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Behaviour of the conductivity in metallic ^{70} Ge:Ga close to the metal-insulator transition

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Abstract. The electrical transport properties in sample 1 of impurity concentration n=xx of the ^{70}Ge: Ga system are studied in the absence of a magnetic field and at low temperature in the range 0.53 to 0.017 K. It is noted that the electrical conductivity of sample 1 exhibits a metallic behavior. We found that the exponent S is equal to 0.5 ($\sigma=\sigma(T=0)+mT^s$). This result is in agreement with the theory of weak localization (WL) at 3D and the theory of electron-electron interactions (EEI). We also found that sample 1 is located near the metal-insulator transition (MIT) of the metallic side.

Keywords: *^{70}Ge: Ga semiconductor, low temperature, impurity concentration, electron-electron interactions, weak localization, transport properties.*

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1 Introduction and theoretical part

Depending on their electrical properties, materials can be classified as metallic or insulating systems. The three-dimensional (3D) insulating samples display a conductivity that tends towards zero at T = 0 K. whereas, the metallic 3D samples have a strictly positive conductivity at T = 0 K.

On the metallic side of the metal-insulator transition (MIT), the temperature dependence of electrical conductivity for three-dimensional metallic samples at low temperatures can be expressed as follows:

$$\sigma = \sigma(T = 0) + m\,T^S \qquad (1)$$

Where, m, T and S represent respectively the conductivity at zero temperature, the
magnitude of the correction term, the temperature and the exponent which is an adjustable parameter. This formula is used for doped crystalline and amorphous semiconductors [1-6].

On the insulating side of the MIT, the electrical transport is dominated by variable range hopping (VRH) [7-13], corresponding to the strong localization regime; the electrical conductivity of doped semiconductors varies according to an exponential law with the temperature of the type:

$$\sigma(T) = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)^p\right] \qquad (2)$$

Where σ_0 is the prefactor, is the characteristic temperature, and is an exponent. The possible values of n are 0 or 2. In order to determine the metallic or insulating behavior of a sample, we used the graphical procedure developed by Zabrodskii and Zinoveva [14]. Using the equation (2), Zabrodskii and Zinoveva [14] establish the following function:

$$w(T) = \ln\left[\frac{d\ln(\sigma)}{d\ln(T)}\right] = \ln(p) + p\ln(T_0) - p\ln(T) \qquad (3)$$

When the slope of the curve of $w(T)$ versus $\ln(T)$ is negative, the sample is on the insulating side of the TMI. Whereas, the positive slope of the plot $w(T)$ versus $\ln(T)$ a positive or zero slope however indicates that the sample is metallic.

2 Results and discussion

We have reanalyzed experimental data for the 70Ge:Ga system prepared and report-ed by Itoh et al. in Reference [15]. In Figure 4, we have plotted the variation of the function w (T) as a function of ln (T) (procedure of Zabrodskii and Zinoveva [14]) for sample 1(n=1.861×1017cm-3 in the absence of magnetic field and in the tempera-ture interval 0.017 K -0.53 K. According to this figure, the slope of this plot is strictly positive which indicates that sample 1 is on the metallic side of the MIT.

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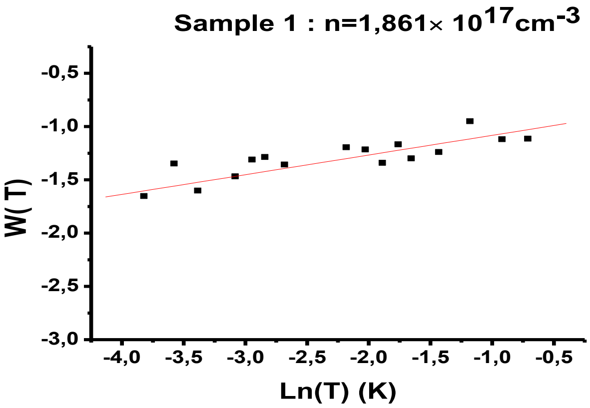

Fig. 1. Variation of the function w (T) as a function of ln (T) for sample 1.

