Weak localization of two-dimensional electrons in GaAs-$Al_xGa_{1-x}As$ heterostructures

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We have studied the transport and low-field magnetotransport of the two-dimensional electron gas in GaAs-$Al_xGa_{1-x}As$ heterostructures in the weak-localization regime and determined the localization parameter ($\alpha=0.75-0.85$), the interaction coefficient ($1-F=0.5-3.2$), the inelastic scattering time τ_{in}, and its temperature exponent ($P=1.0$). The experiment shows unambiguously the importance of both the localization effect and the interaction effects. While the observation of $\alpha<1$ is explained by the importance of the Maki-Thompson scattering process, also operative in our case of the repulsive electron-electron interaction, several outstanding features of the data remain unexplained. They include the following: (1) τ_{in} being 10 times larger than theory, (2) $1-F$ at a high density being 5 times its expected value, and (3) a temperature-sensitive negative magnetoresistance in parallel $\vec{B}$.

I. INTRODUCTION

Recently, the study of electrical transport in disordered two-dimensional systems received a great impetus from the scaling theory of localization of Abrahams, Anderson, Licciardello, and Ramakrishnan,[1] (AALR), which was based on localization concepts developed earlier by Thouless.[2] AALR showed that no true metallic conduction could exist in a two-dimensional system and that the conductance had a smooth and continuous transition from the exponential localization regime to the weak logarithmic localization regime, where the conductivity increased logarithmically with temperature. Measurements of the temperature dependence of resistance per square ($\Omega/\square$) in several two-dimensional systems[3-6] have clearly verified this prediction.

Subsequently, the magnetic field effect was considered in this weak-localization regime by Altshuler *et al.*[7] and by Hikami *et al.*[8] According to their formulations, a perpendicular magnetic field suppresses the localization correction to the conductivity and gives rise to a negative magnetoresistance. In case of the two-dimensional electron gas (2D EG) in semiconductor inversion layers, the negative magnetoresistance has been observed by several groups, e.g., in the Si-MOSFET (metal-oxide—semiconductor field-effect transistor) system by Kawaguchi *et al.*[9] Uren *et al.*[10], Wheeler,[11] and Bishop *et al.*[12] and in the GaAS-$Al_xGa_{1-x}As$ heterojunction system by Poole *et al.*[13] The observation of this negative magnetoresistance has provided a direct method for determining the inelastic scattering time τ_{in} of the electron and has made it possible to study the inelastic scattering mechanisms in these two-dimensional systems.

In addition to the localization effect mentioned above, Altshuler *et al.*[14] and Fukuyama[15] pointed out that a similar logarithmic behavior is expected if the mutual Coulomb interaction of the electrons is considered. The interaction effects are less sensitive to the magnetic field and therefore can be separated by suppressing localization with a perpendicular magnetic field. Although the importance of the interaction effect was recognized long ago, systematic studies to separate this effect from the localization effect have only been realized recently. The only report on the value of $1-F$, which is the interaction coefficient characterizing the strength of the interaction effect, was given for the Si-MOSFET devices by Bishop *et al.*[12] who employed the parallel field magnetoresistance measurement. Their large values of F for different carrier densities are unexpected. Owing to the large electron screening constant K of Si, F is expected to be close to 1 theoretically, i.e., $1-F\sim 0$. In the case of GaAs-$Al_xGa_{1-x}As$ heterostructures, the interaction effect is expected to be significant, due to its smaller electron screening constant. This fact makes it a better system for studying the interaction effect. But until now no experimental values of F have been reported. Moreover, GaAs has a single-conduction-electron valley, and the complication of band-structure effects, such as intervalley scattering encountered in Si-MOSFET's, is absent here in determining the value of the weak-localization parameter α. It allows us to obtain a clearer picture of the role of Anderson localization in the transport of two-dimensional systems.

In this paper, we report our studies of the transport and the low-field magnetotransport of the 2D EG in GaAS-$Al_xGa_{1-x}As$ heterostructures. The temperature dependences of the conductivity of three samples was studied in the absence of any external magnetic field B and in the presence of $\vec{B}$ applied perpendicular to the 2D EG. At

$B=0$, logarithmic T dependence were observed in the conductivity of all three samples. The localization parameter α, the inelastic scattering time τ_{in}, and their T dependences were determined from detailed fittings of the low-field negative magnetoresistance, taken in perpendicular $\vec{B}$, to the localization theory. In a sufficiently high perpendicular $\vec{B}$, the localization effect can be suppressed completely, and the logarithmic T correction to the conductivity arises entirely from the interaction effect. The values of the interaction coefficient $1-F$ were determined directly from the temperature dependence of the conductivity in this perpendicular $\vec{B}$ limit. In one of the samples, we also measured the magnetoresistance in the parallel $\vec{B}$ configuration and did not observe the positive magnetoresistance expected from the Zeeman splitting. We conclude that in our samples, the interaction coefficient $1-F$, cannot be determined from the parallel field magnetoresistance measurement, previously employed by Bishop *et al.* in Si-MOSFET's.

