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Review

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The transport mechanism in the heterostructure GaAs/AlGaAs at very low temperature in the vicinity of the metal insulator transition

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ABSTRACT

The objective of this work, is to study the transport mechanism contributing to the low temperature electrical conductivity of a two-dimensional GaAs hole gas in the metal and insulating side of the Metal Insulator Transition, for T less than 1K. We reanalyzed the data obtained by Qiu et al published in [*R. L.J. Qiu, X.A.A. Gao, L.N. Pfeiffer and K. W. West, PRL 108, 106404 (2012)*].

In insulating systems, the electrical transport in a disordered system occurs by the phenomenon of Variable Range Hopping (VRH), which is widely observed, analyzed in several studies and described by $\sigma = \sigma 0 \exp(-T0/T)^{p}$. In this case, the holes move between localized states while traveling different distances, giving rise to two regimes: the Efros & Shklovskii regime (ES VRH) and the Mott regime (Mott VRH).

For the metal samples, we studied the temperature dependence of the resistivity ρ and its impact on the metallic behavior of the system with high hole densities (when $d\rho/dT > 0$), beyond a critical density ($psc=0,8x10^{10}cm^{-2}$). The results were verified graphically and confirmed by the percentage of deviation method.

KEYWORDS

Electrical conductivity; Two-dimensional GaAs hole; Metal insulator transition; Disordered system; Variable range hopping.

INTRODUCTION

In the two dimensional hole gas system, several theories were developed to explain the low temperature electric transport phenomena. Research continues to study the conduction properties of the two-dimensional system when disorder and interactions compete. This led to studying the localization of electrons and probing the insulating metal transition in GaAs/AlGaAs heterostructures.

In the 1980s, all two-dimensional electron gases were considered insulating at low temperatures before the discovery of SV Kravchenko et al[1]. They observed a metallic behavior in Si MOSFETs, explained by a decrease in resistivity ρ when the temperature T is decreased. This has been reproduced in various samples, including GaAs/AlGaAs heterostructures. Therefore, research laboratories and researchers rush for the theoretical understanding of this mystery of condensed matter physics.

Review

In this work, we will try to model experimental measurements obtained by Qiu *et al.*[2], in figure to highlight phenomenom than can occur in the metallic and insulating side of the MIT. The measurements were performed on GaAs sample which were grown on (*311*) using Al0.1Ga0.9As with a mobility $\mu=5x10^5\ cm^2/Vs$ in the temperature range *0-1K*. The carrier densities *p* vary between $0.55x10^{10}cm^{-2}$ and $1.33x10^{10}cm^{-2}$. The critical density $p_c \approx 0.8x10^{10}cm^{-2}$ represents the boundary between the metallic and insulating samples.

STUDY OF THE CONDUCTIVITY IN THE INSULATING SIDE OF THE MIT

In the insulating systems, the electrical transport through a disordered system occurs by variable range hopping (VRH) phenomenon. Carriers moves between localized states while traveling different distances although the energetic won interval is the same. This conduction can be provided under a single particle-hopping model or a collective hopping.

When the Variable Range Hopping Conduction (VRH conduction) is possible, we define two regimes: Mott and Efros-Shklovskii. In the Mott VRH regime[3], the electrical conductivity σ is proportional to $\left[\left(-\frac{1}{T}\right)\right]^{\frac{1}{D+1}}$, expressed as:

$$\sigma \propto \left[\left(-\frac{1}{T}\right)\right]^{\frac{1}{D+1}} \quad (1)$$

Where T is the temperature and D the dimensionality of the system. Mott derives this law by assuming a constant density of states (DOS) at the Fermi energy. In this model, Mott ignores the Coulomb interactions in two-dimensional systems and the hopping conductivity is given by:

$$\sigma = \sigma_0 exp\left[-\left(\frac{T_M}{T}\right)^{1/3}\right] \quad (2)$$

ES-VRH regime[4] is due to the Coulomb interactions between carriers, which produces a Coulomb gap (CG) around the Fermi energy *E* and the DOS is proportional to $|E-E|$ for two-dimensional (2D) systems. In Efros-Shklovskii model, the hopping conductivity with a Coulomb gap is given by:

$$\sigma = \sigma_0 exp\left[-\left(\frac{T_{ES}}{T}\right)^{1/2}\right] \quad (3)$$

with T_M et T_{ES} are the hopping energies in each regime and σ0 is the pre-exponential factor.

