International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE
ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com
December 2021 | Issue 49 | Volume 13 | Number 4 | Pages 170-178

LOW TEMPERATURE ELECTRICAL TRANSPORT IN ^{70}GE:GA SAMPLE IN MAGNETIC FIELDS

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Abstract- In this paper, we have presented the electronic transport phenomena of a three-dimensional ^{70}Ge: Ga material at sufficiently low temperatures. In particular, we study the temperature (*T*) and magnetic field (*B*) dependences of the low-temperature electrical conductivity $\sigma(B,T)$. We find that in the metallic face of the metal- insulating transition (MIT), the $\sigma(B,T)$ can be described by $\sigma(B,T)=\sigma(B,\ T=0\ K)+mT^S$, where S = 1/3 or 1/2 in the transport regime where weak localization (WL) and the electron-electron interactions (EEI) are the dominant conduction mechanisms. However, in the insulator face of the MIT, the electric conduction generally tracks the Mott variable range hopping (VRH) $\left(\ln(\sigma(B,T))\propto T^{-0.25}\right)$ for B > 5.3 T. The effect of the applied magnetic field on the characteristic conductivity of Mott σ_M, the characteristic temperature of Mott T_M, the localization length ξ, the electronic density of states (DOS) near the Fermi energy E_F and the Mott hopping distance R_M has been studied. The experimental data are taken on a ^{70}Ge:Ga material which was prepared by Itoh and co-workers [Phys. Rev. B 60, 15817 (1999)].

Keywords: Electronic Transport, Low Temperature, Density of States, Metal-Insulator Transition, Variable Range Hopping Conduction, Metallic Electrical Conductivity, Weak Localization, Electron-Electron Interactions.

1. INTRODUCTION

Electronic components are fundamental building blocks in the technology industry and have an important part in our daily lives. By living in a generation of electricity, from waking up by the alarm clock of the cell phone to the extinction of the lights, we are surrounded by objects whose functionalities only exist thanks to the electronic components manufactured following technological development of condensed-matter physics [1-3].

In solid-state physics, the disorder effects on the electronic transport properties of a disordered system have led to the discovery of a phase transition. When the disorder is weak, the system behaves like a conductor, where electrons move by diffusion in the weak localization regime. It becomes insulating when the disorder is large enough. As a result, the diffusive transport is completely destroyed, leading to the strong localization. This transition is called the metal-insulator transition (MIT) or Anderson transition between a diffusive low disorder regime and a localized high disorder regime [4, 5]. Consequently, the wave function of electrons takes between a spatially extended state into a spatially localized state over a characteristic length called the localization length [4-7].

In this work, we will report our investigation of the electrical transport of a three-dimensional ^{70}Ge:Ga system [7] at low temperatures. In our system, the MIT is performed by the applied *B* magnetic field. The impurity concentration of ^{70}Ge: Ga system is n = 2.004×10^{17} cm^{-3} [7]. The objective of this work is to study the electrical conductivity at different temperatures (*T*) and magnetic fields (*B*) on both sides of the MIT. The effect of the *B* on the ξ, the DOS near the E_F, and the R_M will be reported.

2. THEORETICAL BACKGROUND

2.1. Study of Electrical Conductivity in Metallic Regime

Electrical transport does not occur in the form of VRH in the metallic face of the MIT. This is a region where the electronic states are not localized in the sense of Anderson localization. The quantum nature of conduction electrons implies that they do not only behave as particles, but also as waves propagating in the disordered medium. That is, electrons are described by their wave functions. On the other hand, we add that in this region, weak localization and electron-electron interactions are the two dominant transport mechanisms in disordered metals and doped semiconductors. These two effects lead to additional corrections to the electrical conductivity [8-10].

For three-dimensional metallic samples [11-14] on the metal side of the MIT, at sufficiently low temperatures the *B* and *T* dependences of the electrical conductivity can be expressed by

$$\sigma(B,T)=\sigma(B,\ T=0\ \text{K})+mT^{S} \quad (1)$$

where, $\sigma(B,\ T=0\ \text{K})$, m and S correspond to the conductivity at T = 0 K, the magnitude of the correction term and the parameter, respectively.

Note that the aforementioned relationship was widely used in several doped and disordered semiconductors on the metal side of the MIT [14, 15]. The possible exponents are 1/3 $\left(\delta\sigma \propto T^{1/3}\right)$ and 1/2 $\left(\delta\sigma \propto T^{1/2}\right)$.

2.2. Variable Range Hoping in Insulating Regime

When E_F is slightly below the mobility edge, E_C, the electron searches for the most energetically favorable site which is not necessarily the closest neighbor. An electron jumps from one localized site to another by traveling a different distance from that traveled by the other electron. The electrical conduction can occur therefore by VRH.

The conduction regime described by VRH is a theory widely adopted to describe the mechanism of electrical transport that is observed in non-crystalline systems (disordered materials or amorphous materials) on the insulating side of the MIT. According to Mott [16, 17], VRH dominates the low-temperature electrical conduction in disordered semiconducting materials, for which the energy states are generally localized in Anderson's sense near the E_F. When VRH is the dominant mechanism in a system, the temperature-dependent electrical conductivity follows the general power law:

$$\sigma=\sigma_0\exp[-(T_0/T)^{p} \quad (2)$$

where, σ_0, T_0, and p are the conductivity factors, the characteristic temperature depends on the hopping mechanism, and the parameter $p=n+1/n+4$, respectively. Note that the probable values of n are 0 or 2.

