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ARTICLE

Efros-Shklovskii Variable Range Hopping Conduction in ^{70}Ge:Ga Semiconductor at Very Low Temperature

Mohamed Errai[a,b], **Mohammed Bellioua**[b], **Ahmed Tirbiyine**[b], **Abderrhman Nait Alla**[c], **Khalid Abbiche**[a], **Abdelhamid El kaaouachi**[d], **Lahcen Ait benali**[e], **El Mahdi Kamili**[a], **Reda El Abbadi**[a] and **Mohamed Boumdyan**[a]

[a] *LAMISNE Laboratory, Polydisciplinary Faculty of Taroudant, Ibn Zohr University, 80000 Agadir, Morocco.*

[b] *LMS3E Laboratory, Faculty of Applied Sciences Ait Melloul, Ibn Zohr University, 80000 Agadir, Morocco.*

[c] *Faculty of Applied Sciences Ait Melloul, Ibn Zohr University, 80000 Agadir, Morocco.*

[d] *Physics Department, Ibn Zohr University, Faculty of Sciences, Agadir, Morocco.*

[e] *CPA-Centre Régional des Métiers de l'Enseignement et Formation CS, Casablanca, Morocco.*

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Abstract: In this study, we focused on investigating the electrical transport processes within the three-dimensional ^{70}Ge:Ga system at low temperatures, ranging from 0.05 K to 0.25 K, in the absence of a magnetic field. Our analysis specifically targeted the insulating side of the metal-insulator transition (MIT). The five samples studied had Ga concentrations n ranging from 1.753 10^{17} to 1.844 10^{17} cm^{-3}. We established that the temperature T dependence of the electrical conductivity follows the Efros-Shklovskii variable range hopping (ES-VRH) mechanism between the localized states located around the Fermi level (E_F). This behavior indicates that the density of states (DOS) is canceled very close to the E_F, the formation of a soft Coulomb gap (CG) near E_F. Notably, we did not observe any transition to the Mott-VRH regime with $T^{-0.25}$, which is characterized by a nearly constant and non-zero DOS near E_F. Furthermore, we estimated some Efros and Shklovskii hopping parameters to further understand the electrical transport properties of the ^{70}Ge:Ga system.

Keywords: Variable range hopping, Electrical transport properties, Coulomb gap, Density of state, Electrical conductivity, ^{70}Ge:Ga semiconductor.

1. Introduction

Germanium, as a semiconductor material, holds significant importance in the microelectronics industry [1] due to its remarkable electrical transport properties. It finds diverse applications in various industrial sectors, including field effect transistors [2], photovoltaic cells [3], laser diodes, temperature sensors [4], photodetectors, magnetic field sensors, and fiber optic manufacturing. Additionally, germanium is widely utilized as an alloy with silicon to create high-performance integrated circuits, further extending its impact in modern electronic devices.

On the insulating side of the metal-insulator transition (MIT), the low-temperature electrical transport in insulators, amorphous, and disordered semiconductors is primarily governed by the variable range hopping (VRH) conduction mechanism [5–21]. This mechanism involves

Corresponding Author: Mohamed Errai **Email**: errai2013@gmail.com

charge carriers hopping between localized electronic states, as defined by Anderson's localization [22, 23], situated near the Fermi level (E_F). Specifically, this behavior is observed in materials where the Fermi energy lies below the mobility edge. VRH conduction establishes a relationship between electrical conductivity (σ) and temperature (T), providing insights into how the electrical conductivity varies with changes in temperature, offering valuable information about the transport properties of the materials in question.

The temperature-dependent electrical conductivity of ^{70}Ge:Ga material has been extensively studied near the MIT. Errai *et al.* [9] provided a comprehensive analysis of the transport mechanisms on both sides of the transition. For n > nc (metallic regime), the conductivity behavior is governed by weak localization and electron-electron interaction effects, while for n < nc (insulating regime), VRH conduction dominates. Their study highlighted the critical role of impurity concentration in determining the transport behavior across the MIT. Additionally, in a subsequent study focusing on the insulating side, Errai *et al.* [11] investigated the VRH conduction mechanism at very low temperatures, emphasizing the density of states (DOS) near E_F and the hopping processes between localized states. These foundational studies provide essential context for the current investigation, particularly regarding the interplay between disorder and electronic interactions in ^{70}Ge:Ga.

