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Effective mass enhancement in two-dimensional electron systems: the role of interaction and disorder effects

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Abstract

Recent experiments on two-dimensional (2D) electron systems have found a sharp increase in the effective mass of electrons with decreasing electron density. In an effort to understand this behavior we employ the many-body theory to calculate the quasiparticle effective mass in 2D electron systems. Because the low density regime is explored in the experiments we use the GWΓ approximation where the vertex correction Γ describes the correlation effects to calculate the self-energy from which the effective mass is obtained. We find that the quasiparticle effective mass shows a sharp increase with decreasing electron density. Disorder effects due to charged impurity scattering plays a crucial role in density dependence of effective mass.

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There has been a large amount of experimental and theoretical activity in recent years to understand the ground state properties of homogeneous two-dimensional (2D) electron systems. Advances in fabrication techniques have made it possible to probe various quantities of interest in high quality and very low density samples. Most notably, the observation of a metal–insulator transition [1] in these systems provides a major motivation to study the various physical properties. In recent experiments the spin susceptibility, Lande g-factor, and effective mass are measured for 2D electron systems made of Si-MOSFETS and GaAs quantum-well structures [2–7]. In particular, Shashkin et al. [3,4] reported a sharp increase of effective mass near the critical density at which the system starts to show deviations from the metallic behavior. At the same time, Pudalov et al. [2] have also found similar enhancement of the spin susceptibility in their samples.

There has been a number of calculations of the quasiparticle properties including the effective mass of 2D electron gas employing a variety of approximations [8]. More recent theoretical calculations of the effective mass of 2D electrons concentrated on the density, spin polarization and temperature dependence [9–13].

In view of the different experimental results and their controversial interpretation, we have addressed in this work the density dependence of the effective mass in an interacting electron system at $T = 0$ in the presence of charged impurities. We employ the GWΓ approximation [14] which includes the vertex corrections in an approximate way to calculate the quasiparticle effective mass. The local-field factor describing the correlation effects which enters the vertex function Γ is obtained within the memory function formalism and the self-consistent field method. We had previously shown [15] that such an approach correctly describes the anomalous behavior of the thermodynamic compressibility of 2D electron systems as reported experimentally [16]. In the present work, we extend our earlier considerations to calculate the effective mass. We find that

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the quasiparticle effective mass is greatly enhanced at low density in the same region when the compressibility diverges.

In the following we first outline the theoretical framework with which we calculate the quasiparticle effective mass of 2D electron system. We next present our results within various levels of approximations. We discuss the results of our calculations in view of other theoretical approaches and experimental findings. We conclude with a brief summary.

We consider a 2D electron system interacting via the long range Coulomb interaction $V_q = 2\pi e^2/(\epsilon_0 q)$ where ϵ_0 is the background dielectric constant. The system is characterized by the dimensionless interaction strength $r_s = 1/(\pi n a_B^{*2})^{1/2}$, where n is the 2D electron density and $a_B^* = \hbar^2\epsilon_0/(me^2)$ is the effective Bohr radius defined in terms of the band mass m of electrons in the semiconductor structure.

We use the theoretical framework developed by Thakur et al. [17] employing the memory-function formalism and the self-consistent field method to calculate the density–density response function of a disordered electron system. The effect of disorder is to dampen the charge–density fluctuations and modify the response function. In a number-conserving approximation the density–density response function for noninteracting electrons is given by

$$\chi_0(q,\omega;\gamma) = \frac{\chi_0(q,\omega+i\gamma)}{1-\dfrac{i\gamma}{\omega+i\gamma}\left[1-\dfrac{\chi_0(q,\omega+i\gamma)}{\chi_0(q)}\right]} \tag{1}$$

where γ is the scattering rate. The correlation effects are described by the generalized random-phase approximation (RPA) for the interacting system density–density correlation function

$$\chi(q,\omega;\gamma) = \frac{\chi_0(q,\omega;\gamma)}{1-V_q[1-G(q)]\chi_0(q,\omega;\gamma)} \tag{2}$$

in which the static local-field factor $G(q)$ embodies the correlation effects. In this work we use the self-consistent field method of Singwi et al. [18] to calculate $G(q)$. As a simplified model we also consider the Hubbard local-field factor given as $G(q) = q/2\sqrt{q^2+k_F^2}$.