It is interesting to recall that there are two types of VRH conduction in three-dimensional systems: VRH of Mott-type [17, 18] (n = 0 then p = 0.25) and VRH of Efros-Shklovskii (E-S) type (ES) [19, 20] (n = 2 then p = 0.5).

In the case of ES-type VRH, the Coulomb interactions [20, 21] between electrons in disordered systems reduce the DOS near the Fermi level, thus creating a parabolic pseudo gap called the "Coulomb gap" [22]. In this case, the electronic density around the Fermi level varies according to the equation:

$$N(E)\propto(E-E_F)^2 \quad (3)$$

The electrical conductivity can be written in the model

$$\sigma=\sigma_{ES}\exp[-(T_{ES}/T)^{0.5}] \quad (4)$$

In this regime, characteristic temperature is given by:

$$T_{ES}=\beta_1 e^2/k_B k\xi, \quad (5)$$

where, β_1, e, k_B and k are a constant that was estimated at 2.8 by Shklovskii and Efros [20], the electron charge, the Boltzmann constant and the dielectric constant of material, respectively.

Moreover, in the Mott regime, the DOS is almost constant [23, 24] in near the E_F, in three-dimensional systems, the temperature-dependent electrical conductivity may be given by:

$$\sigma=\sigma_M\exp[-(T_M/T)^{0.25}] \quad (6)$$

where, σ_M is the characteristic Mott conductivity and T_M represents the characteristic hopping temperature of Mott, this localization temperature is expressed as:

$$T_M=\beta_2/k_B N(E_F)\xi^3 \quad (7)$$

where, β_2 is a value constant calculated numerically by the percolation method. In three dimensions $\beta_2=18\pm1.2$ [20] and $N(E_F)$ represents the DOS at E_F, respectively.

2.3 Practical Method Proposed by Zabrodskii and Zinoveva

The starting point is the general formula for VRH $\left(\sigma=\sigma_0\exp[-(T_0/T)^{p}\right)$. Applying the natural logarithm function on both sides of the VRH law, we have

$$\ln(\sigma)=\ln(\sigma_0)+C_1^{te}T^{-p} \ \text{with}\ C_1^{te}=-(T_0)^{p} \quad (8)$$

By differentiating this equation, we will have:

$$d\ln(\sigma)=-C_2^{te}T^{-p-1}dT=-C_2^{te}T^{-p}\,d\ln T \quad (9)$$
$$=-C_2^{te}T^{-p}\,d\ln T\ \text{with}\ C_2^{te}=p\,C_1^{te}$$

Now introducing the function $W(T)=d\ln(\sigma)/dlT$:

$$W(T)=dLn(\sigma)/dlT=-C_2^{te}T^{-p} \quad (10)$$

Finally, we find the expression of Zabrodski and Zinovera [25]:

$$\ln(W(T))=A-p\ln T\ \text{with}\ A=C^{te} \quad (11)$$

The graphical procedure of Zabroudskii and Zinoveva [26] is used to specify the insulating or metallic behavior of a sample. This method consists of plotting the curve $\ln(W(T))$ versus $\ln T$ over the whole temperature range. The negative slope p of this plot, that is, $\ln(W(T))$ decreases with increasing $\ln T$, suggests that the sample is located in the insulator face of the MIT and therefore electronic transport is described through VRH. In this case, -p>0 (that is, $\ln(W(T))$ increases when $\ln T$ increases) means that the system is in the metallic face of the MIT. In this case, the electronic states are not localized in the Anderson sense. In this region, quantum interference and Coulombic interactions between electrons play a vital role in the transport mechanism.

It is interesting to note that Equation (11) is equivalent to the derivative form of Equation (2). Furthermore, since we are working on derivatives, the average values of $\ln T$ and $\ln(W(T)$ will be determined as follows:

For a given experimental point i, we can write:

$$\ln(T_i)=\frac{\ln(T_{i+1})+\ln(T_{i-1})}{2}$$
$$\ln(W(T_i))=\ln\left[\frac{\ln(\sigma_{i+1})-\ln(\sigma_{i-1})}{\ln(T_{i+1})-\ln(T_{i-1})}\right] \quad (12)$$

3. RESULTS AND DISCUSSION

We have re-analyzed the data obtained on ^{70}Ge:Ga material developed and reported by Itoh, et al. [7].

Figure 1 shows the $\sigma(B,T)$ of the system ^{70}Ge:Ga as versus $T^{1/2}$ for different B ranging from 1 and 8 T. The temperature range is from 0.048 K to 0.65 K. We use the linear regression method to extract the values of $\sigma(B,\ T=0\ \text{K})$ for various B. For B >5.3 T, the values of $\sigma(B,\ T=0\ \text{K})$ appear negative which have no physical significance. However, we note that the magnetic field B=5.3 T is the boundary between the insulating side (B<5.3 T) and the metallic side (B>5.3 T). To verify the aforementioned results, we are going to use very complex procedures and theoretical models to explain the different electrical transport phenomena on both the metallic and insulting sides of the MIT.

