Renormalization of the spectrum of in-depth excitations below the Fermi level in a two-dimensional electron system with strong interaction

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The dependence of quasiparticle Fermi energy on electron density is investigated by analyzing radiative recombination spectra of two-dimensional electrons with photoexcited holes bound to remote acceptors. This method enables us to measure the dependence of renormalized quasiparticle mass on the concentration of two-dimensional electrons. It is established that with decreasing electron density (increasing parameter r_s up to 4.5) the density-of-states effective mass of quasiparticles increases by 35% compared to the cyclotron electron mass. It is shown that in a perpendicular magnetic field the concept of quasiparticles in a two-dimensional Fermi liquid is applicable not only near the Fermi level but also deep below the Fermi surface, down to the bottom of the size-quantization band, since the broadening of excitations appears to be much less than their energy. The effective mass and broadening of quasiparticles were found to be significantly dependent on their energy measured from the Fermi surface down to the very bottom of the size-quantization band.

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I. INTRODUCTION

In 1956 Landau proposed his theory of Fermi liquid to describe the low-temperature properties of electron systems with strong interaction [1]. The fundamental idea of this theory is that at low temperatures all the properties of such a strongly correlated system can be described in terms of noninteracting quasiparticles whose number is equal to that of real electrons; the distribution function of quasiparticles is described by Fermi statistics, and their dispersion can be strongly modified by the interaction. The simplest example of such a modification is mass renormalization as a result of which the quasiparticle mass can essentially differ from the electron mass, and the stronger the interaction is, the stronger the effects of mass renormalization are. The measure of the electron-electron interaction strength is the parameter

$$r_S = 1/[a_B(\pi n_S)^{1/2}], \tag{1}$$

where n_S is the concentration of two-dimensional electrons and a_B is the Bohr radius, equal to the ratio between Coulomb and Fermi energies. The modified quasiparticle mass is independent of temperature and magnetic field and is a theory parameter dependent only on the strength of electron-electron interaction. Another conclusion of the Landau Fermi-liquid theory is that the quasiparticle energy calculated from the Fermi surface is also characterized by an imaginary part (attenuation) which is minimal on the Fermi surface and grows quadratically as the energy deviates from the Fermi surface. This results in the conclusion of the Landau theory that the quasiparticles are well defined only near the Fermi surface and cease to exist well below the Fermi surface. For Landau's theory this statement is acceptable as it claims to describe the low-temperature properties of the electron system, i.e., when only a small number of excitations originates thermally near the Fermi surface. These thermal excitations are neutral pairs of quasielectrons and quasiholes created above and below the Fermi surface, respectively. The Fermi-liquid theory was constructed [1–5] for three-dimensional electron systems, yet as shown later, the basic conclusions of the theory are also applicable to two-dimensional electron systems [6,7] and magnetic field [8].

For the weak interaction in the three-dimensional case Abrikosov and Khalatnikov [5] derived the relationship connecting the renormalized mass in an electron Fermi liquid m_e^{FL} and the electron-electron interaction potential $V(r)$:

$$\frac{m_e^{\mathrm{FL}}}{m_e} = 1 + ak_F^2, \tag{2}$$

where k_F is the Fermi momentum, m_e is the electron mass, and a is the scattering length that, in the Born approximation, is given by the expression

$$a = \frac{m_e}{4\pi\hbar^2}\int V(r)d^3x. \tag{3}$$

The experimental techniques of the investigation of the Fermi-liquid effects in the strongly interacting electron system usually involve temperature studies of the transport properties, namely, analysis of the Shubnikov–de Haas oscillation amplitude [9–13]. Such studies claim to estimate the effect of electron mass renormalization only near the Fermi energy and do not allow analysis of quasiparticle dispersion changes deep below the Fermi surface. These measurements can yield integral Fermi-liquid parameters, $F_0^{a,s}$ and $F_1^{a,s}$, corresponding to the characteristics of the electron-electron scattering potential [14]. A review of the current status of the experimental research performed with an electron Fermi liquid in silicon-based two-dimensional (2D) structures can be found in [15].

However, in two-dimensional semiconductor quantum wells there is an experimental technique that enables direct measurements of the properties of a strongly interacting electron Fermi liquid [16]. The method is based on the measurement of the radiative recombination spectrum of two-dimensional electrons with photoexcited holes bound to remote acceptors. In this case the luminescence spectrum directly reflects the distribution function, the density of states, and quasiparticle (quasihole) attenuation in the Fermi liquid. Indeed, if the acceptor center is located a sufficiently large distance from the two-dimensional channel (an easily satisfied requirement [17]), then, in the initial and final states, the acceptor's influence on the two-dimensional electron properties can be neglected. As a result, in accordance with Fermi's golden rule, the radiative spectrum will appear as a convolution of the quasiparticle density of states (quasiholes in the Fermi sea of two-dimensional electrons) and the acceptor-bound photoexcited hole state. As the energy distribution function of acceptor-bound holes corresponds to the δ function of energy equal to acceptor energy, the radiative spectrum is the product of the density of states and the distribution function of quasiparticles whose spectrum is renormalized by the electron-electron interaction. The recombination process herein looks just like an act of removing an electron (leaving a quasiparticle in its place) from the Fermi sea followed by placing the electron at infinity. Attenuation of such a quasiparticle is greater the deeper it is from the Fermi surface, which is associated with the short scattering time of the quasiparticle upon its rising to the Fermi surface. In a perpendicular magnetic field, as shown in numerous experiments [16], the radiative recombination spectrum of two-dimensional electrons with photoexcited holes bound to remote acceptors is split into Landau levels. The splitting clearly reveals the position of the size-quantization band bottom and the position of the Fermi level. It also allows direct measurements of cyclotron splitting and Landau-level width as functions of quasiparticle energy calculated from the Fermi surface. Thus, this experimental technique makes it possible to measure the key parameters of two-dimensional electron Fermi liquids and their changes with varying electron density.

