Quantum corrections to conductivity: From weak to strong localization

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The results of detailed investigations of the conductivity and Hall effect in gated single-quantum-well GaAs/InGaAs/GaAs heterostructures with two-dimensional electron gas are presented. A successive analysis of the data has shown that the conductivity is diffusive for $k_F l = 25-2$. The absolute value of the quantum corrections for $k_F l = 2$ at low temperature is not small; e.g., it is about 70% of the Drude conductivity at $T = 0.46$ K. For $k_F l = 2-0.5$ the conductivity looks like the diffusive one. The temperature and magnetic field dependences are qualitatively described within the framework of the self-consistent theory of Vollhardt and Wölfle. The interference correction is therewith close in magnitude to the Drude conductivity so that the conductivity σ becomes significantly less than e^2/h. We conclude that the temperature and magnetic field dependences of the conductivity in the whole $k_F l$ range are due to changes of the quantum corrections.

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I. INTRODUCTION

The weak-localization regime in two-dimensional (2D) systems at $k_F l \gg 1$ (k_F and l are the Fermi quasimomentum and the mean free path, respectively), when the electron motion is diffusive, is well understood from the theoretical point of view.[1] In this case the quantum corrections to conductivity, which are caused by electron-electron interaction and interference, are small compared with the Drude conductivity $\sigma_0 = \pi G_0 k_F l$, where $G_0 = e^2/(2\pi^2\hbar)$. Experimentally, this regime was studied in different types of 2D systems. Qualitative and in some cases quantitative agreement with the theoretical predictions was found. However, important questions remain to be answered: what happens to these corrections (i) with a decrease of $k_F l$ down to $k_F l \simeq 1$ and (ii) with a decrease of temperature T when the quantum corrections become comparable in magnitude[2] with the Drude conductivity?

It is clear that, sooner or later, the increase of disorder leads to a change of the conductivity mechanism from a diffusive one to a hopping one. The question is, when does it happen? To answer this question the temperature dependence of the conductivity is analyzed usually. It is supposed that the transition to the hopping conductivity occurs when the conductivity becomes lower than e^2/h and a strong temperature dependence arises.[3–7] From our point of view, it is not enough to analyze the $\sigma(T)$ dependence only. The low conductivity and its strong temperature dependence can result from a large value of the quantum corrections as was proposed in some pioneer papers on weak localization.[8,9]

The aim of this paper is to study the role of quantum corrections over wide range of $k_F l$ and to understand what happens when the quantum corrections become comparable with the Drude conductivity. We try to answer these questions by studying the quantum corrections in 2D systems with the simplest and well-known electron energy spectrum, starting from the well-understandable case $k_F l \gg 1$.

We report experimental results obtained for single-well gated GaAs/$In_xGa_{1-x}As$/GaAs structures with one 2D subband occupied. An analysis of the experimental data shows that the conductivity is diffusive when $k_F l$ varies from 25 to approximately 2 and looks like diffusive one at $k_F l = 2-0.5$. At low temperature and $k_F l \simeq 1$ the total quantum correction is not small. It is close in magnitude to the Drude conductivity so that the conductivity is significantly less than $e^2/h \simeq 3.86\times10^{-5}\ \Omega^{-1}$ at low temperature. For instance, it is about $3\times10^{-8}\ \Omega^{-1}$ for $k_F l \simeq 0.5$ and $T = 0.46$ K—that is, 600 or so times less than σ_0. Thus, in this range the strong temperature and magnetic field dependences are caused by the change of quantum corrections.

II. SAMPLES

The heterostructures investigated were grown by metal-organic vapor-phase epitaxy on a semi-insulator GaAs substrate. They consist of a 0.5-μm-thick undoped GaAs epilayer, a Sn δ layer, a 60-Å spacer of undoped GaAs, a 80-Å $In_{0.2}Ga_{0.8}As$ well, a 60-Å spacer of undoped GaAs, a Sn δ layer, and a 3000-Å cap layer of undoped GaAs. The samples were mesa etched into standard Hall bars with dimensions $1.2\times0.2\ \mathrm{mm}^2$ and then an Al gate electrode was deposited onto the cap layer by thermal evaporation. The measurements were performed in the temperature range 0.4–12 K at magnetic fields B up to 6 T. The electron density was found from the Hall effect and from Shubnikov–de Haas oscillations when it was possible. These values coincide with an accuracy of 5%.

The gate voltage dependences of the electron density and conductivity are presented in Fig. 1(a) and Fig. 1(b), respectively. Varying the gate voltage V_g from 0.0 to -3.3 V we changed the electron density in the quantum well from 7.5×10^{11} to $1.2\times10^{11}\ \mathrm{cm}^{-2}$ and the conductivity σ at $T = 4.2$ K from 2.1×10^{-3} to $6\times10^{-7}\ \Omega^{-1}$. The straight line in Fig. 1(a) shows the V_g dependence of the total electron density in the quantum well and δ layers, calculated from the simple electrostatic consideration $n_t(V_g) = n(0) + V_g C/|e|$, with $n(0)$ as a fitting parameter and $C = \varepsilon/(4\pi d)$, where d

