Variable range hopping conduction in n-CdSe samples at very low temperature

M Errai[1,†], A El Kaaouachi[1], and H El Idrissi[2]

[1]Physics Department, Ibn Zohr University, Faculty of Sciences, Agadir, Morocco
[2]Laboratoire Electronique, Électrotechnique, Automatique et Traitement de l'Information, Département Génie Electrique, Faculté des Sciences et Techniques de Mohammedia, Université Hassan II Mohammedia Casablanca, BP 146 Quartier Yasmina, Mohammedia

Abstract: We reanalyzed experimental data already published in Friedman J R, Zhang Y, Dai P, *et al.* Phys Rev B, 1996, 53(15): 9528. Variable range hopping (VRH) conduction in the insulating three-dimensional n-CdSe samples has been studied over the entire temperature range from 0.03 to 1 K. In the absence of a magnetic field, the low temperature conductivity σ of the three samples (A, B and C) obeys the Mott VRH conduction with an appropriate temperature dependence in the prefactor ($\sigma = \sigma_0 \exp[-(T_0/T)]^p$ with $p \approx 0.25$). This behavior can be explained by a VRH model where the transport occurs by hopping between localized states in the vicinity of the Fermi level, $E_{\rm F}$, without creation of the Coulomb gap (CG). On the contrary, no Efros-Shklovskii VRH is observed, suggesting that the density is constant in the vicinity of the $E_{\rm F}$.

Key words: n-CdSe samples; low temperature; variable range hopping; density of state
DOI: 10.1088/1674-4926/36/12/122001 **EEACC:** 2520

1. Introduction

Variable range hopping (VRH) is a mechanism of electrical transport by carriers between localized states[1−5] at sufficiently low temperatures. It has been invoked to explain the conduction in several compounds, such as crystalline and amorphous semiconductors[6−10], semiconductor–metal alloys[11] and granular films[12,13].

The temperature dependence of the electrical conductivity σ was shown by Mott[1,2] to behave like $\ln\sigma \propto T^{-1/4}$. This dependence was obtained by optimizing the hopping probability and assuming a slowly varying density of state (DOS) near the Fermi level $E_{\rm F}$.

However, Efros and Shklovskii (ES)[3,4] predicted that long range electron–electron interaction reduces the DOS at the Fermi level and creates a soft Coulomb gap (CG), which takes the form $N(E) \propto (E - E_{\rm F})^\nu$ with $\nu = 2$. The existence of the CG leads to the ES VRH regime. In this case, the electrical conductivity can be described as a power law of the form $\ln\sigma \propto T^{-1/2}$.

In the insulating regime at low temperatures, the electrical transport property is dominated by VRH; the temperature dependence of the conductivity can be described by a general VRH law in zero magnetic field:

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

where σ_0 is the prefactor and T_0 is the characteristic temperature. $p = (\nu + 1)/(\nu + 4)$ is an exponent that allows one to conclude the profile of the DOS. In fact, Equation (1) remains quite universal when $\nu = 0$, the DOS is constant and $p = 0.25$, corresponding to the Mott regime. However, when $\nu = 2$, the DOS varies in the vicinity of the Fermi level and $p = 0.5$ corresponding to the ES VRH regime. It is interesting to note that recently some theoretical studies and a few experiments have shown that the exponent p can be different from 0.25 and 0.5. Moreover, Mott VRH and ES VRH regimes have been widely observed in many types of disordered materials and doped semiconductors[6−10].

2. The study of the electrical conductivity of zero magnetic field

In order to determine which of the VRH regimes (Mott VRH regime or ES VRH regime) is observed in the insulating samples, we used the practical method proposed by Zabrodskii and Zinovera[14]. By using Equation (1), they determined the function $W(T)$ given by the relation:

$$W(T) = \ln\frac{{\rm d}\ln\sigma}{{\rm d}\ln T} = \ln p + \ln T_0 - p\ln T, \tag{2}$$

where σ is the electrical conductivity.

3. Results and discussion

We reanalyzed the experimental data for the three-dimensional n-CdSe samples prepared and reported by Friedman *et al.* in Reference [15].

Figures 1 and 2[15] present respectively the variation of $\ln\sigma$ versus $T^{-0.25}$ and $T^{-0.5}$ in the temperature range 0.03–1 K at zero magnetic field. As we see in Figures 1 and 2, the linearity is not clear enough. It is difficult therefore to determine which of the both hopping regimes is observed. In order to find a physics solution to this problem, we use the method proposed by Zabrodskii and Zinovera first and the method of the percentage deviation afterwards.