This study focuses on investigating the temperature-dependent electrical conductivity of ^{70}Ge:Ga material on the insulating side of the MIT in the absence of a magnetic field. By analyzing five samples with varying impurity concentrations (see Fig. 1), the research aims to elucidate the VRH conduction mechanism in this material and to characterize the DOS near E_F. The critical impurity concentration, n_c = 1.859×10^{17} cm^{-3}, marks the transition between metallic ($n > n_c$) and insulating ($n < n_c$) regimes. This investigation seeks to deepen our understanding of the transport properties of ^{70}Ge:Ga and explore the implications of these findings for potential technological applications. It is worth noting that we have reanalyzed the experimental data for the ^{70}Ge Ga system, which was prepared and reported by Itoh *et al.* [24].

2. Theoretical Background

In the strong localization regime, electrons hop via tunneling between spatially distant but energetically close sites, and the hopping is not necessarily limited to nearest neighbors. Consequently, electronic conduction occurs through the variable range hopping (VRH) mechanism involving states close to the E_F. In this case, the temperature dependence of the hopping conductivity follows a universal form at low temperatures, expressed as:

$$\sigma = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)^x\right] \quad (1)$$

where σ_0 represents the hopping conductivity prefactor, T denotes the Kelvin absolute temperature, and T_0 symbolizes the hopping temperature characteristic. The hopping exponent, x, depends on the dimension of the system and the specific hopping conduction mechanism. Indeed, it takes on values 1/3 and 1/4, respectively, for two-dimensional (2D) and three-dimensional (3D) materials in the case where the electrical transport is governed by the Mott variable range hopping (Mott-VRH) mechanism [25-29]. On the other hand, if x = 0.5, irrespective of the system's dimensions, the electrical conduction occurs within the Efros-Shklovskii variable range hopping (ES-VRH) regime [25-29]. In Mott 3D-VRH conduction, the hopping electrical conductivity exhibits the following behavior:

$$\mathrm{Ln}(\sigma) \propto T^{-0.25} \quad (2)$$

This dependence arises from the fundamental assumptions of Mott's theory, which states that the DOS is nearly constant around the E_F or varies very slowly. Furthermore, it assumes that long-range Coulomb interactions between charge carriers are negligible. Under these conditions, the hopping exponent takes the value x = 0.25 for 3D materials, and the temperature dependence of electrical conductivity can be expressed in a universal form known as Mott's law:

$$\sigma = \sigma_{Mott} \exp\left[-\left(\frac{T_{Mott}}{T}\right)^{0.25}\right] \quad (3)$$

where σ_{Mott} denotes a conductivity prefactor in the Mott regime and T_{Mott} represents the Mott characteristic temperature, indicating the degree of disorder, given by the relationship [37]:

$$T_{Mott} = \beta_{Mott}/k_B N(E_F)\ \xi^3 \quad (4)$$

The constant β_{Mott} is determined through numerical calculations employing the percolation method, and for 3D systems, it is evaluated as $\beta_{Mott} = 16$. In the context of Eq. (4), k_B refers to the Boltzmann constant, $N(E_F)$ represents the DOS at the E_F, and ξ signifies the localization length of the electronic wave function at zero magnetic field.

On the contrary, as per the ES-VRH model, electronic interactions gain significance between localized states, leading to a reduction in the DOS near the E_F. This interaction results in the formation of a parabolic pseudo-Coulomb gap [38, 39] at the E_F, commonly known as the soft Coulomb gap (CG). Under such conditions, the conductivity exhibits the following behavior:

$$\mathrm{Ln}(\sigma) \propto T^{-0.5} \tag{5}$$

Furthermore, it is essential to note that within the ES-VRH conduction mechanism, the DOS vanishes precisely at the E_F and exhibits a parabolic variation in the vicinity of E_F, particularly in three dimensions.

$$N(E) = \frac{3k^3}{\pi e^6}(E - E_F)^2 \tag{6}$$

The presence of the CG leads to the ES-VRH regime, where the power-law temperature dependence of electrical conductivity applies universally across all dimensions, and it is expressed as follows:

$$\sigma = \sigma_{ES} \exp[-(T_{ES}/T)^{1/2}] \tag{7}$$

In the ES regime, the conductivity prefactor is denoted as $\sigma_{ES,}$ and T_{ES} represents the characteristic ES temperature. As per the ES model, the temperature T_{ES} can be expressed using the following relation:

$$T_{ES} = \frac{\beta_{ES} e^2}{(4\pi\varepsilon\varepsilon_0)\ k_\beta\ \xi} \tag{8}$$

The expression (8), involves various parameters, where β_{ES},e, ε, ε_0, k_B, and ξ are denoted as follows: β_{ES} is a constant evaluated to be 2.8 by Shklovskii and Efros, e represents the charge of an electron, ε denotes the dielectric constant of the material (in Ge, ε is 15.4), ε_0 symbolizes the permittivity of vacuum, k_B stands for the Boltzmann constant, and ξ signifies the localization length of the wave function in zero magnetic field.

