Interaction correction to conductivity of Al$_x$Ga$_{1-x}$As/GaAs double quantum well heterostructures near the balance

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The electron-electron interaction quantum correction to the conductivity of the gated double well Al$_x$Ga$_{1-x}$As/GaAs structures is investigated experimentally. The analysis of the temperature and magnetic field dependences of the conductivity tensor allows us to obtain reliably the diffusion part of the interaction correction for the regimes when the structure is balanced and when only one quantum well is occupied. The surprising result is that the interaction correction does not reveal resonant behavior; it is practically the same for both regimes.

I. INTRODUCTION

The double quantum well (DQW) structures exhibit a number of salient features. For instance, the resistance of the structures with different mobilities in the wells strongly depends on the potential profile of the quantum wells and has a peak when the latter is symmetric. The DQW systems are convenient system to study a wide variety of the oscillatory phenomena originated from the peculiarities of the Landau quantization of the energy spectrum. The quantum corrections to the conductivity are also expected to demonstrate peculiar behavior when the population of the quantum wells and/or the interwell transition rate is varied. The interference quantum correction in DWQ's is studied in Refs. $^3$-$^9$ and gives antilocalization correction for ordinary semiconductors. The correction due to the electron-electron (e-e) interaction is investigated significantly less. $^{12,14}$

The contribution of e-e interaction to the conductivity is determined by two terms: singlet and multiplet. The singlet term does not depend on interaction constant and it favors localization, i.e., it leads to the conductivity decrease with lowering temperature. In contrast, the contribution of the interaction in the multiplet channel depends on the interaction constant $F_0$ [or $\gamma_2 = -F_0^2/(1 + F_0^2)$] and gives antilocalization correction for ordinary semiconductor structures. For diffusion regime ($T\tau \ll 1$, where $\tau$ is the transport relaxation time), the interaction correction to the conductivity is as follows: $^{23}

$$
\delta\sigma_{ee} = K_{ee}G_0\ln(T\tau),$$

$$K_{ee} = 1 + (4n_v^2 - 1) \left[ 1 - \frac{1 + \gamma_2}{\gamma_2} \ln(1 + \gamma_2) \right], \tag{1}$$

where $G_0 = e^2/\pi\hbar \simeq 1.23 \times 10^{-5}$ Ohm$^{-1}$, $n_v$ is the number of valleys. This correction is independent of the magnetic field, while the Zeeman splitting is sufficiently small, $g\mu_B B \ll T$, where $g$ is the Landé $g$-factor. The first and second terms correspond to the contributions in the singlet and multiplet channel, respectively.

Let us demonstrate how strongly the coefficient $K_{ee}$ in front of the logarithm in Eq. (1) (just its value is determined experimentally) depends on the valley degeneracy. For the 2D gas with the single valley spectrum, $n_v = 1$, at $\gamma_2 = 0.28$, that corresponds to the electron density $n \simeq 10^{12}$ cm$^{-2}$ for GaAs according to Ref. $^{16}$ the multiplet contribution is less than the singlet one and $K_{ee} = 0.61$. For the case of the two valleys electron spectrum, as it takes place in [100] Si-MOS 2D structures, the correction in the multiplet channel is larger than that in the singlet one and the coefficient $K_{ee}$ for the same electron density should have opposite sign, $K_{ee} = -0.93$, i.e., the correction should be antilocalizing.

It seems that double quantum well heterostructures based on the single valley semiconductors should demonstrate analogous behavior. The crucial change of the interaction contribution to the conductivity should be observed when changing the relation between the electron densities in the wells with the help of gate electrode, for example. If one naively supposes that the total correction is the sum of the interaction contributions from each of the wells, the value of $K_{ee}$ about 1.07 should be observed for particular case of the different but close electron densities in the wells, $n_1 \approx n_2 \approx 5 \times 10^{11}$ cm$^{-2}$. When the electron density is the same in the wells, $n_1 = n_2 = 5 \times 10^{11}$ cm$^{-2}$, we should deal with the analog of the two valleys structure, for which the coefficient in the multiplet term becomes equal to 15, the interaction contribution becomes antilocalizing with $K_{ee} = -0.91$. But unlike the Si-MOS structure, for this case one can easily change the relation between the singlet and multiplet contributions by varying the densities ratio in the wells. Of course, such the giant change of $K_{ee}$ can be observed in special structures only. Namely, the electron densities and mobilities in the wells should be close. Moreover, the scatterers should be common for the carriers in the different wells in the sense that each specific impurity should scatter the carriers of the lower and upper wells identically. In addition to that, the interwell distance $d$ should be small, $\kappa d < 1$, where $\kappa$ is the inverse screening length, but the interwell transition time $t_{12}$ should be large, $t_{12} \gg 1/T$. In reality, it is very dif-
TABLE I. Parameters of the structures investigated