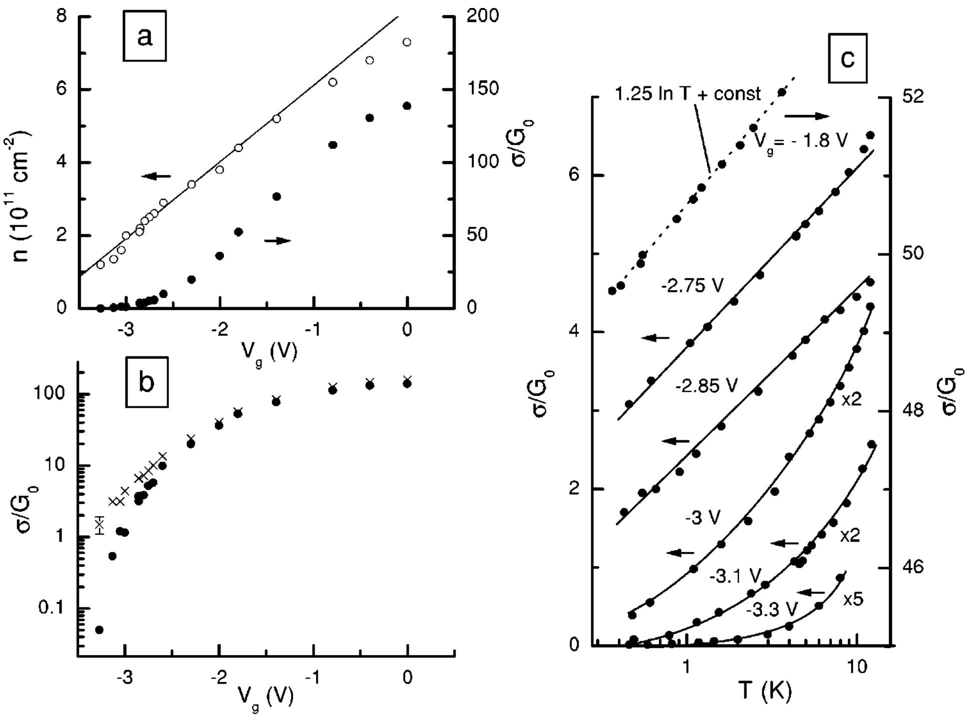

FIG. 1. (a) The gate voltage dependence of the conductivity at $T=4.2$ K (solid circles) and electron density in quantum well (open circles). The line is the dependence $n_t(V_g)$ calculated from the electrostatic consideration (see text). (b) The gate voltage dependences of conductivity at $T=4.2$ K (circles) and the Drude conductivity (crosses). (c) Temperature dependences of the conductivity for different gate voltages. The solid lines are provided as a guide to the eye; dotted line is Eq. (7) with $(1+3/4\lambda)=0.35$ and $p=0.9$ (see text).

$=3000$ Å is the cap-layer thickness, $\varepsilon=12.5$. The deviation of the experimental data from the line, which is evident at $V_g>-1$ V, is a result of the fact that the fraction of electrons occupies the states in the δ-doped layers. In the present paper we will not consider this gate-voltage range, because the appearance of the states at the Fermi energy in the doped layers leads to additional specific features in transport, some of which have been already discussed earlier.[10]

III. RESULTS AND DISCUSSION

The temperature dependences of the conductivity for several gate voltages are presented in Fig. 1(c). It is clearly seen that the temperature dependences of σ are close to the logarithmic ones for $V_g\geqslant-2.85$ V. For lower V_g when the conductivity is less than e^2/h a significant deviation from logarithmic is observed. The conductivity in such a case is usually interpreted as the hopping conductivity.[4–7] We will show below that quantum corrections can lead to such a behavior if they become close in magnitude to the Drude conductivity.

To clarify the role of quantum corrections at low conductivity when $k_F l\simeq 1$ let us analyze the experimental data starting from $k_F l \gg 1$ where the conventional theories of the quantum corrections are applicable. Following the sequence of data treatment described in Ref. 11 we will assure at first that the quantum correction theories describe the temperature and low- and high-magnetic-field behavior of the conductivity. After that we will find the contributions of the electron-electron interaction and quantum interference to the conductivity and then trace their changes with lowering of $k_F l$.

A. Case $k_F l \gg 1$

In Fig. 2 the magnetic field dependences of the components of the resistivity tensor ρ_{xx} and ρ_{xy} measured at different temperatures are presented for the gate voltage $V_g=-1.8$ V. Two different magnetic field ranges are evident in Fig. 2(a): the range of sharp decrease of ρ_{xx} at low magnetic field $B\leqslant 0.1-0.2$ T (see also Fig. 4) and the range of moderate dependence $\rho_{xx}(B)$ at higher field. A characteristic feature of the data presented is the existence of the crossing point at $B=B_{cr}$, at which all the ρ_{xx}-versus-B curves cross each other.

At high magnetic field the behavior of $\rho_{xx}(B,T)$ and $\rho_{xy}(B,T)$ can be explained by the contribution of the electron-electron interaction to the conductivity. It fully corresponds to the theory developed in Ref. 1, which predicts that the electron-electron interaction contributes to the diagonal component of the conductivity tensor σ_{xx}, and does not contribute to the off-diagonal component σ_{xy}. For the actual case $g\mu_B B/kT\lesssim 1$, where μ_B is the Bohr magneton, the correction $\delta\sigma_{xx}^{ee}$ is independent of the magnetic field and has the form

$$\delta\sigma_{xx}^{ee}(T)=G_0\left(1+\frac{3}{4}\lambda\right)\ln\left(\frac{kT\tau}{\hbar}\right) \tag{1}$$

and hence

$$\rho_{xx}(B,T)\simeq\frac{1}{\sigma_0}-\frac{1}{\sigma_0^2}(1-\mu^2B^2)\,\delta\sigma_{xx}^{ee}(T), \tag{2}$$

when $\delta\sigma_{xx}^{ee}\ll\sigma_0$. Here, τ is the quasimomentum relaxation time, μ is the electron mobility, and λ is the parameter of the electron-electron interaction, calculated in Ref. 12. It is clearly seen from Eq. (2) that the ρ_{xx}-versus-B plots taken at different temperatures are to cross each other at magnetic field $B=1/\mu$. Inspection of Figs. 2(a) and 2(b) shows that