In Figure 1, we plot the electrical conductivity σ against the temperature *T* only for high carrier densities in the insulating side of the MIT ($p < pc$). We noticed that the conductivity increases by increasing temperature indicating that the samples are well insulators.

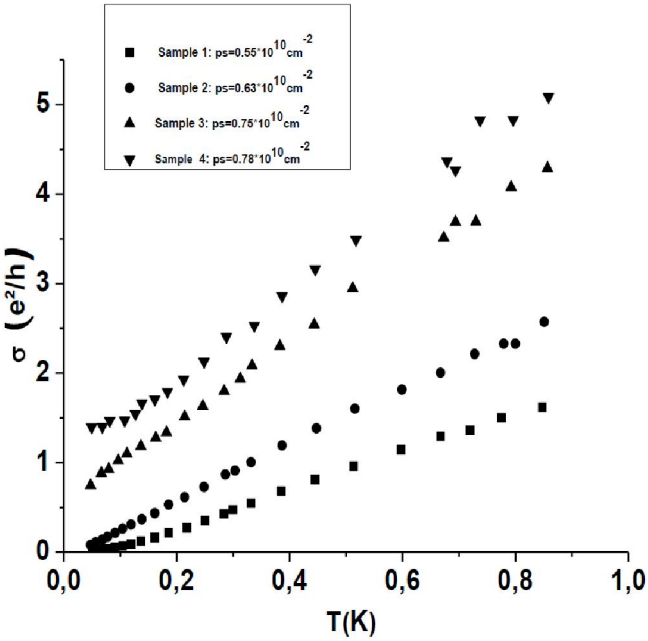

Figure 1: Electrical conductivity in unit of (e^2/h) as a function of temperature for different carrier densities in the insulating side of the MIT.

In the insulating side of the MIT, when the ES VRH regime occurs, the electrical conductivity σ is described by equation (3). The parameter T_{ES} present the strength of the Hartree interactions that only depends on the carrier densities in 2D systems. T_{ES} is related to the localization length ξ, when the carrier moves individually (uncorrelated system) and given by:

$$T_{ES} = \frac{C_{ES} e^2}{4\pi\varepsilon_0\varepsilon_r k_B \xi} \quad (4)$$

where *CES* is a constant characterizing the single hopping amplitude. *CES = 6.2* in *2D* systems and *CES=2.8* in 3D systems[5,6], *e* is the electron charge, ε is the dielectric constant and k_B is the Boltzmann constant.

However, when the Mott VRH regime occurs σ is

given by equation (2) and the parameter T_M is equal to:

$$T_M = \frac{\beta}{k_B N(E_F)\xi^d} \quad (5)$$

β is the single-electron hopping constant which is equal to *13.8* in 2D systems[5] and *d=2*.

Figure 2 shows respectively the variation of the electrical conductivity as a function of $T^{-1/2}$ and of $T^{-1/3}$ in the temperature range *0-1K*, for several carrier densities below the critical density in the insulating side of the MIT.

By analyzing this figure, we notice that for the three samples respectively referenced *2, 3* and *4* in case (a), we obtain straight lines in good agreement with equation (3) only for *T* in the range [*0.18-1K*].

For *T* less than *0.18 K*, we observe a change of slope of the straight lines indicating no evidence of the existence of the Efros VRH regime in this region of temperature. For sample referenced *1*, we obtain the same behavior with a slight change of the slope for *T* less than *0.1 K*.