| Structure | #3243 | #3154 |
|-----------|-------|-------|
| Regime    | SQW   | SQW   |
| $V_g$ (V) | balance | balance |
| $n$ (10$^{11}$ cm$^{-2}$)$^a$ | 7.0 | 7.5 |
| $\mu$ (10$^8$ cm$^2$/Vs) | 14.5 | 15 |
| $K_{ee}$ | 0.60 | 0.57 |
| $K_{ee}$ | 0.59 | 0.72 |

$^a$ The electron density per quantum well.

In the diffusive regime: the interaction gives contribution to the one component of the conductivity tensor, namely, to $\sigma_{xx}$, whereas $\delta \sigma_{xy} = 0$. At low interwell transition rate the components of the conductivity tensor in the double well structures are simply the sum of the components of each well, $\sigma_{xx,xy} = \sigma_{xx,xy}^{(1)} + \sigma_{xx,xy}^{(2)}$. Therefore the temperature dependence of $\sigma_{xx}$ at the high magnetic field, $B > B_{tr}$ (where $B_{tr} = h/2eL^2$ is the transport magnetic field, $l$ is the transport mean free path), when the temperature dependence of the WL correction is mainly suppressed, is determined by the interaction correction only. This dependence should be logarithmic and the slope of $\sigma_{xx}$ vs $\ln T$ dependence should give the value of $K_{ee}$.

The situation becomes more complicated at $T\tau > 0.1$, when the ballistic contribution of interaction becomes important. This contribution results in the temperature dependent correction to the mobility, in its turn this leads to appearance of the magnetic field dependence of $\Delta \sigma_{xx} = \sigma_{xx}(T) - \sigma_{xx}(T_0)$ and the temperature dependence of $\Delta \sigma_{xy}$:

$$
\Delta \sigma_{xx}(B, T) = \sum_{i=1}^{2} \frac{1 - \mu_i^2(T_0)B^2}{[1 + \mu_i^2(T_0)B^2]^2} \epsilon_{ii} \mu_i(T)
+ \left[C_{ee}^{(1)} + K_{ee}^{(2)}\right] G_0 \ln \left(\frac{T}{T_0}\right),
$$

$$
\Delta \sigma_{xy}(B, T) = \sum_{i=1}^{2} \frac{2\mu_i(T_0)B}{[1 + \mu_i^2(T_0)B^2]^2} \epsilon_{ii} \mu_i(T),
$$

where $\Delta \mu_i(T) = \mu_i(T) - \mu_i(T_0)$. As seen from Eq. (2) the temperature dependence of $\sigma_{xx}$ in this case is determined not only by $K_{ee}^{(1)}$ and $K_{ee}^{(2)}$, but by $\mu_1$, $\mu_2$, $\Delta \mu_1$, and $\Delta \mu_2$ also. Things will get better preferably when the mobilities in the wells are close to each other. Then, as seen from Eq. (2), the temperature dependence of $\sigma_{xx}$ at $B = 1/\mu$ is determined by diffusion interaction correction only. Therefore, let us start analysis of the data from this case.

Detailed analysis of the gate voltage dependencies of the electron densities and mobilities performed for these structures in Ref. [13] shows that the close values of the mobility in the wells occur near the balance, $n_1 = n_2$, which happens for the structures 3243 and 3154 at $V_g = -1.5$ V and $V_g = -2$ V, respectively. The magnetic field dependences of $\sigma_{xx}$, $\sigma_{xy}$, and $\Delta \sigma_{xx,xy} = \sigma_{xx,xy}(4.2$ K$) - \sigma_{xx,xy}(1.35$ K) taken for the structure 3243 at $V_g = -1.5$ V are presented in Fig. [1a] and Fig. [1b], respectively. One can see that $\Delta \sigma_{xx}$ decreases strongly up to $B = 1$ T therewith $\Delta \sigma_{xy}$ is not small over the whole magnetic field range. (The value of $B_{tr}$ at this gate voltage is about 10$^{-2}$ T so the variation of $\sigma_{xx}$ and $\sigma_{xy}$ does not associated with the contribution of the weak localization correction). Such variations of $\Delta \sigma_{xx}$ and $\Delta \sigma_{xy}$ with the changing temperature and magnetic field not match to the diffusion interaction correction. It is not surprising because the parameter $T\tau = 0.08 - 0.25$ is not small within this temperature range.
range and the ballistic part of interaction correction gives significant contribution.