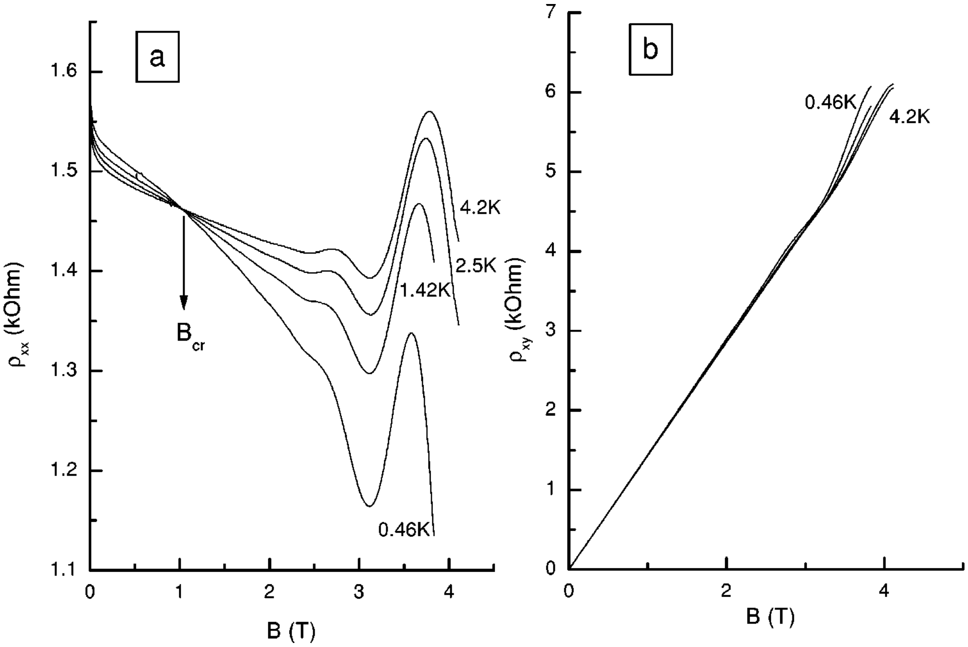

FIG. 2. The magnetic field dependences of ρ_{xx} (a) and ρ_{xy} (b) for different temperatures at $V_g = -1.8$ V ($k_F l = 17.9$).

the value of $B_{cr} = 1$ T is really close to $1/\mu$ with $\mu = 0.99$ m^2/(V sec) obtained as $\mu = \rho_{xy}/(\rho_{xx}B)$ at $B = B_{cr}$ (see Ref. 11 for details).

The temperature dependences of σ_{xx} and σ_{xy} calculated from ρ_{xx} and ρ_{xy} are presented for high magnetic field in Fig. 3. As seen σ_{xy} is temperature independent within experimental error. The temperature dependence of σ_{xx} is close to the logarithmic one. The slope of the σ_{xx}-versus-ln T plot does not depend on the magnetic field. Thus, the high-magnetic-field behavior of the conductivity tensor components agrees completely with the theoretical predictions for the correction due to electron-electron interactions. It allows us to determine the value of $(1 + 3/4\lambda)$ [see Eq. (1)]. So for $V_g = -1.8$ V we obtain $(1 + 3/4\lambda) = 0.35 \pm 0.05$.

We turn now to the low-magnetic-field behavior of ρ_{xx}, which is a consequence of suppression of the interference correction by magnetic field (Fig. 4). An analysis shows that at $B < 0.5 B_{tr}$, where $B_{tr} = \hbar/(2el^2)$ is the so-called transport magnetic field,[13] the dependences $\Delta\sigma(B) = 1/\rho_{xx}(B) - 1/\rho_{xx}(0)$ are described by the well-known expression[14]

$$\Delta\sigma(B) = \alpha G_0 \left\{ \psi\left(\frac{1}{2} + \frac{\tau}{\tau_\varphi}\frac{B_{tr}}{B}\right) - \psi\left(\frac{1}{2} + \frac{B_{tr}}{B}\right) - \ln\left(\frac{\tau}{\tau_\varphi}\right) \right\}, \tag{3}$$

with α and τ_φ given in this figure. In Eq. (3), $\psi(x)$ is a digamma function and τ_φ is the phase breaking time. A difference of the prefactor α from unity, which is more pronounced at higher temperature, is a consequence of the low τ_φ/τ ratio. For instance, $\tau_\varphi/\tau \simeq 20$ for $T = 4.2$ K, which is clearly not enough for the diffusion approximation.[15] Nevertheless, as shown in Ref. 15 the use of Eq. (3) for the fit of experimental data in this regime gives a value of τ_φ very close to the true one.

The temperature dependence of τ_φ found from the fit is well described by the power law $\tau_\varphi \propto T^{-p}$ with $p \simeq 0.9$ (Fig. 5). It must be noted that not only the temperature dependence but the absolute value of τ_φ obtained experimentally is close to the theoretical ones:

$$\tau_\varphi^{-1} = \frac{kT}{\hbar}\frac{2\pi G_0}{\sigma_0}\ln\left(\frac{\sigma_0}{2\pi G_0}\right). \tag{4}$$

So we can determine the absolute value of the interference correction at $B = 0$ using the well-known expression[16]

$$\delta\sigma^{int} = -G_0 \ln\left(\frac{\tau_\varphi}{\tau} + 1\right). \tag{5}$$

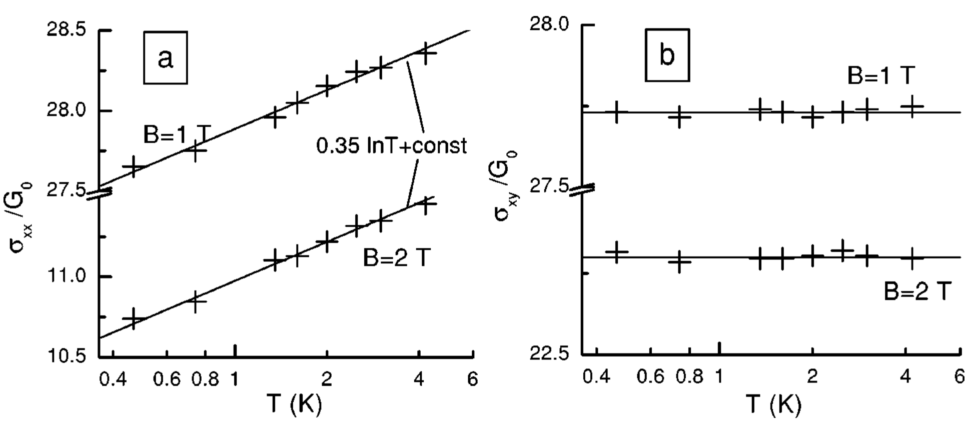

FIG. 3. The temperature dependence of σ_{xx} (a) and σ_{xy} (b) for two magnetic fields; $V_g = -1.8$ V.