Our results show that, in the range of T from 42 to 770 mK, α is 0.76, 0.75, and 0.85 for the three samples with density $n=0.87\times10^{11}/\text{cm}^2$, $2.86\times10^{11}/\text{cm}^2$, and $7.11\times10^{11}/\text{cm}^2$, independent of T, and $\tau_{in}=\tau_0(1K/T)^p$ with $p=1$. τ_{in} at 1 K is $\tau_0=2.05\times10^{-11}$ sec, 5.2×10^{-11} sec, and 4.83×10^{-11} sec. The value of $1-F$ is 0.5, 0.95, and 3.2 respectively. The fact that α is less than unity is attributed to the electron-electron scattering described by the Maki-Thompson diagrams in the theory on fluctuations in superconductivity.

In Sec. II, we give some theoretical background emphasizing the fact that different effects can be dominant in different field ranges. The characteristic magnetic field for each effect is given. Details on the experimental techniques and the sample structures are given in Sec. III. Our results are presented in Sec. IV and the discussions are made in Sec. V. A summary is given in Sec. VI.

II. THEORETICAL BACKGROUND

In the weakly localized regime, the quantum interference between the e^{ikr} states and their backscattered e^{-ikr} states cause spatially localized states, which produce a correction term $\Delta\sigma_L$ to the classical Drude conductivity σ_0. According to AALR,[2] this correction term depends logarithmically on a characteristic length L and is given by

$$\delta\sigma_L\equiv\sigma(L)-\sigma(L_0)=-2\alpha\sigma_N\ln(L/L_0)\ . \tag{1}$$

Here, α is a constant prefactor of unity and $\sigma_N=se^2/4\pi^2\hbar$. The factor s is the product of the spin and orbital degeneracies, and for the case of GaAs-$\text{Al}_x\text{Ga}_{1-x}\text{As}$, $s=2$. At finite temperature, the characteristic length scale is the Thouless length L_T given by $L_T^2=D\tau_{in}$ (Ref. 16); D is the electron diffusion constant and τ_{in} is the inelastic scattering time. Usually, the temperature dependence of τ_{in} is expressed as $\tau_{in}\propto T^{-p}$, and the correction in conductivity, due to localization at finite T, is

$$\Delta\sigma_L(T)=\alpha p\sigma_N\ln(T/T_0)\ . \tag{2}$$

This first-order correction term increases logarithmically with temperature because the length scale decreases as the temperature increases. Consequently, the conductivity is enhanced.

In the presence of a perpendicular $\vec{B}$, the localization contribution $\Delta\sigma_L$ decreases with B and is quenched as the cyclotron radius given by $l_B=(\hbar/2eB)^{1/2}$ becomes much less than L_T. This magnetic field effect results in a negative magnetoresistance[7,8,14] given by

$$\Delta\sigma_L(B,T)\equiv\sigma_L(B,T)-\sigma_L(0,T)$$
$$=\alpha\sigma_N\left[\psi(a+\tfrac{1}{2})-\psi(a'+\tfrac{1}{2})+\ln\left[\frac{l_{in}}{l_{el}}\right]\right] \tag{3}$$

where ψ is the digamma function,

$$a=\frac{\hbar}{4DeB\tau_{in}},\quad a'=\frac{\hbar}{4DeB\tau_{el}}\ ,$$

and τ_{el} is the elastic scattering time obtained from the conductivity σ_0.

Equation (3) introduces two characteristic fields, which we define as

$$B_1=\frac{\hbar}{4eD\tau_{in}} \tag{3.1}$$

and

$$B_2=\frac{\hbar}{4eD\tau_{el}}\ . \tag{3.2}$$

In the temperature range of interest $B_1<B_2$. For $B<B_1$, $\Delta\sigma_L\sim\alpha\sigma_N(B/B_1)^2$. For intermediate fields, $B_1<B<B_2$, we find the familiar logarithmic field dependence $\Delta\sigma_L=\alpha\sigma_N\ln(B/B_0)$. The value of $\Delta\sigma_L$ approaches saturation at $B>B_2$ and is given by $\Delta\sigma_L=\alpha\sigma_N\ln(\tau_{in}/\tau_{el})$. In practice, quantum oscillatory effects set in before this high-field limit is reached. In our experiment, the field of interest is in the range $B<B_2$.

The exchange and the Hartree interaction will contribute to the conductivity correction and also results in a logarithmically temperature-dependent correction term. Altshuler *et al.*[14] and Lee *et al.*[17] included only the particle-hole scattering channel, which gives the correction term as

$$\Delta\sigma_I(T)=(1-F)\sigma_N\ln(T/T_0)\ , \tag{4}$$

where the Hartree parameter F, defined by

$$F=\int_0^{2\pi}\frac{d\vartheta/2\pi}{1+(2k_F/K)\sin(\vartheta/2)}\ , \tag{5a}$$

is determined from the angular average of the statically screened Coulomb interaction. Here, k_F is the Fermi wave vector and K is the 2D electron screening constant, given by

$$K=\frac{m^*e^2}{2\pi\epsilon\hbar^2}\ . \tag{5b}$$

Fukuyama[15] also considered the particle-particle scattering channel and wrote the correction term in the form

TABLE I. Sample parameters.

