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Evidence for the correlated hopping mechanism in p-GaAs near the 2D MIT AT B=0T

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We investigated the temperature dependence of resistivity in the absence of the magnetic field near the metal-insulator transition of a high mobility of holes system in two dimensions grown on the (311) surface GaAs. We provide evidence of correlated hopping by observing the low Coulomb energy T_{ES} and the concomitantly smaller than predicted C_{ES} in single-electron hopping picture. Even in the presence of multi-electron hopping, single-particle scaling form is maintained. Hence, we use the scaling form to manifest the crossover between Coulomb hopping and screened Mott hopping. The consequence of correlated hopping is that electrons in localized states hop collectively when the interaction is strong enough and that the collective behavior leads to the transport with a lower hopping amplitude than the one estimated from direct tunneling measurements. The localization length diverges as power law when the hole density approaches a critical value. Indeed, we see that the inverse of the localization length follows a power law with the critical exponent consistent with the percolation theory.

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1. Introduction

It is well known that when the temperature is enough weak, Mott showed that the resistance between two close neighbors is not any more the lowest resistance, but that it is necessary to take into account more remote neighbors [1]. This mechanism is the one of variable range hopping. In two dimensions the law of Mott [2] is described by:

$$\rho(T) \approx \rho_0 exp(T_{SM}/T)^{1/3} \quad (1)$$

where T_{SM} is the Mott's characteristic temperature and the pre-exponential factor ρ_0 can be independent [3] or temperature-dependent [4,5] depending on the type of scattering [6] and the interaction mechanism.

The calculation of Mott supposes that the density of states is constant around the level of Fermi E_F. However, Efros and Shklovskii (ES) have shown that, because of the Coulomb interactions between carriers, the density of states $N(E)$ has to vanish at the Fermi level E_F following a law which depends on the temperature T and the dimensionality of the space D [7] : $N_c(E) \propto |E-E_F|^{D-1}$. The experimental situation has been confusing for some time, with both regimes observed in many types of disordered materials [8-12].

The gap of energy so created is said "soft gap" because the density of states does not vanish in a single point, and not on an interval of energy. The opening of the band gap at the Fermi level E_F plays an important role in determining the resistivity. At first, the opening of a forbidden gap in the density of states will not be "felt" if the interval in energy responsible for hopping is very large compared with the typical width of the forbidden gap Δ_c. This condition can be reduced to a condition on the system temperature ($T >> T_c$). When the temperature is well above this temperature T_c, we find the exponent ($1/D+1$) of Mott. By against, for $T << T_c$, it is necessary to redo the calculation of Mott with the new density of states, which drives to the ES law for the resistivity is described by [7]:

$$\rho(T) \approx \rho_0 exp(T_{ES}/T)^{1/2} \quad (2)$$

T_{ES} is the hopping energy in the regime of Coulomb hopping. In a single-particle hopping mechanism, T_{ES} is related to the localization length ξ by:

$$T_{ES} = C_{ES}e^2/k_B\varepsilon\xi_{ES} \quad (3)$$

Where the constant C_{ES} depends on the percolation lattice type used and the space dimensionality. In two dimensions, C_{ES}=6.2 [13], k_B is the Boltzmann constant; e is the carrier charge and $\varepsilon = \varepsilon_0\varepsilon_r$ is the material dielectric constant.

In the case of variable range hopping (VRH), the Mott's characteristic temperature T_{SM} leads to the localization length ξ_{SM}:

$$\xi_{SM} = (\beta e^2 d/4\pi\alpha\varepsilon k_B T_{SM})^{1/2} \quad (4)$$

Where $\beta=13.6$ and $\alpha=0.1$ [14]

It may be noted that a hard gap at the Fermi level (ie cancellation of the density of states in an energy range) leads to an activated type conduction, so with exponent *1* in the exponential ($\rho \propto exp(1/T)$) (this mechanism has been suggested to interpret some experiments [15]).

In this case nearest neighbors hopping (NNH) the resistivity is described by:

$$\rho(T) \approx \rho_0 exp(T_0/T) \quad (5)$$

And we define the distance between neighbors nearest sites ξ by:

$$\xi_0 = C_0 e^2/4\pi\varepsilon k_B T_0 \quad (6)$$

where C_0=1. For structures with a metal gate, such as MOSFETs Si or heterostructures which the electron density can be varied by field effect, Aleiner and Shklovskii have shown that screening of Coulomb interactions between electrons, reduces the scope of these interactions [16].