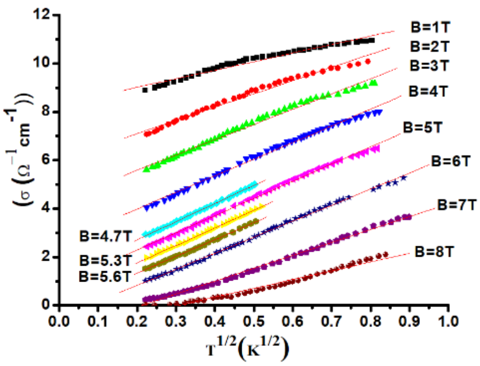

Figure 1. Evolution of $\sigma(B,T)$ versus $T^{1/2}$ at B ranging from 1-8 T. As stated beforehand, we reanalyzed the data published in reference [7]

We have now used the practical method proposed by Zabrodski and Zinovera [25]. For this, we have represented on the figures the variations of $\ln(W(T))$ as a function of $\ln T$ over the entire temperature range and for the magnetic fields: $2\text{T} \le B \le 5.3\text{T}$. As we can see in Figure 2, all the curves are practically straight lines with strictly positive slopes (-p>0). This allows us to conclude that for $2\text{T} \le B \le 5.3\text{T}$, the sample shows a metallic behavior and is located in the metallic face of the MIT. We presented $\sigma(B,T)$ versus $T^{1/3}$ and $T^{1/2}$ in temperature range T = 0.048–0.65 K and for magnetic fields between B=2 T and B = 5.3 T in Figures 3 and 4, respectively. Considering the good linearity of the curves in these two figures (Figures 3 and 4), it not possible to clearly choose between the two behaviors ($\delta\sigma \propto T^{1/3}$ and $\delta\sigma \propto T^{1/2}$) of the metallic conductivity based only on these two graphs.

To tackle this issue, we have exploited the method of the percentage of deviation [26, 27].

In order to determine the parameter S, we exploit the procedure of Dev(%). For this, we vary the exponent S $\left(\sigma(B,T) = \sigma(B,\ T=0\ \text{K}) + mT^{S}\right)$ from 0 to 1 in steps of 0.01. For each value of S, using the linear regression method, we deduce the values of conductivity at T=0 K and m for different magnetic fields ranging from 2 T to 5.3 T.

Finally, we calculate every time, the Dev (%) between the expression $\sigma(B,T) = \sigma(B,T=0K) + mT^{S}$ and the extracted values of the electric conductivity.

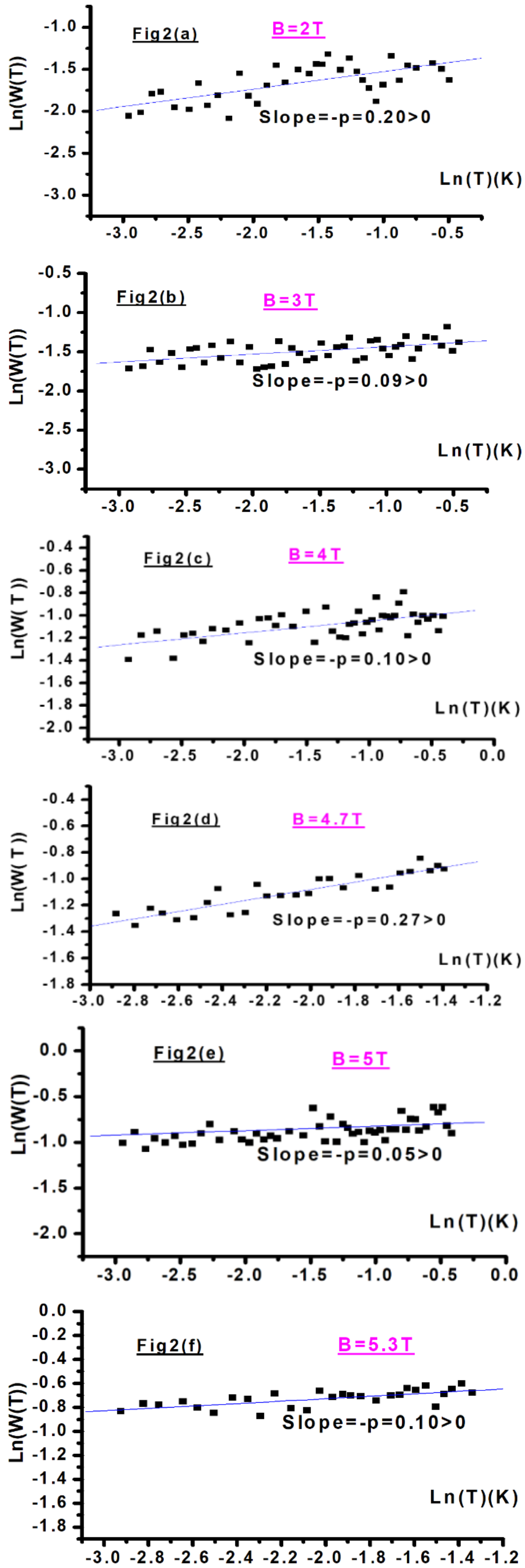

Figure 2. Function ln($w(T)$), (a) B=2 T, (b) B=3 T, (c) B=4 T, (d) B=4.7 T, (e) B=5 T and (f) B=5.3 T as a function ln(T) in Equations (11) and (12) for sample metallic 70Ge:Ga, as indicated