Sample no.	n_s(4.2 K) (cm^{-2})	μ(4.2 K) (cm^2/V sec)	k_F (cm^{-1})	v_F (cm/sec)	$k_F l_e$	l_e (Å)	D (cm^2/sec)
1	0.87×10^{11}	1.65×10^4	0.74×10^6	1.27×10^7	5.91	799	50.9
2	2.86×10^{11}	0.55×10^4	1.34×10^6	2.31×10^7	6.43	480	55.4
3	7.11×10^{11}	2.99×10^4	2.11×10^6	3.63×10^7	87.4	4140	753

$$\Delta\sigma_I(T)=g_F\sigma_N\ln(T/T_0)\ , \tag{6}$$

where

$$g_F=g_1+g_2-2(g_3+g_4)\ . \tag{7}$$

Here, g_1 and g_3 are the particle-hole channel coupling constants due to the exchange and Hartree interaction, respectively. Similarly, g_2 and g_4 are due to the corresponding contributions in the particle-particle channel and are of the order of F. In general, the particle-particle channel is only important for short-range interactions[17] and is sensitive to the perpendicular magnetic field.[18] It leads to a positive magnetoresistance when the cyclotron radius l_B becomes comparable to the thermal length given by $l_T=(\sqrt{\hbar D/\pi k_B T})$. This fact suggests a third characteristic field, defined by $B_3=2\pi k_B T/4eD$. Our experiments were performed in the range of perpendicular $B\lesssim B_3$.

In addition to the g_2 and g_4 correction terms, a magnetic field (either perpendicular or parallel) will produce a correction term from the antiparallel-spin-electron Hartree contribution. Since the magnetic field will split the antiparallel electrons into spin-up and spin-down subbands with an energy gap of $g\mu_B B$, this Hartree contribution cuts off when $g\mu_B B>k_B T$. This results in a Zeeman-splitting term in the conductivity given by[17]

$$\Delta\sigma_{ZS}(B,T)=-\tfrac{1}{2}F\alpha_N G(B/B_4) \tag{8a}$$

and

$$G(h)=\int_0^\infty dw\frac{d^2}{dw^2}\left[\frac{w}{e^2-1}\right]\ln\left|1-\frac{h^2}{w^2}\right|\ , \tag{8b}$$

where the characteristic field $B_4=k_B T/g\mu_B$. Equations (8) predict a positive magnetoresistance given by

$$\Delta\sigma_{ZS}=-\tfrac{1}{2}F\alpha_N\ln B \tag{9}$$

for $B>B_4$. If the particle-particle channel is taken into account $\frac{1}{2}F$ in Eqs. (8) is replaced by g_3+g_4. Since the characteristic field B_4 is greater than B_1 and B_3 in our GaAs samples, we expect no contribution from the Zeeman term in perpendicular fields less than B_3. However, in the parallel field geometry, the Zeeman term is the only known contribution to magnetoresistance and the magnetoresistance in this geometry has been used by Bishop *et al.*[12] to determine F in Si-MOSFET's. In addition, we must point out that the equations describing the conductivity correction terms in the presence of a perpendicular $\vec{B}$ are valid only in the classically weak-field limit, $\omega_c\tau=\mu B<1$. This defines another characteristic field, $B_5=\mu^{-1}$.

III. EXPERIMENTAL PROCEDURE

The GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructures were grown by molecular beam epitaxy (MBE) on Cr-doped GaAs substrates. The heterostructures consisted of a 1-μm-thick undoped GaAs epilayer, a 100-Å spacer of undoped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$, a 600-Å -thick Si-doped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer, and a 200-Å -thick GaAs cap layer to facilitate Ohmic contacts. The samples were cut into standard Hall bridges and the low-field Hall measurements were performed to determine their electron densities and mobilities. In addition, high magnetic field measurements were also made to observe the quantum oscillations from the 2D electrons. The agreement between the electron density determined from these quantum oscillations and that from the low-field Hall measurements indicated that no parallel channel conduction existed in our samples. Altogether three different samples with electron densities $n=7.11\times10^{11}/\mathrm{cm}^{-2}$, $2.86\times10^{11}/\mathrm{cm}^2$, and $0.87\times10^{11}/\mathrm{cm}^2$ were studied and their electrical characteristics are listed in Table I.

The samples were attached by Apiezon N grease on a silver plate, which was in direct metallic contact with the mixing chamber of a dilution refrigerator capable of reaching 10 mK. The external magnetic field was generated by a superconducting solenoid. The conductance of the samples was obtained from four-terminal resistance measurements using an ac bridge operating at 11 Hz. The measuring current was always adjusted to levels where non-Ohmic behavior was not observed.