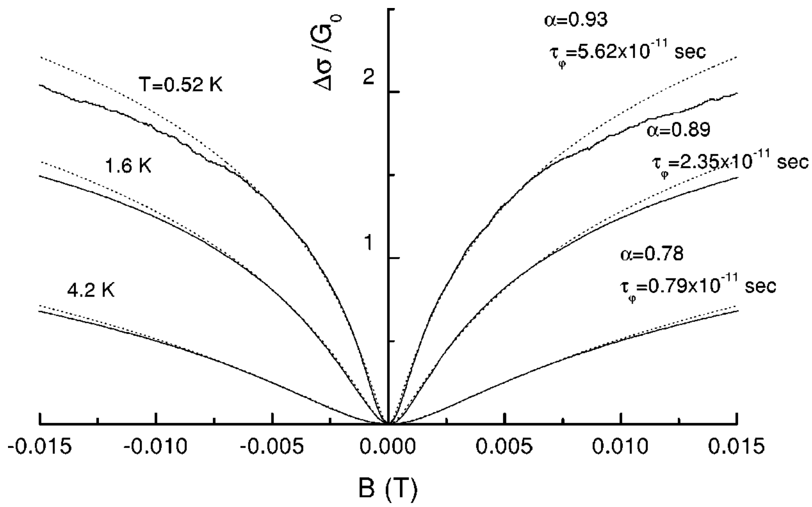

FIG. 4. The magnetic field dependence of $\Delta\sigma(B)=1/\rho_{xx}(B)-1/\rho_{xx}(0)$ for different temperatures; $V_g=-1.8$ V. Solid curves are the experimental data. Dashed lines are the best fit to Eq. (3) made over the magnetic field range from 0 to $0.25\,B_{tr}$, $B_{tr}=0.03$ T. The parameters of the best fit are given near the corresponding curves.

Figure 6 shows the results obtained for $T=0.46$ K. As seen $\delta\sigma^{int}$ is practically independent of $k_F l$ while $k_F l \geqslant 2$.

Now, when we have experimentally found the values of the electron-electron and interference contributions to the conductivity, we can determine the value of the total quantum correction $\delta\sigma(T)=\delta\sigma^{int}(T)+\delta\sigma^{ee}(T)$ and, hence, the value of the Drude conductivity:

$$\sigma_0=\sigma(T)-\delta\sigma(T). \tag{6}$$

If the experimental results are adequately described by the theory of the quantum corrections, we have to obtain the same values of σ_0 from the data taken at different temperatures. Really, this procedure gives close values. The scatter is about $(0.5\text{–}1)G_0$ for $T=0.46\text{–}10$ K in the whole gate voltage range. The Drude conductivity obtained in this way as a function of V_g is presented in Fig. 1(b).

The found value of σ_0 can be further compared with $\rho_{xx}^{-1}(B_{cr})$. Both quantities are to be equal to each other as it follows from Eq. (2). As an example we consider the case of $V_g=-1.8$ V. The value of σ_0 obtained with the help of Eq. (6) is equal to $(56.4\pm0.5)G_0$. Inspection of Fig. 2 gives $\rho_{xx}(B_{cr})^{-1}=55.6G_0$. It is slightly lower than σ_0. The reason for this difference is obvious.[11] It is due to the remainder of the interference correction which is not fully suppressed by magnetic field even at $B=B_{cr}\simeq 30B_{tr}$.

Finally, the temperature dependence of the conductivity at zero magnetic field is determined by the overall temperature dependences of $\delta\sigma_{xx}^{ee}$ [Eq. (1)] and $\delta\sigma^{int}$ [Eq. (5)]. Thus,

$$\sigma(T)\propto G_0\left(1+\frac{3}{4}\lambda+p\right)\ln T. \tag{7}$$

The dotted line in Fig. 1(c) demonstrates a good agreement of the experimental data with Eq. (7) when one uses $(1+3/4\lambda)=0.35$ and $p=0.9$ obtained above.

As is clear from the above the observation of crossing of the ρ_{xx}-versus-B curves at one point is very important. It allows us to carry out so thorough an analysis. Unfortunately the crossing is not evident at low gate voltage. The decrease of V_g leads to a mobility decrease and hence to a shift of the crossing to high magnetic field. At $V_g<-3.0$ V the crossing runs out of our magnetic field range.

The following should be emphasized here. We could not use Eq. (2) for the analysis at low gate voltage even if we had a high magnetic field and observed the crossing at $B>6$ T. There is a physical restriction of applicability of this expression. It is valid when the quantization of the energy spectrum in a magnetic field can be ignored, i.e., when the cyclotron energy $\hbar\omega_c$ is less than both the Landau level broadening and the Fermi energy. The absence of the Shubnikov–de Haas oscillations in those magnetic fields where the crossing is evident testifies to the fact that the Landau levels are really strongly broadened. As for the second requirement, it is violated with a decrease of the gate

