TWO-DIMENSIONAL ELECTRON-HOLE METALLIC LIQUIDS

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ABSTRACT

The ground state energy of two-dimensional electron-hole liquids is calculated in the generalized random phase approximation. It is shown that the cohesive energy per electron-hole pair exceeds the binding energy of a two-dimensional exciton in the case of a system with two conduction band minima and a single valence band maximum with a heavier effective mass. A possibility of producing electron-hole "pancakes" in layer-type semiconductors is pointed out. The many-body correction of the effective masses and dispersion relations of collective modes are also derived. Finally the condition for occurrence of excitonic phases is discussed.

I. INTRODUCTION

Electron-hole metallic liquids in semiconductors such as Ge and Si have been investigated in detail. Theoretical analyses[1)] have shown that the nature of band structures of these semiconductors plays an important role in stabilizing the liquid phase. Recently remarkable progress has also been made in study of semiconductors with large anisotropy. It would be interesting to see how strong anisotropy in energy bands influences the stability of the electron-hole metallic liquid (EHL). From this standpoint we will study a system of two-dimensional (2D) electron-hole metallic liquids in this paper.[2)] Such a system will be realized in layer-type semiconductors with both conduction and valence bands being two-dimensional. We note that the observation of 2D indirect excitons has been reported in a layer-type semiconductor GaSe.[3)] The binding energy of a 2D free exciton is four times larger than that of a 3D one. In this paper we show that the cohesive energy of the 2D EHL is more than four times larger than that of the 3D one in the case of a system with a suitable many-valley structure in energy bands. This means that the EHL in the 2D system is energetically more stable than that in the 3D one. We also calculate excitation spectra of quasi-particles and collective modes. Further we discuss a possibility of the formation of electron-hole "pancakes" in highly excited layer-type semiconductors. Effects of van der Waals interaction between layers is also examined. Finally the condition for the occurrence of excitonic phases is discussed.

II. GROUND STATE ENERGY

We consider a 2D model of a layer-type semiconductor in which electrons in a conduction band and holes in a valence band with effective masses m_e and m_h respectively are confined in a single layer. The coulomb interaction in an anisotropic medium with dielectric tensor components $\epsilon_\parallel$ and $\epsilon_\perp$ is given by

$$V(\rho,\ Z) = \frac{e^2}{\sqrt{\epsilon_\parallel \epsilon_\perp}} \left(\rho^2 + \frac{\epsilon_\perp}{\epsilon_\parallel} Z^2\right)^{-\frac{1}{2}}, \quad \rho = (x,\ y)\ . \tag{1}$$

The ground state energy per electron-hole pair of the metallic state is calculated as a function of the interparticle spacing r_s defined by $\pi(r_s a_B)^2 = S/N_p$, where a_B is the exciton Bohr radius $\sqrt{\epsilon_\parallel \epsilon_\perp}\hbar^2/\mu e^2$, N_p/S the density of electron-hole pairs. First we consider a simple system in which each of conduction and valence bands has a single valley. Then the ground state energy ε_{tot} is given by

$$\varepsilon_{tot} = r_s^{-2} - 2.401\ r_s^{-1} + \varepsilon_{corr}\ , \tag{2}$$

where energies are measured in unit of the effective Rydberg defined as $e^2/(2\sqrt{\epsilon_\parallel \epsilon_\perp}\, a_B)$. The correlation energy ε_{corr} depends on the effective mass ratio $\sigma \equiv m_e/m_h$ of electrons to holes and is calculated in the generalized RPA. The calculated results of ε_{tot} are shown in Fig. 1,[2] where those of the 3D system are also shown for comparison. The results