IV. RESULTS

All our samples show a logarithmic temperature dependence in their conductivity in the absence of B and a negative magnetoresistance in a perpendicular $\vec{B}$. We plot in Fig. 1 the conductance of sample 2 as a function of B, which was applied perpendicular to the plane of the 2D electrons, at several different temperatures. A logarithmic dependence on B is seen in the data taken at all six temperatures, and the range of this logarithmic dependence is larger at the lower temperatures. In this sample, the characteristic magnetic fields, discussed in Sec. II, are $B_1=5.8\times10^{-4}$ T at 1 K, $B_2=0.14$ T, $B_3=2.5\times10^{-2}$ T at 1 K, $B_4=2.9$ T at 1 K, and $B_5=1.8$ T. Since the data shown in Fig. 1 were taken with $B<B_2$ and B_4 and $B\lesssim B_3$, the observed negative magnetoresistance is due to the suppression of Anderson localization. Consequently,

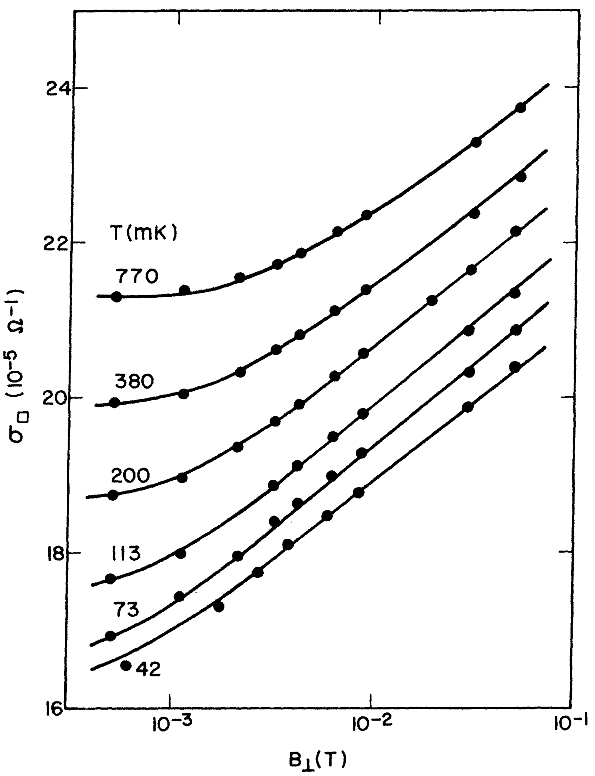

FIG. 1. Conductance of sample 2 as a function of perpendicular $\vec{B}$. Dots are measured data and solid lines are theoretical fits to Eq. (3) with values of α and τ_{in} given in Table II.

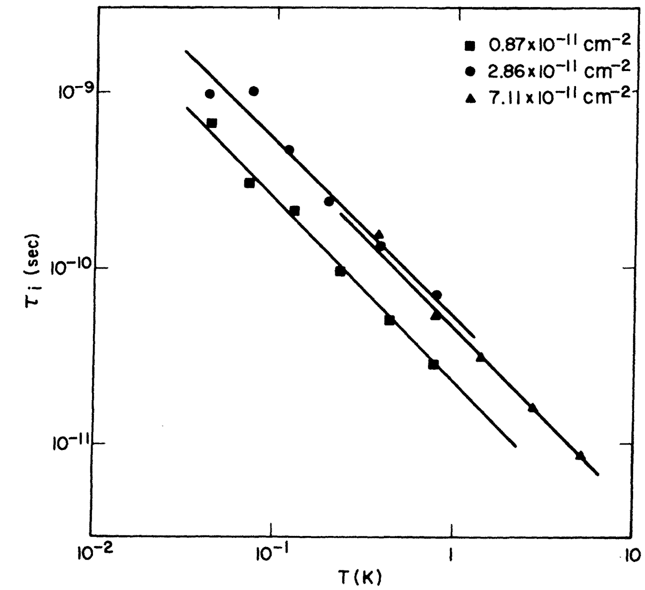

FIG. 2. Temperature dependencies of the inelastic scattering time for three different samples.

the localization parameter α and the inelastic scattering time τ_{in} can be extracted from the least-squares fits of the data to Eq. (3). The solid lines represent the best fits to the data with $\alpha=0.75\pm0.03$ (independent of T) and the values of τ_{in} plotted as solid dots in Fig. 2. Similar data taken from samples 1 and 3 yield $\alpha=0.76\pm0.05$ and 0.85 ± 0.07, respectively (see Table II). In the temperature range from 42 mK to 4.2 K, the inelastic scattering time extracted from fitting the data from all three samples, as shown in Fig. 2, follows $\tau_{in}=\tau_0(1\mathrm{K}/T)^p$, with $p=1.00\pm0.08$. The value of τ_0 for the three samples are listed together with their other parameters in Table II.