Regarding to case (b), we remark that for the three samples respectively referenced *3* and *4*, we obtain straight lines in good agreement with equation (2) only for *T* in the range *0.15-1 K*. For the sample referenced *1* and *2*, we obtain a straight line in all the interval of temperature indicating the existence of the Mott VRH regime conduction in this sample. Except in the case of sample referenced 1 and 2 for which we obtain a straight line with the same slope over the entire temperature range (0-1 K) which could suggest that in this sample we obtain a Mott VRH regime.

This analysis shows that is difficult to choose between the Mott VRH regime and the ES VRH regime by using this graphical method. In order to dispel this confusion, we will use a numerical method based on the calculation of the percentage of deviation[7,8].

We consider the general expression of electrical conductivity as a function of temperature in the case of the VRH conduction regime given by:

$$\sigma 0 = \sigma_0 \, exp\left[-\left(\frac{T_o}{T}\right)^S\right] \quad (6)$$

Where $S = 0.33$ for the Mott VRH regime $(T_0=T_M)$ and $S = 0.5$ for the ES VRH regime $(T_0=T_{ES})$.

The percentage deviation is defined by:

$$Dev(\%) = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{100}{\sigma_i}\left(\sigma_0 \, exp\left[-\left(\frac{T_o}{T}\right)^S\right]-\sigma_i\right)\right)^2\right]^{\frac{1}{2}} \quad (7)$$

We plot the variation of the Dev(%) as a function of exponent S for each sample as is shown in Figure 3:

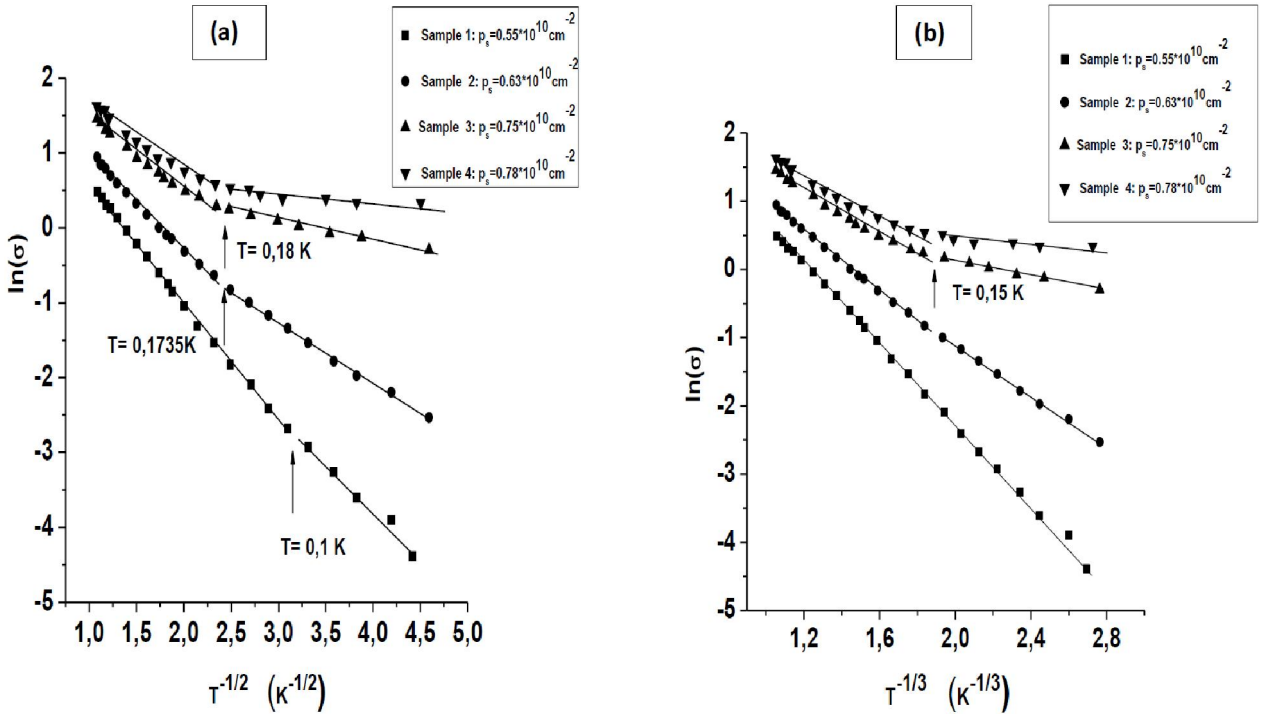

Figure 2: ln(σ) against $T^{-1/2}$ and $T^{-1/3}$ for different carrier densities in the insulating side of the MIT.