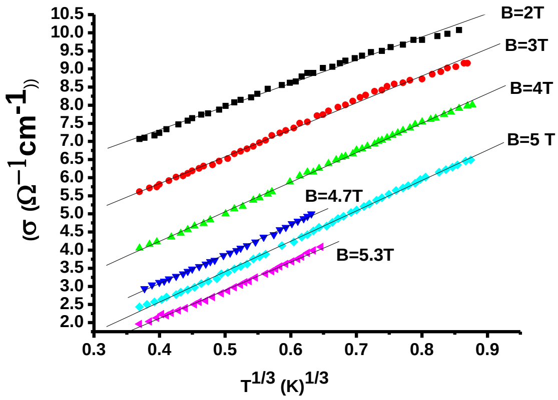

Figure 3. $\sigma(B,T)$ versus $T^{1/3}$ for the metallic sample ^{70}Ge:Ga ($0.048\text{K} \le T \le 0.65\text{K}$)

The *Dev*(%) [26, 27] can be calculated as follows:

$$Dev(\%) = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100}{\sigma_i}\left([\sigma(B,\ T=0\ \text{K})+mT^S]-\sigma_i\right)\right)^2\right]^{1/2} \quad (13)$$

where, n is the number of data points and σ_i denotes the extracted values of the $\sigma(B,T)$ at different T_i and for each magnetic field value. It should also be noted that the minimum of *Dev*(%) represents the right value of the parameter *S*.

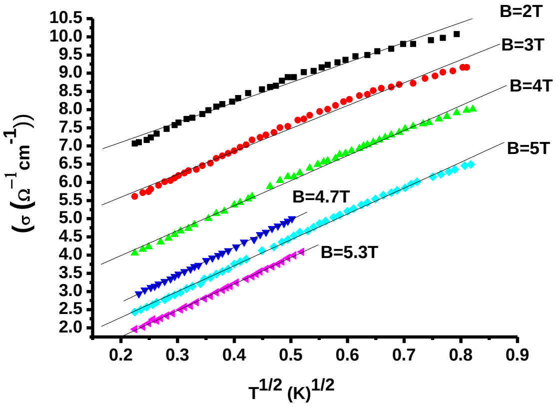

Figure 4. Plots $\sigma(B,T)$ versus $T^{1/2}$ of $0.048\text{K} \le T \le 0.65\text{K})$ in ^{70}Ge:Ga system

In Figure 5, we have plotted the *Dev*(%) versus *S* throughout temperature range and for magnetic fields from *B*=2 T to *B*=5.3 T. From Figure 5, we see that the minimums of *Dev*(%) are obtained for values close to 1/3 $\left(\delta\sigma \propto T^{1/3}\right)$ (*S* = 0.2 for *B*=2 T (Figure 5(a)), *S* = 0.26 for *B*=3 T (Figure 5(b)) and *S* = 0.33 for *B*=4 T (Figure 5(c)). On the other hand, Figure 6 shows minimums of the *Dev*(%) for values of *S* very close to 1/2 $\left(\delta\sigma \propto T^{1/2}\right)$ (*S* = 0.53 for *B*=4.7 T (Figure 6(a)), *S* = 0.45 for *B*=5 T (Figure 6(b)) and *S* = 0.6 for *B*=5.3 T (Figure 6(c)). Note that this last result is predicted by the 3D WL and EEI theories [9, 10].

Note that the transition between the law $T^{1/2}$ to $T^{1/3}$ is not always verified in all the metallic materials. Indeed, this passage is recorded for example in the compensated *n*-type ln*P* [28] and in the ^{70}Ge:Ga system [7]. Rosenbaum et al. [11], Narjis et al. [14] and Errai et al. [29] did not report this passage in their films close to the MIT.

In addition, it is important to note that the transition from the $T^{1/2}$ $\left(\delta\sigma \propto T^{1/2}\right)$ to the $T^{1/3}$ $\left(\delta\sigma \propto T^{1/3}\right)$ is often explained by the competition between the interaction length L_{int} and the correlation length L_{cor}.

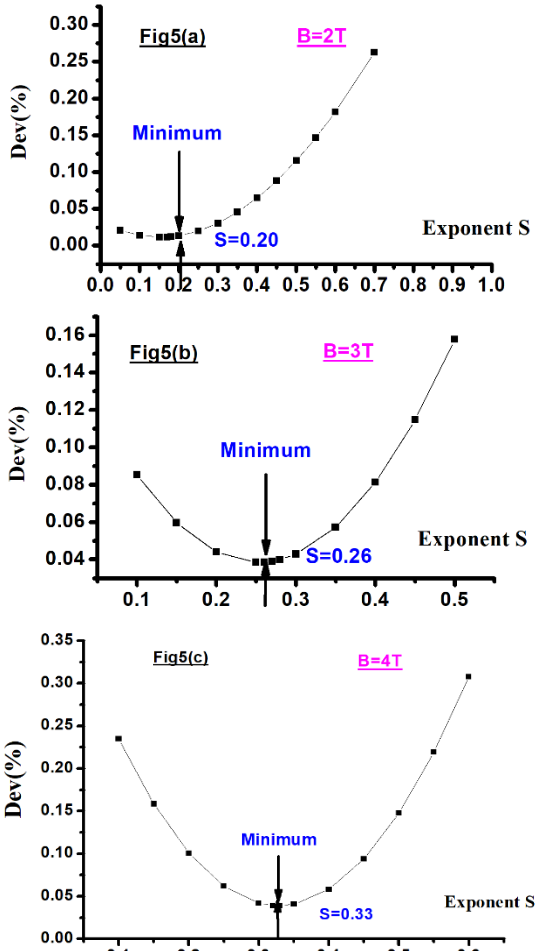

Figure 5. The plot of *Dev*(%) as function of exponent *S* in Equation (1) for ^{70}Ge:Ga, in the case, (a) B=2 T, (b) B=3 T and (c) B=4 T, Which the minimum is close to 1/3

When $L_{cor} < L_{int}$ we obtain a regime in $T^{1/2}$ [9]. On the other hand, the regime in $T^{1/3}$ is observed for $L_{cor} > L_{int}$. In this regime the only scale length that depends on the temperature is interaction length L_{int} [27].

