A possible role of $D^-$ band in hopping conductivity and metal-insulator transition in 2D structures

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Abstract

A simple two-band model is suggested explaining recently reported unusual features for hopping magnetoresistance and the metal-insulator transition in 2D structures. The model implies that the conductivity is dominated by the upper Hubbard band ($D^-$-band). Experimental studies of hopping magnetoresistance for Si $\delta$-doped GaAs/AlGaAs heterostructure give additional evidences for the model.

I. INTRODUCTION

In recent papers [1,2], the existing data on the hopping magnetoresistance for the nearest neighbor hopping were reconsidered with a conclusion that in many cases the magnetoresistance is related to a suppression of a contribution of the upper Hubbard band due to a spin alignment. A signature of such a behavior is a universal magnetic field behavior of the activation energy related to the Zeeman splitting. It was the surprisingly good agreement between the $g$-factor values extracted from the experimental data with corresponding handbook values which lead to the conclusion given above.
While this conclusion emphasizing a role of the upper Hubbard band or $D^-$ band was formulated for the nearest neighbor hopping (where it manifests itself as the Zeeman addition to the activation energy), a possible contribution of $D^-$ band in the variable range hopping regime was studied theoretically first by Kurobe et al. [3]. It was shown that a presence of $D^-$ band at the Fermi level leads to a suppression of some hopping channels by the magnetic field and manifests itself as a plateau-type feature in the magnetoresistance curve. Recently a presence of corresponding feature for doped CdTe crystals was observed [4].

However, the picture considered in [3] implies that without external magnetic field, the contribution of the upper Hubbard band to the conductivity is smaller or at least comparable with that one of the lower Hubbard band. In what follows we are going to analyze a different situation assuming that at zero magnetic field the contribution of the $D^-$ band dominates. This assumption is not an exotic one since the localization length in the $D^-$ band is known to be much larger than in the standard impurity band; so the contribution of the $D^-$ band can dominate even if the corresponding density of states is much less than for the standard band.

We will assume that a finite density of states related to the upper Hubbard band ($D^-$ band) exists at the Fermi level; moreover, we assume that it is this band that mainly contribute to the current because of the larger localization length. The lower Hubbard band, although having a larger density of states, is supposed to give much less contribution to the current and - probably - has localized states at the Fermi level.

We will show that such a simple two-band model can consistently explain the unusual crossover from variable range hopping conductivity to activated hopping in strong magnetic field reported recently for 2D electron layers in [5]. Moreover, it reproduces the main features of temperature and magnetic field behavior of the 2D metal-insulator transition extensively studied in recent years (see e.g. [6–8]).

To make a deeper insight into the experimental situation of [5] we present here the results of measurements of the magnetic field dependence of the activation energy of resistivity and its variation with the gate voltage.

II. THE MODEL

Note that, although a presence of $D^-$ channel was never disputed, during last years the hopping conductivity was typically considered as related to ”standard” hopping within lower impurity band [3]. This point of view was, on the one hand, related to the fact that the only temperature dependence of conductivity does not allow to discriminate clearly
between the contributions of different Hubbard bands and to estimate the Hubbard energy from experimental data. On the other hand, the theoretical estimates of the Hubbard energy seem to be too large to allow \( D^\pm \) band contribution. Thus it seemed that any effect of the upper band can exist only for nearly completely occupied lower band which corresponds to a Mott-type metal-insulator transition.

However the existing experimental estimates of the activation energies for \( \varepsilon_2 \) nearest-neighbor hopping conductivity give values much less than theoretical estimates (about 10 meV) - as small as to say 1 meV and even smaller (see e.g. [2] and references given in this paper and also [10]). The most reliable of these estimates were based on studies of magnetoresistance which give a unique possibility to reveal the \( D^\pm \) band contribution. According to our analysis of existing experimental data [1], not only nearly non-compensated samples, but a great deal of experimental data for nearest neighbor hopping (with \( K = 0.4 - 0.7 \)) show a signature of \( D^\pm \) band contribution.

Here we are not aimed to discuss in detail a problem why the Hubbard energy can be as small. The polaron-type effects we refer can be an explanation. One has to keep in mind that not only small Hubbard energies, but even negative (and large!) Hubbard energies are possible for many centers (to say for \( DX \)-centers). Then, the Hubbard energy is known to be suppressed near the metal-insulator transition due to a divergency of both localization length and dielectric constant, the suppression being more effective than a suppression of a width of the impurity band.