3. Results and Discussions

We conducted a thorough reanalysis of the experimental data for the ^{70}Ge:Ga system, as reported by Itoh *et al*. [24]. In Figs. 1 and 2, we present the logarithmic variations of the electrical conductivity ln(σ) versus $T^{-0.25}$ and $T^{-0.5}$ on the insulating side of the MIT for the five samples of the 3D system ^{70}Ge:Ga, within the temperature range of 0.02-0.25 K and at zero magnetic field.

Upon examining Figs. 1 and 2, we observe that both plots show nearly straight lines of similar quality. As a result, it becomes challenging to distinctly differentiate between the two laws, $T^{-0.25}$ (Mott VRH) and $T^{-0.5}$ (ES-VRH), solely based on these graphical representations. In order to determine an acceptable and accurate physical solution, we implemented the graphical procedure proposed by Zabrodskii and Zinoveva [40], along with the percentage deviation procedure [41-43]. These techniques facilitate the identification of the most appropriate conduction mechanism for the ^{70}Ge:Ga system in the insulating regime.

Zabrodskii and Zinoveva employed the general formula of VRH ($\sigma = \sigma_0 \exp[-(T_0/T)^x]$) to calculate the mathematical function w(T). This function exhibits a variation with temperature T, which can be expressed using the following formula:

$$w(T) = \ln\left[\frac{d\ln(\sigma)}{d\ln(T)}\right] = \ln(x) + x\ln(T_0) - x\ln(T) \tag{9}$$

Notably, Eq. (9) is equivalent to the form derived from Eq. (1). For a given point i, we can calculate the average values of w(T) and ln(T) as follows:

$$\overline{w(T_i)} = \mathrm{Ln}\left[\frac{\mathrm{Ln}(\sigma_{i+1}) - \mathrm{Ln}(\sigma_{i-1}))}{\mathrm{Ln}(T_{i+1}) - \mathrm{Ln}(T_{i-1})}\right] \tag{10}$$

with:

$$\mathrm{Ln}(T_i) = \frac{\mathrm{Ln}(T_{i+1}) + \mathrm{Ln}(T_{i-1})}{2}$$

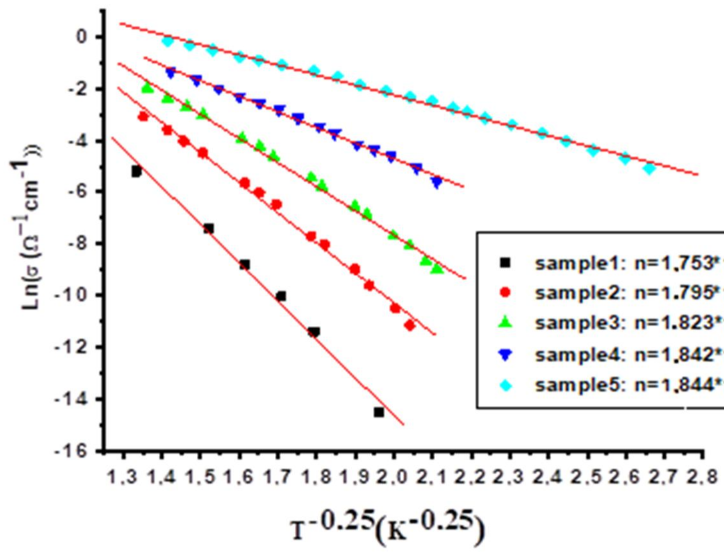

FIG. 1. Logarithmic variation of the electrical conductivity at zero field as a function of $T^{-0.25}$ for the five samples of the three-dimensional ^{70}Ge:Ga system over the full temperature range 0.05-0.25 K.