In the present work we investigate the dependence of quasiparticle Fermi energy on electron density by analyzing radiative recombination spectra of two-dimensional electrons with photoexcited holes bound at remote acceptors, which enables us to measure the dependence of renormalized quasiparticle mass on the concentration of two-dimensional electrons. It is established that with decreasing electron density (increasing parameter r_s up to 4.5), the density-of-states effective mass of quasiparticles increases by 35% compared to the cyclotron electron mass. It is also shown that in the two-dimensional electron system placed in a magnetic field the energy broadening of the quasiparticle levels increases with increasing energy calculated from the Fermi energy, yet this broadening turns out to be less than the quasiparticle energy down to the very bottom of the size-quantization band.

II. EXPERIMENTAL METHOD AND STRUCTURES

We studied high-quality GaAs/AlGaAs quantum wells with a width of 50 nm grown by molecular beam epitaxy in which an acceptor carbon monolayer with an approximate concentration of 0.5×10^{10} cm^{-2} was built at a distance of 40 nm from the heterostructure. In all the structures the thickness of the undoped AlGaAs layer (spacer) was 100 nm, which ensured high mobility of two-dimensional electrons ($\sim 10^7$ cm^2/V s at an electron concentration $\sim 10^{11}$ cm^{-2}). The electron density was varied using specially grown structures with various doping levels, and in addition, the electron concentration could be varied over a certain interval by the photodepletion method [18]. All the structures were enabled to study and compare the recombination spectra and kinetics of two-dimensional electrons with free holes and holes bound to the acceptor monolayer.

As shown earlier [16], in the case of recombination of two-dimensional electrons with photoexcited holes bound to remote acceptors the luminescence spectrum directly reflects the density of states of two-dimensional electrons. The influence of the acceptor center on the luminescence spectrum can be reduced and made negligible by ensuring sufficient distance between the acceptor layer and the two-dimensional channel [17]. The significant spatial separation of the electron channel and the acceptor layer also enables us to increase recombination times up to several microseconds, which, in turn, allows reaching really low temperatures of the two-dimensional electron system (down to 20 mK) even in photoexcitation conditions [16]. All the necessary requirements for spatial separation of electrons and holes were fulfilled in the measurements presented, and therefore, the luminescence spectra could be used for direct measurements of the energy spectrum of the electron Fermi liquid. For instance, in zero magnetic field the luminescence spectrum reflected the constancy of the density of states of two-dimensional electrons, and in perpendicular magnetic field the luminescence spectrum splits into well-defined Landau levels which could be characterized by spectral splitting and broadening. The number of Landau levels observed in the luminescence spectrum corresponded strictly to the filling factor of the electron system. The measurements were made using the optical fiber technique in a dilution cryostat at a base temperature of 20 mK in a magnetic field up to 15 T. Photoexcitation was produced by a tunable titanium:sapphire laser; the characteristic power on the sample did not exceed 50 nW. The luminescence spectra were measured with the use of a U-1000 double spectrometer and a CCD camera cooled by liquid nitrogen. We also studied the concentration dependence of the cyclotron mass of two-dimensional electrons using microwave magnetoplasmon resonance in order to compare this dependence with the similar dependence of the renormalized quasiparticle mass. The cyclotron mass of two-dimensional electrons was determined from analysis of dimensional microwave magnetic plasmon resonance measured by the optical detection method [19]. Within the standard approach it was possible to determine separately the plasma and cyclotron contributions to the hybrid magnetoplasmon resonance frequency, while the electron cyclotron mass was measured from the magnetic field dependence of the cyclotron frequency. An Agilent microwave generator was used to measure the magnetoplasmon resonance in the frequency range of 1–40 GHz.

It was extremely important to develop a very reliable technique which gives the possibility to extract electron density under illumination conditions (especially in the case of samples with very low concentrations). The first method of extraction of electron density is based on measurements of dimensional plasma resonance. It is well known that in the case of finite size of the sample the 2D electron system supports a dimensional plasma mode and the plasma frequency ω_p depends on both the electron density and diameter d of the sample:

$$\omega_p^2 = \frac{4\pi e^2 n_S}{m\epsilon d}, \tag{4}$$

where ϵ is the effective dielectric permittivity of the surrounding medium. Therefore, this method gives the possibility to measure 2D electron density with rather high accuracy even at extremely low concentrations [19].

