Electron-electron interaction and tunnel density of states at the Fermi level in high-density two-dimensional electron system

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Abstract.

The zero bias anomaly (ZBA) of the tunnel conductivity are investigated in the Al/δ-GaAs tunnel structure with 2D electron concentration in δ-layer to be equal to \(c_f^*\). We find that the dip (ZBA) in the tunnel density of states near the Fermi level \(E_F\) reveals logarithmic dependence on the energy \(\varepsilon\) in the range \(kT < \varepsilon < \hbar/\tau\). Here \(\varepsilon\) is the energy relative to \(E_F\) and \(\tau\) is the elastic relaxation time of 2D electrons. The depth of the ZBA is proportional to \(\ln(T/T_0)\) in the range \(T = 0.1 - 20\) K. These results are in agreement with Aronov-Altshuler theory in which the correction to the 2D density of states is due to the electron-electron interaction in the diffusion channel. The unusual behavior of the tunnel magnetococonductivity is observed.

1. Introduction

Localization effects in the 2D electron system (2DES) in semiconductor structures are intensively investigated, see for review [1,2]. The main interest in such structures is study of the tunneling density of states (TDOS) near the Fermi level of 2DES. Theory [3] predicts manifestations of inter-electronic interaction in the regime of weak localization of carries when electrons concentration sufficiently high \((k_Fl \gg 1)\). In this case for the diffusion 2D channel in the TDOS \(\rho(\varepsilon)\) at the Fermi level \(E_F\) of 2DES should be observed a considerable increase of the dip \(\Delta\rho/\rho \sim \ln(kT/\hbar)\), when energy \(|\varepsilon| = |E - E_F| < kT\) and \(L_{ee} = V_F(\hbar\tau/kT)^{1/2} \gg l\). Here \(\tau\) is the elastic relaxation time and \(l = V_F\tau, L_{ee}\) is the phase relaxation length due to electron-electron collisions. Measurements of the TDOS, which confirmed results of [3], were made on the metal-films (see, for example [4,5]), where conditions of the ”dirty limit” for metal conductivity is easy to realize. In the semiconductor 2D structures the corrections to the 2DES conductivity had been studied until now, see for example [6,7]. The ”dirty limit” in the semiconductor structures with 2DES is well-satisfied in GaAs structures in which 2DES with Fermi energy \(\approx 100\) meV is situated in the self-consistent potential of the δ-layer [8-10]. In this work we present studies of the first investigations of TDOS for the semiconducting structure Al/δ-GaAs \((k_Fl \approx 10)\) in the temperature range 0.03 – 30 K and magnetic field up to 14 Tesla.
2. Samples

![Image of tunnel conductivity and spectrum](image)

**Figure 1.** Tunnel conductivity \((\sigma = dI/dU)\) and tunnel spectrum \((dln\sigma/dU)\) of the sample “d” with short gate measured at 4.2 K. The arrows \((E_0\) and \(E_1)\) indicate the steps in the tunnel conductivity for occupied 2D subbands or the dip in tunnel spectrum.

![Image of tunnel conductivity of sample “e”](image)

**Figure 2.** Tunnel conductivity of the sample “e” with long gate measured at 4.2 K. Points - conductivity data \(\sigma (U)\), thin line - symmetrized conductivity \(\sigma_{\text{sym}}(U) = (\sigma(U) + \sigma(-U))/2\), thick line is the background for \(\sigma_{\text{sym}}(U)\). The inset shows curves \(\sigma (U)/\sigma (-2mV)\) for two cases: at \(B=0\) - superconducting gap in Al gate and at \(B=0.16T\) - tunnel zero bias anomaly, \(T=0.03K\).

