Interference induced metallic-like behavior of a two-dimensional hole gas in asymmetric GaAs/In$_x$Ga$_{1-x}$As/GaAs quantum well

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(Dated: March 23, 2022)

The temperature and magnetic field dependences of the conductivity of the heterostructures with asymmetric In$_x$Ga$_{1-x}$As quantum well are studied. It is shown that the metallic-like temperature dependence of the conductivity observed in the structures investigated is quantitatively understandable within the whole temperature range, $T = 0.4 \text{–} 20 \text{ K}$. It is caused by the interference quantum correction at fast spin relaxation for $0.4 \text{ K} < T < 1.5 \text{ K}$. At higher temperatures, $1.5 \text{ K} < T < 4 \text{ K}$, it is due to the interaction quantum correction. Finally, at $T > 4 – 6 \text{ K}$, the metallic-like behavior is determined by the phonon scattering.

PACS numbers: 73.20.Fz, 73.61.Ey

Transport properties of two dimensional (2D) systems reveal the intriguing features. One of them is a metallic-like temperature dependence of the conductivity, $\sigma$, at low temperature $d\sigma/dT < 0$. As a rule, such a behavior is observed in the structures with strong hole-hole ($h$-$h$) or electron-electron ($e$-$e$) interaction characterized by large value of the gas parameter $r_s = \sqrt{2/(a_B k_F)} \gg 1$, where $a_B$ and $k_F$ are the effective Bohr radius and the Fermi quasimomentum, respectively. That is why the $e$-$e$ ($h$-$h$) interaction is considered as the main reason for the metallic-like $T$-dependence of $\sigma$. The theory of the interaction quantum correction developed beyond the diffusive regime is widely applied to treat the experimental results.

On the other hand, there is a mechanism, which could in principle result in the metallic-like behavior of the system of weakly interacting electrons (holes). It is the interference quantum correction to the conductivity.

$$
\delta \sigma^{\text{WaL}} = G_0 \left\{ - \frac{1}{2} \ln \left( \frac{\tau}{\tau_0} \right) + \ln \left( \tau \left[ \frac{1}{\tau_\phi} + \frac{1}{\tau_s} \right] \right) 
+ \frac{1}{2} \ln \left( \tau \left[ \frac{1}{\tau_\phi} + \frac{2}{\tau_s} \right] \right) \right\}, \quad G_0 = \frac{e^2}{2\pi^2\hbar}, \quad (1)
$$

where $\tau_s$, $\tau_\phi$ and $\tau$ are the spin, phase, and transport relaxation time, respectively. The sign of $d\sigma/dT$ for this mechanism depends on the relation between $\tau_s$ and $\tau_\phi$. When $\tau_s$ is appreciably shorter than $\tau_\phi$ the interference correction is

$$
\delta \sigma^{\text{WaL}} \simeq \frac{1}{2} G_0 \ln \frac{\tau_\phi}{\tau}. \quad (2)
$$

Since the phase relaxation time at low temperatures is determined by electron-electron collisions, it is inversely proportional to the temperature, and, thus, the sign of $d\sigma/dT$ given by Eq. (2) is negative. In contrast to the weak localization characterized by the positive sign of $d\sigma/dT$, this phenomenon is known as the weak antilocalization (WaL). If the interference correction dominates the interaction correction, such a 2D system should demonstrate the metallic-like behavior.

![FIG. 1: (Color online) The cross section and calculated valence band profile for the structure investigated at $V_g = 0 \text{ V}$.](image-url)
lence band profile calculated self-consistently is shown in Fig. 1. Similar results were obtained for both samples. Here we present the data obtained for one of them which parameters for some gate voltages are presented in Table I.

The temperature dependences of the conductivity measured for different gate voltages in the absence of a magnetic field are presented in Fig. 2. It is seen that they are metallic-like at the high hole density and mostly insulating at lower one. In order to understand the origin of such a behavior, the magnetic field dependences of the resistivity and the Hall effect has been investigated. The $\Delta \sigma$ and $\phi$ are the fitting procedure performed at $B < 0.2 B_{tr}$ (dashed lines) and $B < 0.1 B_{tr}$ (dotted lines). (b) and (c) – The $T$-dependence of $\tau_\sigma$ and $\tau_\phi$ obtained from the fit of the magnetoconductivity curves for $V_g = 0$ V and $1.3$ V, respectively at $B < 0.2 B_{tr}$ (solid symbols) and $B < 0.1 B_{tr}$ (open symbols). Lines are the interpolating dependences which are used in calculation of $\delta \sigma^{WaL}$ and $\sigma(T)$ presented in Figs. 2 and 3.

are shown in Fig. 3(a). Since the theory was developed within the diffusion approximation, the fit was performed for the relatively low magnetic fields, $B < 0.1 B_{tr}$ and $B < 0.2 B_{tr}$, where $B_{tr} = \hbar/(2eI^2)$ is the transport magnetic field, $I$ is the transport mean free path.