In Fig. 3, the conductance of sample 2 is plotted as a function of T in the absence of B and in perpendicular fields $B=0.03$ and 0.3 T. Again, logarithmic regions are apparent in all three curves. The deviation from a strictly logarithmic T dependence at the lowest T is believed to be due to electron heating. In the case where $B=0$, both the localization effect and the Coulomb interaction effect contribute to the observed logarithmic T dependence and, as seen in Eqs. (2) and (3), the slope of the straight line directly determines the value of $\alpha p+(1-F)$. However, the localization contribution can be suppressed by the application of a perpendicular $\vec{B}$. With $B\geq0.03$ T the localization contribution is sufficiently suppressed that the observed effect is dominated by the Coulomb contribution. For $B=0.3$ T the localization contribution is suppressed completely, and the observed effect is due entirely to the Coulomb contribution. As a result, the data for $B=0.03$ and 0.3 T follow two straight lines almost parallel to each other. The slope of the straight line through the $B=0.3$ T data gives us a direct measure of $1-F$. In Fig. 4, the value of $1-F$ determined for the three samples are plotted as a function of their $2k_F/K$.

At this point, two remarks should be made concerning our data analysis. First, our direct determination of the interaction coefficient $1-F$ allows us to make an independent determination of the localization coefficient αp. This is accomplished by taking the difference between the value of $\alpha p+(1-F)$ and the value of $1-F$, obtained from the data in Fig. 3 at $B=0$ and 0.3 T, respectively. On the other hand, fitting of the low-field magnetoresistance to the localization theory gives us α and τ_{in}, and the temperature dependence of τ_{in} directly gives us p. The product of α and p thus determined, as shown in the lower

TABLE II. Experimental and calculated parameters in the weak-localization regime.

Sample no.	$2k_F/K$	α	Measured τ_0 (sec)	p	$1-F$	αp	Calculated τ_0 (sec)
1	0.76	0.76 ± 0.05	2.05×10^{-11}	1.04	0.50 ± 0.05	0.71 ± 0.07	0.25×10^{-11}
2	1.38	0.75 ± 0.03	5.20×10^{-11}	1.0	0.95 ± 0.05	0.77 ± 0.07	0.26 ± 10^{-11}
3	2.18	0.85 ± 0.07	4.83×10^{-11}	1.02	3.2 ± 0.2	0.90 ± 0.1	2.13×10^{-11}

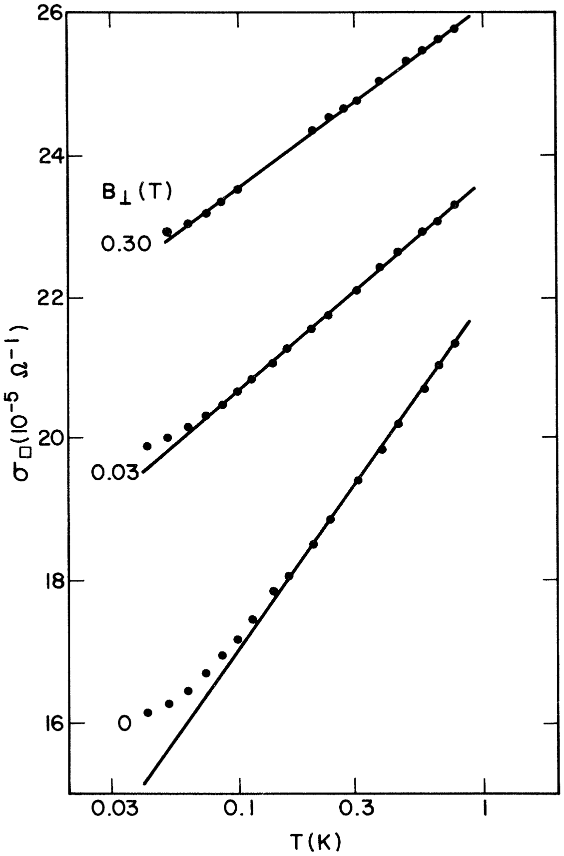

FIG. 3. Conductance of sample 2 as function of T at $B=0$, 0.03, and 0.3 T perpendicular to the sample.

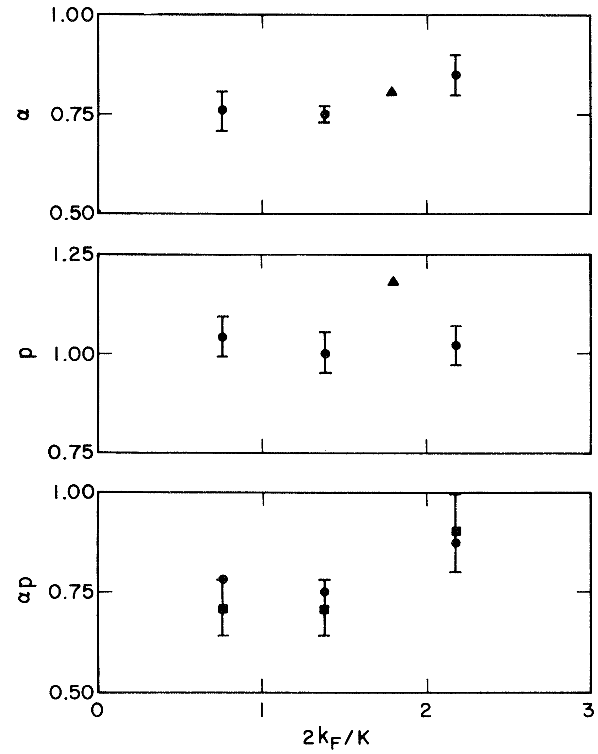

FIG. 5. In the upper and middle panels, the dots show the values of α and p determined from the magnetoresistance data (Fig. 1); triangles (▲) are from Ref. 13. In the lower panel, the dots show the product of α and p and the squares show the αp determined from the logarithmic temperature-dependent data (Fig. 3).