4. ELECTRICAL CONDUCTION IN INSULATING REGIME

Now highlight the study of the electric transport of ^{70}Ge:Ga material [7] from the insulating side of the MIT by evidencing the vastly different conduction the behavior. In the following, we will examine the measured $\sigma(B,T)$.

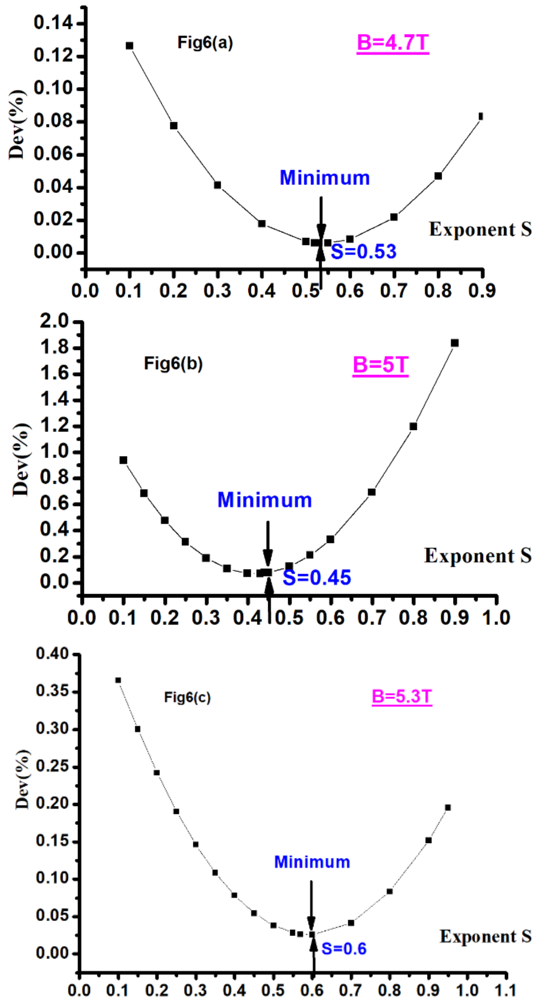

Figure 6. The plot of *Dev*(%) as function of exponent *S* in Equation (1) for ^{70}Ge:Ga, in the case, (a) *B*=4.7 T, (b) *B*=5 T, and (c) *B*=5.3 T, which the minimum is close to 1/2

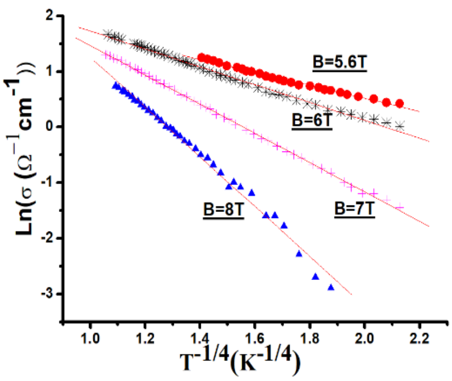

Figure 7. $\ln(\sigma(B,T))$ versus $T^{-1/4}$ in the insulator face of the MIT for sample ^{70}Ge:Ga

We started this part of the result by the graphical representation of the evolution of $\ln(\sigma(B,T))$ versus $T^{-0.25}$ (Figure 7) and versus $T^{-0.5}$ (Figure 8) in the whole temperature interval and for magnetic field *B*>5.3 T. Analysis shown in Figures 7 and 8 does not allow us to tell whether the Mott VRH or the ES VRH is the dominant transport mechanism.

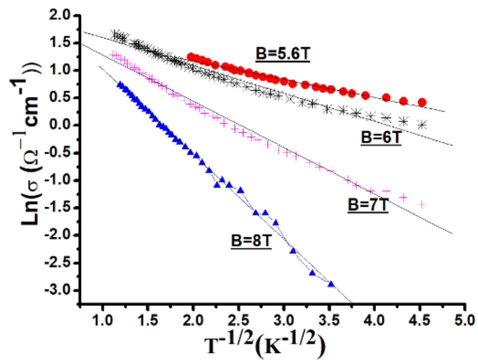

Figure 8. $\ln(\sigma(B,T))$ versus $T^{-1/2}$ in the insulator face of the MIT for sample ^{70}Ge:Ga

In order to correctly specify which of the hopping regime that occurs in the ^{70}Ge:Ga material, we will follow the work described in Ref. [25], then the method based on the percentage deviation [26, 27].

Moving now to test the procedure of Zabrodski and Zinovera for the magnetic field *B*>5.3 T. For this reason, we have also plotted as the figures 9 and 10 show the variations of $\ln(W(T))$ versus of $\ln T$ over the whole *T* range. The analysis of these figures allows us to see that for each magnetic field, we can model the experimental points by a single straight line of negative slope (-*p*<0). Indeed, this result indicates that the ^{70}Ge:Ga is now on the MIT insulating face.