As we mention just below Eq. 3 the interaction contribution can be extracted in this situation by analyzing the $\Delta \sigma_{xx}$ vs $T$ behavior at $B = 1/\mu$. Such the dependence plotted in Fig. 1(c) shows that the temperature dependence of $\Delta \sigma_{xx}$ is really close to the logarithmic one and its slope gives $K_{ee} = 0.55 \pm 0.05$.

The diffusion part of the interaction correction has to lead to the temperature dependence of the Hall coefficient, $\Delta R_H/R_H \simeq -2\Delta \sigma_{xx}/\sigma_{xx}$, and, hence, the diffusion contribution can be independently obtained from the $T$ dependence of the Hall coefficient. As seen from Fig. 1(c) $\Delta \sigma_{xx}$ found as $[R_H(T) - R_H(4.2 K)]\sigma_{xx}(4.2 K)/2R_H(4.2 K)$ agrees well with the data obtained by the first method.

Finally, the diffusion contribution $\delta \sigma_{ee}$ can be obtained even over the whole magnetic field range by eliminating the ballistic part of interaction with the use of the method described in Ref. 13. Because the ballistic part of the interaction correction is reduced to the renormalization of the mobility and the diffusion part of the correction does not contribute to the off-diagonal component of the conductivity, one can obtain the $\mu$ vs $T$ dependence from $\sigma_{xy}$ knowing the electron density (from the period Shubnikov-de Haas oscillations)

$$\mu(T) = \left( \frac{\sigma_{xy}(T)}{en\sigma_{xy}(T)B}\frac{1}{B} \right)^{1/2} \quad (4)$$

and find the correction $\delta \sigma_{ee}(T)$ as the difference between the experimental value of $\sigma_{xx}(T)$ and the value of $en\mu(T)/(1 + \mu^2(T)B^2)$. The results of such a data treatment are presented in Fig. 2(a) as the $\Delta \delta \sigma_{ee}$ vs $lnT$ plot, where $\Delta \delta \sigma_{ee} = \delta \sigma_{ee}(T) - \delta \sigma_{ee}(1.35 \text{ K})$. It is clearly seen that the slopes of $\sigma_{xx}$ vs $lnT$ dependences are practically independent of the magnetic field and give $K_{ee} = 0.57 \pm 0.05$ that agrees well with the value of $K_{ee}$ obtained by the two previous methods.

Thus, three different methods for obtaining of the diffusion interaction correction give the same results. The correction $\delta \sigma_{ee}$ is logarithmic in the temperature, and the value of the parameter $K_{ee}$ is $0.57 \pm 0.05$.

Let us inspect the data for the case when only one well is occupied. For the structure 3243 it occurs at $V_g \cong -4 \text{ V}$. There are no additional difficulties in the extraction of $K_{ee}$ for this case. All three methods give also the same results. As an example we have plotted in Fig. 2(b) the temperature dependence of $\Delta \delta \sigma_{ee}$ taken at different magnetic field at $V_g = -4.1 \text{ V}$ when the electron density and mobility are close to those for each well at the balance. One can see that the temperature dependences of $\Delta \delta \sigma_{ee}$ taken at different $B$ for this case are close to each other also. The slope of the $\Delta \delta \sigma_{ee}$ vs $lnT$ dependence gives $K_{ee} = 0.60 \pm 0.05$ that corresponds to $E_0^* = -0.225$. This value is in a good agreement with the theoretical estimate $E_0^* = -0.237$.16

The surprising thing is that the value of $K_{ee}$ in the balance practically coincides with that for the regime when only one quantum well is occupied. Such coincidence seems strange. It does not agree with both cases discussed qualitatively in Section I.