panel of Fig. 5, is in good agreement with αp for all three samples. This agreement shows the internal consistency of our data analysis and also provides evidence that the Coulomb interaction effect, operative at $B=0$, is operative at finite B, when the localization effect is quenched. Second, Bishop *et al.* first demonstrated the use of parallel magnetoresistance measurements to determine the interaction parameter F. They recognized that the application of a parallel $\vec{B}$ should have no effect on localization,

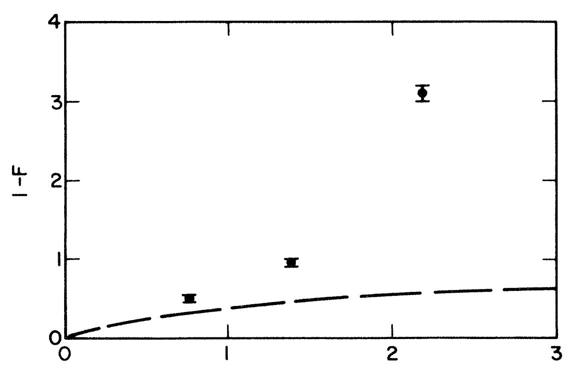

FIG. 4. $1-F$ as a function of $2k_F/K$ for three samples. Broken curve is the theoretical curve calculated from Eq. (5).

and the resulting positive magnetoresistance is due to the Zeeman-splitting term given by Eqs. (8). However, this method cannot be used to determine F in our GaAs-$Al_xGa_{1-x}As$ samples in which a negative magnetoresistance was observed in the range of parallel $\vec{B}$, where the Zeeman term is expected to be appreciable. Figure 6 shows the percentage change in the conductivity as a function of parallel $\vec{B}$ at $T=0.11$, 0.77, and 7.1 K. A positive magnetoresistance was observed only in the data for $B>6$ T taken at $T=7.1$ K.

V. DISCUSSIONS

This experiment demonstrated unambiguously the importance of the electron-electron interaction effect in the weak-localization regime of the two-dimensional electrons in the GaAs-$Al_xGa_{1-x}As$ heterostructure. We determined directly the interaction coefficient $1-F$, the localization parameter α, the electron inelastic scattering time τ_{in}, and its temperature exponent p. In this section, we discuss these results in view of current theoretical expectations and point out the difficulties in understanding the data in their entirety within the theoretical framework outlined in Sec. II. It is suggested that scattering by the Maki-Thompson process of fluctuations in superconductivity is operative in these samples, and it constitutes an

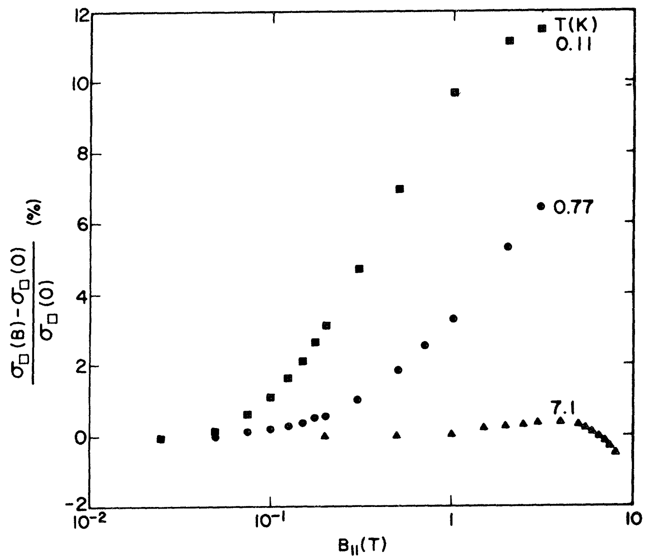

FIG. 6. Percentage change in the conductivity as a function of parallel $\vec{B}$ at $T=0.11$, 0.77, 7.1 K from sample 2.

additional contribution to the temperature and the magnetic field dependences in this regime.

A. The localization parameter

According to the one-electron scaling theory, $\alpha=1$, our result, as shown in Fig. 5, shows that α is clearly less than 1. This fact that $\alpha<1$ is consistent with the earlier result from Ref. 13, and it cannot be attributed to the dominance of spin-orbit interactions, which was not taken into account in our analysis. The spin-orbit interaction in GaAs is well known[19] and is sufficiently weak in comparison to the inelastic scattering given by τ_{in}.

