Temperature-dependent disorder and magnetic field driven disorder: experimental observations for doped GaAs/AlGaAs quantum well structures

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We report experimental studies of conductance and magnetoconductance of GaAs/AlGaAs quantum well structures where both wells and barriers are doped by acceptor impurity Be. Temperature dependence of conductance demonstrate a non-monotonic behavior at temperatures around 100 K. At small temperatures (less than 10 K) we observed strong negative magnetoresistance at moderate magnetic field which crossed over to positive magnetoresistance at very strong magnetic fields and was completely suppressed with an increase of temperature. We ascribe these unusual features to effects of temperature and magnetic field on a degree of disorder. The temperature dependent disorder is related to charge redistribution between different localized states with an increase of temperature. The magnetic field dependent disorder is also related by charge redistribution between different centers, however in this case an important role is played by the doubly occupied states of the upper Hubbard band, their occupation being sensitive to magnetic field due to on-site spin correlations. The detailed theoretical model is present.

PACS numbers: 72.80.Ng, 73.61.Jc, 72.20.Ee

INTRODUCTION

It is a common wisdom to consider disorder of different sorts as an important source of electric resistance for conductors on both sides of metal-insulator transition. At the same time it is typical to consider the degree of the disorder as some given feature of a specific sample not depending on external perturbations like temperature or magnetic field. This statement seems to be indeed undisputable for standard metals where the disorder has a structural character and is related to structural defects, in particular, to some impurities. However it is questionable for semiconductors where the main source of disorder is related to charged defects. The charge states of the defects can depend on temperature due to charge redistribution between different carrier states. Then, one should also take into account an existence of double-occupied carrier states (so-called upper Hubbard band). Due to spin correlations within such double-occupied states their occupation numbers can also depend on external magnetic field and thus the contribution of these states to disorder becomes magnetic-field dependent. However, as far as we know, the concept of temperature-dependent disorder was first introduced only in 2000 in [1] in a course of an attempt to explain features of the apparent metal-insulator transition in 2D structures (its nature is still far from complete understanding). Then, the similar attempt lead to a concept of magnetic-field driven disorder (that is, disorder dependent on external magnetic field) [2, 3] while a discussion of these two concepts was given in [3]. At the same time both temperature dependent disorder and magnetic field dependent disorder were not studied in detail for systems where the disorder is related to well defined localized states. To our opinion, the attractive system is related to a structure of quantum wells where both wells and barriers are doped. The properly selected doping of both wells and barriers facilitates a creation of double occupied states in a controlled way due to tunneling of carriers from the barriers to the wells. In our earlier work we reported long-term relaxations within the response to external magnetic field for GaAs/AlGaAs structures doped by Be which we explained as the Coulomb glass effects [4, 5]. An important ingredient of our explanation was related to an effect of magnetic field on the charge distribution within the Coulomb glass. While the papers [4, 5] described the effects of non-stationary relaxations related to pulses of external magnetic field, in this paper we are going to present our results of both experimental and theoretical studies of stationary temperature dependence of resistance and magnetoresistance for GaAs/AlGaAs structures (similar to the ones studied in [4, 5]). Note, however, that in these previous investigations we studied dilute system of dopants within the barrier where the collective effects were neglected. Thus the densities of impurity states were completely controlled by pair configurations of charged states within the barrier and closest charged states within the well. In our case we deal with significantly larger acceptors concentration than in [4, 5] which leads to significant band broadening related to the collective effects, in other words - to the effects of random potential.

Our results include, first, an unusual non-monotonic temperature dependence of resistance exhibiting it saturation in course of temperature increase which terminate initial resistance growth (typical for phonon mechanism of resistance). The importance of this result is evidenced by a statement given in [6]: "Understanding of non-monotonic behavior of temperature dependence of resistance $R(T)$ is a central issue in the correlated 2D carriers in clean semiconductors in studies of metallic
state and metal-insulator transition”. Second, we observed an unusually strong negative magnetoresistance at small temperatures which could not be ascribed to standard interference mechanisms. We explain these unusual features as a direct manifestation of temperature-dependent disorder and magnetic field dependent disorder. The theoretical model for the structures under study is in a qualitative agreement with the experimental data.