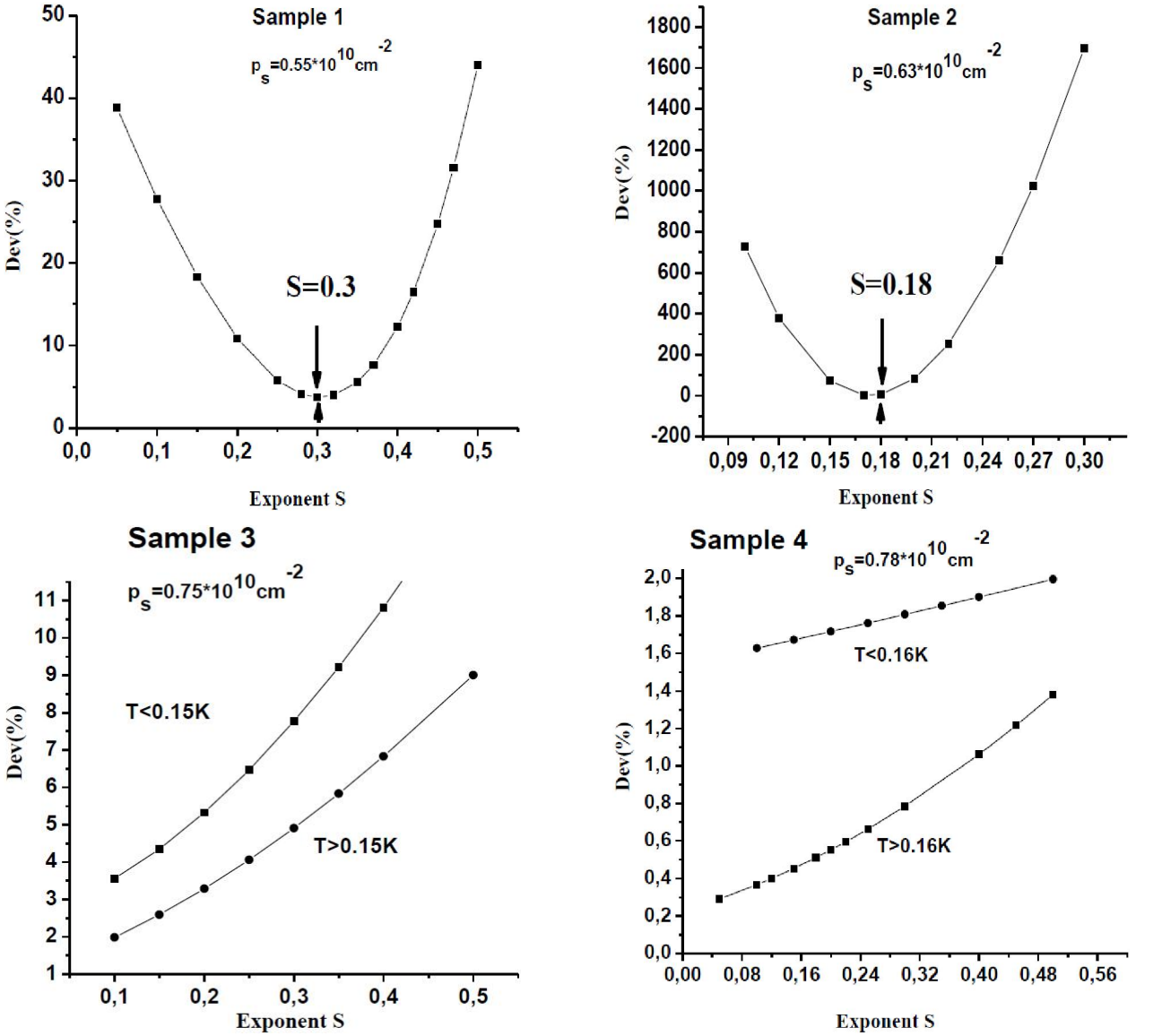

Figure 3: The variation of *Dev(%)* as a function of exponent S in equation *(5)* for sample 1,2,*3* and *4*.

For sample 1, we notice that the minimum of *Dev(%)* is equal to *0,3*. This value is very close to *1/3* indicating the existence of the Mott VRH regime conduction in this sample.

For sample 2, the minimum of *Dev(%) is defined in 0,18* . This value is close to *1/3* indicating the existence of the Mott VRH regime conduction in this sample. The jump will occur at the energetically favorable site.

For the samples referenced *3* and *4* (p_S = *0.75* $10^{10}cm^{-2}$ and p_S =*0.78* $10^{10}cm^{-2}$), we observed:

- For p_s = *0,75*10^{10}cm^{-2}, S <0,1* at *T <0,15K* and *T> 0,15K*.
- For p_s = *0,78*10^{10}cm^{-2}, S <0,1*at T*<0,16K* and *S = 0,05* at *T> 0,16K*.

Dev(%) increases with the exponent *S* without reaching a minimum, which makes it possible to reject the VRH hypothesis. Thus, neither conduction regime is determined to describe the mode of transport for the two samples.

We conclude, that for only the samples referenced *1* and *2* (p_S=*0.55 x10^{10}cm^{-2} and* p_S=*0.63 x10^{10}cm^{-2}*) respectively, the evidence for a Mott VRH conduction regime indicating that the density of states (DOS) in the vicinity of the Fermi level E_F, is constant. Those samples are situated on the insulating side of the MIT and quite far from the critical density $p_{sc} \approx 0.8\ x10^{10}cm\text{-}^{2}$ (*S = 0.3* for sample *1* and *S = 0.18* for sample *2*). The samples become purely insulating (according to equation

(6)) and Coulomb interactions become weak and neglected in the system since the conduction mechanism according to ES VRH has not been verified. Different authors have observed these two VRH conduction mechanisms in other materials[9-12].

STUDY OF THE CONDUCTIVITY IN THE METALLIC SIDE OF THE MIT

The metallic character is a manifestation of a delocalization of electrons that results in a metal having a finite resistivity (or zero) at T = 0K, while the electrical resistivity ρ of an insulator is infinite. At very low temperatures, localized electrons can always exchange energy with the thermal bath (in this case phonons of the crystal lattice), with a probability of changing quantum state and moving. The resistivity at non-zero temperatures is different from zero for metallic states and infinite for insulators.

In the first part of this paper, we have studied the conduction in the insulating side of the TMI in the GaAs / AlGaAs. In this part, we will present an experimental study of the conduction in the metal side of the TMI of the same heterostructure as a function of temperature for different samples with different hole densities.

It is recalled that the data obtained by Qiu et al.[2]. The measurements were carried out at a very low temperature (*<1K*), on the GaAs / AlGaAs heterostructure. The metal densities of the holes are respectively *0.86, 0.94, 1.14,* and *1.33* in units of $10^{10}cm^{-2}$ with a critical density $p_c \approx 0.8x10^{10}cm\text{-}^{2}$.