We would like also to note that in the 2\( D \) structures, the number of electrons in the 2D layer at the dielectric side of MIT can be even larger than the total number of localized centers within this layer since, in contrast to 3D samples, the neutrality condition holds only for the whole structure including remote dopants far away from the layer (note that this fact was noted by Klapwijk and Das Sarma [11]. This latter fact in a natural way favors a formation of \( D^\pm \) centers.

First let us recall the scenario of occupation of the \( D^\pm \) band considered earlier in [1]. According to these estimates the doubly occupied centers have a distribution function

\[
n_{D^-} = \frac{1}{\exp\left(\frac{2\varepsilon + U - 2\mu}{T}\right) + 2 \exp\left(\frac{\varepsilon - \mu + U}{T}\right) \cosh\left(\frac{\mu_0 g H}{2T}\right) + 1} \tag{1}
\]

where \( \mu \) is chemical potential; in the case when the total number of electrons is dominated by single-occupied sites while the total number of \( D^- \) sites is small

\[
\mu = \mu(H = 0) - T \ln(\cosh\left(\frac{\mu_0 g H}{2T}\right)). \tag{2}
\]

As it is seen, the choice between the two exponentials in the denominator depends on sign of \( \varepsilon - \mu \): for \( \varepsilon - \mu > 0 \) the first one dominates, while for \( \varepsilon - \mu < 0 \) the second one
dominates. However, the magnetic field contribution is the same to both of the exponent since the factor $2 \cosh(\cdot)$ is actually an addition to the exponent equal to $\mu - \mu(H = 0)$.

Let us show that the presence of $D^-$ band can lead to a pronounced positive spin magnetoresistance for hopping conductivity.

One expects the $D^-$ states to be formed in tail of the standard impurity band. Thus let us discuss in more detail the features of band-tail hopping. Let us assume that the tail can be described by an exponential decay

$$\nu(\varepsilon) = \nu_0 \exp\left(\frac{\varepsilon - \varepsilon_0}{\varepsilon_1}\right)$$

where $\varepsilon_0$, $\varepsilon_1$ are some constants; $\varepsilon < \varepsilon_0$. Actually for $D^-$ band the position of the Fermi level is by the value $U$ lower than for single-occupied states (so in the distribution given by Eq. (1) one should take $\varepsilon \to -\varepsilon - U$). Let us first consider a situation with no Coulomb gap. If the energy $\varepsilon_1$ characterizing a decay of the bandtail is larger than the typical hopping energy band, the hopping is of standard Mott type. However, if the hopping band is larger than $\varepsilon_1$, the situation is different. Indeed, paying a higher activation energy one is able to find a closer hopping site (then typical for standard VRH) because of a strong density of states increase with energy increase. Since the hopping length corresponding to site energy $\varepsilon$ is

$$r \sim (n_0(\varepsilon)\varepsilon)^{-1/3}$$

one can find $\varepsilon$ in a standard way comparing tunneling and activation contribution to the hopping exponent:

$$\left[\nu(\mu) \exp\left(\frac{\varepsilon - \mu}{\varepsilon_1}\right)\right]^{1/3}(\varepsilon - \mu) \sim \frac{2T}{a}$$

and thus

$$\frac{\varepsilon - \mu}{3\varepsilon_1} \sim \ln \frac{T}{(\varepsilon - \mu)^{4/3}a\nu(\mu)^{1/3}}$$

Thus one has for the conductivity

$$\sigma \propto \exp\left(\frac{-\varepsilon - \mu}{T}\right) = \exp\left(-\frac{3\varepsilon_1 \ln[T/(\varepsilon_0 - \mu)^{4/3}a\nu(\varepsilon_0)^{1/3}]}{T} + (\varepsilon_0 - \mu)\right).$$

As it is clearly seen, the tail hopping has a character of activated behavior (if logarithmic term is considered as a constant).

Certainly one would have a purely Arrenius law if the $D^-$ band would have a sharp edge and the chemical potential would cross this edge after the application of a strong magnetic field. It is the bandtail states with exponential decrease of density of states that
ensure a presence of the logarithm term. As it is seen, the latter makes the temperature behavior to be weaker than the Arrenius law. Note that if we would assume a power decrease of DOS in the tail ($\propto \varepsilon^{-\alpha}$, $\alpha >> 1$) we would obtain a power law addition in the numerator of the exponent in Eq. (3) of the sort $\sim -\varepsilon_1[(\varepsilon_0 - \mu)^{4/3}a n(\varepsilon_0)^{1/3}/T]^{1/\alpha}$. One notes that in our situation the activation is to the states corresponding to the boundary of the tail region which is characterized by $\varepsilon_0$.