In order to study microwave dimensional plasma modes of electrons, disk-shaped mesas were fabricated with diameters of 0.5 and 1 mm. Microwave excitation was transferred to the sample by a microwave cable with an antenna at the end. For optical detection of plasma resonances, the sensitivity of the luminescence spectra to resonant microwave absorption was exploited. The technique is based on a comparison between spectra in the absence and presence of microwave radiation. At zero magnetic field, luminescence spectra with and without microwave excitation were recorded consecutively. The differential luminescence spectrum is obtained by subtracting the spectrum without microwave irradiation from the spectrum obtained under microwave excitation. Subsequently, we integrated the absolute value of the averaged differential spectrum over the entire spectral range, and this value was proportional to the microwave absorption amplitude. The same procedure was then repeated for different microwave frequencies. As a result we obtained a spectrum of resonant microwave absorption corresponding to the plasma resonance. This method allowed us to measure the plasma resonance at rather low microwave frequencies (1–30 GHz) under illumination conditions simultaneously with measurements of luminescence spectra.

In Fig. 1(a) we present spectra of resonant microwave absorption measured for two samples with low concentrations. Dimensional plasma resonance is clearly detected in both cases, and the small width of the resonance defines the rather high accuracy of the measured resonant frequency. In order to test the validity of the procedure we investigated the dependence of the resonant plasma frequency on the size of the sample. It is clear from Fig. 1(b) that resonant frequency depends on electron density and the diameter of the structure, in good agreement with formula (4). This fact means that the method based on plasma resonance gives the possibility to detect electron density with high accuracy.

We also used the second method to measure electron density, and this approach is based on the observation of Landau levels in the luminescence spectrum in magnetic field [see Fig. 2(a)]. The filling factor of the 2D electron system is obvious from the number of occupied Landau levels visible in the spectrum. It was possible to extract the 2D electron density from the variation of occupied Landau levels as a function of magnetic field. Such a procedure provides very accurate measurements of electron density for higher concentrations; however, at low densities this method becomes less accurate.

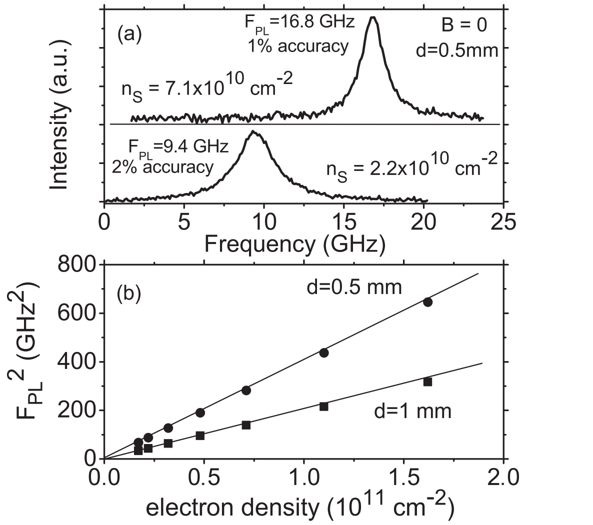

FIG. 1. (a) Spectra of resonant microwave absorption measured at $B = 0T$ for two samples with low concentrations, $d = 0.5$ mm. (b) Dependencies of resonant plasma frequency on electron density measured for two diameters: $d = 0.5$ mm and $d = 1$ mm.

In Table I we present values (and accuracy) of electron densities extracted for seven low-density samples using two methods. Table I illustrates the high reliability of the

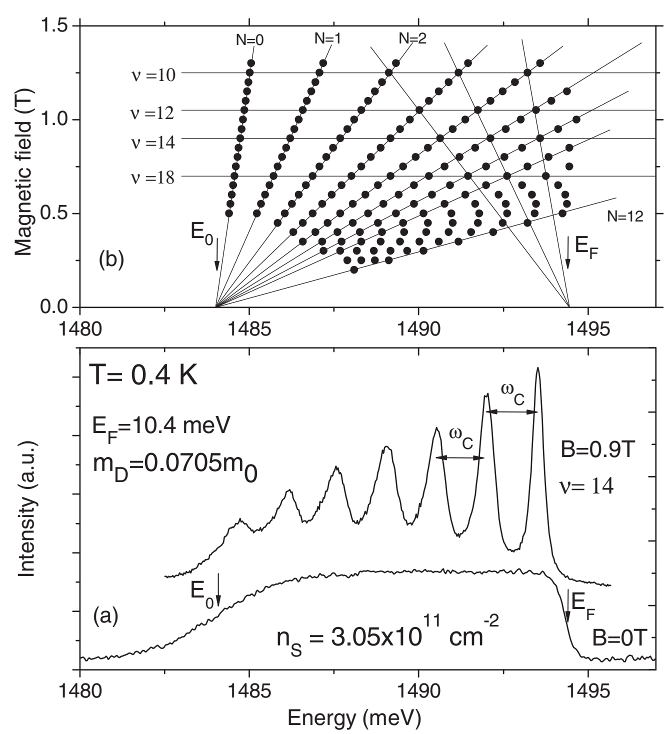

FIG. 2. (a) Radiative recombination spectra of two-dimensional electrons with photoexcited holes bound to remote acceptors measured in magnetic fields $B = 0$ and 0.9 T ($\nu = 14$). (b) The Landau level fan diagram used to determine the spectral position of the size-quantization band bottom and the Fermi energy. The electron concentration in the sample is equal to 3.05×10^{11} cm^{-2}. $T = 0.4$ K.

TABLE I. Values (and accuracy) of electron densities extracted by two methods.