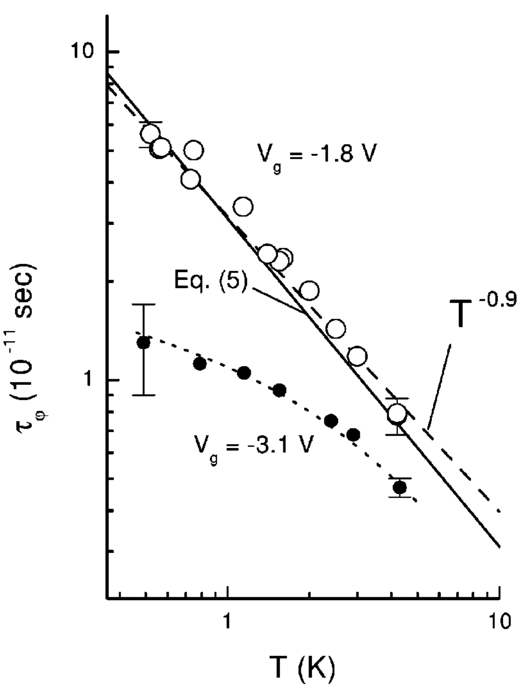

FIG. 5. The temperature dependences of τ_φ at $V_g=-1.8$ V, $k_F l=17.9$ (open circles) and $V_g=-3.1$ V, $k_F l\simeq 1$ (solid circles). Solid line is the theoretical dependence given by Eq. (6); dashed line is the power law $T^{-0.9}$, dotted line is a guide for the eye.

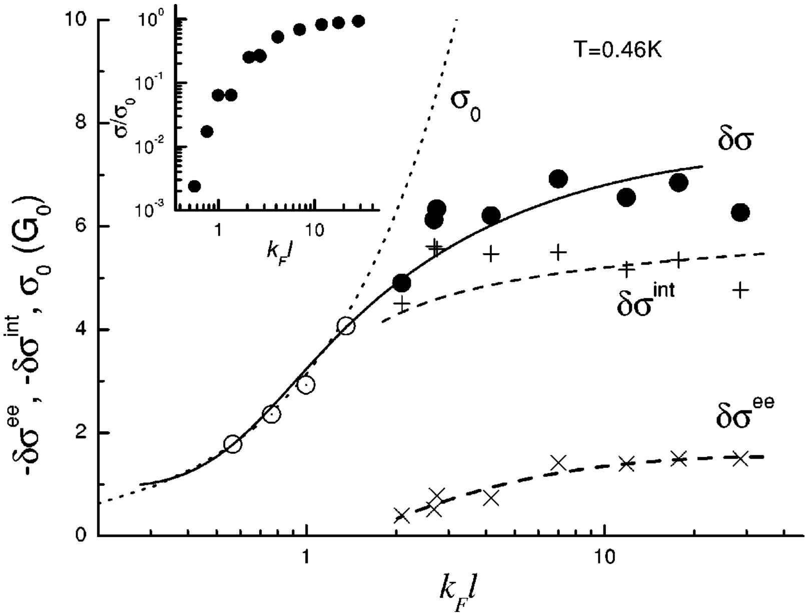

FIG. 6. The contributions to the conductivity due to electron-electron interaction $\delta\sigma^{ee}$, interference $\delta\sigma^{int}$, and the total contribution $\delta\sigma$ as a function of $k_F l$. The dotted curve is $\sigma_0 = \pi k_F l$; other curves are a guide for the eye. Solid and open circles are obtained as described in Sec. III A and Sec. III B, respectively. Inset shows the ratio of the conductivity in zero magnetic field at $T = 0.46$ K to the Drude conductivity plotted as a function of $k_F l$.

voltage due to a lowering of the Fermi energy and electron mobility. Analysis of the experimental data presented in Figs. 1(a) and 1(b) shows that the value of $\hbar\omega_c$ at $B = \mu^{-1}$ becomes greater than the Fermi energy at $V_g \simeq -2.9$ V, when the electron density and mobility fall down to $\simeq 2 \times 10^{11}$ cm^{-2} and $\simeq 0.2$ m^2/(V sec), respectively. Namely, for $V_g > -2.9$ V when $k_F l > 2$ good agreement with all theoretical predictions is observed.

Thus, we maintain that at $k_F l \gtrsim 2$ just the quantum corrections determine the temperature and low- and high-magnetic-field dependences of the conductivity in two dimensions. The total value of the corrections decreases only slightly at decreasing $k_F l$ (see Fig. 6); the contribution due to electron-electron interaction is 25%–30% of the interference contribution at $k_F l \simeq 25$ and only 10% at $k_F l \simeq 2$. The significant point is that the quantum corrections at low temperature can be comparable in magnitude with the Drude conductivity; e.g., at $k_F l \simeq 2.3$ ($V_g = -2.85$ V), their value is about two-thirds of σ_0 for $T = 0.46$ K. So the strong temperature dependence of the conductivity at $B = 0$ in this case [see Fig. 1(c)] is caused by the decreasing of the quantum corrections with temperature.

Now we consider the behavior of the electron-electron contribution with k_F changing. Experimental k_F dependences of $(1+3/4\lambda)$ and, for comparison, the theoretical results from Ref. 12 are presented in Fig. 7. One can see that at $2k_F/K > 1.5$ ($K = 2/a_B$ is the screening parameter, and a_B is the effective Bohr radius) when $k_F l > 5$ the experimental data lie somewhat below the theoretical curve but follow quite parallel to it. In this range of $2k_F/K$ the present results are close to those obtained in Ref. 11. The strong deviation of $(1+3/4\lambda)$ at $2k_F/K < 1.5$ can result from the fact that the strong inequality $k_F l \gg 1$ which is required by the theory is not fulfilled under experimental conditions.

B. Case $k_F l \simeq 1$

Let us analyze the data for $V_g < -2.9$ V when the conductivity is low and the crossing point is not observed. First of all, one can see from Fig. 1(c) that the temperature dependence of σ is not logarithmic in this case. It is not surprising because Eqs. (1) and (5) are valid only when the corrections are small compared with the Drude conductivity. When the temperature tends to zero, Eqs. (1) and (5) give a negative value of the conductivity which is meaningless.