If one includes the Coulomb gap into considerations, it would lead to a quadratic gap near the Fermi level, but the strong energy dependence of "bare" density of states does not allow for this gap to develop up to its nominal value according to the value of $n(\mu)$ due to a cut-off at energies $\sim \varepsilon_1$ controlling the DOS decay.

Now let us turn to the magnetic field dependence which is the most important for us. As it is clearly seen, the main effect is a dramatic decrease of DOS at Fermi level. Thus one expects that if at $H = 0$ the DOS at the Fermi level is large enough and the Coulomb gap hopping can be observed, the gradual deepening of Fermi level with $H$ increase would change the situation to the activation-like behavior with no significant region for Mott-type hopping.

III. EXPERIMENT

The sample investigated here is a delta-doped GaAs/AlGaAs heterostructure which has been used in previous studies [12,13], where full details of the layer composition, doping and device fabrication are given. The low-temperature measurements of conductivity in strong magnetic fields were carried out in the Cavendish Laboratory, University of Cambridge. The longitudinal resistivities at different carrier concentrations $n$, temperature $T$ and magnetic field $B$ were measured from the Ohmic part of the dc four probe $I - V$ characteristics. The data presented here correspond to field parallel to the 2D plane and current being parallel to the field. We have also measured the case where the magnetic field is parallel to the 2D field and perpendicular to the current and no anisotropy was observed.

Figure 1 shows the logarithm of resistivity plotted versus $1/T$ for $n = 9.52 \times 10^{10} \text{cm}^{-2}$ at $B = 0$ (bottom), 6 (middle) and 8 Tesla (top curve). At $B = 0$, the data follow $T^{-1/3}$ behavior for $T > 1$ K while it follows $T^{-1/2}$ behavior for $T < 1$ K [13]. However, application of magnetic field causes a strong increase in resistivity which is larger at lower temperatures. This causes a change in hopping behavior. At $B = 6$ and 8 T the data follow $T^{-1/2}$-law for $T > 1$ K and $T^{-0.8}$ behavior for $T < 1$. Similar results were obtained for $n = 9.84 \times 10^{10}$ cm$^{-2}$ and $n = 9.18 \times 10^{10}$ cm$^{-2}$ for the magnetic field regime of $B=4$,
6, 8 and 10 T although at lower magnetic field the transition to the $T^{0.8}$ behavior shifts towards lower temperature while at higher field it shifts towards higher temperature. For the limited interval of temperatures, one can approximate the experimental curves by simple Arrenius law with constant energy of activation $E$.

On the Fig. 2 scaling of the magnetoresistance at different temperatures in terms of the ratio $H/T$ is demonstrated for $n = 9.18 \times 10^{10}$ cm$^{-2}$. It is seen that the slope is the same for all the fields studied while a slight shift of the curve with an increase of magnetic field is related to (small) orbital contribution to magnetoresistance.

Figure 3 shows the activation energy $E$ plotted versus $B$ for different carrier concentration. The slope of the straight lines correspond to $g\mu_B$. From these slopes we calculate the values of $g$ as 0.08, 0.10 and 0.115 at $n = 9.84$, 9.52 and $9.18 \times 10^{10}$ cm$^{-2}$ respectively. The values of $g$ are substantially lower than that of the bulk GaAs value ($g = 0.44$) and are decreasing with increasing $n$.

IV. DISCUSSION

Now we would like to compare theoretical predictions with the experimental data. In the previous paper [5], the $T^{-0.8}$ behavior was interpreted as $T^{-1/2}$ law with the temperature-dependent prefactor. This interpretation is based on the assumption that mechanism of conductivity in strong magnetic fields is still VRH, but with reconstruction of the phonon assistance. However, there is another possible interpretation of the $T^{-0.8}$ behavior: one can suggest that it is slightly corrected Arrenius law ($T^{-1}$) as it is shown on Fig. 1. This means that the mechanism of conductivity in strong fields is changed and is determined by excitation of localized carriers to the states in the upper Hubbard band with larger radius of localization. In the present paper we investigate this possibility.