It is possible that the structure 3243 at $V_g = -1.5 \text{ V}$ is close to the balance but not exactly in it. Let us analyze the data at the gate voltages in the vicinity of $-1.5 \text{ V}$. In this situation the mobilities in the wells are distinguished and strictly speaking the method used for $V_g = -1.5 \text{ V}$ is not applicable. However, one can easily assure that by using the total electron density $n_1 + n_2$ and the average mobility $\mu^* = \sigma^*/e(n_1 + n_2)$ (where $\sigma^* = 1/\rho_{ee}$ at $B = 1/\mu^*$) in the data processing one obtains the value of $K_{ee}$ very close to its average value. The results obtained by

FIG. 1. (Color online) (a) The magnetic field dependences of $\sigma_{xx}$ and $\sigma_{xy}$ taken at $T = 1.35 \text{ K}$. (b) The magnetic field dependences of $\Delta \sigma_{xx,xy} = \sigma_{xx,xy}(4.2 \text{ K}) - \sigma_{xx,xy}(1.35 \text{ K})$. (c) The temperature dependences of $\Delta \sigma_{xx} = \sigma_{xx}(4.2 \text{ K}) - \sigma_{xx}(T)$ at $B = 1/\mu = 0.67 \text{ T}$ (squares) and that found from the Hall effect as described in text (diamonds). $V_g = -1.5 \text{ V}$.

FIG. 2. (Color online) The temperature dependence of the diffusion $e-e$ interaction correction $\Delta \delta \sigma_{ee} = \delta \sigma_{ee}(T) - \delta \sigma_{ee}(1.35 \text{ K})$ for different magnetic fields near the balance (a) and under the condition when only lower quantum well is occupied (b).
the specific impurity scatters the carriers of the lower and upper wells differently. Besides, the interwell distance is not sufficiently small in our case. The parameter $\kappa d$ reduces the interaction contribution to the conductivity.

It is clear that for the adequate understanding of the role of the e-e interaction in the double well structures, the theory, which properly takes into account the interaction in the singlet and multiplet channels and specifics of the screening for different interwell distances, is necessary. Such theoretical consideration is presented in Ref. [21]. The authors analyze both the interaction and weak localization corrections to the conductivity of the double layer structures in framework of the random phase approximation. The interaction effect is considered for the case of the identical layers. Unexpected result is that the multiplet contribution even in the case of common scatterers does not win the singlet contribution for actual parameter $\kappa d > 1$ and, consequently, does not result in the change of the $K_{ee}$ sign, as we have naively reasoned in the Section I.

Let us compare the theoretical results [21] with the experimental data. For both structures 3243 and 3154, the experimental and theoretical values of $K_{ee}$ for SQW regime and for the balance are presented in Table I. The calculations have been performed with the electron densities listed in the table, $\kappa = 2 \times 10^6$ cm$^{-1}$, and $d = 1.8 \times 10^{-6}$ cm. Because no fitting parameters have been determined, the agreement with the experimental data is not very high. Nevertheless, the qualitative features of $K_{ee}$ are reproduced by the model.
been used, agreement between the theory and experiment can be considered as reasonably good.

Figure [1] illustrates the sensitivity of $K_{ee}$ to the inter-well distance. The theoretical and experimental values of $K_{ee}$ corresponding to the sample 3243 are marked by open and solid circles, respectively. Inspection of this figure shows that contrary to our expectation the value of $K_{ee}$ does not change the sign at any real inter-well distances, all the more it does not acquire the value $K_{ee} \approx -1$, which corresponds to the equal contributions of 15 multiplet channels. Besides, the other limiting case of independent contributions coming from each well is achieved at very large distance, $\varepsilon d > 30$ (see inset in Fig. [1]). This is clear indication of great importance of the specific feature of the screening of electron-electron interaction in the double layer systems.

IV. CONCLUSION

We have studied the electron-electron interaction correction to the conductivity of 2D electron gas in the gated double quantum well $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heterostructures. Using three different methods we have obtained the diffusion part of the interaction correction under the conditions when one and two quantum wells are occupied. It has been found that the interaction correction, contrary to naive expectations, is practically independent of whether two or one quantum well contribute to the conductivity. This observation is consistent with the results of the paper by Burnistrov, Gornyi and Tikhonov in which the theory for the dephasing and electron-electron interaction in the double well structures is developed.

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