It is obvious that another theoretical approach should be used in this situation. Self-consistent calculations,[17,18] which take into account the fact that the diffusion coefficient itself depends on the correction value, lead to the following equation for the conductivity:

$$\frac{\sigma(T)}{\sigma_0} = 1 - \frac{1}{\pi k_F l} \ln\left(1 + \frac{\tau_\varphi(T)}{2\tau}\frac{\sigma(T)}{\sigma_0}\right). \tag{8}$$

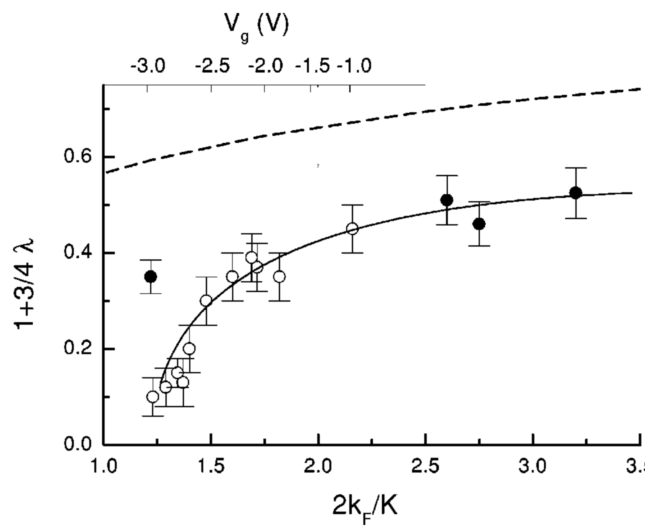

FIG. 7. The value of multiplier $(1+3/4\lambda)$ in Eq. (1) as a function of $2k_F/K$. The open circles are the results obtained for the structure investigated (the upper axis indicates the gate voltage). The solid circles are the results from Ref. 11. The dashed curve represents the theoretical result from Ref. 12. The solid curve is a guide for the eye.

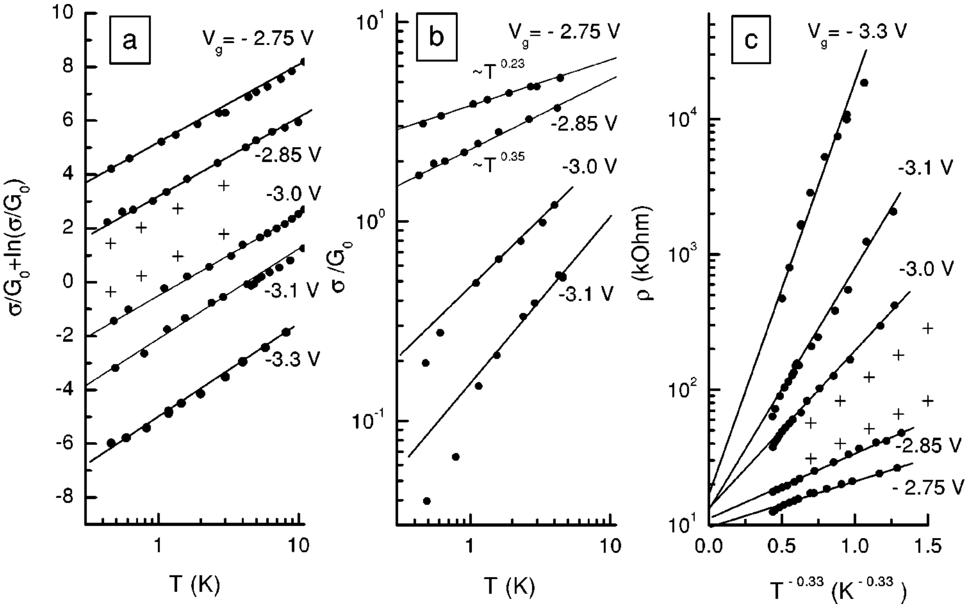

FIG. 8. The temperature dependence of σ (a, b) and ρ (c) in the coordinates corresponding to self-consistent calculation [Eq. (9)] and power-law localization and variable-range hopping [Eq. (11) with $m=1/3$], respectively. The circles are our data; the crosses are the results from Ref. 7. The values of k_Fl from $V_g=-2.75$ V to -3.3 V are the following: $k_Fl\simeq 3$, 2.1, 1.4, 1.0, and 0.5.

When $\tau_\varphi \gg \tau$ it can be rewritten as follows:

$$\frac{\sigma_0}{G_0}+\ln\left(\frac{\sigma_0}{G_0}\right)-\left[\frac{\sigma(T)}{G_0}+\ln\left(\frac{\sigma(T)}{G_0}\right)\right]=\ln\left[\frac{\tau_\varphi(T)}{\tau}\right]. \quad (9)$$

At $\sigma_0-\sigma(T)\ll\sigma_0$ this equation coincides with Eq. (5) and gives the logarithmic temperature dependence of the conductivity. Besides, Eq. (9) gives a reasonable behavior of $\sigma(T)$: the conductivity goes to zero when $\tau_\varphi(T)/\tau$ increases with the temperature decrease.

In Fig. 8(a) we present our experimental results as a $[\sigma(T)/G_0+\ln(\sigma(T)/G_0)]$-versus-ln T plot in accordance with Eq. (9). It is evident that the experimental data are well described by this theory in the whole k_Fl range.

Strictly speaking, the theory in Refs. 17 and 18 was developed for arbitrary values of the correction but for $k_Fl \gg 1$. In our case the value of k_Fl is close to 1 for $V_g < -2.75$ V; therefore, a more detailed quantitative analysis makes no sense.

In Ref. 9 a so-called conception of power-law localization[8] was used to analyze the experimental data in the case of a large quantum correction. It was shown that, as long as the Fermi energy was above the mobility edge,

$$\frac{\sigma(T)}{\sigma_0}=\left(\frac{\tau}{\tau_\varphi(T)}\right)^{\gamma}. \quad (10)$$

For $\gamma=1/(\pi k_Fl)$ this expression gives just the same result as Eq. (5) when the temperature is relatively high so that $k_Fl \gg \ln(\tau_\varphi/\tau)$. When $\tau_\varphi(T)$ tends to infinity with a temperature decrease, $\sigma(T)$ follows the power-law vanishing at $T=0$.