The parameters $\tau_\sigma$ and $\tau_\phi$ found from the fit at different temperatures for $V_g = 0$ V and $1.3$ V are shown in Figs. 3(b) and 3(c), respectively. For $V_g = 0$ V, the data obtained from the different fitting range of magnetic field practically coincide. For $V_g = 1.3$ V, they are somewhat different that indicates an accuracy in determination of the phase and spin relaxation times. One can see that both $\tau_\phi$ and $\tau_\sigma$ demonstrate reasonable behavior. The $\tau_\sigma$ vs $T$ dependence is close to $T^{-1}$-law that is typical for the 2D systems. Within the limits of experimental error the spin relaxation time $\tau_\sigma$ is mostly independent of the temperature as should be in the degenerated gas of carriers.

The value of $\tau_\sigma$ is significantly less than that of $\tau_\phi$ only at $T \lesssim (1 - 3) \ $K depending on the gate voltage, that should provide the metallic-like temperature dependence of the conductivity only at the lowest temperatures. This is justified by the calculation results presented in Fig. 1. The dashed lines in this figure show the temperature dependence of the conductivity calculated as $\sigma(T) = \sigma_0 + \delta \sigma^{WaL}(T)$, where $\sigma_0 = e^2T n/m$ is the Drude conductivity determined in the given case by the ionized impurity scattering. The dependences $\delta \sigma^{WaL}(T)$ have been calculated from Eq. 1 with $\tau_\sigma$ and $\tau_\phi(T)$ presented in Table I that well interpolate the corresponding experimental data shown in Figs. 3(b) and 3(c).

TABLE I: The parameters of structure for different gate voltages

| $V_g$ (V) | $p$ (cm$^{-2}$) | $\tau_\phi$ (ps) | $\tau_\sigma$ (ps) | $F_0^{\phi}$ | $F_0^{\sigma}$ |
|---------|----------------|-----------------|-----------------|-------------|-------------|
| 0       | $6.5 \times 10^{11}$ | 0.73             | 28/T            | 4.8         | -0.39       | -0.34       |
| 1.3     | $4.8 \times 10^{11}$ | 0.48             | 20/T            | 11.0        | -0.405      | -0.36       |
| 1.6     | $4.4 \times 10^{11}$ | 0.39             | 27/T            | 17          | -0.378      | -0.322      |
Thus, the weak antilocalization explain the negative sign of $d\sigma/dT$ only at lowest temperatures.

A different mechanism which can contribute to the temperature dependence of the conductivity is the h-h interaction. It can be conventionally subdivided into the ballistic and diffusion parts $\delta\sigma^b_{hh}$ and $\delta\sigma^d_{hh}$, respectively.

\[
\begin{align*}
\delta\sigma^b_{hh}(T) &= \delta\sigma^b_{hh}(T) + \delta\sigma^d_{hh}(T), \\
\delta\sigma^b_{hh}(T) &= 2\pi G_0 \frac{T_T}{h} \left[ 1 - \frac{3}{8}f(T_T) \right] \\
&+ \frac{3\tilde{F}^\sigma}{1 + F_0^\sigma \left( 1 - \frac{3}{8}t(T_T, \tilde{F}^\sigma_0) \right)}, \\
\delta\sigma^d_{hh}(T) &= -G_0 \left[ 1 + 3 \left( 1 - \frac{1}{\ln(1 + F_0^\sigma)} \right) \right] \ln \frac{h}{T_T}.
\end{align*}
\]

where the functions $f(T_T)$ and $t(T_T, \tilde{F}^\sigma_0)$ are given in Ref. 2. The values of the Fermi-liquid constants $F_0^\sigma$ and $\tilde{F}^\sigma_0$ (see Table I) have been found as described in Ref. 15, where the interaction correction was thoroughly studied in analogous systems.

Dotted and dash-dotted curves in Fig. 4 are drown with taking into account only the diffusion and ballistic parts of the interaction correction, respectively. It is seen that their contributions to the temperature dependence are of different sign: $\delta\sigma^b_{hh}$ reveals the metallic like behavior whereas $\delta\sigma^d_{hh}$ is insulating. Thin solid lines in Fig. 4 are the total conductivity calculated as $\sigma(T) = \sigma^0 + \delta\sigma^{Wal}(T) + \delta\sigma^{hh}(T)$. It is seen that the consideration of both quantum corrections allows us to describe the experimental data in wider temperature range quantitatively. A good agreement is already evident up to $T \simeq 4 - 6$ K.