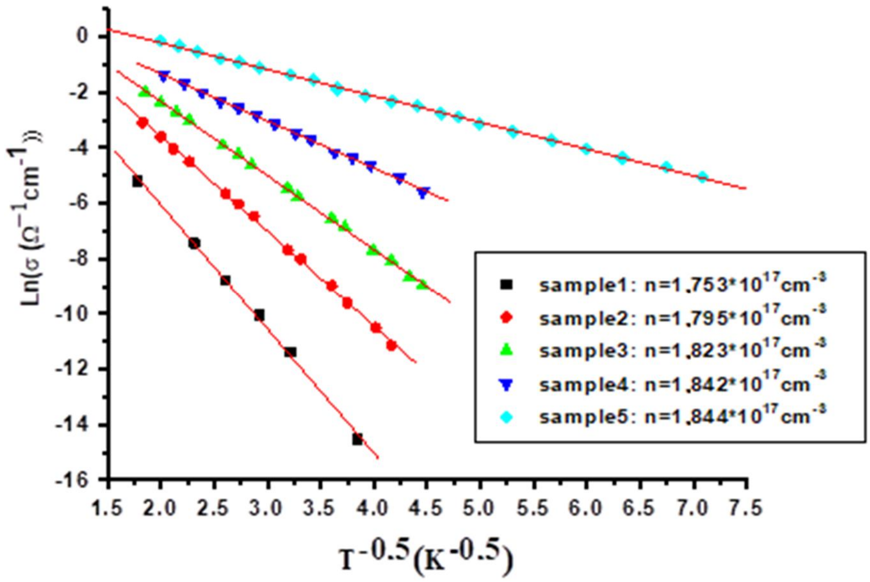

FIG. 2. Logarithmic variations of the electrical conductivity at zero field as a function of $T^{-0.5}$ for the five samples of the three-dimensional ^{70}Ge:Ga system over the full temperature range 0.05-0.25 K.

Note that the procedure of Zabrodskii and Zinoveva involves plotting the graphical representation of the function w(T) against ln(T) throughout the temperature range. This plot typically forms a straight line with a slope equal to –x, where w(T) = A-x.ln(T) and A is a constant.

If –x > 0, the sample exhibits metallic behavior and is situated on the metallic side of the MIT. On the other hand, if –x < 0, the sample is located on the insulating side of the MIT, and electrical conduction takes place through the VRH mechanism. In this scenario, two possibilities arise: x = 0.25, representing Mott-VRH conduction, and x = 0.5, indicating ES-VRH conduction.

We will now apply the procedure proposed by Zabrodskii and Zinoveva [40]. To do so, we have plotted Figures 3(a), 3(b), 4(a), 4(b), and 5, showcasing the variations of the function w(T) as a function of ln(T) for the five samples of ^{70}Ge:Ga at zero magnetic field. Upon analyzing these figures, we observe that all the plots of w(T) against ln(T) exhibit straight lines with negative slopes (–x < 0).

This clear result indicates that all five studied samples exhibit insulating behavior and are located on the insulating side of the MIT. Additionally, the values of the exponent x closely approach 0.5, with no indication of a change in slope towards x = 0.25 across the entire temperature range of T = 0.02-0.25K (see Figs. 3, 4, and 5). This compelling finding, x = 0.5, strongly suggests that the electrical transport mechanism occurs through the ES-VRH regime at very low temperatures for these samples.

In the ES-VRH regime, the DOS is sensitive to Coulomb interactions, leading to the emergence of a parabolic Coulomb gap near the E_F at zero magnetic field. The values of the hopping exponents obtained through the Zabrodskii and Zinoveva procedure for the five insulating samples of ^{70}Ge:Ga are presented in Table 1.

In order to clearly determine the conduction type through the VRH mechanism and the values of the jump exponent for the five samples, we will employ the percentage deviation procedure. To begin, we linearize the general expression of hopping by introducing the natural logarithm. As a result, we obtain the following expression:

$$Ln(\sigma) = ln(\sigma_0) - (T_0/T)^x \tag{11}$$

Next, for each sample, we systematically vary the exponent x of the previous formula within the range of 0.1 to 1, with steps of 0.05 and 0.01 near the minimum deviation. By performing the linear regression, we can extract the corresponding values of σ_0 and T_0 for each value of x.