Figure 8(b) presents our data in double-logarithmic scale. It is evident that the experimental temperature dependence of the conductivity follows a power law only at high gate voltages $V_g \gtrsim -2.9$ V ($k_F \gtrsim 2$) and noticeably deviates from it at lower V_g. The exponent increases with the k_Fl decrease, but differs from $1/(\pi k_Fl)$ by a factor of about 2.

Thus, as follows from comparison with both the self-consistent theory[17,18] and the power-law conception[8] the strong temperature dependence of the conductivity, which appears with a k_Fl decrease, is the result of quantum interference but not the transition to the hopping regime.[19]

Moreover, a negative magnetoresistance is observed for small k_Fl values too. The shape of the $\Delta\sigma$-versus-B dependence is the same as for large k_Fl. It is illustrated by Fig. 9(a) where $\Delta\sigma$-versus-B data for $V_g=-1.8$ V ($k_Fl=17.9$) and $V_g=-3.3$ V ($k_Fl\simeq 0.5$; see below for details) are presented. It is evident that these data sets practically coincide. From our standpoint this fact indicates that at both small and large k_Fl values the negative magnetoresistance results from the magnetic field suppression of the interference correction to the conductivity.

Let us try to estimate the phase breaking time from the negative magnetoresistance. To our knowledge there is no adequate theory of the negative magnetoresistance for the case $k_Fl\simeq 1$; therefore, we have used Eq. (3). By analogy with the temperature dependence of σ [see Eq. (9)] we have analyzed the magnetic field dependence of $\sigma(B)/G_0+\ln[\sigma(B)/G_0]-\{\sigma(0)/G_0+\ln[\sigma(0)/G_0]\}$ rather than $\sigma(B)-\sigma(0)$ as in Eq. (3). Note that the way of finding the value of B_{tr} used in the case $k_Fl\gg 1$ (see Ref. 13) is poor now because σ strongly differs from σ_0. Therefore, we have used a successive approximation method. For the first approximation we set $\sigma(0)$ equal to σ_0, found B_{tr}, and, then, determined τ_φ/τ from the fit of the magnetoresistance. After that we substituted this ratio into Eq. (9) and found the corrected value of σ_0 and so on. So the output of this procedure is the value of the Drude conductivity σ_0 and the ratio τ_φ/τ. A convergence of the described procedure is illustrated by Fig. 9(b). One can see that it is sufficient to make from six to seven iterations to achieve an accuracy in the determination of σ_0 and τ_φ/τ better than 10%.

We realize that Eqs. (3) and (9) have been applied beyond the framework of their workability. Nevertheless, let us consider the results. It has been found that the lowering of V_g down to -3.3 V leads to a fall of the Drude conductivity down to $\simeq 1.5G_0$ [see Fig. 1(b)]—that is, $k_Fl\simeq 0.5$. The val-

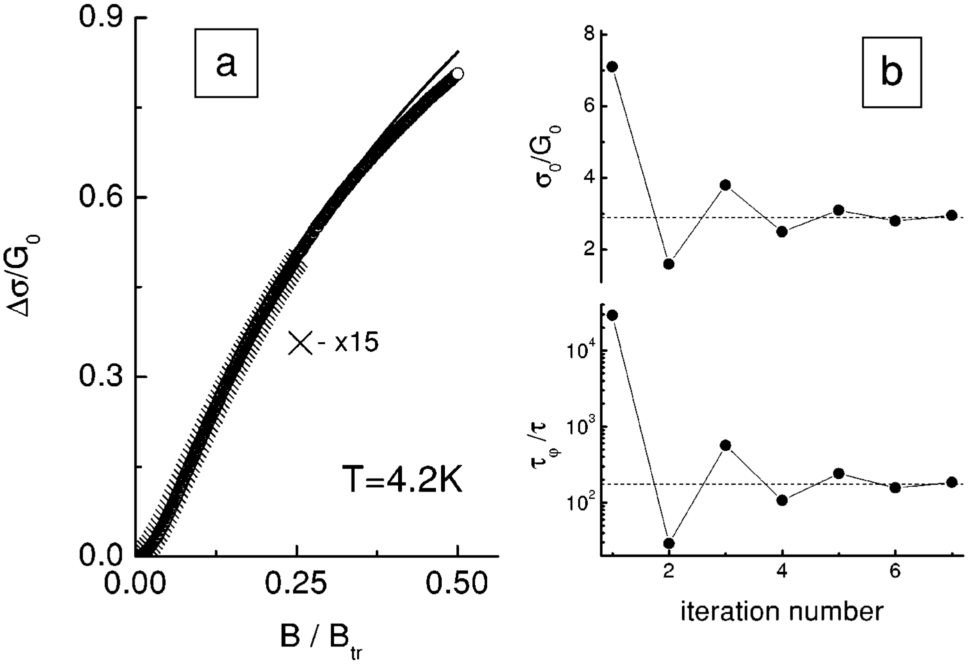

FIG. 9. (a) The negative magnetoresistance for $V_g=-1.8$ V ($k_Fl=17.9$) (circles) and $V_g=-3.3$ V ($k_Fl\simeq0.5$). Solid line is Eq. (3) with parameters corresponding to the best fit for $V_g=-1.8$ V: $\alpha=0.78$, $\tau_\varphi=0.79\times10^{-11}$ sec, and $B_{tr}=0.03$ T. (b) Convergence of the procedure of determination of σ_0 (upper panel) and τ_φ/τ (lower panel), described in Sec. III B, $V_g=-3.1$ V, $T=1.55$ K.

ues of the fitting parameters τ_φ and α therewith change slowly and monotonically over the whole k_Fl range. It is clearly seen from Fig. 10 in which the results for $k_Fl>2$ are presented as well. Moreover, τ_φ behaves naturally with temperature: it increases with the temperature decrease (Fig. 5). From our point of view some saturation of τ_φ evident at low temperature for the case $k_Fl\simeq1$ means no more than the saturation of the fitting parameter but not the saturation of the phase breaking time. At low k_Fl, Eqs. (3) and (9) can give only its rough estimation.