We represent in Figure 4, the variation of the resistivity as a function of the bass 0-1K temperature on the metal side of the TMI. The metallic behavior is well observed for the high densities of holes, the resistivity increases as the temperature increases until *T = 0.2K*, then we obtain a saturation of the resistivity ρ for the whole range of the temperature T between *[0.2K, 1K]*.

In the vicinity of the TMI, for the density ps = $0.86x10^{10}cm^{-2}$, we notice that there is a small increase in the resistivity up to a value of the temperature T = 10mK, then we see a decrease for the rest of the temperature range up to 1K. This indicates a transition from the metallic behavior to the insulating behavior and consequently the charge carriers begin to locate themselves.

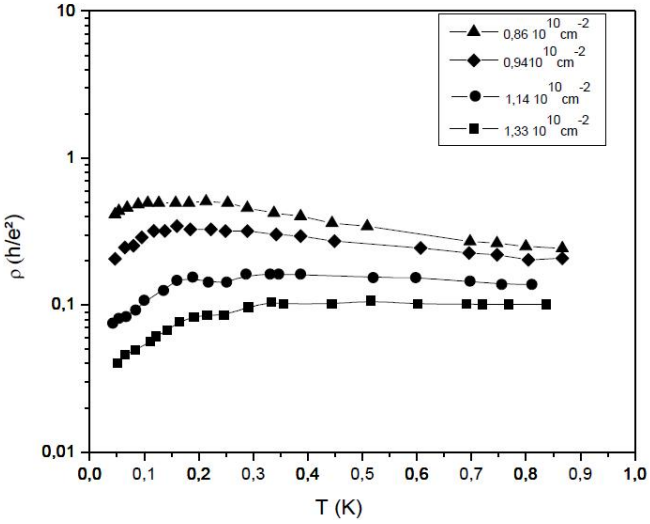

Figure 4: The variation of the resistivity ρ (h / e²) as a function of the temperature T for different values of hole densities $1.33x10^{10}cm^{-2} < ps < 0.86x10^{10}cm^{-2}$.

On the metallic side, the increase of the resistivity with the temperature is given by the expression[13]:

$$\rho(T) = \rho_1 + \rho_2 \exp(-T_1/T)^s \qquad (8)$$

with: - ρ_0, ρ_1: adjustment parameters relating to the densities of holes; - S: the critical exponent equal to 1 according to Hanein *et al.*[14] and Papadakis *et al.*[15], and 0.5 for p-SiGe by Coleridge et al.[16].

In order to remove any ambiguity and to confirm our graphical results we opted for a numerical method, that of the percentage of deviation to further confirm this metallic behavior described by the previous law.

The percentage of deviation is defined by:

$$Dev(\%) = \left[\frac{1}{N} \sum_{i=1}^{N} \left(\frac{100}{\rho_i} \left(\left(\rho_0 + \rho_1 \exp\left[-T_1 / T \right]^s \right) - \rho_i \right) \right)^2 \right]^{1/2} \qquad (9)$$

As shown in Figure 5, the Dev (%) is plotted against the exponent S for each density.

It turned out that the minimum deviation is found to be very close to 1 satisfying the condition of the exponent S of the equation (V-8). Therefore, this verifies the metallic behavior of the 2D system as given by Pudalov's law[13]. It can be noted more, that the further one moves away from the critical density $ps = 0.8x10^{10}cm^{-2}$ (MIT), the more the exponent S approaches 1 and the more the sample becomes more and more metallic.

For $ps = 0.86x10^{10}cm^{-2}$, no minimum deviation is

obtained which means that the equation (8) is no longer valid at this level of carrier density. This can only confirm the transition to another behavior that can only be insulating.