As it is seen, there is at least qualitative agreement between theoretical model discussed above and the experiment. Indeed, the experiment exhibits a transition from Efros-Shklovskii type of hopping to nearly Arrenius law (with an exponent $(T'/T)^{0.8}$) when a strong magnetic field is applied. The difference between this behavior and the Arrenius law can be explained by the finite density of states in the bandtail according to a scenario discussed above.

The magnetic field behavior of the activation energy is close to linear law in strong field limit. The value of the effective $g$-factor extracted from a comparison of experimental curves with the strong field limit of Eq. (2) gives a value about 4 times lower than the handbook values for GaAs. However, one has in mind that we deal with AlGaAs-GaAs heterostructure rather than with the bulk GaAs. The $g$-factor values for AlGaAs
quantum wells were calculated theoretically \[14\]. It was shown that due to the fact that in such structures one has a mixture of GaAs states (for which the $g$-factor $\sim -0.45$ is negative) and AlGaAs states (where $g$ -factor is positive) the effective $g$-factor depends on the well width $d$ and can even vanish for $d \sim 5$ nm. Such theoretical predictions agree with experimental data (see e.g. \[15\]). Since we deal with a similar system where the effective width is controlled by the gate voltage we believe that these considerations can be applied. In particular, a decrease of gate voltage makes the effective field in the structure to be stronger which corresponds to a decrease of the well width (for the electrons at the Fermi level) and leads to a decrease of $g$-factor. Fig. 2 clearly demonstrates such a decrease of $g$-factor with a decrease of the gate voltage in agreement with above mentioned considerations.

Let us estimate quantitatively the variation of $g$-factor with the gate voltage. First we estimate the derivative $d g / d F$ where $F$ is an effective electric field within the well. Using the values of $g$-factors reported in \[14\] for biased GaAs-AlGaAs quantum wells for two different biases, one could estimate $d g / d F \sim 0.2 \cdot 10^{-5} \text{ V}^{-1} \text{ cm}$ which gives $\delta g \sim 0.02$ for the experimental variation of $V_g$ equal to 0.01 V. Unfortunately, both limited set of biases and finite well widths (in contrast to our case) make this estimate to be a rough one. Another approach to estimate the derivative in question may use the fact that the decrease of $g$-factor with respect to its bulk value observed for our structures is related to the effective electric field $F$; thus one can estimate $d g / d F \sim (g - g_{\text{bulk}}) / F$. Then, the variation of $F$ due to variation $\Delta V$ of the gate potential can be estimated as $\Delta n / n \sim \Delta F / F$ where $\Delta n$ is a variation of the carrier concentration. Thus one has $\Delta F \sim (\Delta n / n) F$ and, consequently, $\Delta g \sim (g - g_{\text{bulk}})(\Delta n / n)$ which for $g \sim 0.1$, $g_{\text{bulk}} = 0.45$, $\Delta n / n \sim 0.075$ one has $\Delta g \sim 0.025$. Since the variation of $g$ observed is about 0.035 one can conclude that the agreement with our rough estimates is at least a reasonable one.

Thus we believe that both the values of $g$-factor extracted from the magnetoresistance data and its voltage dependence give an evidence for our theoretical model.

Since the system studied is rather close to ones exhibiting 2D MIT, we find it of interest to consider a possible consequences of our model for explanation of the details of this MIT.

Since our results imply a significant role of $D^-$ band for the structures in question, we believe that due to much larger value of the localization length, the conductance is controlled by $D^-$ states even if they have smaller DOS at the Fermi level than single-occupied states. In other words, we believe that MIT takes place in the upper Hubbard band (when chemical potential crosses a mobility edge in $D^-$ band) and thus has features of Mott transition.
Moreover, one can expect that for the lower Hubbard band the mobility edge is situated above the chemical potential at some energy $\varepsilon_{1,m}$, that is the corresponding states are localized. In this case we expect the situation completely controlled by the value of the DOS at the Fermi level of $D^-$ band given by Eq. (4) for $\varepsilon = \mu - U$.

First, one notes that an external magnetic field can in this case lead to a decrease of DOS due to a gradual lowering of the Fermi level in $D^-$ band according to the behavior of the chemical potential, Eq. (2). However we believe that the MIT takes place when DOS is still high enough to support the metallic conductivity, and its energy dependence near MIT is not as strong as in the scenario of activated hopping discussed above.