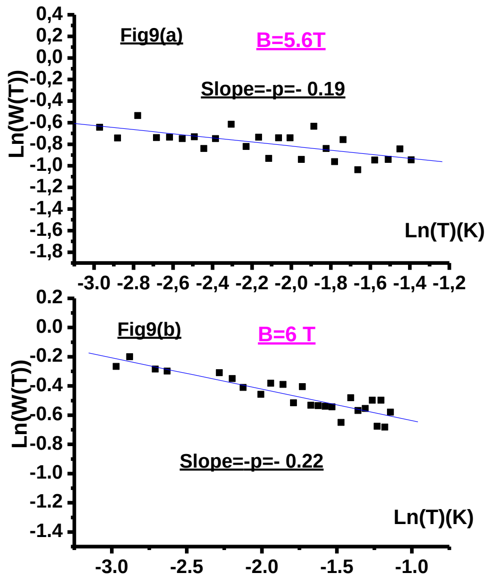

Figure 9. $\ln(W(T))$ versus $\ln T$ in Equation (2) in insulating regime for ^{70}Ge:Ga sample

Returning to the examination of these figures, we found *p*=0.19 for *B*=5.6 T (Figure 9(a)), *p*=0.22 for *B*=6 T (Figure 9(b)), *p*= 0.27 for *B*=7 T (Figure 10(a)) and *p*=0.2 for *B*=8 T (Figure 10(b)). These values of *p* are close to 0.25, showing that the electric transport is dominated by the hopping of Mott regime over the whole *T* range and for *B* >5.3 T, without seeing the transition to the ES regime (*p* close to 0.5).

In order to confirm our results obtained by the graphical procedure described in Ref. [25], we also used the percentage deviation method [26, 27]. Note that the technique of this method is similar to that we developed on the metal side of the MIT.

In the VRH regime, the deviation percentage, $Dev(\%)$, can be described by

$$Dev(\%)=\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100}{\sigma_i}\left(\sigma_0\exp\left[-\left(T_0/T\right)^p\right]-\sigma_i\right)\right)^2\right]^{1/2} \quad (14)$$

where, n is the number of data points. It should also be emphasized the good value of the exponent p is characterized by a minimum value of the $Dev(\%)$, respectively.

Within Figures 11 and 12, we have plotted the $Dev(\%)$ as for various p, over the entire temperature range and for the magnetic field B>5.3 T.

For B=5.6 T, we did not record a minimum deviation (Figure 11(a)). This is due to the fact that for this magnetic field the ^{70}Ge:Ga is near to the MIT on the insulating side. However, we are only based on the result that we obtained by the Zabrodski method which allows us to deduce that the electrical conductivity is best described by the VRH hopping law $\ln(\sigma)\propto T^{-0.25}$.

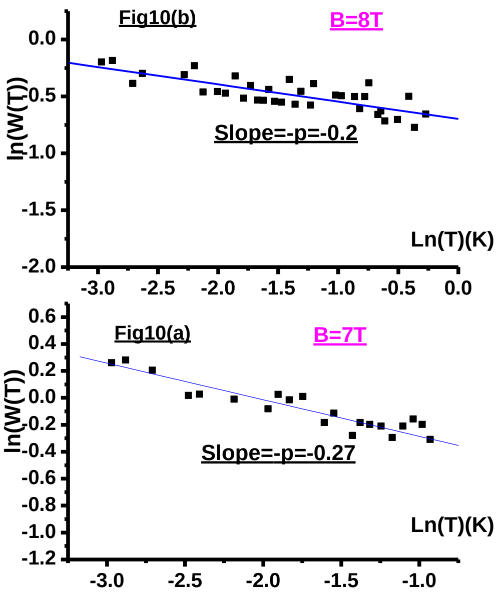

Figure 10. Function $\ln(W(T))$ versus $\ln T$ in Equation (2) in insulating regime for ^{70}Ge:Ga sample

On the other hand, we found that the minimum of $Dev(\%)$: p = 0.13 for B=6 T (Figure 11 (b)), p = 0.2 for B=7 T (Figure 12(a)) and p = 0.30 for B=8 T (Figure 12 (b)). We therefore deduce that all the values of p are closer to 0.25 than to 0.5, showing that the electric transport takes place in the Mott regime over the entire temperature range for the material ^{70}Ge:Ga. This means that the DOS is almost constant near the E_F and that the interactions between electrons become negligible.

We can now evaluate the characteristic conductivity of Mott σ_M and also the values of the characteristic temperature of Mott T_M for B>5.3 T. Using the general Mott law ($\sigma=\sigma_M\exp[-(T_M/T)^{1/4}]$) we will have:

$$\ln(\sigma)=\ln(\sigma_M)-(T_M)^{1/4}\times(T)^{-1/4} \quad (15)$$

For each magnetic field, we obtained σ_M and T_M by the linear regression technique employing the data within Figure 7. The results are presented in Table 1. On the other hand, in Mott's model, the characteristic conductivity σ_M is generally given by the following formula

$$\sigma_M=\frac{3e^2\nu_{ph}}{2}\left(\frac{N(E_F)\,\xi}{2\pi k_B}\right)^{1/2} \quad (16)$$

where, $\nu_{ph}\approx 10^{13}$ Hz is the typical phonon frequency.