Since the soft gap obtained by ES [7] is due to the long-range of Coulomb interactions, we expect a change in the form of the density of states near the Fermi level for screened interactions. If the interaction is screened beyond a distance r_s, the interaction between electrons separated from a lower energy than $E_s=e^2/4\pi\varepsilon r_s$ is negligible. Thus the density of states is constant for the energy states E as $|E-E_F| < E_s$, and then increase linearly as expected by ES. For screening by a metal gate located at a distance d of the electron gas, the screened Coulomb energy takes the form [16]:

$$U(r)=e^2/4\pi\varepsilon(1/r-1/(r^2-4\pi d^2)^{1/2}) \quad (7)$$

So d is the length of screening and the screening energy is then written $E_s=e^2/4\pi\varepsilon d$. The density of states is constant for energies below E_s and is $N_c(E_s)=4\pi\alpha\varepsilon/e^2 d$.

This model leads to an increase in the conductance in the presence of screening because of the higher density of states. This model explains more than low temperatures, when the average distance of the hopping is maximum, the Coulomb gap is suppressed and the exponent in the resistivity increased from *1/2* (ES) to *1/3* (VRH, in 2D). The transition temperature below which the Mott regime is recovered was calculated by a numerical method [14]:

$$T_\xi \approx 0.013 e^2 \xi/k_B \varepsilon d^2 \quad (8)$$

This development assumes that the length of screening is greater than the localization length. The localization ξ dependent carrier density p_s, this condition allows us to deduce a density value beyond which the ES regime is no longer observed, and we observe the Mott regime whatever the temperature.

In this paper, we present experimental data that show the existence of a crossover due to the screening phenomenon, and we provide evidence for the correlated hopping mechanism. Furthermore, we observe the extrapolation of $1/\xi$ to zero as the carrier concentration p_s approaches a critical value p_{sc}. The behavior of the localization length ξ power law near p_{sc} indicates a metal-insulator transition induced by the percolation phenomenon. Our results are consistent with other experiments using high mobility samples [15]. The GaAs heterostructures used in this study were fabricated by MBE growth on (311) A substrates, utilizing silicon as the acceptor dopant. Sample is patterned into Hall bars aligned along the $[\bar{2}33]$ direction. Sample is consisted of a *200 Å* GaAs quantum well, modulation doped on one side with Si as the acceptor. The carrier density ps was varied with a $p+$ back-gate, formed using a combination of in situ ion implantation and MBE regrowth [17, 18], *360nm* below the quantum well. Sample has a peak mobility of $\mu=2.5\times10^5 cm^2V^{-1}S^{-1}$.

2. Results and discussion

Transport theory between localized states by VRH gives precise predictions of the expected temperature dependences. To test the validity of this model in our case, the curves of $\rho(T)$ were fitted by equations 1, 2 and 5. Where ρ_0, T_0 , T_{ES} et T_{SM} are the adjustment parameters, see Figs. (1, 2(a) and 3(a)), these parameters are given in Tables 1 and 2. Conduction's theories by hopping provide a prefactor ρ_0 depending on the temperature following a power law $\rho_0 \propto T^P$, and to test the influence of this prefactor we plotted $\rho(T)/T^P$ in Figures (2(b) and 3(b)), with the exponent $P = 0.8$ used by Van Keuls et al [3] versus $T^{-1/2}$ and $T^{-1/3}$, this exponent P can vary between *0.6* and *1*, but it has been shown that the difference does not change very significantly this analysis [19]. Although this dependence is weaker than the exponential law, it can sometimes influence the fit's parameters. It may be noted that in our results, the behavior of the resistivity in the insulating phase in quantum wells p-GaAs is qualitatively consistent with the laws laid down by the theories of localized electrons without interaction. In particular, there is a transition between a regime of NNH at high temperature and VRH at low temperatures as predicted by theory [2]. Not found unequivocally the ES's law, as it was observed in Si MOSFETs [19;22;23]. It is indeed not possible to distinguish Mott's law from that of ES. It is worth notice that we can obtain the crossover from ES to Mott's *VRH* regime in 2D gas in the same temperature range while whanging the carrier densities [20] or by introducing magnetic field [21].