We believe that scattering by the Maki-Thompson process of fluctuations in superconductivity is an additional correction to the conductivity. It was pointed out by Larkin[20] that in the particle-particle channel, scattering of electrons by the same process that gives rise to fluctuations in superconductors can affect the low-field magnetoresistance. This additional channel of scattering produces a positive magnetoresistance which has the same functional form as the negative magnetoresistance due to localization. This correction term can be expressed as

$$\Delta\sigma_{MT}(B,T)=-\frac{\pi^2 g_M^2}{6}\Delta\sigma_L(B,T),\quad g_M \ll 1 \tag{10}$$

where g_M is a normalized coupling constant related to the phonon exchange and the Coulomb interaction. Consequently, $\alpha=1-\pi^2 g_M^2/6$, and g_M obtained from our results is ~ 0.4. The higher value of α observed in the sample with $n=7.1\times10^{11}/\text{cm}^2$ may be attributed to the decrease of g_M at higher n.

B. The inelastic scattering time

Abrahams *et al.*[21] showed that in the dirty limit the inelastic scattering time τ_{in} due to electron-electron scattering is given by

$$\frac{\tau_e}{\tau_{\text{in}}}=\frac{-k_B T}{\epsilon_F}\ln\frac{T}{T_1}\ , \tag{11}$$

where ϵ_F is the Fermi energy, τ_e is the elastic scattering time, and T_1 is given by

$$k_B T_1=\frac{\hbar^3 D^3 K^4 \epsilon^2}{e^4}\ .$$

Here, ϵ is the dielectric constant. For our three samples, $T_1=4.3\times10^4$, 5.6×10^4, and 1.4×10^8 K, and the $\ln(T/T_1)$ contribution is so weakly dependent on T that τ_{in} is expected to be strictly proportional to T^{-1}.

Our results from all three samples show $\tau_{\text{in}}=\tau_0(1\text{ K}/T)$ (Figs. 2 and 5). This T^{-1} dependence agrees with previous observations on Si-MOSFET's and is consistent with the explanation that electron-electron scattering is the dominant inelastic scattering process that destroys the electron's phase memory. However, the values of τ_0 (Table II) are an order of magnitude higher than that predicted by Eq. (11). A similar discrepancy has also been found by Bergmann[22] in thin metal films, and the importance of electron-phonon processes was invoked as a possible explanation. In our case, an additional electron-phonon process of similar importance will decrease the expected value for τ_{in} and further increase the observed discrepancy. We believe that the strictly T^{-1} dependence observed in all the samples is sufficient evidence for the dominance of electron-electron scattering and that the magnitude of τ_{in} still cannot be explained by the present theory.

C. The interaction coefficient

In our samples, the screening constant K is small and $2k_F/K \gtrsim 1$ (Table I). Consequently, the interaction effect given by Eqs. (4), (5a), and (5b) is expected to be comparable to the localization effect given by Eq. (2). Unlike previous experiments on Si-MOSFET's, where $2k_F/K$ is small and this interaction term is negligible at $B=0$, this experiment makes it possible to test the theory quantitatively. In Fig. 4, the value of $1-F$ calculated from Eqs. (5) is shown as the dashed curve to compare with our experimental results. For the two lower-density samples, which have small $2k_F/K$, the trend of increasing $1-F$ with increasing $2k_F/K$ is observed. However, the trend towards saturation expected for large $2k_F/K$ is not observed in the high-density sample with $2k_F/K=2.2$. Moreover, the magnitude of $1-F$ determined from the experiment is larger than that calculated in all three samples. At $2k_F/K=2.2$, the observed $1-F$ is 5 times that expected from theory. Particle-particle channel scattering, whose contribution was already found in α, could account for some of this difference [Eq. (6)]. However, the additional g_2-2g_4 contribution, which is of the order of F, cannot explain the large value of $(1-F)$ found in sample 3. We should note that $F>1$ was previously observed in the parallel $\vec{B}$ magnetoresistance data of Si-MOSFET's and a value as large as $F=3.5$ was observed when $k_F l_e \sim 3$. The approach towards exponential localization at $k_F l_e \simeq 1$ was suspected as the cause for this breakdown of the theory. In our case, $F=-2.2$ in the sample with $n=7.1\times 10^{11}/\mathrm{cm}^2$, $2k_F/K=2.2$, and $k_F l_e=87$. It is in the limit $k_F l_e \gg 1$ where the theory is expected to be valid.

D. Parallel field magnetoresistance

A parallel $\vec{B}$ does not alter the orbital motion of the 2D EG and is expected to have no observable effect on localization. As a result, only the positive magnetoresistance term described by Eqs. (8) can be operative. The strongly temperature-dependent negative magnetoresistance observed in Fig. 6 cannot be attributed to either the localization effect or the interaction effects. Scattering by magnetic impurities[23] is an unlikely explanation since no evidence for such magnetic scattering was observed in the magnetoresistance in the perpendicular $\vec{B}$ geometry. Furthermore, the mechanism due to suppression of intersubband scattering previously invoked by Englert *et al.*[24] to explain the negative magnetoresistance in high-density samples is also inapplicable. The next subband is at least 5 meV above E_F in the sample from which the data shown in Fig. 6 were taken. Finally, we note that similar parallel field negative magnetoresistance has also been observed in the 2D EG in ZnO (Ref. 23) and in InAs (Ref. 25).