Figure 3 shows the plot of the function $W(T) = \ln[d\ln\sigma/d\ln T]$ as a function of $\ln T$ in the temperature range

† Corresponding author. Email: errai2013@gmail.com
Received 6 April 2015, revised manuscript received 9 June 2015

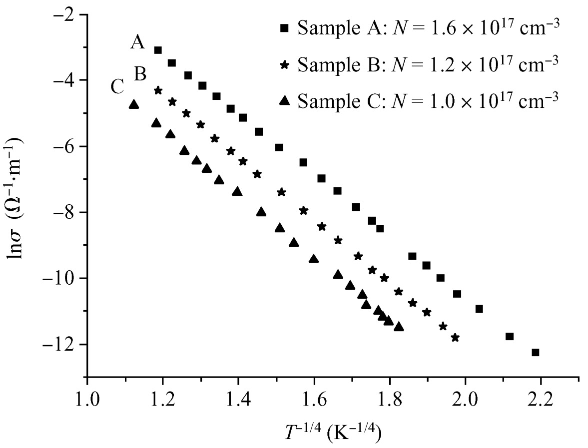

Figure 1. Electrical Conductivity in zero field as a function of $T^{-1/4}$ on a semi logarithmic scale for three insulating, n-type CdSe. Experimental data are reproduced from Reference [15].

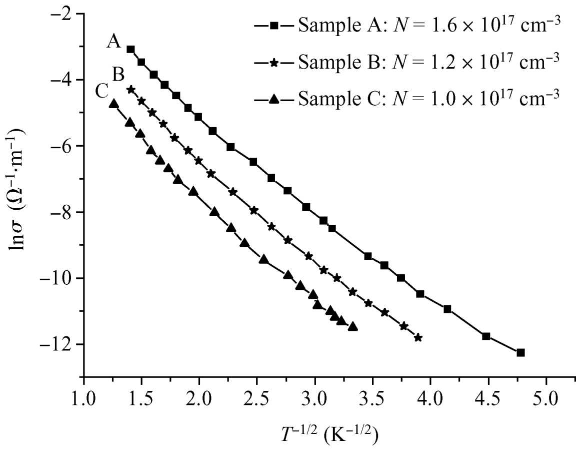

Figure 2. Electrical Conductivity in zero field as a function of $T^{-1/2}$ on a semi logarithmic scale for three insulating, n-type CdSe.

0.03–1 K at zero magnetic field. We noticed that for our samples A[15] (see Figure 4(a)), B[15] (see Figure 4(b)) and C[15] (see Figure 4(c)), the slopes p are approximately equal to 0.25 without observing any crossover to 0.5, indicating the existence of the Mott VRH conduction regime in all the whole temperature range. We present in Table 1 the values of the p slopes for the three samples[15].

We will now use the percentage deviation method[16, 17] to thoroughly check the values of the exponent p that we found by using the method of Zabrodskii and Zinovera.

In this procedure, the values of the conductivity σ_i (T_i) at different temperatures T_i were fitted to the universal equation given by Equation (1), using σ_0 and T_0 as adjustable parameters. We varied the exponent p from 0.01 to 1 with steps of 0.05 (and 0.01 near the minimum deviation). For each value of p, we have extracted the values of σ_0 and T_0. Then the deviation Dev (%) is given by the relation following:

$$\mathrm{Dev}(\%) = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100}{\sigma_i}\left\{\sigma_0 \exp\left[-\left(T_0/T\right)^p\right] - \sigma_i\right\}\right)^2\right]^{1/2}, \tag{3}$$

where n is the number of experimental points. It is interesting to note that the minimum deviation corresponds to the best value of the exponent p.