In this case one can write for the change of the electron concentration in $D^-$ band

$$\Delta n(H) = n(H) - n(0) = \nu(\mu(H = 0))\delta \mu = -\nu T \ln(\cosh \frac{\mu_0 g H}{2T})$$  

(7)

Since the decrease of concentration near MIT leads to a corresponding decrease of conductivity, one expects that at least for small $\Delta n$ this decrease can be described as

$$\Delta \sigma = \sigma(H, T) - \sigma(0, T) = \frac{\partial \sigma}{\partial n} \delta n \equiv \sigma'_n(T) \delta n(H, T)$$  

(8)

Considering $\Delta \sigma(H, T)$ behavior one concludes that $H - T$ scaling law is given by

$$\sigma'_n(T)\nu T \ln(\cosh \frac{\mu_0 g H}{2T}) = \text{const}$$

and thus depends on the temperature dependence of conductivity.

However, deep at the insulating side of MIT, when the activation to the mobility edge in $D^-$ band dominates, the conductivity is controlled by a corresponding activation exponent, the magnetic-field dependent contribution to this exponent is equal to

$$\frac{\delta \mu(H)}{T} = \ln(\cosh \frac{\mu_0 g H}{2T})$$  

(9)

which depends only on a ratio $H/T$.

The paper [7] reported a suppression of the metallic phase at strong magnetic field followed by a saturation of resistance, the behavior exhibited $H/T$ scaling while the most representative data corresponded to the dielectric side of MIT. We would like also to mention the paper [16] reporting large positive magnetoresistance deep in the dielectric side of 2D MIT followed by the saturation plateau. We believe that the arguments given above can explain such a behavior. (Note that the qualitative arguments relating magnetoresistance on the dielectric side of 2D MIT to an elimination of the condition for electron pairs binding were also given by Klapwijk and Das Sarma in [11]). We would like also to emphasize that the saturation behavior observed at strong field limit at the insulating
side of MIT in [7][10], can be easily explained in our model as a result of a competition between suppressed $D^-$ band contribution and a contribution of lower Hubbard band not affected by magnetic field (a similar behavior was predicted in [1] for nearest-neighbor hopping). Note that a decrease of resistance at saturation observed in [16] with an increase of electron concentration can be explained as a result of an increase of conductivity supported by the lower Hubbard band. Another important feature reported in [16] is a fact that while for dielectric side of MIT the magnetoresistance is pronounced already at weak fields, for the metallic side there exists a region of weak fields with no significant magnetoresistance, and the width of this region increases with increase of concentration. This behavior is in agreement with our model where the pronounced magnetoresistance corresponds to a position of the chemical potential within the band tail of $D^-$ band while at metallic state initial position of the chemical potential corresponds to high enough DOS.

Now let us discuss the temperature behavior of conductance in our model for the metallic side of MIT. One sees that while at $T = 0$ all the single-occupied states are localized, at elevated temperatures an activation takes place to the mobility edge within the bandtail of the 2D conductance band. As a result, the empty (positively charged) centers are created which are effective scatterers for the conducting electrons of the $D^-$ band. Thus one expects that an increase of temperature is accompanied by an increase of resistance.

The corresponding increase of resistivity is obviously proportional to a number of empty states under the mobility edge. Thus at small temperatures the resistance is expected to follow the law

$$\rho(T) = \rho_0 + \rho_1 \exp\left(-\frac{T_s}{T}\right)$$

where $T_s = \epsilon_{m,1} - \mu(T = 0)$. If the effective width of the single-occupied band is of the order or less than $\epsilon_{m,1} - \mu(T = 0)$, one expect that the resistance is saturated when $T >> T_s$ that is the law Eq. (10) holds approximately for all temperatures. The exact temperature behavior should take into account the temperature dependence of chemical potential calculated for the given details of the band density of states.

One also notes that if there is some gap between the band of localized states and 2D conductance band the scenario discussed above holds even if nearly all of the localized states are occupied that is when the position of the Fermi level within the lower Hubbard band is high and the initial number of charged scatterers is small. In this case the situation $\rho_0 << \rho_1$ (observed, in particular, in [1]) can be realized.