**EXPERIMENT**

We studied GaAs quantum wells structures (with a width 15 nm) separated by \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) barriers (with a width 25 nm). The growth procedure was described in detail in [4]. Central regions (with a width of 5 nm) of both wells and barriers were \( p \)-doped with Be (concentration \( (3 - 7) \times 10^{17} \) atoms/cm\(^3\)), which is close to the critical concentration for metal-insulator transition). Note that in the bulk material the metal-insulator transition takes place at impurity concentration close to \( (1 - 2) \times 10^{18} \) atoms/cm\(^3\), [4]. The contacts were made by 2 min burning at 450° C in deposited gold containing 3% of Zn. The samples were shaped as Hall bars. The resistance was determined from the voltage between the voltage probes at a fixed current of 1-10 nA. The samples were relatively low-Ohmic (10\(^5\) – 10\(^6\) Ohms/□ at 4 K). In our opinion, it is due to the fact that the impurity band formed by \( A^+ \) centers is rather close to the valence band. We checked that for all our measurements the \( I - V \) curves were linear within the temperature region 4.2-1.35 K.

The temperature dependencies of the resistance are shown on fig.1 for 3 samples with different concentrations of dopants. Separately, fig.2 presents the low temperature behavior of conductivity for sample 5-482. As it can be seen from Fig.1, at some regions of high temperatures we observe a decrease of conductance with an increase of temperature. Although typically such a decrease would be ascribed to electron-phonon scattering, such a mechanism is not expected to be effective for samples impurities concentrations as high as we have in our samples since the impurity scattering strongly dominates the phonon scattering. When the temperature becomes lower the conductivity increases with temperature increase which is explained by activation of the holes from the upper Hubbard band to the valence band (the activation energy \( \varepsilon_2 \) for different samples is \( \sim (5 - 7) \text{meV} \)). At higher temperatures several samples exhibited steep increase of conductivity with high activation energies \( \varepsilon_1 \sim (20 - 30) \text{meV} \). We believe that such a behavior is related to ionization of carriers from the lower Hubbard band (see Fig. 1).

At very low temperatures (up to 1.2 K) the conductance is supported by weakly localized states within the upper Hubbard band. The weak localization of the carriers responsible for the conductivity is evidenced by a logarithmic temperature dependence of the conductivity (see Fig. 2).

![FIG. 1: Temperature dependencies of conductivities (in arbitrary units) of three samples with different impurity (Be) concentrations in wells and barriers (f-348 -(3)\( \times 10^{17} \)/cm\(^3\), f-261 -(5)\( \times 10^{17} \)/cm\(^3\), 5-482 -(7)\( \times 10^{17} \)/cm\(^3\))](image)

![FIG. 2: Temperature dependencies of conductivity for sample 5-482 -(7)\( \times 10^{17} \)/cm\(^3\) at low temperatures](image)

The magnetoresistance curves were measured at high magnetic fields (up to 15 T). The observed behavior is strongly different for different temperatures (at temperature region 1.6 - 10 K we observe a crossover from giant negative MR at 1.6 up to weakly positive MR at 10, see Fig.3).

**DISCUSSION**

a) Temperature-dependent disorder.

Let us consider an effect of temperature dependent disorder. It is related to a lifting of non-linear screening of localized states by some carriers (see, e.g., [4]). The non-linear screening implies a capture of the carrier by
the (charged) localized state. Depopulation of the corresponding trap due to activation of the carrier to the delocalized state inevitably leads to a creation of charged center giving a contribution to the (static) disorder. As for the trapped carriers, in our case we deal with two types of centers. 1) $A^+$ center where a hole is trapped by neutral $A^0$ center. In this case the activation of a hole leaves a neutral $A^0$ center. Thus in this case the temperature increase leads to a partial suppression of the disorder rather than to increase of disorder. 2) $A^0$ centers created by an acceptor within the barrier screened by a hole situated near the interface. Here indeed an activation of a hole leaves (deeply localized) negative $A^-$ center contributing to the total disorder potential. Note that in the latter case depopulation of $A^0$ center leads simultaneously to a creation of a free hole (increasing the conductance) and of a charged scatterer (decreasing the conductance). While an addition to the conductance is controlled by a charge of a hole, the strength of the barrier where the collective effects were neglected. 1) the valence band, 2) $A^+$ band, 3) $A^0$ band. Naturally one has for the partial concentrations:

$$N_{A^+} = \int_{(A^+)} d\varepsilon g_{A^+}(\varepsilon) F_0(\varepsilon)$$

$$N_{A^+} = \int_{(A^0)} d\varepsilon g_{A^0}(\varepsilon) F_0(\varepsilon)$$

$$N_v = \int_{\varepsilon_v} d\varepsilon g_v(\varepsilon) F_0(\varepsilon)$$

$$N_{A^+} + N_{A^0} + N_v = N_b; \quad F_0 = \frac{1}{\exp(\varepsilon - \Omega) + 1} \quad (1)$$

Here for each of the subbands the integration is carried over the corresponding energy band. Actually here we have the equation for the chemical potential $\Omega$.

We will discriminate between 2 temperature regions. The first one corresponds to low temperatures when the chemical potential nearly coincides with the Fermi level $\varepsilon_F$. We will assume that the Fermi level is near the bottom of $A^+$ band and, correspondingly, near the top of the $A^0$ band. It can be related to the fact that the magnitude of the binding potential for $A^0$ states is in average larger than the binding energy of $A^+$ center. In this temperature region one can neglect a finite population of the valence band. Note that the temperature behavior of resistance (see Fig. 1) at $T \to 0$ demonstrates nearly metallic behavior. Thus one can conclude that the states at the Fermi level are delocalized, although the mobility edge (we specify it as the energy separating strongly and weakly localized states) is rather close to $\varepsilon_F$ since the conductance is rather small.

At high enough temperatures the carriers are activated to the valence band. They are also activated to the upper states within the $A^+$ band which are expected to be well delocalized (being far away from the mobility edge). For a simplicity we will not discriminate between these well delocalized states of $A^+$ band and the valence band (assuming that the bands are well overlapped). Correspondingly, we will still define some boundary energy separating "well delocalized states" and "poor delocalized states" ascribing it to the bottom of the "effective valence band".

Figure 3: Magnetoresistance curves for sample 5-482 - (7)10$^{17}$ /cm$^3$ for different temperatures.
Let us consider now redistribution of the holes within this simplified picture including only $\tilde{A}^0$ band and the (modified) valence band. (see Fig.4).

![Graph](image)

**FIG. 4:** a) Energy spectrum including upper Hubbard band (emerging to the valence band) and $\tilde{A}^0$ band. $\varepsilon_m$ specify a position of the mobility edge. The positions of the chemical potential at $T = 0$ and finite $T$ (to describe experimental behavior it is of the order of 100 K). b) Energy spectrum of $\tilde{A}^0$ states and of $A^-$ states (corresponding to ionized $\tilde{A}^0$ states) for two values of temperature mentioned above. To emphasize the complex dipolar character of $\tilde{A}^0$ states some of them are confined by elliptical curves.

While at $T = 0$ chemical potential coincides with the Fermi level, at finite temperature it is shifted downwards:

$$\delta \Omega = T \frac{g_v}{g_{\tilde{A}^0}} \exp(-\varepsilon_F/T)$$

where $g_v$ is density of state for valence band. Thus we have for the partial depopulation of $\tilde{A}^0$ band:

$$\Delta N_{\tilde{A}^0} = \frac{g_{\tilde{A}^0}g_v}{g_{\tilde{A}^0}} T \exp(-\varepsilon_F/T)$$

Now let us consider a behavior of conductance controlled by the valence band:

$$\sigma = \frac{e^2}{m} \frac{\delta N_{\tilde{A}^0}}{\tau_{\tilde{A}^0}(\varepsilon_0)} + B$$

where

$$B = \int_{\varepsilon_F}^{\mu} d\varepsilon \frac{m}{\tau_{\tilde{A}^0}(\varepsilon)} g_{\tilde{A}^0}$$