To quantitatively compare our results to models with VRH, we extracted the localization lengths from adjustments (see Tables 1 and 2).These lengths are very high compared to the size of the sample, which calls into question whether the analysis in terms of VRH, which is the numerical value of the coefficients C_{ES} and β in the evaluation of localization lengths. On the other hand, due to the remote grid of $d = 360nm$ compared to gas holes, one would expect to see a interactions screening and therefore to find Mott's law [16]. One can also notice that the taking into account of temperature dependent prefactor changes the localization lengths slightly in the Mott's case and strongly in the ES case. A reason this poor evaluation may be related to collective effects [23]. Which would lead to a reduction of a factor about 10 the localization lengths, leading to more reasonable values of $0.7\mu m$ and $0.8\mu m$ between in the VRH case and between $0.8\mu m$ and $1.11\mu m$ in the ES case for a temperature dependent prefactor. We can also be asked about the dielectric constant ε_r in an insulator Anderson, who can be very different from that in the bulk semiconductor. In particular, for a system with a localization length ξ, the dielectric constant is proportional to ξ^2, which leads to a high value of this constant. [24]. We can report that the problems associated with this analysis is the proximity of the MIT. Even though there is no real phase transition. Is expected, however, at a transition between the low localization (with a logarithmic divergence of resistivity) and strong localization (with exponential divergence of resistivity). Between these two types of plans can be encountered any a range of behaviors not determined as power laws, as shown in Fig. 1- (a). The fact that the hopping laws are no longer valid near the MIT has been observed in Si by authors of reference [25].

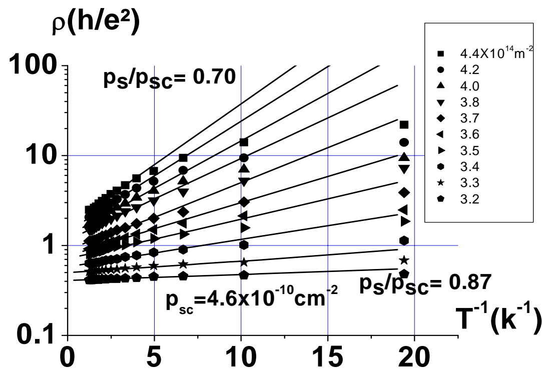

Fig 1. Resistivity versus temperature inverse for dilute 2D GaAs hole system sample for carrier densities p_s=3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 4.0, 4.2 and 4.4×10^{14}m^{-2}.

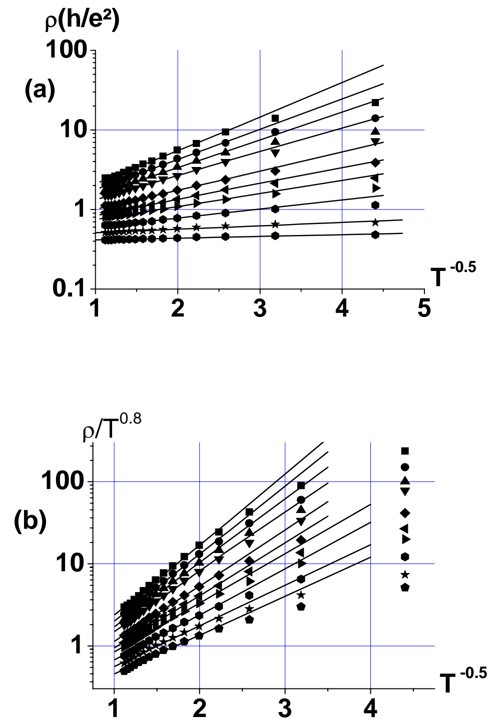

Fig 2 : Temperature dependence of resistivity and linear fits in the case of Coulomb's hopping where a): the prefactor is dependent on temperature and b): the prefactor is not dependent on temperature.

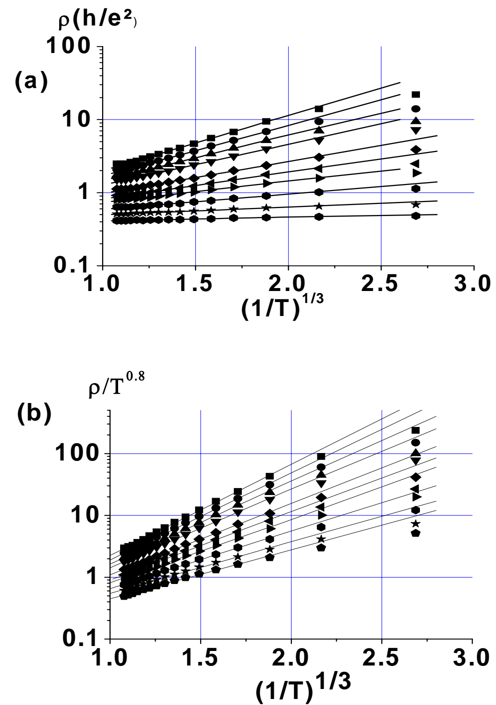

Fig 3. Temperature dependence of resistivity and linear fits in the case of Mott's hopping where a): the prefactor is dependent on temperature and b): the prefactor is independent on temperature.