Note that the temperature behavior of resistance can be also affected by a variation of a number of electrons in the $D^-$ band with temperature increase due to electrons exchange
between the two Hubbard bands which would correspond to temperature dependencies of both \( \rho_0 \) and \( \rho_1 \). However we would like to note that we assume that the MIT takes place not at the "bandtail" of \( D^- \) band, but when the Fermi level is far in the \( D^- \) band and the behavior of density of states in the \( D^- \) band is not strong. Thus if the number of electrons in \( D^- \) band increases with temperature, it can lead to weak decrease of resistance with temperature increase which is indeed observed after initial (exponential) growth.

We would like to note that the latter mechanism of resistance in the metallic state can be considered as a modification of the mechanism suggested earlier by Altshuler and Maslov [17] to describe the experimental data in question. The difference is that Altshuler and Maslov have related the scattering centers with some traps with energies close to the Fermi level situated within the insulating layer of the MOSFET's. At the same time Altshuler and Maslov have also considered a possibility of double occupation of the trap leading to a spin mechanism of magnetoresistance due to effect of magnetic field on the charge states of the scatterers.

In our picture we consider MIT within the upper Hubbard band and relate the scattering centers to the single-occupied states of the lower Hubbard band. In contrast to Altshuler and Maslov, the magnetoresistance in our case originates due to magnetic-field driven change of a position of \( D^- \) band with respect to the Fermi level and thus is related to change of carrier concentration rather than to a change in the scatterer system. In our model the latter is expected to be related to the lower Hubbard band states, their occupation numbers being independent of magnetic field.

For our scenario, a presence of scattering centers able to change their charge states at low temperatures is an inherent property of the model and does not need any additional assumption. Then, our model can also explain features of the 2D MIT observed in gated GaAs heterostructures [8] where the significant concentration of traps is not expected.

The latter devices seem to be similar to devices studied in this paper experimentally. We believe that these facts give evidence to support our model. Indeed, it describes features observed for the devices in question both in the dielectric limit (Ref. [5] and this paper) and near the MIT, Ref. [8].

Now let us discuss in some more detail a possible realization of the scenario discussed above in our Si \( \delta \)-doped GaAs-AlGaAs heterostructure. If there would be no delta-dopants, the application of the gate potential depleting the 2DEG would lead to localization of electrons in the large-scale potential created by doping impurities situated beyond the spacer. The delicate feature is that the parameters of this potential depend on screening and thus on the electron concentration in the quantum well. The delta-dopants, which act as strong Coulomb centers situated nearly in the 2D conducting layer,
apparently manifest itself as "embryos" for localization. Namely, we can expect that the localization in course of depletion would start just from filling these states. If so, we can expect that at certain gate potential one would have electrons localized at delta-dopants and, in addition, some delocalized electrons or electrons localized in the rest of large-scale potential. The system of the delta-dopants in this case could be considered as a completely occupied impurity band with energies situated some lower than to say energies of the large-scale potential. We can speculate that just the delta-dopant states form the $D^-$ band.

To conclude, we have suggested a model allowing to explain unusual features of hopping conductivity in parallel magnetic fields and metal-insulator transition recently reported for 2D structures. The model implying a dominant role of the upper Hubbard band explains in a natural way both the suppression of the metal state by the magnetic field with $B/T$ scaling and magnetic-field driven crossover from VRH to activated hopping as a result of the on-site spin correlations. The dramatic increase of resistance with temperature increase observed in metallic state is ascribed to activation of electrons from initially localized single-occupied states to the mobility edge in the tail of 2D conductivity band leading to a creation of additional scattering centers in a way similar to the one considered by Altshuler and Maslov [17]. The experimental studies of the hopping magnetoresistance for Si $\delta$-doped GaAs-AlGaAs heterostructure give additional evidence for the model.

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Figure captions

Fig.1 Resistivity $\rho$ of Si $\delta$-doped GaAs-AlGaAs heterostructure plotted as $\ln \rho$ versus $1/T$ for $B=0, 6, 8$ Tesla (from bottom to top) at $n = 9.52 \times 10^{10}$ cm$^{-2}$.

Fig.2 Magnetoresistance as a function of $H/T$ for $n = 9.18 \cdot 10^{10}$ cm$^{-2}$.

Fig.3 Activation energy of conductivity $E$ plotted versus $B$ for electron densities $n = 9.18, 9.52$ and $9.84 \times 10^{10}$cm$^{-2}$ (from 1 to 3).
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