In our experiments, we were using the MBE grown Al/\(\delta\)-GaAs tunnel structure. Al gate was grown in situ to achieve high quality of the Al/GaAs interface. \(\delta\)-layer was grown at the distance of \(\approx 20\) nm from the Al/GaAs interface and the concentration of Si \(\delta\)-doping was \(\approx 7\times10^{12}\) cm\(^{-2}\). Epitaxial GaAs was slightly unintentionally p-doped at the level of \(\approx 10^{16}\) cm\(^{-3}\). The samples were prepared in the form of the Hall bars with the width of the 2D channel of 0.5 mm and the full length of 1.5 mm. We studied two types of samples. One of them had two tunnel gates of the length of \(10\) \(\mu\)m close to the ends of the Hall bar (sample “d”), another one (sample ”e”) had the gate length 1.3 mm. The \(\rho\)-contacts were between the gates in the first case and under the gate in the second one. The tunnel characteristics for the sample “d” are shown in Fig.1. It is known, that tunnel conductivity is \(\sigma \propto D\ast\rho_{2D}\), where D is the tunnel barrier transparency and \(\rho_{2D}\) is 2D density of states in the 2DES electrode. So the steps of \(\rho_{2D} (\varepsilon =-eU)\) can be observed in \(\sigma(U)\) dependence, as in Fig.1 [11]. These steps become the dips in tunnel spectrum. So the positions of the dips at positive bias gives us the values of energies (with respect to Fermi level or \(U=0\)) for the occupied subband bottoms of \(E_0 \approx 120\) meV and \(E_1 \approx 20\) meV in our samples. The Hall measurements and the tunneling data permit to determine the electron concentrations and mobilities in the 2D channel under the gate. These values are \(n_0 = 3.1 \times 10^{12}\) cm\(^{-2}\) and
\begin{align*}
n_1 &= 5.1 \times 10^{11} \text{cm}^{-2} \quad \text{and} \quad \mu_0 = 400 \text{cm}^2/\text{Vs} \quad \text{and} \quad \mu_1 = 1000 \text{cm}^2/\text{Vs} \quad \text{for} \quad \text{the} \quad \text{ground} \quad \text{and} \quad \text{the} \\
\ 
\text{first-excited subbands, respectively.}
\end{align*}

We are interested in the ZBA that is seen in Fig.1 as weak feature in \( \sigma(U) \) at \( U=0 \). The region of the ZBA, which associated with the TDOS near the Fermi level, is shown on Fig. 2. The inset in Fig.2 shows the superconducting gap in Al gate of \( Al/\delta\cdotGaAs \). The gap is observed at \( T < 1.1 \text{ K} \) and magnetic field \( B=0 \) that confirms the high quality of our \( Al/\delta\cdotGaAs \) structures and the possibility to measure effects in density of states at Fermi level in electrodes. Since TDOS near the Fermi level is symmetrical function of energy \( \varepsilon = E - E_F \), we will used symmetrized tunnel conductivity \( \sigma_{sym} \) (Fig.2) to investigate the ZBA behavior.

3. Results and discussions

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{Fig3.jpg}
\caption{Symmetrized tunnel conductivity dependences near zero bias at temperatures 0.03 – 0.3 – 1.2 – 4.2 K (width of lines increases with T). Dashed line shows lnU dependence.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{Fig4.jpg}
\caption{Dependence of the \( \Delta \sigma_{sym}/\sigma_{bkg} \propto \Delta \rho/\rho \) on temperature for the sample “e” (open circles and cross). Points - another sample with \( n_{2D} \approx 10^{12} \text{cm}^{-2} \).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{Fig5.jpg}
\caption{Tunnel conductivity \( \sigma_{sym} \) in magnetic field \( B \) perpendicular to \( \delta \)-layer plane for sample “e” at 0.03 K. Dashed lines - \( \sigma_{bkg} \) for different B.}
\end{figure}