Within the memory-function formalism the scattering rate is expressed in terms of the screened disorder potential and the relaxation function as [17,19]

$$i\gamma = -\frac{n_i}{2mn}\sum_q q^2\frac{\langle|U_{imp}(q)|^2\rangle}{\varepsilon^2(q)}\frac{\phi_0(q,i\gamma)}{1+i\gamma\dfrac{\phi_0(q,i\gamma)}{\chi_0(q)}} \tag{3}$$

where $U_{imp}(q) = V_q e^{-qd}$ is the impurity potential for charged impurities located at a distance d away from the 2D electron layer, and n_i is the impurity concentration. The relaxation function is given by [17,19] $\phi_0(q,i\gamma) = [\chi(q,i\gamma) - \chi_0(q)]/(i\gamma)$ and $\varepsilon(q) = 1 - V_q[1-G(q)]\chi_0(q)$ is the static screening function. Because the scattering rate γ depends on the screening function $\varepsilon(q)$ which itself is determined by the disorder included response function the above set of equations are solved self-consistently.

The quasiparticle properties of the 2D electron system are obtained from the self-energy function [14] $\Sigma(k,\omega)$ which we calculate at zero temperature. Since we are interested in exploring the interaction effects we include the vertex corrections to the self-energy and employ the GWΓ approximation [14]. The self-energy in the GWΓ approximation is written as a sum of two terms $\Sigma(k,\omega) = \Sigma^{line}(k,\omega) + \Sigma^{pole}(k,\omega)$, where

$$\Sigma^{line}(k,\omega) = -\sum_q V_q\int_{-\infty}^{\infty}\frac{d\omega'}{2\pi}\frac{\Gamma(q,i\omega')}{\varepsilon(q,i\omega')} \times\frac{1}{\omega+i\omega'-\xi_{k+q}} \tag{4}$$

and

$$\Sigma^{pole}(k,\omega) = \sum_q V_q[\theta(\omega-\xi_{k+q}) - \theta(-\xi_{k+q})] \times\frac{\Gamma(q,\xi_{k+q}-\omega)}{\varepsilon(q,\xi_{k+q}-\omega)} \tag{5}$$

in which $\xi_k = k^2/2m - E_F$ is the single-particle energy measured relative to the Fermi energy. The vertex function in the local-approximation is given as [14]

$$\Gamma(q,\omega) = \frac{1}{1+V_q G(q)\chi_0(q,\omega;\gamma)} \tag{6}$$

in terms of the local-field factor $G(q)$ describing correlation effects beyond the RPA. The dielectric function appearing in Eqs. (4) and (5) is given by $\varepsilon(q,\omega) = 1 - V_q\chi_0(q,\omega;\gamma)\Gamma(q,\omega)$. The above expressions for the self-energy reduce to the GW–RPA results when we set $G(q) = 0$. Furthermore, taking $\gamma = 0$, we recover the results for a clean system.

We use the on-shell approximation to the self-energy in the single particle spectrum $E_k = \xi_k + \Sigma(k,\xi_k)$ to obtain the effective mass perturbatively [8,11,14]

$$\frac{m^*}{m} = \left[1+\frac{\partial\Sigma}{\partial\omega}+\frac{m}{k}\frac{\partial\Sigma}{\partial k}\right]^{-1}, \tag{7}$$

where the frequency and momentum derivatives of $\Sigma(k,\omega)$ are evaluated at the Fermi surface. Such an approach is argued to be more appropriate over solving the full Dyson's equation $E_k = \xi_k + \Sigma(k,E_k)$, since the self-energy is calculated using the noninteracting Green function. The resulting scheme incorporates the higher order diagram contributions better [8,11,14].