Taking into account the relation of T_M, we can deduce the expression of $N(E_F)$.

$$N(E_F)=\beta_2/k_BT_M\,\xi^3 \quad (17)$$

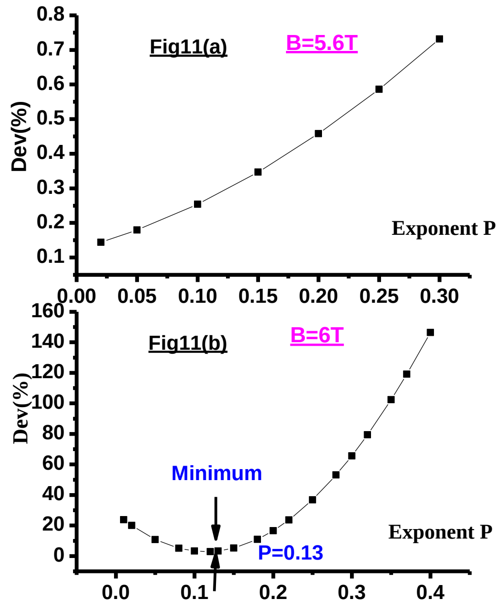

Figure 11. Plots of $Dev(\%)$ against exponent p in Equation (2) on insulating side of the MIT for material ^{70}Ge:Ga

Replacing the expression of $N(E_F)$ in the relation of σ_M, we get:

$$\sigma_M=\frac{3e^2\times\nu\times\sqrt{\beta_2}}{2(2\pi)^{1/2}k_B}\times(T_M)^{-1/2}\times\xi^{-1} \quad (18)$$

From this last relation, we deduce the expression of the localization length ξ

$$\xi=\frac{3e^2\times\nu\times\sqrt{\beta_2}}{2(2\pi)^{1/2}k_B}\times(T_M)^{-1/2}\times(\sigma_M)^{-1} \quad (19)$$

We replace the constants by their values and after calculation, we finally obtain the expression of ξ

$$\xi=0.04708807\times(T_M)^{-1/2}\times(\sigma_M) \quad (20)$$

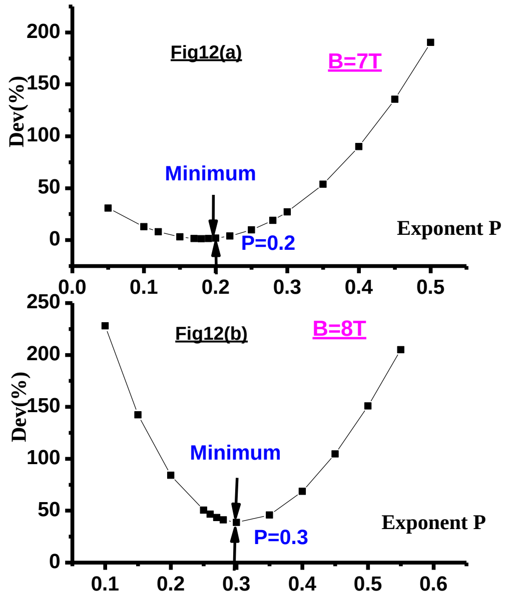

Figure 12. Plots of *Dev*(%) against exponent *p* in Equation (2) on the insulating side of the MIT for material ^{70}Ge: Ga

From this last relation and for each value of σ_M and T_M that we have calculated previously, we can deduce the localization length ξ in the studied hopping regime. In addition, and by applying the expression for the DOS at E_F $(N(E_F)=\beta_2/k_B T_M\,\xi^3)$, we can also determine the value of $N(E_F)$ in the Mott regime. The results are reported in Table 1.

Table 1. T_M, σ_M, ξ and $N(E_F)$ for the sample ^{70}Ge:Ga in the temperature range 0.048-0.65 K

	T_M (K)	σ_M $(\Omega.\text{m})^{-1}$	ξ (m)	$N(E_F)$ $(\text{eV}^{-1}.\text{m}^{-3})$
B=5.6 T	1.87	1737.27	1.98×10^{-5}	1.43×10^{19}
B=6 T	5.15	2348.61	8.83×10^{-6}	5.89×10^{19}
B=7 T	47.95	6005.73	1.13×10^{-6}	3.00×10^{21}
B=8 T	402.61	30981.33	7.57×10^{-8}	1.19×10^{24}

From the analysis of the data in Table 1, we can see that the parameters T_M, σ_M and $N(E_F)$ increase with increasing the magnetic field, i.e., when the sample moves away from the MIT on the insulating side and the localization becomes very strong and consequently the electronic states become purely localized. On the other hand, the localization length is inversely proportional to the magnetic field. We will now try to verify the criterion of dominance of Mott mechanism in localized materials: $(R_M/\xi)\geq 1$, where, R_M is the average hopping distance of Mott and ξ the length of the localization.

The average hopping distance of Mott is given by the following relation:

$$R_M=\left(\frac{9\ \xi}{8\pi k_B T\, N(E_F)}\right)^{1/4} \tag{21}$$

Replacing $N(E_F)$ by its expression in function of ξ and T_M in this last relation, we have after calculation and simplification

$$R_M=\left(\frac{9}{8\pi\,\beta_2}\right)^{1/4}\times(T_M)^{1/4}\times T^{-1/4}\times\xi \tag{22}$$

Finally, we have:

$$R_M/\xi=\left(\frac{9}{8\pi\,\beta_2}\right)^{1/4}\times(T_M)^{1/4}\times T^{-1/4} \tag{23}$$

Let us now plot the graphs R_M/ξ versus $T^{-1/4}$ (Figures 13 and 14) in the whole temperature range, for each value of magnetic field *B*=5.6; 6; 7 and 8 T.