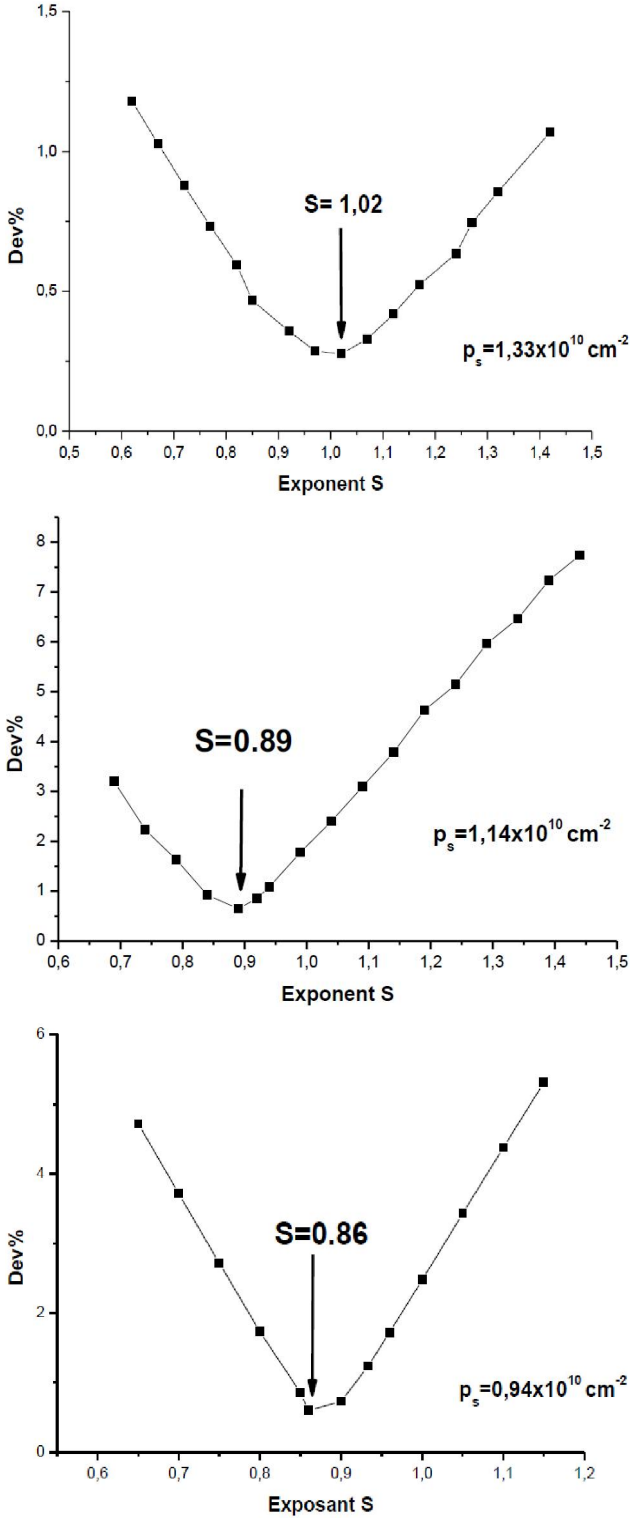

Figure 5: Variation of Dev% as a function of the exponent S for p_s=0.94x10^{10}cm^{-2}, p_s=1.14x10^{10}cm^{-2} and p_s=1.33x10^{10}cm^{-2}

CONCLUSION

This article highlights the study of metallic and insulating behavior in the GaAs/$Al_{0.1}Ga_{0.9}As$ two dimensional hole gas at very low temperature (less than 1K). The critical density is equal to $p_{sc}=0.8x10^{10}cm^{-2}$.

Beyond the critical density, for high densities, the system becomes purely metallic. This indicates that at this stage the metallic behavior is attributed to the effects of electron-electron interactions, which promote the transport of loads without stabilizing the metal phase. Below this value ($p_{sc}=0.8x10^{10}cm^{-2}$) and the further away from MIT, the more the system becomes insulating and the evidence for a Mott VRH conduction regime indicate that the density of states (DOS) in the vicinity of the Fermi level E_F, is constant. These results have been proven graphically and mathematically. It can also be noted that when we are close to MIT, it becomes difficult to determine the type of conduction of the densities of the holes.

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