Finally, we calculate the percentage deviation Dev (%) [41- 43] using the following formula:

$$\mathrm{Dev}(\%) = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100}{\sigma_i}\left(\sigma_{0\exp}[-(T_0/T)^x] - \sigma_i\right)\right)^2\right]^{1/2} \tag{12}$$

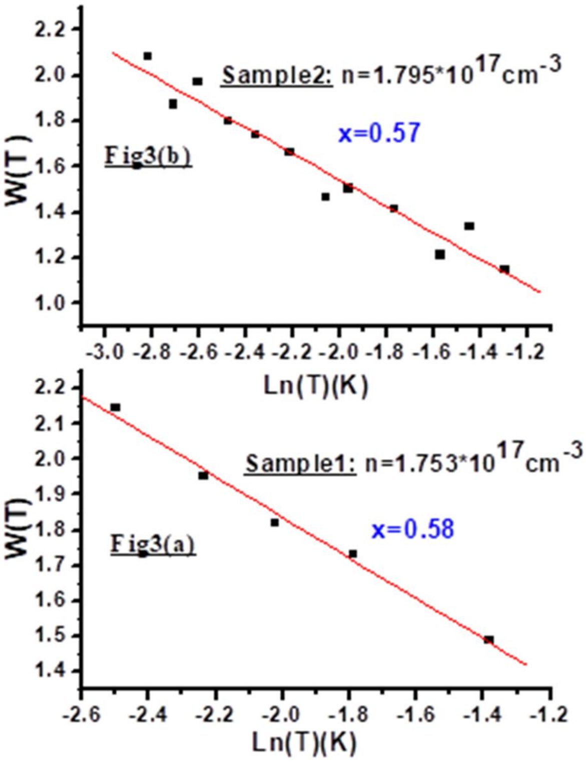

FIG. 3. Variation of the function w(T) as a function of ln(T) for samples 1 and 2 in the temperature range 0.02-0.25 K.

This process is performed for each sample and for various values of the exponent x, over the entire temperature range. It is essential to note that the minimum deviation Dev (%) corresponds to the best value of the exponent x.

The procedure involves calculating the percentage deviation Dev (%) based on the formula mentioned earlier, where n denotes the number of data points, and σ_i represents the experimental value of the electrical conductivity.

In Figs. 6(a), 6(b), 7(a), 7(b), and 8, we have presented the variations of Dev (%) plotted against the exponent x for all five insulating samples of ^{70}Ge:Ga within the temperature range T = 0.02-0.25 K.

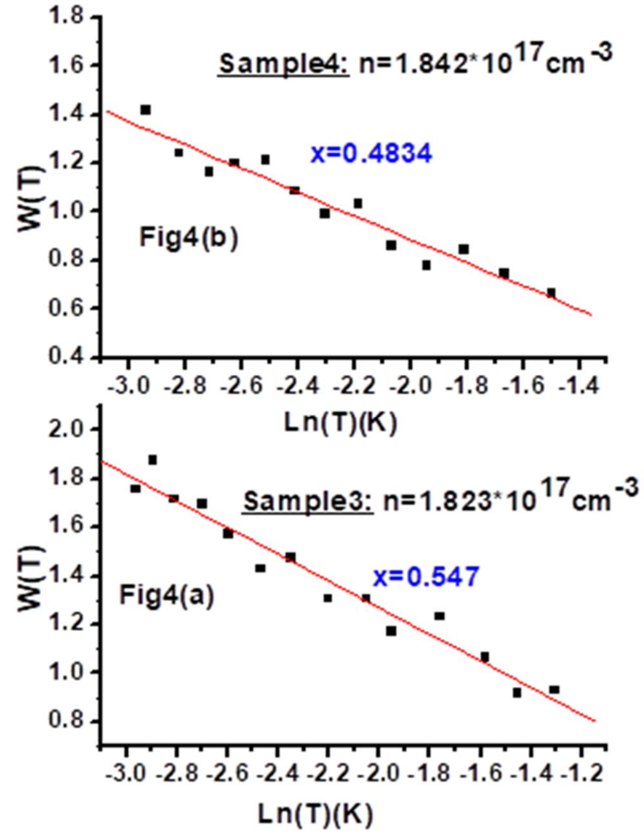

FIG. 4. Variation of the function w(T) as a function of ln(T) for samples 3 and 4 in the temperature range 0.02-0.25 K.