Finally, the decrease of the conductivity at higher temperature, $T \gtrsim 4 - 6$ K, is simply due to the phonon scattering, which cannot be ignored in heterostructures based on the piezoelectric crystals as our analysis shows. The dashed-double-dotted lines in Fig. 4 are the theoretical $T$-dependence of the Drude conductivity calculated taking into account the phonon scattering $\sigma^0_{ph} = e^2_m (\tau - 1 + \tau_{ph}^{-1})^{-1}$, where $\tau_{ph}^{-1}$ is the phonon contribution to the scattering rate. The latter is calculated in Ref. 16 and represented in the form $\tau_{ph}(T) = a(T_0/T)^3 \left[ 1 + b(T/T_0)^2 \right]$, where $T_0 = \sqrt{2m_E E_F S^T_1}$ with $E_F$ and $S^T_1$ as the Fermi energy and transverse sound velocity, respectively. The parameters $a$ and $b$ depend on the carriers parameters and crystal properties, and have been calculated according to Ref. 16 with $m = 0.16 m_0$. One can see that $\sigma^0_{ph}(T)$ really exhibits a considerably strong decrease explaining, thus, the experimental dependence $\sigma(T)$ at $T \gtrsim 4 - 6$ K.

The bold lines in Fig. 4 are calculated taking into account all three effects considered above: the interference quantum correction, the hole-hole interaction quantum correction, and the temperature dependence of the Drude conductivity due to phonon scattering:

\[
\sigma(T) = \sigma^0 + \delta\sigma^{Wal}(T) + \delta\sigma^{hh}(T).
\]

It is clearly seen that the calculation results are in excellent agreement with the experimental ones (see also Fig. 2).

Let us briefly discuss what type of the temperature dependence of the conductivity is expected at millikelvin temperatures. It is governed by competition between the interference and interaction quantum corrections. The interference correction $\delta\sigma^{Wal}$ at low temperatures has the form given by Eq. (2) and provides the logarithmic metallic-like behavior of $\sigma(T)$.

The diffusion part of the interaction correction $\delta\sigma^d_{hh}$ is logarithmic as well as $\delta\sigma^{Wal}$, but cannot be, however, described by Eq. (3a). The fact is that the second term in square brackets in Eq. (2) is suppressed at low temperature, $T \ll h/\tau_s$, so that the expression for $\delta\sigma^d_{hh}$ consists of only the Fock term $\delta\sigma^0_{ph}$.

\[
\delta\sigma^d_{hh}(T) \simeq \delta\sigma^d(T) \simeq -G_0 \ln \frac{h}{T_T}, \quad T \ll h/\tau_s.
\]

In contrast to $\delta\sigma^d_{hh}$ the ballistic contribution of the interaction correction $\delta\sigma^{hh}$ is insensitive to the Bychkov-Rashba spin-relaxation mechanism 12 and vanishes at $T \to 0$ in accordance with Eq. (3). This is because the relevant ballistic paths contain two segments with opposite momenta, the spin rotation on the first segment is exactly canceled by counter-rotation of spin on the second segment.

Thus the total quantum correction $\delta\sigma^{Wal} + \delta\sigma^{hh}$ should be negative at very low temperatures, and the $T$-dependence of the conductivity is anticipated to be insulating-like

\[
\sigma(T) \propto \delta\sigma^{Wal}(T) + \delta\sigma^{hh}(T) = -\frac{1}{2} G_0 \ln \frac{h}{T_T}.
\]

Using the values of $\tau_s$ from Table I we estimate that this regime should happen in our samples at $T \ll 0.4 - 1.5$ K.
The experiments intended to verify this prediction are in our plan for the future.

In conclusion, we have experimentally studied the temperature dependence of the conductivity of 2D hole gas in asymmetrical GaAs/In$_x$Ga$_{1-x}$As/GaAs quantum well heterostructures. It is shown that there is not one universal mechanism which is responsible for the metallic-like temperature dependence of the conductivity in the whole temperature range for the structures investigated. There are three physically different mechanisms: the weak antilocalization, the hole-hole interaction, and the phonon scattering. Each of them is the main within the corresponding temperature range. The first one dominates at $T \simeq 0.4 - 1.5$ K. At higher temperatures, $T \simeq 1.5 - 4$ K, the interaction quantum correction becomes essential. Finally, the phonon scattering becomes important at $T \gtrsim 4 - 6$ K.

We are grateful to I. V. Gornyi for very useful discussions. This work was supported in part by the RFBR (Grant Nos. 05-02-16413, 06-02-16292, and 07-02-00528), the CRDF (Grant No. Y3-P-05-16), and by a Grant from the President of Russian Federation for Young Scientists.

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