VI. SUMMARY

We have studied the transport and the low-field magnetotransport of the 2D EG in three GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructure samples in the weak-localization regime. We found that both localization and interaction contributions are important in the logarithmic temperature and logarithmic magnetic field dependences of the conductivity. The localization parameter α, the inelastic scattering time τ_{in}, and the screening parameter $1-F$ were determined from fitting the perpendicular field magnetoresistance to the theory of Altshuler *et al.*[7] and Lee *et al.*[18] in a consistent manner. The values of α we obtained are clearly less than unity (0.75 ± 0.03 to 0.85 ± 0.07). This result is different from that previously obtained from Si-MOSFET's,[12] and the difference can be explained by the importance of the interaction effect in this system, where the screening constant K is small and $2k_F/K \gtrsim 1$.

We believe that scattering by the Maki-Thompson process that gives rise to fluctuations in superconductivity is also operative in the case of the repulsive electron-electron interaction in our system. This leads to a positive magnetoresistance correction which is similar to the negative magnetoresistance due to the suppression of the localization effects and reduces α from 1. We found from the Maki-Thompson correction that the particle-particle channel corrections are comparable to the particle-hole channel contribution. The temperature exponent p of τ_{in} is 1.00 ± 0.08, in agreement with the theory of inelastic electron-electron scattering.[21] However, the absolute values of τ_{in} are about an order of magnitude larger than the theoretical prediction. The experimental values of $1-F$ are found to increase with increasing $2k_F/K$, in qualitative agreement with the theoretical prediction. However, $1-F=3.2$ at $n=7.11\times10^{11}\ \mathrm{cm}^{-2}$ is 5 times that expected from theory, and this large discrepancy remains unexplained. We also found a negative magnetoresistance in the case of parallel $\vec{B}$. Thus the positive magnetoresistance due to the Zeeman splitting, previously employed to determine F, was not observed.

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1E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).

2D. J. Thouless, Phys. Rep. 13C, 93 (1974).

3G. J. Dolan and D. D. Osheroff, Phys. Rev. Lett. 43, 72 (1978).

4N. Giordano, Phys. Rev. B 22, 5635 (1980).

5D. J. Bishop, D. C. Tsui, and R. C. Dynes, Phys. Rev. Lett. 44, 1153 (1980); 46, 360 (1981).

6M. J. Uren, R. A. Davis, and M. Pepper, J. Phys. C 13, L986 (1980).

7B. L. Altshuler, D. Khmelnitzkii, A. I. Larkin, and P. A. Lee, Phys. Rev. B 22, 5142 (1980).

8S. Hikami, A. I. Larkin, and Y. Nagaoka, Progr. Theor. Phys. 63, 707 (1980).

9Y. Kawaguchi and S. Kawaji, J. Phys. Soc. Jpn. 48, 699 (1980).

10M. J. Uren, R. A. Davis, M. Kaveh, and M. Pepper, J. Phys. C 14, L395 (1981).

11R. G. Wheeler, Phys. Rev. B 24, 4645 (1981).

12D. J. Bishop, R. C. Dynes, and D. C. Tsui, Phys. Rev. B 24, 773 (1982).

13D. A. Poole, M. Pepper, and R. W. Glew, J. Phys. C 14, L995 (1981).

14B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. 44, 1288 (1980).

15H. Fukuyama, J. Phys. Soc. Jpn. 48, 2169 (1980).

16D. J. Thouless, Phys. Rev. Lett. 39, 1167 (1977).

17P. A. Lee and T. V. Ramakrishnan, Phys. Rev. B 26, 4009 (1982).

18H. Fukuyama, J. Phys. Soc. Jpn. 50, 3407 (1981).

19R. C. Miller, D. A. Kleinman, W. H. Nordland, Jr., and A. C. Gossard, Phys. Rev. B 22, 863 (1980).

20A. I. Larkin, Zh. Eksp. Teor. Fiz. Pis'ma Red. 31, 239 (1980) [JETP Lett. 31, 219 (1980)]; B. L. Altshuler, A. G. Aronov, A. I. Larkin, and D. Khmelnitzkii, Zh. Eksp. Teor. Fiz. 81, 768 (1981) [Sov. Phys. JETP 54, 411 (1981)].

21E. Abrahams, P. W. Anderson, P. A. Lee, and T. V. Ramakrishnan, Phys. Rev. B 24, 6783 (1981).

22G. Bergmann, Z. Phys. B 48, 5 (1982).

[23]Y. Goldstein, Y. Grinshpan, and A. Many, Phys. Rev. B 19, 2256 (1979).

[24]Th. Englert, J. C. Maan, D. C. Tsui, and A. C. Gossard, Solid State Commun. 45, 989 (1983).

[25]S. Kawaji and Y. Kawaguchi, in *Proceedings of the 9th International Conference on the Physics of Semiconductors, Moscow, 1968* (Nauka, Leningrad, 1968), p. 730.