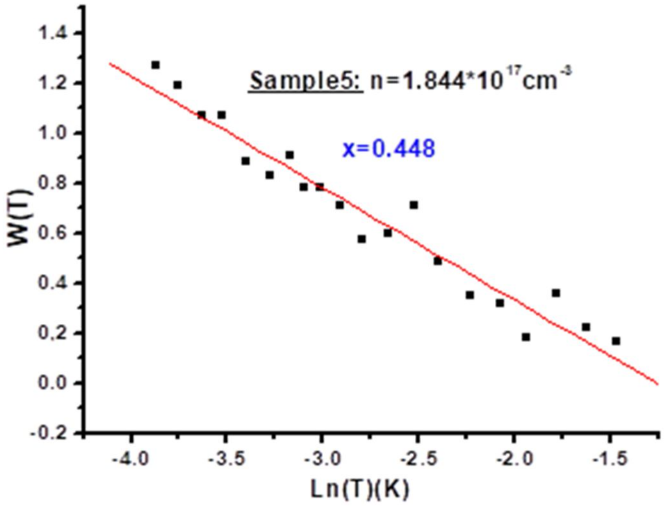

FIG. 5. Variation of the function w(T) as a function of ln(T) for sample 5 in the temperature range 0.02-0.25K.

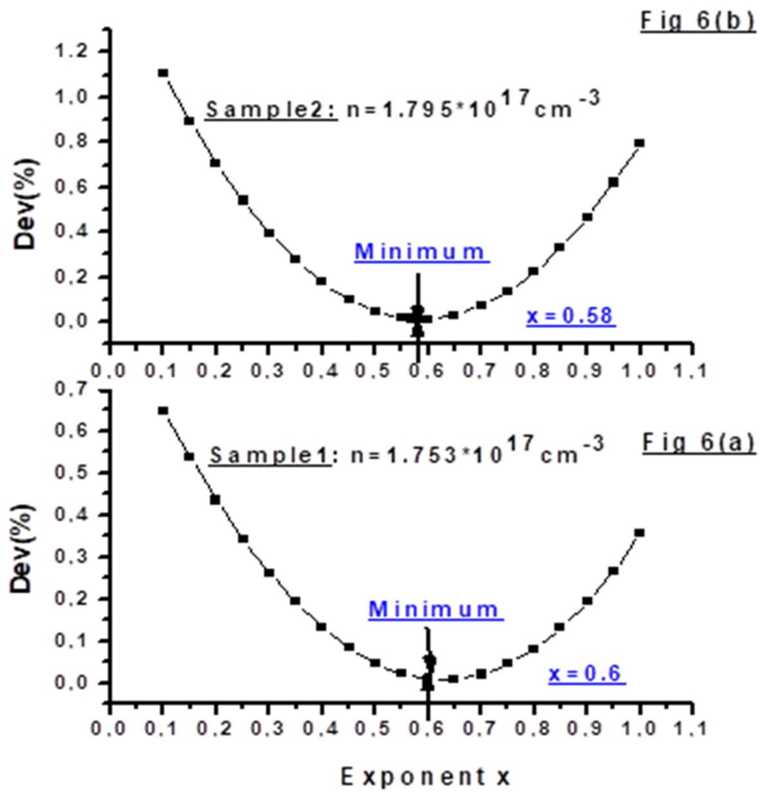

FIG. 6. Percentage deviation Dev (%) versus exponent x for insulating samples 1 and 2 in the temperature range 0.02-0.25 K.

According to these figures, the minimum values of Dev (%) are obtained for exponents x close to 0.5: x = 0.6 for sample 1, as seen in Fig. 6(a), x = 0.58 for sample 2, as seen in Fig. 6(b), x = 0.55 for sample 3, as seen in Fig. 7(a), x = 0.5 for sample 4, as seen in Fig. 7(b), and x = 0.45 for sample 5, as seen in Fig. 8. These results strongly corroborate our previous findings obtained through the procedure of Zabrodski and Zinoveva. The close agreement between the two methods provides robust evidence for the validity of the values of x determined, indicating the dominance of the ES-VRH conduction mechanism at very low temperatures for these five samples.

The latest findings from our study provide clear evidence that the dominant hopping conduction mechanism in the five ^{70}Ge:Ga samples is the ES-VRH, rather than the Mott 3D-VRH, across the entire temperature range.

This indicates that electron interactions are significant and influence the behavior of the DOS near the E_F, resulting in the creation of a parabolic pseudo-Coulomb gap at zero magnetic field. Furthermore, the values of the hopping exponent x, obtained through the numerical deviation percentage procedure [41, 43] for the five ^{70}Ge:Ga samples, are compiled in Table 1 for reference and further analysis. These results contribute to a comprehensive understanding of the electrical transport properties of the materials and emphasize the importance of considering electron-electron interactions in the insulating side of the MIT.