To better position the sample1 on the metallic side of the TMI, we will now use the theory of weak localization [15-18] where the electrical conductivity at T = 0 K is given by the following expression:

$$\sigma_0 = \sigma_B g^2 \left(1 - C / g^2 \left(k_F l_e\right)^2\right) \qquad (4)$$

Where C is a coefficient ranging between 1 and 3, is the factor calculated by Mott representing the decrease in the density of states by the disorder. Note that σ_B is Boltzmann's electrical conductivity given by the following formula:

$$\sigma_B = \frac{ne^2 l_e}{\hbar k_F} \qquad (5)$$

Where n is the electron concentration of impurities, e is the electronic charge, l_e is the elastic mean free path of the electron, $\hbar$ is the Planck constant and $K_F = \left(3\pi^2 n\right)^{1/3}$ is the fermi wave vector. Considering the expression of σ_0 (4) and the relation (5), we arrive at

$$\left(g^2 \frac{ne^2}{\hbar K_F}\right) l_e^2 - \sigma(0) l_e - C \frac{ne^2}{\hbar K_F^3} = 0 \qquad (6)$$

Finally, the physically solution acceptable of the last equation is the elastic mean free path given by:

$$l_e = \frac{\sigma(0) + \sqrt{\sigma^2(0) + C\left(\frac{2gne^2}{\hbar k_F}\right)^2}}{\frac{2g^2ne^2}{\hbar k_F}} \qquad (7)$$

For our sample:

- By using the standard linear regression method, we find the electrical conductivity at T = 0K, that is: $\sigma(0) = \sigma(T=0) = 1.43088(\Omega \cdot \mathrm{cm})^{-1}$.
- The Fermi wave vector : $K_F = \left(3\pi^2 n\right)^{1/3} = 1.76674 \times 10^8\ m^{-1}$
- The elastic mean free path of the electron (7) : $l_0 = 1.9682 \times 10^{-8}\ m$

Finally $K_F l_0 = 3.47742$: This result is in good agreement with the Ioffe-Regel criterion $K_F \times l_0 = \pi$ for the metallic samples which are located in the vicinity of the MIT on the metallic side. Therefore, our sample is located near the TMI on the metal side. The latter belongs to the 70Ge:Ga system prepared and published by Itoh et al. Note that the critical impurity concentration of this system that marks the boundary between the metallic and insulating samples is equal to $n_c = 1.856 \times 10^{17}\ cm^{-3}$.

In order to find the behavior of electrical conductivity as a function of temperature. We have shown in Figures 1 and 2 respectively the variations in electrical conductivity σ as a function of $T^{1/2}$ and $T^{1/3}$ for the metallic sample with an impurity concentration $n_c = 1.861 \times 10^{17}\ cm^{-3}$, in the absence of the magnetic field and in the temperature range 0.53 -0.017 K. We note that it is difficult to distinguish between one or the other of the two laws (T1/2 and T1/3) based only on two figures 1 and 2.

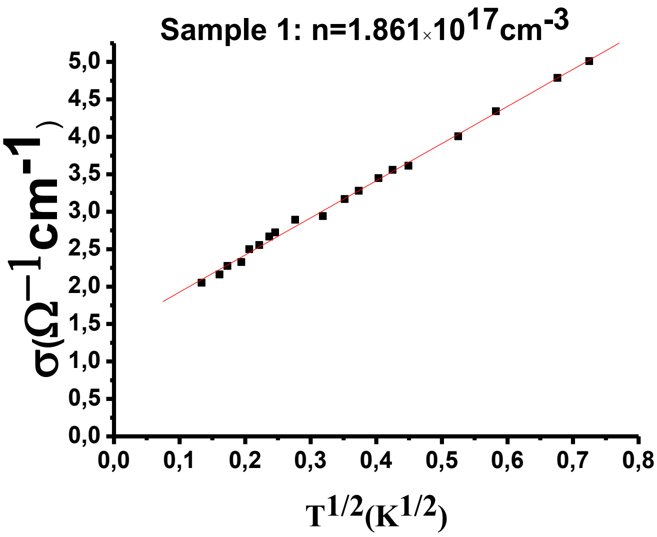

Fig. 2. The variation of the conductivity σ as a function of $T^{1/2}$ for sample 1.