Finally, knowing the Drude conductivity we can find the total value of the quantum corrections as $\delta\sigma(T)=\sigma(T)-\sigma_0$. For $T=0.46$ K, the value of $\delta\sigma$ as a function of k_Fl is depicted in Fig. 6. As the figure illustrates, these results match those obtained for $k_Fl>2$ and discussed in the previous subsection. It is seen that the total quantum correction $\delta\sigma$ is a small part of the Drude conductivity σ_0 at large k_Fl. It is about 70% of σ_0 at $k_Fl\simeq2$ and very close to σ_0 at lower k_Fl. The last leads to the fact that at low temperature the conductivity in zero magnetic field is much less than the Drude conductivity (see the inset in Fig. 6). For instance, $\sigma/\sigma_0\simeq2\times10^{-3}$ at $k_Fl\simeq0.5$ and $T=0.46$ K; the absolute value of σ is about $3\times10^{-8}\ \Omega^{-1}$ which is much smaller than $e^2/h\simeq3.86\times10^{-5}\ \Omega^{-1}$.

Thus, down to $k_Fl\simeq0.5$ the conductivity looks like a diffusive one and its temperature and magnetic field dependences are due to those of the quantum corrections which in turn can be comparable in magnitude with the Drude conductivity at low temperature.

It is usually supposed that for $\sigma<e^2/h$ the conductivity mechanism is the variable-range hopping.[4–7] It is argued by the fact that the temperature dependence of the resistivity

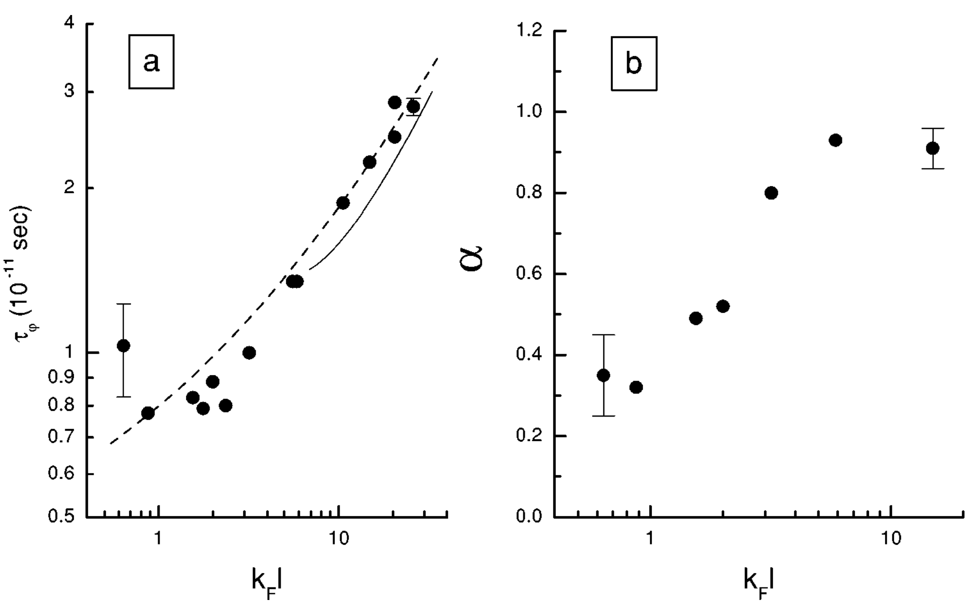

FIG. 10. The conductivity dependence of τ_φ (a) and prefactor α (b) at $T=1.5$ K. Symbols are the experimental results. The solid line in (a) is Eq. (4); the dashed line is a guide for the eye.

$\rho = \sigma^{-1}$ is well described by the characteristic for this mechanism dependence:

$$\rho(T) = \rho_0 \exp\left(\frac{T_0}{T}\right)^m, \tag{11}$$

with $m = 1/2, 1/3$ depending on the ratio of the Coulomb gap width to the temperature. Figure 8(b) shows our experimental results as a $\ln \rho$-versus-$T^{-1/3}$ plot. As seen, our data, being in excellent agreement with Eq. (9) [Fig. 8(a)], are well described by Eq. (11), also. Surprised by this fact we have examined some data from Refs. 4–7, which were interpreted from the position of the variable-range hopping. We have found that while the resistivity is less than $\sim 10^6\ \Omega$ those dependences are well aligned in $\{\sigma(T)/G_0 + \ln[\sigma(T)/G_0]\}$-versus-$\ln T$ coordinates also. For example, the data from Ref. 7 for carrier density 1.085×10^{11} and $0.984 \times 10^{11}\ \mathrm{cm}^{-2}$ are presented in Fig. 8. Thus, it is impossible to identify reliably the mechanism of the conductivity considering only its temperature dependence.

IV. CONCLUSION

We have studied the quantum corrections to the conductivity for single-well gated GaAs/In_xGa_{1-x}As/GaAs structures with 2D electron gas. A thorough analysis shows that the temperature and low- and high-magnetic-field dependences of the components of the conductivity and resistivity tensor are well described within the framework of the conventional theory of quantum corrections down to $k_F l \simeq 2$. The value of the total correction is not small and is about 70% of the Drude conductivity for $T = 0.45$ K. It has been shown that for zero magnetic field the interference contribution to the conductivity exceeds the contribution due to the electron-electron interaction by 3–5 times.

On the further lowering of $k_F l$ down to $\simeq 0.5$ the temperature and magnetic field dependences of the conductivity are in qualitative agreement with the self-consistent theory by Vollhardt and Wölfle,[17] which is applicable for arbitrary values of the quantum corrections. Thus, in a wide range of low-temperature conductivity starting from $\sigma \simeq 3 \times 10^{-8}\ \Omega^{-1}$ the conductivity is of a nonhopping nature. We assume that the transition from the diffusion to hopping occurs at a lower $k_F l$ value.

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