In the numerical calculations we specialize to GaAs systems for which some measurements of the effective mass are undertaken [6]. Since the dominant scattering mechanism is known to be that due to the charged impurities we take $d = 250$ Å, for the setback distance in $U_{imp}(q)$, and consider n_i to be of the order of $\sim 10^{10}$ cm^{-2}. We first solve the self-consistent equations for the scattering rate γ and the

local-field factor $G(q)$ as a function of r_s and impurity density n_i. These quantities determine the dynamic screening function $\varepsilon(q,\omega)$ and the vertex function $\Gamma(q,\omega)$. Afterward the self-energy and its derivatives are evaluated to find the effective mass m^*/m.

In Fig. 1 we show the effective mass m^*/m as a function of r_s calculated in various theoretical approaches. We observe that even at these relatively higher densities there are notable differences between the GW and GWΓ approximations indicating the importance of vertex corrections. It appears that the correlation effects suppress the effective mass renormalization. The disorder effects due to charged impurity scattering tend to increase the effective mass with respect to the clean system. There is still a significant reduction in m^*/m, however, compared to the GW–RPA result.

We next display the quasiparticle effective mass at much lower densities. Strictly speaking, GW approximation is valid only in the high density limit, inclusion of the vertex corrections in GWΓ approximation improves the regime of validity. In any case, we wish to explore the effective mass trends in the low density, strongly interacting region. Fig. 2 shows m^*/m calculated in various theoretical approaches. GW–RPA yields a modest enhancement for the whole density range. The suppression found in Fig. 1 for the GWΓ approximation reverses its behavior around $r_s \approx 4$ and shows an enhancement relative to the GW–RPA results at lower densities. Qualitatively similar behavior is obtained when we use the simple Hubbard local-field factor within the GWΓ approximation. A notable feature of the GWΓ approximation results is that effective mass exhibits a sharp increase around $r_s \sim 8$. That the strong interaction effects would lead to a large enhancement in m^*/m is also evident when the Hubbard local-field factor is used within the GWΓ approximation. Finally, when charged impurity scattering effects are included in the calculation we find that a similar sharp increase in m^*/m occurs at a smaller r_s value. We have also calculated the effect of impurity scattering for different parameter values of d and n_i and found qualitatively similar results.

Although the results of GW and GWΓ approximations at large r_s should be taken in with caution, the low density trends of m^*/m should be indicative. In this perspective our calculations indicate that the effective mass enhancement in 2D electron systems can be accommodated within the Fermi liquid theory when the vertex corrections describing the strong correlation effects are taken into account. In particular, a sharp increase in m^*/m as shown in Fig. 2 is quite suggestive in view of the recent experimental findings [3,4]. Effective mass enhancement is also observed in 2D neutral Fermi systems [20] and represented by a GW-type calculation [21]. Our calculations also show that the r_s value at which m^*/m exhibits a sharp increase can be controlled by disorder effects. In a self-consistent scheme where remote charged impurities are taken into account we find that the large enhancement in m^*/m occurs at a higher density compared to the strongly interacting clean system.

Recent theoretical approaches [9,10] have modeled the low density electron liquid as close to the Wigner crystallization to obtain a strong increase in the effective mass. On the other hand, Morawetz [12] found a divergent behavior in m^*/m at the metal–insulator transition by considering the scattering from heavy impurity ions, and Galitski and Khodel [13] attribute divergence of the effective mass to the