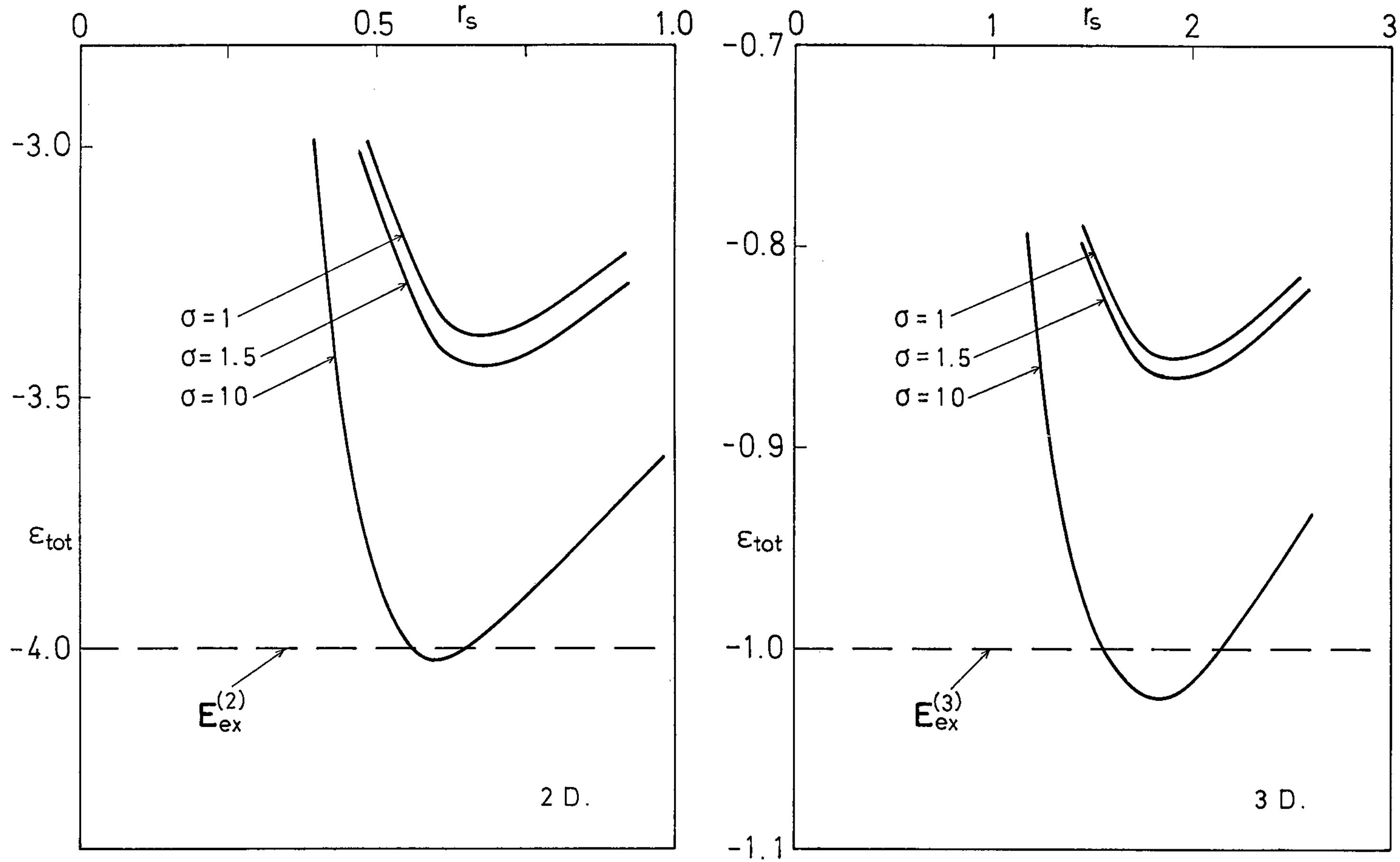

Fig.1. Ground state energies per electron-hole pair in the 2D system (left) and the 3D one (right) without many-valley structures in energy bands. Dashed lines indicate the binding energies of free excitons.

indicate that for each value of σ the minimum of ε_{tot} in the 2D system is about four times as deep as that in the 3D system, and that the values of r_s at the minimum of ε_{tot} are about three times smaller than that in the 3D system. These circumstances may correspond to the difference in binding energies and radii of free excitons in the 2D and the 3D systems.

