ is the single-particle (proper) response function within a layer, $V_{11}(\mathbf{q})$ and $V_{22}(\mathbf{q})$ are the bare Coulomb interactions within each layer, and $V_{12}(\mathbf{q})$ is the bare Coulomb interaction between layers. $V_{11}(\mathbf{q})$, $V_{22}(\mathbf{q})$, and $V_{12}(\mathbf{q})$ all incorporate form factors due to the envelope functions in the direction perpendicular to the layer [27].

The static local field within a layer $G(\mathbf{q})$ is deduced [8, 27] from Monte Carlo numerical simulation data for the ground state of the two-dimensional electron liquid [31]. The $G(\mathbf{q})$ affects the magnitude of the static polarizabilities of the layers which in turn determine the position of the liquid ground state instability. We know from the data in Ref. [31] that even though electron correlations are important in the electron liquid at these densities, a local field can accurately parametrize the ground state properties of each layer.

Elastic scattering by defects in real samples is included by introducing a single-particle memory function $\gamma^s(\mathbf{q},\omega)$ [8] into the expression for $\chi^s(\mathbf{q},\omega)$,

$$\chi^s(\mathbf{q},\omega) = \frac{\chi^0(\mathbf{q},\omega - \gamma^s)}{1 + \frac{\gamma^s}{\omega - \gamma^s}\left[1 - \frac{\chi^0(\mathbf{q},\omega-\gamma^s)}{\chi^0(\mathbf{q})}\right]}\ , \tag{2}$$

where $\chi^0(\mathbf{q},\omega)$ is the finite temperature response function for the noninteracting electron gas (the Lindhard function). For noninteracting electrons Eq. (2) corresponds to Götze's generalized relaxation time approximation [32]. We are mainly interested in relatively clean systems so γ^s can be approximated by a single imaginary parameter $(i\tau)^{-1}$ in which case Eq. (2) agrees with Mermin's expression [33] for the response function. The transport relaxation time τ is the time between successive scatterings of the electron off defects and is related to the electron mobility μ parallel to the layer by the usual Drude expression.

We numerically determined the acoustic plasmon dispersion curve in Fig. 1 by following the zero in the denominator of Eq. (1) for zero T and γ^s.

The charge density wave instability in the liquid state is also caused by the denominator of Eq. (1) going to zero but this time in the limit of $\omega = 0$ in the region near $\mathbf{q} \approx 1.9k_F$. Since our $\mathrm{Re}\chi^0(\mathbf{q})$ is positive for this value of $\mathbf{q}$ the denominator can only vanish if $V_{11}(\mathbf{q})[1 - G(\mathbf{q})] - V_{12}(\mathbf{q})$ is negative. For low densities $G(\mathbf{q})$ develops a peak higher than unity in this region of $\mathbf{q}$. The interlayer potential $V_{12}(\mathbf{q})$ is larger when the layers are close together and this pushes the denominator of Eq. (1) even closer to zero. We conclude from this that the instability is more likely to occur when the layer density is low and the layers are close together.

The instability is not the same as the well-known charge density wave instability which occurs at $\mathbf{q} = 2k_F$ within the Hartree-Fock approximation for the electron liquid. This can be recognized from the fact that the instability results from the vanishing of the denominator in Eq. (1). It does not appear when there is only a single layer.

We have omitted the effect of correlations between electrons from different layers since a more complete calculation including such correlations shows that interlayer correlations do not affect the nature of the transitions nor the low-lying excitation spectrum and for a given layer spacing the density at which charge density wave instabilities occur decreases only fractionally [34].

We conclude that many-body correlations between electrons significantly affect the nature of the low-lying excited states of two-layer electron systems at densities as high as $r_s = 5$. They destroy the lowest-lying RPA plasmon as a separate mode when the separation between layers is still sufficiently large to prevent tunneling and this effect should be observable using currently available samples. The new quasisoft mode peak in the imaginary part of the liquid dielectric response function $\chi_-(\mathbf{q},\omega)$ occurs around $\mathbf{q} = 1.9k_F$ which for an electron liquid at density $r_s = 5$ in gallium arsenide corresponds to a momentum transfer of 5×10^5 cm^{-1}, a value which is within the current observing range for Raman scattering [29]. Experimental observation of this quasisoft mode peak would be strong evidence for the existence of a charge density wave instability.

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