Sample	Density from plasma resonance (10^{11} cm^{-2}) and accuracy (%)	Density from luminescence (10^{11} cm^{-2}) and accuracy (%)
1	0.17, 5%	0.18, 15%
2	0.22, 4%	0.24, 15%
3	0.32, 3%	0.31, 10%
4	0.48, 3%	0.45, 10%
5	0.71, 2%	0.73, 8%
6	1.10, 2%	1.12, 5%
7	1.62, 2%	1.66, 5%

determination of 2D electron concentration, which is very important for our investigations.

III. MEASUREMENT OF DENSITY-OF-STATES MASS

Figure 2(a) shows the characteristic spectra of radiative recombination of two-dimensional electrons with photoexcited holes bound to remote acceptors which were measured at an electron concentration of 3.05×10^{11} cm^{-2} in zero magnetic field and a perpendicular magnetic field $B = 0.9$ T. The distinctive feature of the luminescence spectra at $B = 0$ is that the luminescence intensity is practically independent of energy over a wide frequency range, and the luminescence linewidth appears to be equal to the electron Fermi energy. On the high-energy side the luminescence line exhibits a very sharp threshold, which corresponds to very low temperature of the electron system [see Fig. 2(a), $T = 0.4$ K]. Such a luminescence spectrum reflects the constancy of the density of states of two-dimensional electrons in zero magnetic field as well as the Fermi distribution function. In the simplest model, according to Fermi's golden rule, the recombination spectrum of two-dimensional electrons with remote holes bound to acceptors, at $T = 0$, should be a Θ function with a width equal to the Fermi energy and sharp thresholds on both the high- and low-energy sides. As seen from Fig. 2(a), the spectrum measured in zero magnetic field at low temperatures has a sharp threshold only on the high-energy side, and the low-energy side exhibits broadening occurring due to significant attenuation of quasiparticles (quasiholes below the Fermi level). The observed broadening of the low-energy side of the spectrum does not allow us to reliably and accurately determine the position of the bottom of the size-quantization band. This fact complicates the task of accurate measurement of the Fermi energy of two-dimensional electrons with known electron density. To solve the problem, it is necessary to study the pattern of Landau levels observed in the perpendicular magnetic field.

Figure 2(b) shows a luminescence spectrum measured in the perpendicular magnetic field at $B = 0.9$ T, which corresponds to the filling factor $\nu = 14$ (at electron density 3.05×10^{11} cm^{-2}). It is seen that, in full agreement with filling factor $\nu = 14$, the luminescence spectrum exhibits seven lines (each Landau level is doubly spin degenerate), each of them corresponding to recombination of electrons from different Landau levels. The splitting between the lines is equal to cyclotron energy. A detailed analysis of the spectra shows the following: (a) The widths of the Landau levels are very different; the minimum broadening is observed near the Fermi energy, and the maximum broadening takes place at the bottom of the size-quantization band. (b) The energy splitting between the Landau levels is not the same and depends on the spectral position. The first distinctive feature is in full agreement with the predictions of the Landau Fermi-liquid theory in which quasiparticle broadening is minimal on the Fermi surface and increases appreciably the further it is from the Fermi energy. The other discovered phenomenon is that the quasiparticle mass is not a constant value; instead, the spectrum shows some nonparabolicity.

A detailed study of these phenomena will be given later, but now our first-order interest is the Fermi-liquid density-of-states effective mass of two-dimensional electrons m_e^{FL} and its electron density dependence. To determine the value of m_e^{FL} it is necessary to measure the Fermi energy E_F and then

$$m_e^{\mathrm{FL}} = \frac{\pi \hbar^2 n_S}{E_F}$$

(where $\hbar$ is Planck's constant). Precise measurement of the energy positions of the size-quantization bottom and Fermi energy in the luminescence spectrum requires analysis of the Landau-level fan diagram (the magnetic field dependence of Landau-level energy) presented in Fig. 2(b). The low-energy focus of the fan diagram where all the Landau levels converge allows a highly accurate determination of the position of the size-quantization bottom. The spectral position of the Fermi energy can be also determined by analyzing the energy positions of the Landau levels, bearing in mind that at integer filling (at $\nu = 4, 6, 8, 10, 12, 14, 16, 18, \ldots$) the chemical potential of the electron system lies exactly between the Landau levels, and therefore, the energy of the upper filled level is lower than that of the Fermi level (chemical potential) by half the cyclotron energy. For this reason, if we draw a linear dependence from the magnetic field for the upper filled Landau level at different integer filling factors, this dependence, in the zero magnetic field limit, will point to the spectral position corresponding to the Fermi energy of two-dimensional electrons. This analysis, presented in Fig. 2(b), shows that the Fermi energy value can be measured with high accuracy as the spectral splitting between the foci of the Landau-level fan diagram. For a two-dimensional electron concentration of 3.05×10^{11} cm^{-2} we established that $E_F =$ 10.40 meV, and hence, the density-of-states effective mass $m_e^{\mathrm{FL}} = (0.0705 \pm 0.0002)m_0$.