It is crucial to highlight that within the temperature range of 0.02-0.25 K, no transition from the ES-VRH to the Mott-VRH behavior was observed in any of the five samples. Nonetheless, this transition may take place under various circumstances. For instance, with an increase in temperature, a decrease in impurity concentration, or when the jump energies for each VRH regime become comparable.

In cases where the ES-VRH conduction mechanism is no longer dominant, the Coulomb interactions diminish, resulting in the DOS remaining nearly constant around the E_F. Notably, this transition from Efros-Shklovskii to the Mott VRH has been observed by several researchers across different localized semiconducting materials, including studies by Yamaura [44], Bedoya-Pinto [45], Zhang [46], Bennaceur [47], Errai [48], and Zhaoguo Li [49].

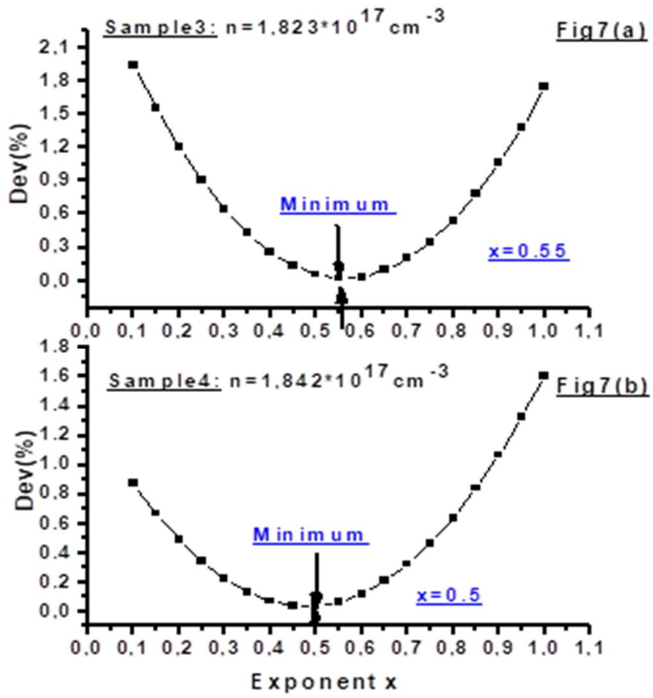

FIG. 7. Percentage deviation Dev (%) versus exponent x for insulating samples 3 and 4 in the temperature range 0.02-0.25 K

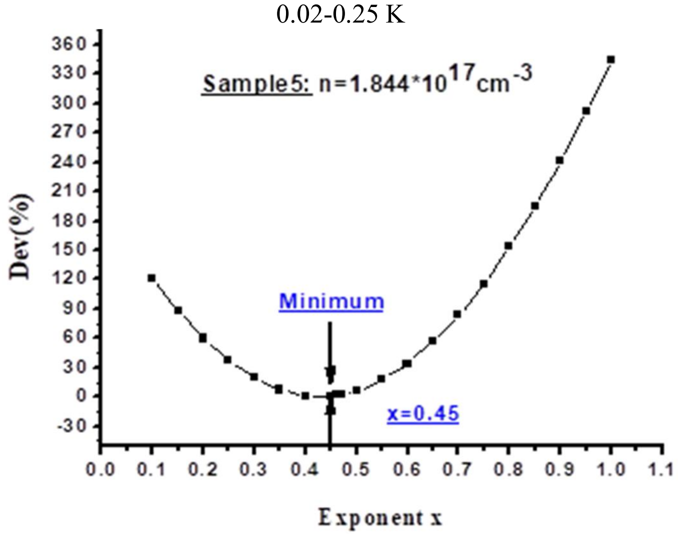

FIG. 8. Percentage deviation Dev (%) versus exponent x for insulating sample 5 in the temperature range 0.02-0.25K.

TABLE 1. Values of the *hopping* exponent x in Eqs. (9) and (12) for the five samples in the temperature range 0.05–0.25 K.