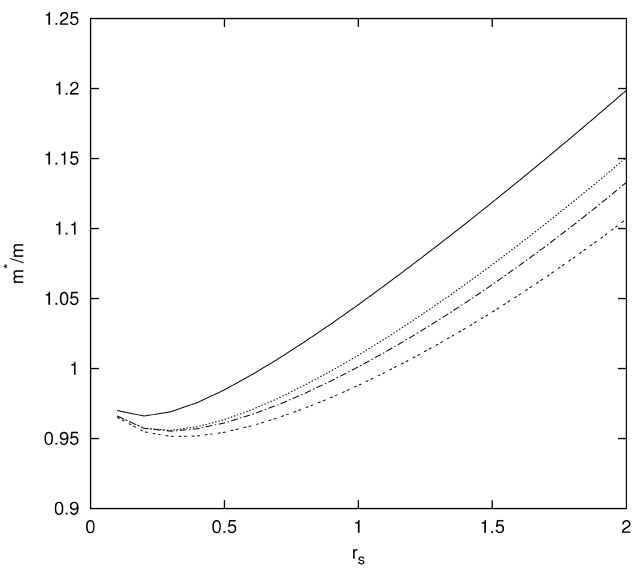

Fig. 1. The quasiparticle effective mass as a function of r_s in the range $0 < r_s < 2$. The solid and dot-dashed lines indicate the GW–RPA and GWΓ approximations, respectively. GWΓ approximation which uses the Hubbard local-field factor is indicated by the dotted line. GWΓ approximation including the charged impurity scattering (with impurity concentration $n_i = 0.5 \times 10^{10}$ cm^{-2}) is shown by the dashed line.

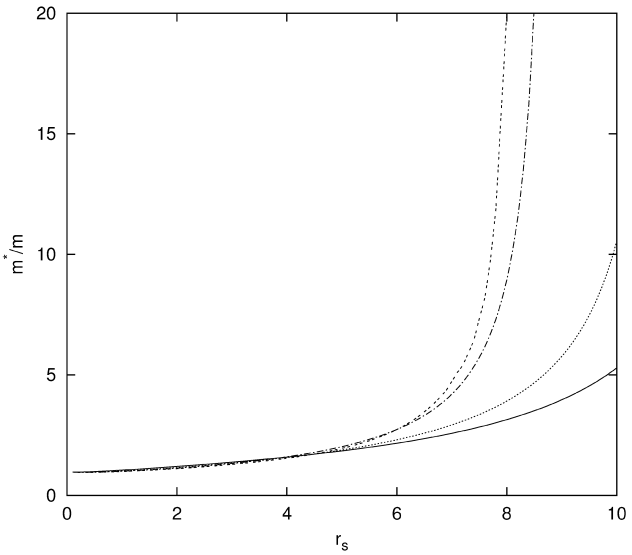

Fig. 2. The quasiparticle effective mass as a function of r_s in the range $0 < r_s < 10$. The solid and dot-dashed lines indicate the GW–RPA and GWΓ approximations, respectively. GWΓ approximation which uses the Hubbard local-field factor is indicated by the dotted line. GWΓ approximation including the charged impurity scattering (with impurity concentration $n_i = 0.5 \times 10^{10}$ cm^{-2}) is shown by the dashed line.

density wave instability. Our theoretical scheme considers the metallic regime, therefore we cannot distinguish the nature of the possible new state beyond the critical r_s value. However, our earlier calculations [15] of the anomalous behavior of the compressibility at around the same range of r_s values points to a possible metal–insulator transition approaching from the metallic side. A related quantity of interest would be the spin susceptibility or the g-factor for which experimental results are available. These quantities require the calculation of density–density response function and the local-field factor as functions of the spin polarization which were not undertaken in this work.

Our calculations were performed at $T = 0$ and for zero thickness 2D electron layers. It would be interesting to extend our work to finite temperatures and to finite width quantum wells to make better contact with experiments. As the Coulomb interaction effects will be less strong in quantum wells, it is expected that the enhancement of m^*/m will be less marked.

In summary, within a many-body approach which takes the electron–electron and electron–impurity interaction effects into account we have calculated the effective mass of a 2D electron system at zero temperature. We have found within the commonly used on-shell approximation that m^*/m is highly enhanced at larger values of the density parameter r_s as a result mainly of the correlation effects. The interplay between the correlation effects and the impurity scattering influences qualitative changes in this behavior. Our comparative results should provide insight into the workings of many-body methods in the strong interaction regime.

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