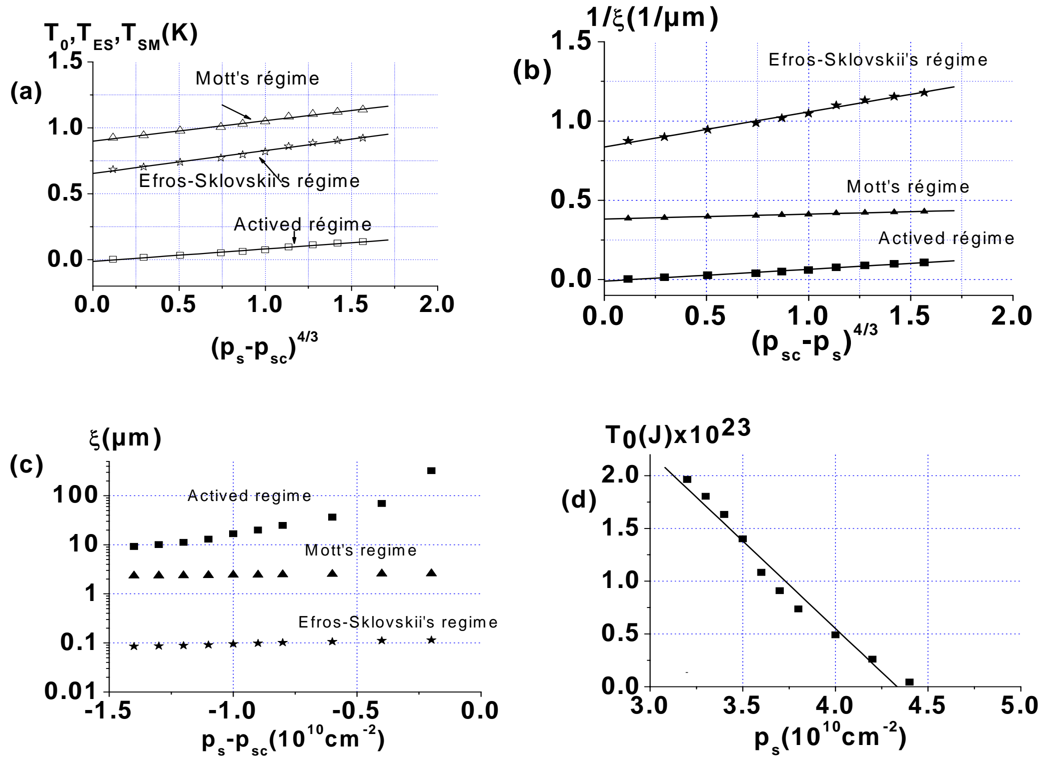

Fig 5. a): Characteristic temperatures versus discrepancy from the critical density for all three regimes. b): The inverse of the localization length follows the prediction percolation study from a power law with the exponent 4/3. c): The length of localization versus holes densities in the three regimes. d): Activation energy versus p_s in the insulating phase.

This remark is an indication that the curves for densities between $p_{sc} = 4.6\times10^{-10}cm^{-2}$ and $p_{sc} = 3.8\times10^{-10}cm^{-2}$ are not characteristic of an insulator but a metal.

Table 1. Temperatures and characteristics lengths deduced resistivity curves adjustments in the insulating phase in p-GaAs, for a temperature independent prefactor.

p_s ($10^{14}m^{-2}$)	T_0 (K)	T_{ES} (K)	T_{SM} (K)	ρ_0 (h/e^2)	ρ_{ES} (h/e^2)	ρ_{SM} (h/e^2)	ξ_0 (μm)	ξ_{ES} (μm)	ξ_{SM} (μm)
3.2	0.136	0.173	0.912	1.241	0.910	0.631	9.25	45.18	8.23
3.3	0.125	0.142	0.882	1.163	0.881	0.633	10.08	55.14	8.37
3.4	0.113	0.119	0.857	1.097	0.848	0.626	11.16	65.68	8.49
3.5	0.097	0.093	0.822	1.050	0.831	0.635	12.99	83.91	8.67
3.6	0.075	0.083	0.757	0.950	0.790	0.641	16.80	94.23	9.03
3.7	0.063	0.042	0.720	0.885	0.752	0.628	19.99	185.66	9.26
3.8	0.051	0.026	0.665	0.750	0.750	0.650	24.69	298.93	9.64
4.0	0.034	0.013	0.592	0.712	0.712	0.645	36.46	589.09	10.2
4.2	0.018	0.003	0.473	0.698	0.698	0.664	69.24	2304.4	11.4
4.4	0.003	-	0.382	0.658	0.658	0.641	324.02	-	12.7