Firstly, we analyse the \( \sigma_{sym}(U) \) dependence near the zero bias at different temperatures (see Fig.3). \( \sigma_{sym}(U) \) can be presented as \( \sigma_{sym}(U)= (\Delta \sigma_{sym} + \sigma_{bkg}) \), where \( \sigma_{bkg} \) is shown in Fig.2 at \( T=4.2 \text{ K} \). \( \Delta \sigma_{sym}(U) \) proportional to the change \( \Delta \rho \) of TDOS near Fermi level and \( \sigma_{bkg}(U) \approx \text{const} \) for the bias range 0 – 4 mV for the \( T \leq 4 \text{ K} \). Consequently the dependencies in Fig.3 demonstrate \( \Delta \rho \) as a function of \( U \) or energy \( \varepsilon \). Aronov and Altschuler [3] have shown that \( \Delta \rho/\rho \sim \ln(\varepsilon \tau/\hbar) \) at \( kT < |\varepsilon | < \hbar/\tau \) and phase relaxation due to electron-electron collision. This dependence is in a good agreement with the data in Fig.3. The low limits of energy region of logarithmic dependence \( \Delta \rho(U) \) are shown with arrows in Fig.3 for each temperature. The upper limit is \( \hbar/\tau \sim 10 \text{ meV} \) as follows from mobility value for our samples. The dependence \( \Delta \sigma_{sym}(U=0)/\sigma_{bkg} \propto \Delta \rho(\varepsilon = 0)/\rho \) as a function of \( T \) is presented in Fig.4. One can see that the data correspond to expected dependence \( \rho(\varepsilon = 0)/\rho \propto \ln(\kappa T \tau/\hbar) \) [3]. At the same time the width of the dip near the Fermi level is linear function of \( T \). This dependence is found at the range of temperatures 0.1 – 20 K. Note that the dip of TDOS \( \rho(\varepsilon = 0) \) is equal to 20% of \( \rho \) at temperature 0.03 K in our experiment (Fig.4). Such result points out to possibility
of localization of 2D carriers in our δ-layer structure at lower temperatures. Data for another sample with $n_{2D} \approx 10^{12}\, \text{cm}^{-2}$ (see point curve in Fig.4) show that the strong localization can be achieved even at 0.1 K. The investigation of such samples are in progress. Thus our results demonstrate that the phase relaxation time $\tau_\phi \sim 1/T$, i.e. $\tau_\phi$ is associated with electron-electron scattering in diffusion channel of our high density 2DES.

Unexpectedly the tunnel conductivity at low bias strongly depends on magnetic field $B$ perpendicular to δ-layer, as can be seen in Fig.5. The positive magnetoconductivity ($\sigma_{bkg}$) was observed at low bias voltages and negative one was found at $|U| > 10 \text{ mV}$. At the same time position of the dip in TDOS does not depend on magnetic field. Additional experiments are needed for the explanation of this effect.

4. Conclusion
We performed the first direct spectroscopic measurements of TDOS near the Fermi level of the high density 2DES in GaAs structure. Logarithmic dependencies of TDOS were obtained in wide ranges of energies, $\varepsilon = 0.02 \sim 5 \text{ meV}$, and temperatures $T$, $T=0.1 \sim 20$. The data are in a good agreement with the Aronov-Al'tshuler theory of the electron-electron interaction in disordered 2D conductors at $k_Fl \gg 1$. We found also the non-monotonic tunneling magnetoconductivity for the magnetic fields perpendicular to the 2DES plane.

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References
[1] Gantmaher V.F., Dolgopolov V.T., Physics-Uspehi, 51, 3 (2008).
[2] Shashkin A.A., Physics-Uspehi, 48, 129 (2005).
[3] Al'tshuler B.I., Aronov A.G. "Electron-electron interaction in disordered conductors", in Electron-electron interaction in disordered systems, (Eds.:Efros A.L., Pollak M.), North-Holland (1985).
[4] White A.E., Dynes R.C., Garno J.P., Phys. Rev. B, 31, 1174 (1985).
[5] Butko V.Yu., DiTusa J.F., Adams P.W., Phys. Rev. Lett., 84, 1543 (2000).
[6] Uren M.J., Davies R.A., Pepper M., J.Phys. C.: Solid St. Phys., 13, L985 (1980).
[7] Van Keuls F.W., Marthur H., Jiang H.W., Dahm A.J., Phys. Rev. B, 56, 13263 (1997).
[8] Khavin Yu., Gershenzon M., Bogdanov A., Phys.Rev B, 58, 8009 (1998).
[9] Dizhur E.M., Vorovskii A.N., Fedorov A.V. et al., ZETPh Letters, 80, 489 (2004).
[10] Kotel’nikov I.N. et al, Abstracts of Advance Research Workshop ”Fundamentals of electronic nanosystems”, S.-Petersburg, Russia, June 28 - July 4, 2008, p.46.
[11] Feiginov M.N. and Kotel’nikov I.N., Appl. Phys. Lett. 91, 083510 (2007).