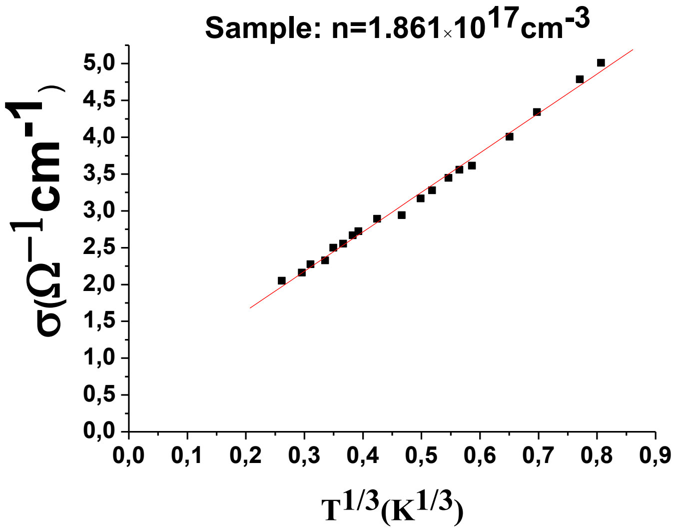

Fig. 3. The variation of the conductivity σ as a function of $T^{1/3}$ for the sample 1.

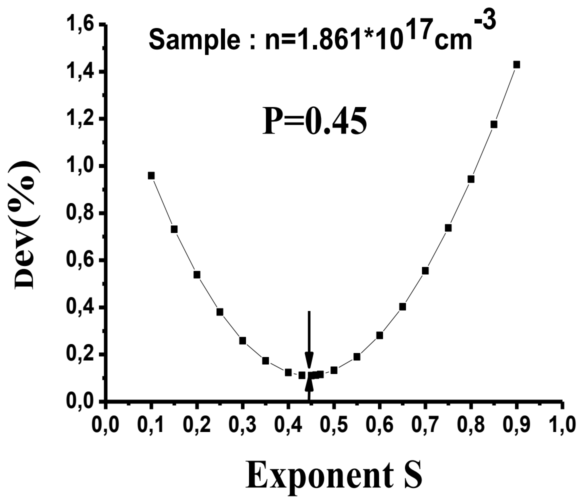

Fig. 4. Percentage of deviation Dev (%) as a function of the exponent S in equation (7) for the metallic sample1, the minimum deviation close to 1/2.

To confirm these results and correctly specify the values of the exponent S, we will use the percentage deviation procedure [19-20]. First, we posed $\sigma=\sigma(T=0)+mT^S$, by varying the exponent S between 0 and 1 by a step of 0.01. For each value of, the conductivity at T = 0K and the coefficient m are evaluated by standard linear regression methods. Thereafter, we calculate each time of the percentage deviation (Dev (%)) between the expression $\sigma=\sigma(T=0)+mT^S$ and the experimental values of the electrical conductivity. The deviation percentage (Dev%) is given by the following formula :

$$Dev(\%)=\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100}{\sigma_i}\left(\left[\sigma(T=0)+mT^S\right]-\sigma_i\right)\right)^2\right]^{1/2} \quad (8)$$

n and σ_i denote respectively the number of experimental points and the experimental values of the conductivity at different temperatures Ti. Note that the minimum deviation corresponds to the best value of the exponent S. In figure 3, we have plotted the percentage deviation Dev (%) as a function of the exponent for the metal sample 1. From this figure, we notice that the minimum of the percentage deviation Dev (%) is obtained for the value of xx very close to 0.5 (S = 0.46 for sample1). This last result is in agreement with the theory of weak localization (WL) at 3D and the theory of electron-electron interactions (EEI) which characterize the phenomena of electronic transport in sample 1.

3 Conclusion

We have studied the electrical transport properties in sample 1 of the system 70Ge Ga in the absence of a magnetic field and at low temperature on the metallic side of the TMI. We used the graphical procedure developed by Zabrodskii and Zinoveva to determine the metallic behavior of the sample 1 and to better place our sample, we used the Ioffe-Regel criterion of the transition $(K_F l_0=\pi)$. We found $K_F l_0=3.47742$, this result shows that the sample is located near TMI on the metal side. Using the percentage deviation method, we found that the minimum deviation is close to 1/2, the latter result in agreement with the theories of weak localization and electron-electron interactions.

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