Next we discuss effects of many-valley structures on the ground state energy of the 2D EHL. As an example we consider a case where a conduction band has two minima and a valence band has a single maximum. The kinetic energy of electrons is reduced by the existence of many valley structure and therefore the EHL is more stabilized.[2)] The calculated results are shown in Fig. 2 together with these in the corresponding 3D system. In the case of $\sigma = 1$ the cohesive energy in the 2D system is again four times as large as that in the 3D one. In contrast with the previous case of a single extremum for each band, however, ε_{tot} in the 2D system depends more strongly on σ. As a result, the cohesive energy in a 2D system becomes more than four times larger than that in a 3D system as σ becomes smaller than unity. We therefore conclude that the effect of many-valley structures on the cohesive energy of the EHL is more prominent in the 2D system when the conduction band has a many-valley structure with the effective mass being lighter than that of the valence band.

III. EXCITATION SPECTRA

We now investigate the excitation spectra of the 2D EHL. First the many-body correction of the effective masses is derived in the generalized RPA and compared with that of the 3D system. We consider the case of a single-valley with $m_e = m_h \equiv m$. The effective mass m^* of an electron-like quasi-particle (or a hole-like quasi-particle) is calculated by the equation

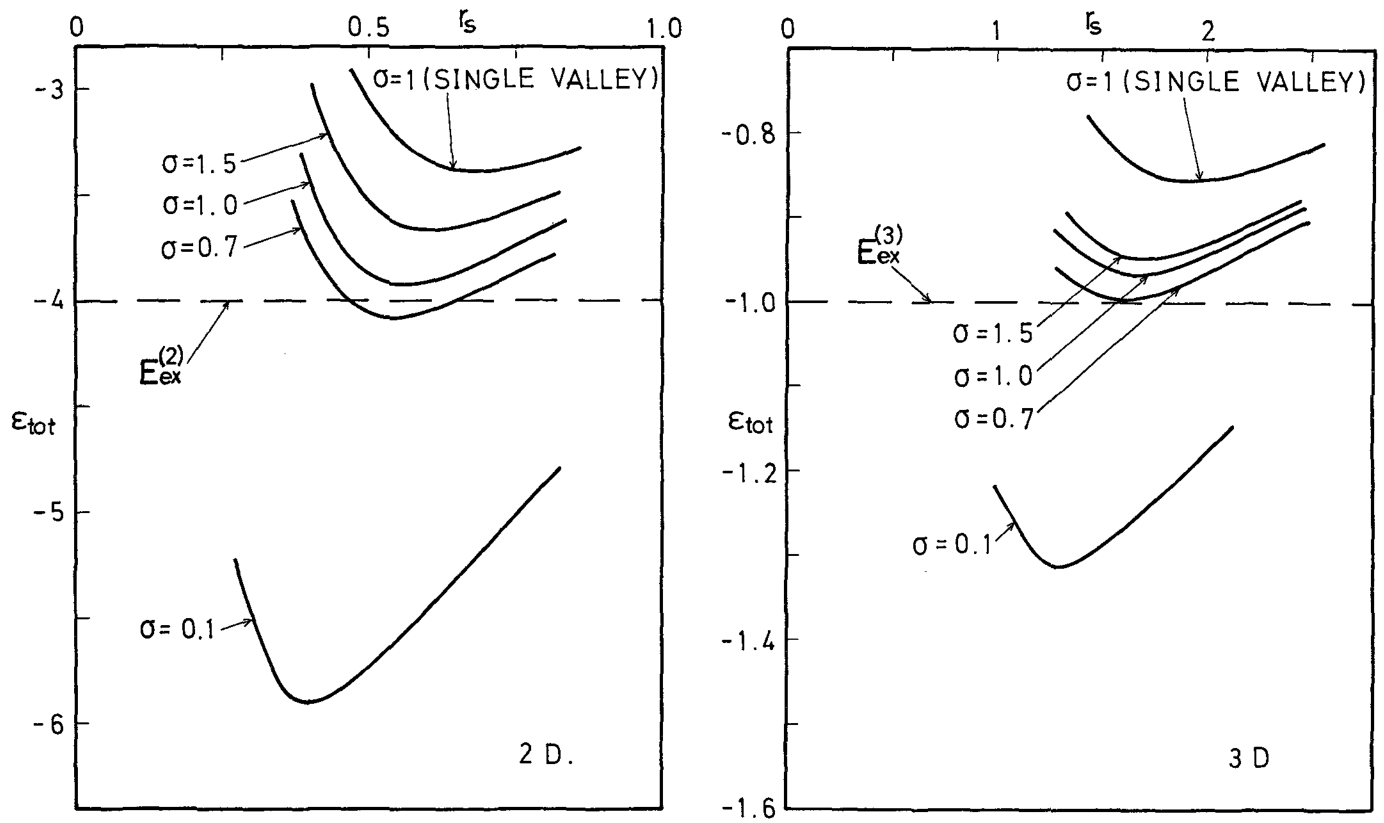

Fig.2. Ground state energies in the case of two minima in the conduction band and a single maximum in the valence band.