A similar procedure for measuring the Fermi energy of two-dimensional electrons and density-of-states effective mass was performed for various electron concentrations in the range from 0.17×10^{11} to 5.4×10^{11}cm^{-2}. Figure 3 presents the luminescence spectra measured for a two-dimensional electron concentration of 0.22×10^{11} cm^{-2} in the zero magnetic field and in a perpendicular field of 0.15 T at filling factor $\nu = 6$. It should be noted that in this case the spectra were measured at much lower temperature, $T = 0.05$ K. At such low concentrations of two-dimensional electrons the luminescence spectrum retains its main features: It clearly exhibits constancy of the density of states in the zero magnetic field as well as the Landau-level fan diagram in the

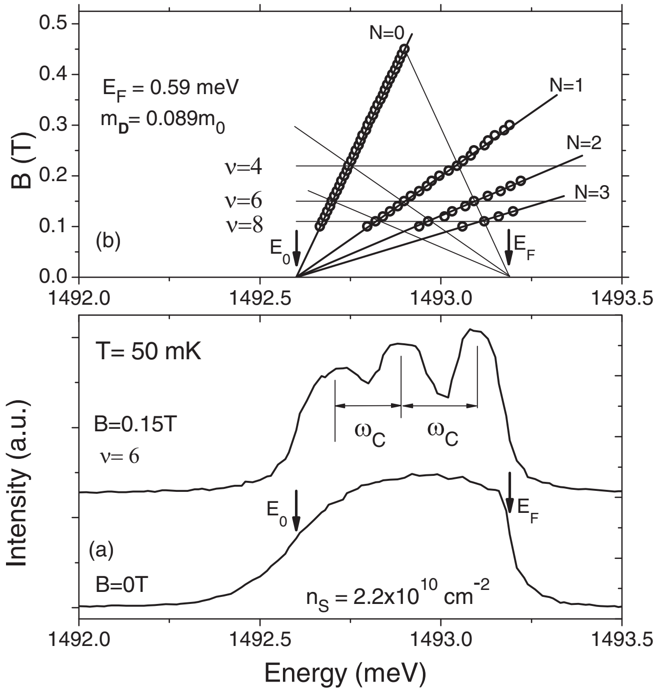

FIG. 3. (a) Radiative recombination spectra of two-dimensional electrons with photoexcited holes bound to remote acceptors measured in magnetic field $B = 0$ and 0.15 T ($\nu = 6$). (b) The Landau level fan diagram used to determine the spectral position of the size-quantization band bottom and the Fermi energy. The electron concentration in the sample is equal to 0.22×10^{11} cm^{-2}. $T = 0.05$ K.

perpendicular field, which enables us to make accurate measurements of the spectral positions of the size-quantization band bottom and the Fermi energy. For a two-dimensional electron concentration of 0.22×10^{11} cm^{-2} we established that $E_F = 0.59$ meV, and hence, the density-of-states mass turned out to be equal to $m_e^{\mathrm{FL}} = (0.0890 \pm 0.0005)m_0$, which by far exceeds the standard cyclotron electron mass in GaAs $m_e = 0.067m_0$. Note that we also observed a similar dependence of the effective mass of quasiparticles on electron density in another 2D electron system realized in ZnO-based heterostructures [20]. Figure 4 shows the measured electron concentration dependence of the density-of-states effective mass in the two-dimensional electron Fermi liquid. It is seen that the increase in parameter r_S from 1 to 4.5 is accompanied by a significant (over 35%) increase in the density-of-states effective mass of electrons. For comparison we studied the variation of the cyclotron mass of two-dimensional electrons in the same range. This dependence is also presented in Fig. 4. It is seen that the measured electron density dependencies of the cyclotron mass and the Fermi-liquid mass are opposite in the low-concentration limit: The cyclotron mass decreases, and the density-of-states effective mass in the electron Fermi liquid increases considerably. It should be emphasized that the discovered increase in the cyclotron mass of two-dimensional electrons with increasing density is due to the nonparabolicity of the electron spectrum in GaAs and in good agreement with previous studies of band mass nonparabolicity [21].

Note that the density dependence of the mass renormalization detected in optical studies agrees completely with

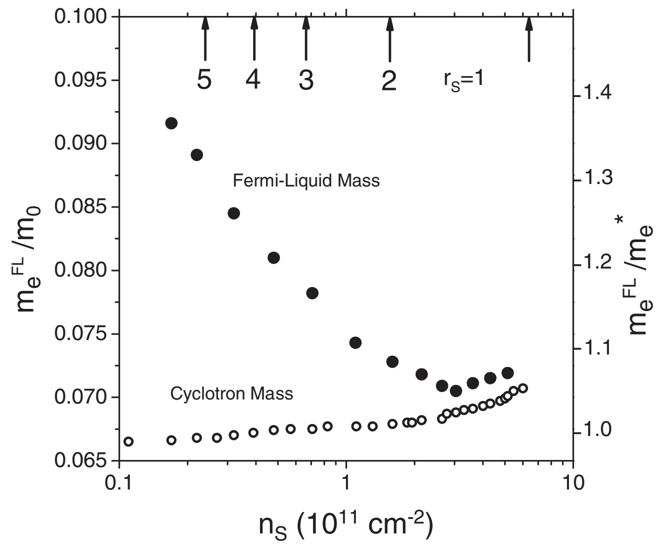

FIG. 4. Concentration dependencies of the renormalized density-of-states effective mass in a two-dimensional electron Fermi liquid (solid symbols) and cyclotron mass (open symbols).

the dependence found in the transport measurements. Crucially, the transport measurement technique measures only the mass changes at the Fermi surface, whereas the optical measurements reveal the mass renormalization effect for all electron energies well below the Fermi surface. The density dependence of the renormalized mass shows qualitative agreement as measured with the transport and optics techniques, which is to be expected as both cases manifest the same interaction effects. However, in the case of optical studies the data obtained are much more comprehensive and ultimately exhaustive, and furthermore, this very method goes far beyond that to give us the tool to measure the energy dependences of the excitation attenuation.