	Exponent x (Zabrodski-Zinova Method)	Exponent x (Minimum of Dev %)
Sample1	0.58	0.59
Sample2	0.57	0.58
Sample3	0.547	0.55
Sample4	0.483	0.5
Sample5	0.448	0.45

Investigating the electrical transport parameters in the ES regime is a fascinating aspect of our study. To achieve this, we utilized the data presented in Fig. 2 and applied the ES hopping formula, using the linear regression method. This enabled us to extract the two crucial parameters, T_{ES} and σ_{ES}. Furthermore, to calculate the localization length ξ, we employed Eq. (8). This calculation allowed us to evaluate the average hopping distance $R_{hop,ES}$ [28, 30] and the average hopping energy $E_{hop,ES}$ [28, 30] using the following two equations:

$$R_{hop,ES} = \frac{1}{4} \left(\frac{T_{ES}}{T}\right)^{1/2} \xi \quad (13)$$

$$E_{hop,ES} = \frac{1}{2} K_B T \left(\frac{T_{ES}}{T}\right)^{1/2} \quad (14)$$

These determinations are vital in comprehending the electrical conduction mechanism in the ES regime and contribute to a deeper understanding of the material's transport properties.

The results obtained for all five insulating samples, covering the entire temperature range of 0.05-0.25 K, are summarized in Table 2.

It is crucial to highlight, based on the analysis of the results in Table 2, that as the impurity concentration n increases while remaining below n_c, the localization length (ξ) increases, whereas the Efros temperature (T_{ES}) decreases $\left(T_{ES} \propto \frac{1}{\xi}\right)$. In this regime, transport is governed by the ES-VRH mechanism, and Coulomb interactions between strongly localized electrons play a predominant role. When n = n_c, ξ becomes very large, and T_{ES} becomes very small, as the electrons become less localized. This leads to the occurrence of a metal-insulator transition (MIT), where electrical transport acquires a metallic character.

TABLE 2. The essential parameters characterizing ES VRH conduction across the five insulating samples of ^{70}Ge:Ga. These measurements were conducted within the temperature range of 0.05–0.25 K.

	n (cm-3)	σ_{ES} (Ω^{-1}cm^{-1})	T_{ES} (K)	ξ (nm)	$R_{hop,ES} \times T^{-0.5}$ (nm.K$^{-1/2}$)	$E_{hop,ES} \times T^{0.5}$ (J.K$^{1/2}$)
Sample1	1.753×10^{17}	18.8350	20.2001	146.50658	164.6169	3.1026×10^{-23}
Sample2	1.795×10^{17}	26.3510	11.7370	252.14635	215.9595	2.3649×10^{-23}
Sample3	1.823×10^{17}	20.4262	7.1387	414.5606	276.9109	1.8444×10^{-23}
Sample4	1.842×10^{17}	8.0396	2.8982	1021.1365	434.5982	1.1752×10^{-23}
Sample5	1.844×10^{17}	5.4660	0.9214	3211.7748	770.7590	0.6626×10^{-23}

4. Conclusion

In this study, we investigated the electrical transport properties of the three-dimensional ^{70}Ge:Ga system on the insulating side of the metal-insulator transition (MIT). Our analysis is done as a function of temperature and in the absence of a magnetic field. Initially, we graphically represented the function ln(σ) as a function of $T^{-0.25}$ and $T^{-0.5}$. Although both plots showed good linearity, it was challenging to differentiate between the Mott-VRH and ES-VRH conduction regimes based solely on these curves.

To resolve this issue and precisely identify the dominant hopping regime in the system, we utilized two methods: the one proposed by Zabrodskii and Zinoveva and the percentage deviation method. Remarkably, for all five samples and across the entire temperature range, the hopping exponent x was found to be very close to 0.5. This strongly suggests that the electrical conductivity follows the hopping law $\sigma = \sigma_{ES} \exp[-(T/T_{ES})^{0.5}]$, indicating that the electrical conduction occurs through the Variable Range Hopping (VRH) mechanism, specifically the Efros-Shklovskii (ES) VRH regime, without any crossover to the Mott VRH regime.

Furthermore, the behavior ln(σ) ~ $T^{-0.5}$ indicates that the long-range Coulomb interactions between the localized charge carriers significantly influence the system. These interactions reduce the density of states (DOS) around the Fermi level, leading to the formation of a pseudo-parabolic Coulomb gap at the Fermi level, known as the Coulomb gap (CG). Additionally, we have determined several hopping parameters within the ES regime, further enriching our understanding of the electrical transport properties of the ^{70}Ge:Ga system on the insulating side of the MIT.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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