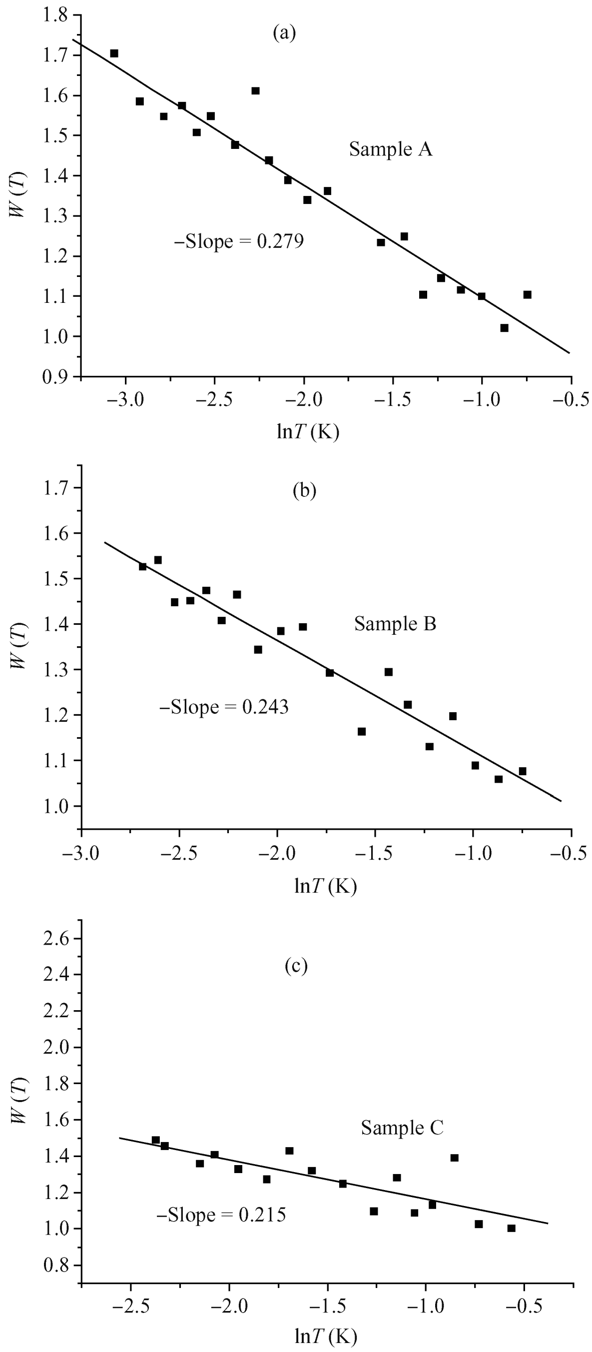

Figure 3. Function $W(T)$ of (a) samples A, (b) B, and (c) C as a function $\ln T$ in Equation (2) for three insulating, n-type CdSe, as indicated.

Figure 4 illustrates the variations of Dev (%) as a function of the exponent p in Equation (1) for the three-dimensional n-CdSe samples for several values of temperature. We found that the minimum of Dev (%): $p = 0.28$ for sample A (see Figure 4(a)), $p = 0.24$ for sample B (see Figure 4(b)) and $p = 0.21$ for sample C (see Figure 4(c)). We thus deduce that all the values of p are very close to 0.25, which suggests the existence of Mott VRH conduction in all the temperature range for the three-dimensional n-CdSe samples, and that equally means that the DOS is almost constant near the Fermi level E_{F}.

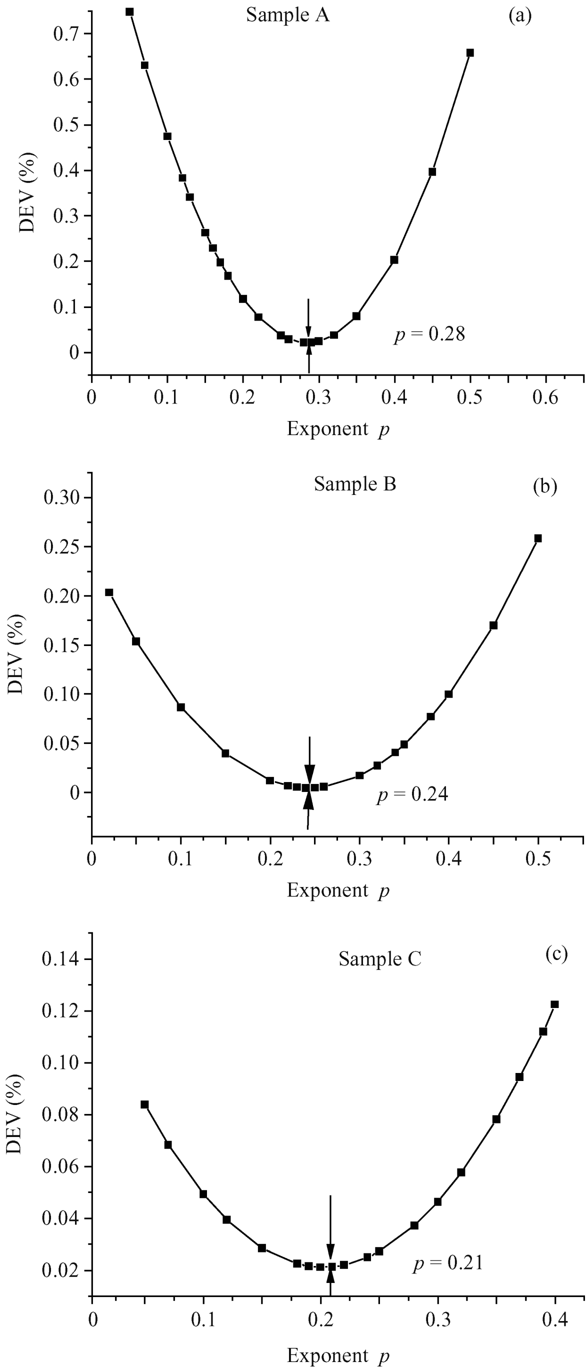

Figure 4. Percentage deviation Dev (%) versus exponent p (Equation (3)) in all the range of temperature 0.03–1 K of (a) samples A, (b) B, and (c) C.