IV. VARIATIONS OF THE LANDAU-LEVEL WIDTH AND SPLITTING BELOW THE FERMI SURFACE

In the previous sections we studied the changes in the mean values of the renormalized density-of-states mass as a function of electron density. To this end, the Fermi energy was measured at different electron concentrations, and the mean density-of-states mass was determined under the assumption that the mass of quasiparticles is independent of their energy. However, as will be clear from further study, this approach is not quite correct, and in fact, there is a significant energy dependence of quasiparticle mass measured from the Fermi surface down to the very bottom of the size-quantization band. To study the nonparabolicity of the quasiparticle dispersion below the Fermi level, we investigated the magnetic field dependence of splitting between the Landau levels at various approximately fixed quasiparticle energy values calculated down from the Fermi energy. The discovered effect of the nonparabolicity of the excitation dispersion was measured at different concentrations of the electron system. In addition, it was found that the Landau-level width was significantly dependent on quasiparticle energy: The broadening was minimal near the Fermi surface and increased substantially

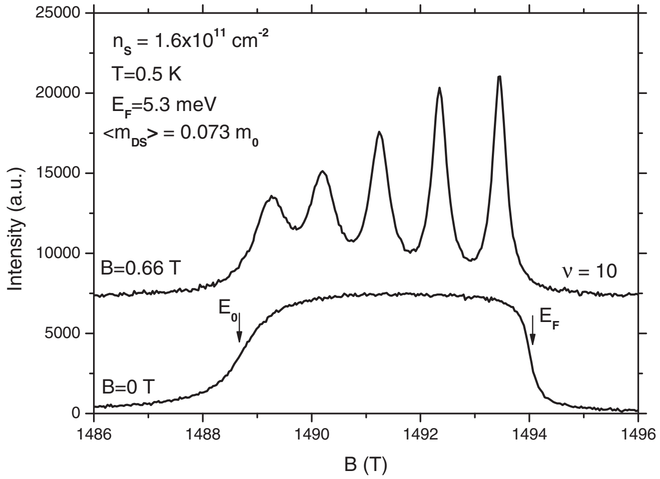

FIG. 5. Radiative recombination spectra of two-dimensional electrons with holes localized to acceptors measured in zero magnetic field and at $B = 0.66$ T for a two-dimensional electron concentration of 1.6×10^{11} cm^{-2}.

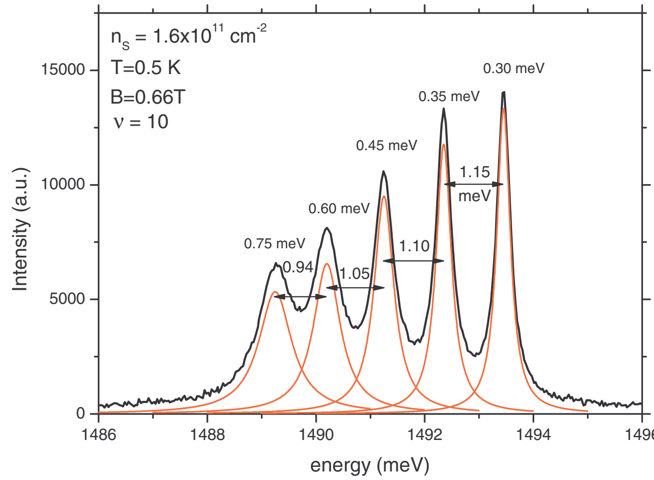

FIG. 6. Separation of spectral line profiles for measurement of Landau-level splitting and the width of the levels.

(almost twofold) deep at the bottom of the size-quantization band.

Figure 5 shows radiative recombination spectra of two-dimensional electrons with holes localized at acceptors measured at a two-dimensional electron concentration of 1.6×10^{11} cm^{-2}. Shown are the spectra measured in zero magnetic field and in magnetic field $B = 0.66$ T, corresponding to the filling factor of the Landau levels $\nu = 10$.

In this case the spectra in the magnetic field were measured for one circular light polarization ($-\sigma$). It is seen that at $\nu = 10$ the luminescence spectrum exhibits five Landau levels (each of them doubly spin degenerate), and their width is not energy independent but varies significantly from the minimal value near the Fermi surface to the maximal value at the bottom of the size-quantization band. For a detailed analysis of the variations of the Landau-level width and splitting energy as functions of quasiparticle energy we approximated the measured spectrum with a sum of five levels of the same integral intensity described by the Lorentz law. The adjustable parameters for each level were (a) its spectral position and (b) its width.