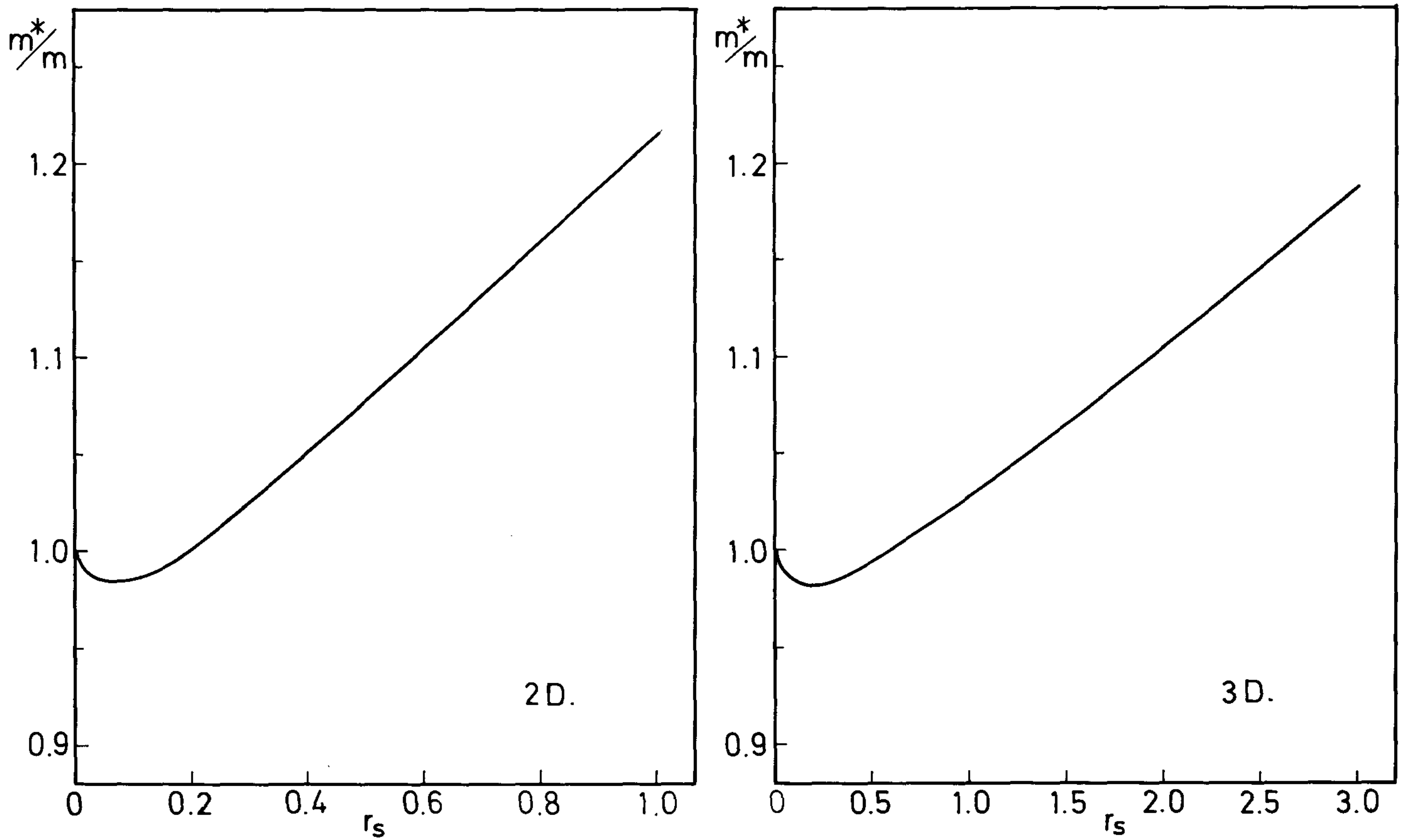

Fig.3. Effective masses of quasi-particles in the 2D system (left) and in the 3D one (right).