Table 2. Parameters deduced adjustments of the resistivity in the insulating phase in p-GaAs, with a temperature dependent prefactor.

p_s ($10^{14}m^{-2}$)	T_{ES} (K)	T_{SM} (K)	ξ_{ES} (µm)	ξ_{SM} (µm)
3.2	0,923	1.137	8.48	7.37
3.3	0,904	1.120	8.66	7.43
3.4	0,886	1.104	8.84	7.48
3.5	0,860	1.084	9.10	7.55
3.6	0,820	1.048	9.54	7.68
3.7	0,797	1.030	9.82	7.74
3.8	0,772	1.006	10.13	7.84
4.0	0,740	0.977	10.57	7.95
4.2	0,704	0.942	11.12	8.10
4.4	0,685	0.924	11.42	8.18

In the VRH case the prefactor $\rho_0 \approx 0.6h/e^2$ is almost independent of density and temperature (see Table 1), this value is very close to that obtained in p-SiGe [26] and this is compatible with mechanism which hopping are engendered by the electron-phonon interaction in a δ-doped $GaAs/Al_xGa_{1-x}As$ heterostructure [28]. In the ES hopping case this prefactor (in case where it is independent of temperature) varies from 0.65 to $0.91h/e^2$ depending on the density (see Table 2). This behavior is different from that which was observed in Si MOSFETs [19;22;23], where a temperature independent universal prefactor and density was obtained, but in agreement with the theories of VRH and can be attributed to another hopping mechanism related to the electron-electron interaction, confirming there again the important role of interactions in the system studied.

The activated law obtained in Fig. 1-(b) can be interpreted by the opening of a "hardgap" in Fermi level due to the Coulomb interaction, as has been suggested in [28;29] . This gap may in particular characterize the ordered electronic phase formation Wigner crystal type, for which a law simply activated is indeed expected [30].

As illustrated in Fig. 3-(d), the activation energy k_BT_0 deduced adjustment decreases linearly when the density increases and tends to 0 at a density $p_{sa} = 4.3\times10^{-10}cm^{-2}$. This analysis associated with the observation of power laws for p_s comprised between 4.6 and $3.2\times10^{-10}cm^{-2}$, to conclude that the true metal-insulator transition seems rather to density $4.2\times10^{-10}cm^{-2}$.

This value is lower than that obtained by estimation based on the slope of the resistivity ($p_{sc} = 4.6\times10^{-10}cm^{-2}$ or p_{sc} is the critical density that separates the metallic phase of the insulating phase) [31]. The activated law can also be due to transport in a percolating system: when the system consists of metallic islands separated by insulating regions, the carrier transport is done by hopping activated of an island to another. This finding is interesting in the framework of the metal-insulator transition in two dimensions for which percolation scenarios were evoked. The temperature characteristic as shown in Fig 3-(a) is proportional to $|p_s-p_{sc}|^{4/3}$ i.e the discrepancy from the critical density. In Figure 3-(c) the localization length diverges when p_s approaches p_{sc} in the NNH case. This divergence is not provided by the scaling theory of localization, which provides a localization length varies continuously between the strong localization regime and the regime of weak localization. Characteristic temperature and the inverse of the localization length (see Fig. 3-a and 3-b) for different regimes studied vary linearly with $|p_s-p_{sc}|^{4/3}$ which means that the system studied is the seat of the percolation phenomenon.

3. Conclusion

In our sample, the transport measurements seem to be qualitatively interpreted by theories of independent electrons. At lower carrier densities, the resistivity dependences presents a law simply activated at low temperature not provided by the theories of independent electrons localized. These characteristics are typical of transport in collective phase hung disorder, but can also be interpreted in the framework of a percolating system. When the system consists of metallic islands separated by insulating regions, the carriers transport is done by hopping activated of an island to another, these observations may also describe the conduction at finite temperature below the percolation threshold.

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