Here $1/\tau(\varepsilon)$ is a contribution of single scatterer to the relaxation rate. As it is seen, initially (at small $T$) $B \approx 0$ and the value of $\sigma$ steeply increases with temperature increase due to exponential increase of $N_{\tilde{A}^0}$. The situation becomes different when the chemical potential is deep within $\tilde{A}^0$ band. In this case it is seen that the integration over $\varepsilon$ in equation for $B$ is controlled by the upper limit since $1/\tau \propto \varepsilon^2$. In its turn, the position of chemical potential is exponentially shifted which leads to steep increase of $B$ and finally it dominates the first term in the denominator (originating from residual scatterers existing at $T = 0$). In general, since $g_{\tilde{A}^0}(\Omega - \varepsilon_F) = \delta N_v$, the integral can be estimated as $e^2 N_v (m/\bar{\tau}(\Omega))$. Thus, after initial exponential increase of $\sigma$, it is followed by a steep decrease due to steep increase of $1/\bar{\tau}$. Then, an increase of $1/\bar{\tau}$ with temperature increase is naturally restricted by some effective value $(1/\bar{\tau})_{\max}$ which leads to a saturation of $\sigma(T)$ at the value

$$\sigma \simeq \frac{e^2}{m(1/\bar{\tau}_{\max})}$$

b) Magnetic field driven disorder.

The main effect of the external magnetic field $H$ on the relation between $A^+$ and $\tilde{A}^0$ centers is related to the Zeeman energy $\mu B g H$ (where $\mu_B$ is Bohr magneton while $g$ is $g$-factor) which should be paid for a creation of $A^+$ center due to on-site spin correlation on the center (see Fig.5).

![Graph](image)

**FIG. 5:** Relation between the number of $A^+$ states and $\tilde{A}^0$ states for different values of external magnetic field

We will denote the corresponding energy as $\delta U_{A^+}$; actually it is an addition to the Hubbard energy. Note that $6U_{A^+}$ is literally equal to the Zeeman energy only at low temperatures $T << \mu_B g H$. Otherwise we have $\delta U_{A^+} \approx (\mu_B g H)^2/4T$. The effect is expected to be pronounced for small temperatures. Thus, to estimate the effect, we can take the densities of states at the Fermi level. One expects that the magnetic field decreases the concentration of $A^+$ centers as

$$\frac{\delta N_{A^+}}{N_A} = -\delta U_{A^+} g_{A^+}$$

If we would deal with a diluted system, the effect would arise from a difference between scattering efficiencies for the dipole potential created by $A^+$ and $A^-$ centers and the dipole potential corresponding to $\tilde{A}^0$ center. Since the latter has significantly smaller intercharge distance, one could expect that the ratio given by Eq.6 describes a relative suppression of the disorder by magnetic field. In particular, it could describe a relative increase of metallic-like conductance observed at low temperature. However one can expect the effect to be much stronger. Indeed, as it was noted above, the low-temperature conductance is undoubtedly close to the metal-insulator
transition. Thus due to a shift of the mobility edge a decrease of disorder can lead to much stronger effect on the conductance than predicted by Eq.6. In particular, one can even expect a magnetic-field driven metal-insulator transition.

CONCLUSIONS

A study of temperature dependent disorder and magnetic field driven disorder for the case of model structures where the disorder originated from well defined localized states is presented. As an example of such systems we used GaAs/AlGaAS quantum wells where both wells and barriers were doped by acceptor impurity Be. Such a doping ensures a partial occupation of the upper Hubbard band where the doubly occupied states are sensitive to external magnetic field due to on-site spin correlations. The main observed features included unusual steep decrease of conductance with temperature increase which can not be ascribed to standard phonon scattering and strong negative magnetoresistance at moderate fields which was suppressed by temperature increase. We developed a consistent theoretical model which is in semi-quantitative agreement with experimental data.

ACKNOWLEDGEMENTS

This work was partly supported by Russian Foundation, Grant N 13-02-00169. We are also indebted to Yu.M.Galperin for reading the manuscript and many valuable remarks.

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