A comparison of the experimentally measured and optimally approximated spectra is presented in Fig. 6. Shown are the results of the line profile separation procedure from which it follows that the Landau-level widths vary from 0.3 meV (lower level) to 0.75 meV (upper level). One can also see from Fig. 6 that the Landau-level splitting in magnetic field $B = 0.66$ T varies from 1.15 meV (near the Fermi surface) to 0.94 meV (near the bottom of the size-quantization band). Figure 7 presents the Landau-level widths as functions of the quasiparticles energy measured from the Fermi surface. It should be noted that the level width measurements were made in different magnetic fields for different numbers of Landau levels, yet the measured excitation energy dependence of the level width appeared to be universal and close to the quadratic function. Similar quasiparticle energy dependencies of Landau-level widths were measured for two concentrations of electrons, 1.6×10^{11} and 3.05×10^{11} cm^{-2}, both shown in Fig. 7. Both dependencies reveal a smooth (close to quadratic) increase in the level width with increasing excitation energy calculated from the Fermi energy. In addition, for lower concentrations we observe a much faster increase in the energy dependence of Landau-level broadening. The discovered dependence of Landau-level broadening on quasiparticles energy can be naturally related to the mechanism proposed by Landau in the Fermi-liquid theory. According to this mechanism, the excitation (quasihole) originating below the Fermi surface flows up to the surface, and therefore, the deeper its origin is, the more capable it is of scattering, and hence, the faster its surfacing is, whereas near the Fermi surface the surfacing processes are slowed down and take much longer. The short scattering and energy relaxation time deep below the Fermi surface indicates a considerable Landau-level broadening, whereas near the Fermi surface there will be practically no level broadening due to very slow relaxation

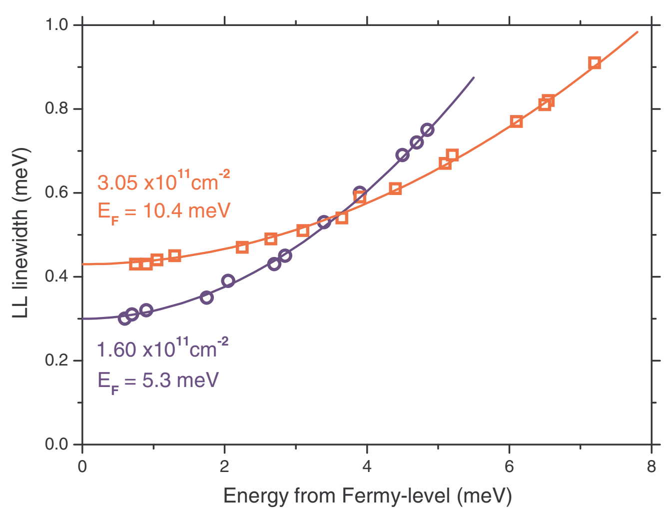

FIG. 7. Landau-level width as a function of excitation energy measured for two concentrations of two-dimensional electrons, 1.6×10^{11} and 3.05×10^{11} cm^{-2}.

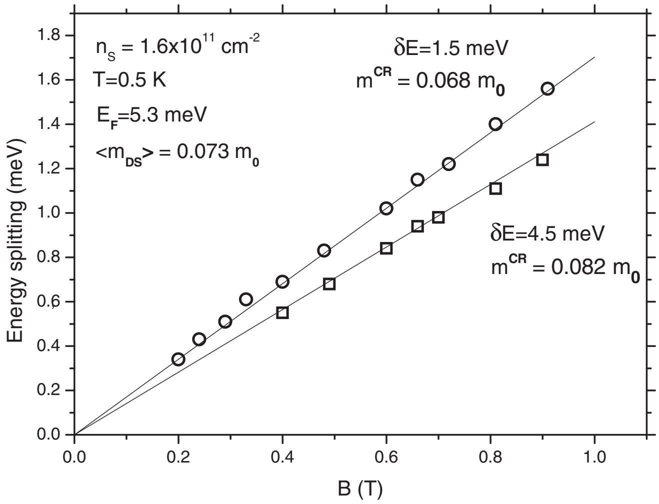

FIG. 8. Magnetic field dependencies of energy splitting between Landau levels measured for two values of quasiparticle energy, 1.5 and 4.5 meV, at an electron density of 1.6×10^{11} cm^{-2}.

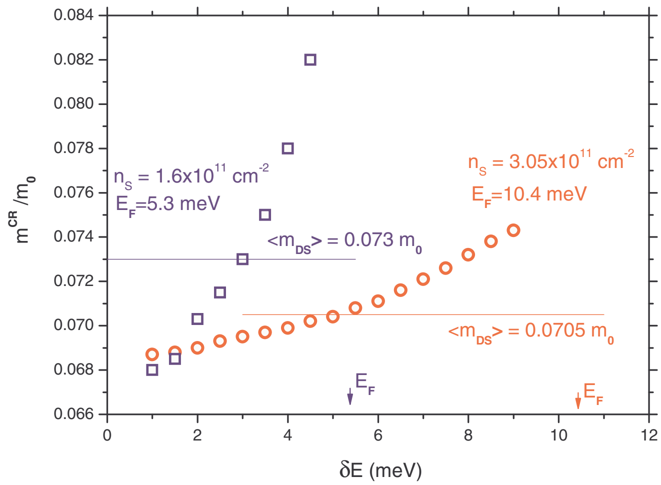

FIG. 9. Energy dependencies of renormalized quasiparticle mass measured for two values of electron density, 1.6×10^{11} and 3.05×10^{11} cm^{-2}. The mean values of the density-of-states mass measured for these concentrations are also shown.

processes. The discovered quadratic energy dependence of level broadening agrees also with the conclusions of the theory. The much weaker increase in the energy dependence of the Landau-level broadening at high concentrations (see Fig. 7) is likely to be associated with the fact that at higher densities of the electron system the Fermi-liquid effects become less important, which is revealed by the suppression of the effects of quasiparticle mass renormalization as well as their energy broadening.