$$\frac{1}{m^*} = \frac{1}{m} + \frac{1}{\hbar^2 k_F}\left[\frac{d}{dk}\,\Sigma\,\left(k,\omega = \frac{\hbar k^2}{2m}\right)\right]_{k=k_F}, \tag{3}$$

where k_F is the Fermi wave number and $\Sigma\,(k,\omega)$ the self-energy of an electron (or of a hole) in the generalized RPA. The computational procedure is similar to that in the case of the 3D electron liquid.[4)] We show the calculated results of m* in Fig. 3 together with those of the 3D EHL. The magnitude of m* in the 2D system is nearly equal to that in the 3D one when r_s in the former system becomes three times smaller than that in the latter one. We note that the effective mass in each system is enhanced by about 10% at the most stable density of the EHL.

Next we discuss collective modes.[2)] One of them is a 2D plasmon mode and its dispersion relation is given by

$$\omega_p(q) = \left(\frac{2\pi e^2 N_p q}{\sqrt{\epsilon_{\parallel}\epsilon_{\perp}}\,\mu S}\right)^{\frac{1}{2}}, \tag{4}$$

in the small wave number region with neglect of small polariton effects.[5)] The $\sqrt{q}$ dependence is explained by the absence of the depolarizing field against the uniform charge displacement in a 2D system. If the holes are quite heavier than electrons (or the other way round), an acoustic mode also becomes a well defined collective mode. Since the screened short-range interaction is responsible for this mode, the dispersion relation in the 2D system is rather close to that in the 3D system.[2)]

IV. DISCUSSION

On the basis of the results obtained in the previous sections we now discuss a possible situation which will occur when a layer-type semiconductor is highly excited by a laser or by other means and 2D electrons and holes are densely generated. If the semiconductor has a suitable many-valley structure as discussed in Sec. II, the EHL state is more stable than a free exciton state and possibly than a state of free excitonic molecules. In such a case we can expect that clusters of the metallic state will appear at low temperatures with appropriate averaged densities of electrons and holes. Since the metallic state thus produced in a 2D layer is supposed to take a pancake shape so as to minimize the boundary energy, we call it an electron-hole pancake (EHP). It is likely to occur that some EHP's in nearby layers aggregate balancing the gain of mutual polarization energy with the cost of entropy of individual motion. The additional contribution of the mutual polarization to the cohesive energy is estimated to be 3% when the spacing of interacting two layers is half the exciton Bohr radius. The interaction between EHP's in different layers is of van der Waals nature and is quite different from the interaction within a layer. Therefore we expect that a possible aggregate of EHP's would also be pancake-shaped and be highly anisotropic. This anisotropy may be observed in light scattering experiments.[6] If the EHL is composed of N layers, the frequency of the plasmon is $\sqrt{N}$ times higher than that given by eq. (4).[2] In the limit of $N = \infty$, it becomes equal to the 3D plasmon frequency which is given by

$$\omega_{p,\infty} = \left(\frac{4\pi e^2 N_p}{\mu \epsilon_\perp c S} \right)^{\frac{1}{2}} \tag{5}$$

where c is the spacing of the successive layers. Therefore the degree of aggregation along the axis perpendicular to layers is reflected on the behavior of the collective mode in an EHL.

Finally we briefly discuss the condition for the occurrence of excitonic phases. As has been shown in the present paper, the EHL phase becomes more stable for more complicated band structures. This means that the occurrence of excitonic phases becomes more severe for more complicated band structures. From this standpoint Kamimura and

Kuramoto[7] have recently investigated a 3D system with a simple band structure of two conduction band minima and a single valence band maximum in order to find the most generous condition for the occurrence of excitonic phases. In this case they have concluded that the excitonic phase occurs only when the effective mass of an electron is 0.7 times heavier than that of a hole. On this ground we suggest that the first order semiconductor-semimetal transition bypassing excitonic phases is likely to occur in many real indirect gap semiconductors when one reduces the energy gap continuously.

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