From these two figures we can see that for *B*=5.6 T, the electrical transport is actually realized by the Mott's VRH mechanism in part of the temperature range (Figure 13(a)). This is due to the fact that the sample is located very close of MIT on the insulating side.

For *B*=6 T, we notice that $R_M/\xi\geq 1$ in a very large part of the temperature interval [0.048, 0.65 K] (Figure 14(a)) this means that the dominant hopping mechanism is that of Mott.

On the other hand, for *B*=7 T and *B*=8 T, as shown in the Figure 14, we find that in the whole temperature range $R_M/\xi\geq 1$.This means that Mott's VRH is the dominant conduction mode in the material ^{70}Ge:Ga. This agrees with the results we found previously (procedure of Zabrodskii and the percentage deviation procedure).

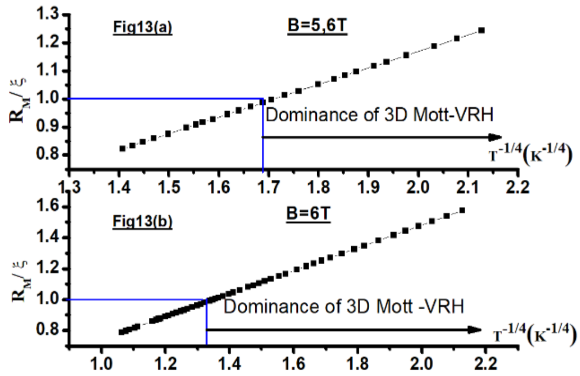

Figure 13. Evolution of R_M/ξ versus $T^{-1/4}$ for *B* = 5.6 T and *B* = 6 T in the temperature range 0.65-0.048 K

According to this detailed study, the dominant hopping conduction is the Mott- VRH without a crossover to the ES- VRH for all the temperatures studied and for *B*>5.3 T. However, the transition between the Mott regime and the ES regime or the opposite within different localized systems in many material systems: Rosenbaum et al. [31], Vaziri et al. [32] Shekhar et al. [33], Abdia et al. [31], Makise et al. [35], Errai et al. [36], and Zhang et al. [37]. Note that this passage generally occurs with a decrease in the concentration of impurities or with growing in temperature and also with the elevation the magnetic field [38].

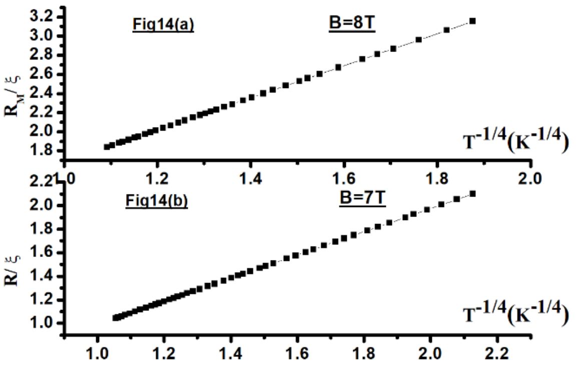

Figure 14. Evolution of R_M/ξ versus $T^{-1/4}$ for B=7 T and B=8 T in the temperature range 0.65-0.048 K

5. CONCLUSIONS

We investigated the low-temperature electrical transport properties of the ^{70}Ge:Ga material [7] at presence of the B ranging from 2-8 T. The study is done on both sides of the MIT, the latter is introduced by the variation of the magnetic field. To differentiate the electric characteristics of the samples metallic and insulating, we applied the Practical method of Zabrodskii et al. [25]. We found that:

- For $2\text{T} \le B \le 5.3\text{T}$: the sample is metallic and therefore the electronic states are not localized.
- For $B \ge 5.6$ T : the sample is an insulating and it is located on insulator face of the MIT. In this case the electrical conduction in the sample is described by VRH.

We note that in the metallic face of the MIT and using the percentage deviation procedure, the electric conductivity obeys the behavior $T^{1/3}$ $\left(\sigma(B,T) = \sigma(B,\ T=0\ \text{K}) + mT^{1/3}\right)$ for B=2 T, B=3 T and B=4 T. On the other hand, the minimum of deviation is very close to 1/2 $\left(\delta\sigma \propto T^{1/2}\right)$, for B=4.7 T and B=5 T. This latter result agrees well with the 3D WL and the EEI theories.

In the insulator face of the MIT and for $5.6\text{T} \le B \le 8\text{T}$: the electrical transport occurs by VRH and to correctly specify the conduction mode VRH of Mott or VRH of ES, we also tested the two procedures of Zabrodskii & Zinoveva and the percentage procedure deviation. We found, for $B \ge 5.6$ T , that the parameter p is near to 1/4 $\left(\sigma = \sigma_M \exp[-(T_M/T)^{1/4}]\right)$. This result indicates the electrical conduction takes place in the Mott VRH regime without transitioning to the ES VRH regime $\ln(\sigma(B,T)) \propto /T^{-1/2}$. Moreover, this suggests that the electron-electron interactions are assumed to be zero and the DOS is almost constant around the Fermi level without opening of a pseudo-gap at Fermi level. We also calculated and studied the effect of the magnetic field on some conduction parameters (σ_M, T_M, ξ, $N(E_F)$) and to specify the Mott's VRH dominance temperature interval, we checked the Mott inequality $R_M/\xi \ge 1$ for each $B \ge 5.6$ T.

ACKNOWLEDGEMENTS

We would like to thank Professor Kohei M. Itoh to has allowed us the permission to re-use their experimental results on ^{70}Ge:Ga in our studies.

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