From Fig. 6 it is also seen that, besides the energy dependence of the Landau-level width, there is an appreciable change in splitting between the Landau levels down from the Fermi surface. For instance, at $B = 0.66$ T the splitting between the levels located near the Fermi surface is equal to 1.15 meV, whereas the splitting between the deeper levels is much less and equals 0.94 meV. The reduction in the cyclotron splitting deep below the Fermi surface implies that the quasiparticle mass is not constant and varies depending on their energies. To study this effect of nonparabolicity of quasiparticle dispersion below the Fermi surface, we investigated the magnetic field dependence of splitting between the Landau levels at various approximately fixed quasiparticle energies calculated down from the Fermi energy.

Figure 8 shows the magnetic field dependencies of the energy splitting between the Landau levels measured for two values of excitation energy, 1.5 and 4.5 meV, at an electron density of 1.6×10^{11} cm^{-2}. It is seen that, provided the magnetic field dependence of the energy splitting between the Landau levels is measured at the fixed quasiparticle energy, this dependence is close to linear. This fact enables us to measure the quasiparticle mass at the specified energy. Moreover, from Fig. 8 it is also seen that the slopes of the magnetic field dependencies measured at different energy values differ markedly. At an excitation energy of 4.5 meV the excitation mass is about $0.082m_0$, which by far exceeds the value of $0.068m_0$ measured for an energy of 1.5 meV. The excitation energy dependencies of the renormalized quasiparticle mass are presented in Fig. 9 for two values of electron density, 1.6×10^{11} and 3.05×10^{11} cm^{-2}. The values of the mean density-of-states mass measured for these concentrations are also shown in Fig. 9. It is seen that the effect of mass nonparabolicity is much more pronounced in the case of low concentration (at 1.6×10^{11} cm^{-2} it reaches 25%, while at 3.05×10^{11} cm^{-2} the effect amounts to only 9%).

V. CONCLUSION

We have investigated the electron density dependence of the Fermi-liquid effects of the quasiparticle effective mass renormalization in the two-dimensional electron system with strong interaction. We established that with decreasing electron density (increasing parameter r_s to 4.5) the density-of-states effective mass of quasiparticles increases by 35% compared to the cyclotron electron mass. We showed that in a perpendicular magnetic field the concept of quasiparticles in a two-dimensional Fermi liquid is applicable not only near the Fermi level but deep below the Fermi surface, down to the bottom of the size-quantization band. The mass and broadening of quasiparticles were found to be significantly dependent on their energy measured from the Fermi surface down to the very bottom of the size-quantization band.

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[1] L. D. Landau, Sov. Phys. JETP **3**, 920 (1956).
[2] L. D. Landau, Sov. Phys. JETP **5**, 101 (1957).
[3] V. P. Silin, Sov. Phys. JETP **7**, 538 (1958).
[4] P. Nozieres and J. M. Luttinger, Phys. Rev. **127**, 1423 (1962).
[5] A. A. Abrikosov and I. M. Khalatnikov, Sov. Phys. JETP **6**, 888 (1957).
[6] R. Freedman, Phys. Rev. B **18**, 2482 (1978).
[7] C. Chamon, E. R. Mucciolo, and A. H. Castro Neto, Phys. Rev. B **64**, 245115 (2001).
[8] Yu. A. Bychkov and A. V. Kolesnikov, JETP Lett. **58**, 352 (1993).
[9] P. T. Coleridge, M. Hayne, P. Zawadzki, and A. S. Sachrajda, Surf. Sci. **361–362**, 560 (1996).
[10] V. M. Pudalov, M. E. Gershenson, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. **88**, 196404 (2002).
[11] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. B **66**, 073303 (2002).
[12] A. A. Shashkin, M. Rahimi, S. Anissimova, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. Lett. **91**, 046403 (2003).
[13] Y. W. Tan, J. Zhu, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **94**, 016405 (2005).
[14] E. M. Lifshits and L. P. Pitaevski, *Statistical Physics, Part 2*, Course of Theoretical Physics Vol. 9 (Nauka, Moscow, 1978).
[15] V. T. Dolgopolov, JETP Lett. **101**, 282 (2015).
[16] I. V. Kukushkin and V. B. Timofeev, Adv. Phys. **45**, 147 (1996).
[17] I. V. Kukushkin, R. J. Haug, K. von Klitzing, K. Eberl, and K. Totemeyer, Phys. Rev. B **50**, 11259 (1994).
[18] I. V. Kukushkin, K. von Klitzing, K. Ploog, V. E. Kirpichev, and B. N. Shepel, Phys. Rev. B **40**, 4179 (1989).
[19] I. V. Kukushkin, J. H. Smet, S. A. Mikhailov, D. V. Kulakovskii, K. von Klitzing, and W. Wegscheider, Phys. Rev. Lett. **90**, 156801 (2003).
[20] V. V. Solovyev and I. V. Kukushkin, Phys. Rev. B **96**, 115131 (2017).
[21] M. A. Hopkins, R. J. Nicholas, M. A. Brummell, J. J. Harris, and C. T. Foxon, Phys. Rev. B **36**, 4789 (1987).