We also noticed that we confirmed the results obtained by the procedure of Zabrodskii and Zinovera. We present the values of p in Table 1.

Since the electrical transport is carried out by Mott VRH, Equation (1) can be written in the form:

$$\sigma = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)\right]^{0.25}, \tag{4}$$

where σ_0 represents a prefactor and T_0 is the characteristic Mott temperature, T_0 is given by:

$$k_B T_0 = \frac{18}{N(E_F)\xi^3}. \tag{5}$$

where k_B, $N(E_F)$, ξ are the Boltzmann constant, the DOS at the Fermi energy and the localization length.

Table 1. Table shows the values of the exponent p in Equations (2) and (3) for samples A, B and C in the temperature range 0.03–1 K.

Sample	Exponent p (method Zabrodski and Zinova)	Exponent p (minimum of deviations)
A	0.27	0.28
B	0.24	0.24
C	0.21	0.21

Table 2. Table shows the values of T_0 (the characteristic Mott temperature) and σ_0 (the prefactor) for samples A, B and C in the temperature range 0.03–1 K.

Sample	$T_0 = T_{Mott}$ (K)	σ_0 $(\Omega\cdot m)^{-1}$
A	7296.78	2694.29
B	8249.093	1096.28
C	8556.91	399.18

We can evaluate the values of T_0 and σ_0 for samples A, B and C by using the data in Figure 1 and Equation (4). We present the results in Table 2.

In the previous study, we have not observed the crossover from VRH Mott to VRH ES. In fact, the electrical transport is dominated by VRH ES with law $\ln\sigma \propto T^{-1/2}$ in all of the temperature range with the reduction of the DOS at the Fermi level and the creation of a soft Coulomb gap (CG). According to the present study, the electrical conductivity follows the VRH-Mott regime without crossover to the VRH-ES regime across the range of temperature, indicating that the DOS becomes almost constant in the vicinity of the Fermi level E_F.

Furthermore, the crossover from the Mott to Efros-Shklovskii variable range hopping (ES-VRH) is observed by many authors in several localized systems; as examples: Errai *et al.*[7], Rosenbaum *et al.*[18], Makise *et al.*[19], Vaziri[20], Shekhar *et al.*[21]. It is carried out with the increase of the temperature or the decrease in the impurity concentration and also when the magnetic field increases[22].

4. Conclusion

In summary, we have studied the electrical transport in the insulating three-dimensional samples n-CdSe at low temperatures. For this, we used the method of Zabrodskii and Zinovera and the percentage deviation method; we found that the exponents p are very close to 0.25 for the three samples A, B and C. This shows that the electrical conductivity follows the hopping law $\ln\sigma \propto T^{-1/4}$ and also indicates the existence of the regime Mott VRH without electron-electron interaction in the entire temperature range. We also conclude that the density of states is almost constant near the Fermi level. We also note that our insulating samples are located far from the metal–insulator transition of the insulating side since the critical concentration of the system is equal $N_c = 2.8 \times 10^{17}$ cm^{-3}[15], where N_c is greatly superior to the doping concentrations of samples A, B and C.

Acknowledgements

We are grateful to Professor M. P. Sarachik who allowed us to re-use experimental results published in the reference "Friedman J R, Zhang Y, Dai P, et al. Phys Rev B, 1996, 53: 9528".

References

[1] Mott N F. Conduction in glasses containing transition metal ions. J Non-Cryst Solids, 1968, 1: 1

[2] Mott N F. Metal–insulator transitions. London: Taylor and Francis, 1974

[3] Shklovskii B I, Efros A L. Electronic properties of doped semiconductors. Berlin: Springer, 1984

[4] Efros A L, Shklovskii B I. Coulomb gap and low-temperature conductivity of disordered systems. J Phys C, 1975, 8: L49

[5] Fogler M M, Teber S, Shklovskii B I. Variable-range hopping in quasi-one-dimensional electron crystals. Phys Rev B, 2004, 69: 035413

[6] Errai M, El Kaaouachi A, El Idrissi H, et al. Hopping conduction in amorphous silicon–chromium films at very low temperature. AIP Conf Proc, 2014, 1574: 291

[7] Errai M, El Kaaouachi A, Narjis A, et al. Crossover from Efros–Shklovskii to Mott variable range hopping in amorphous thin Ni_xSi_{1-x} films. Chinese Journal of Physics, 2014, 52: 251

[8] El Kaaouachi A, Abdia R, Nafidi A. Positive magnetoresistance in the variable range hopping regime in CdSe. Physica E, 2006, 32: 419

[9] Abdia R, El Kaaouachi A, Nafidi A, et al. Variable range hopping conductivity and negative magnetoresistance in n-type InP semiconductor. Solid-State Electron, 2009, 53: 469

[10] Errai M, El Kaaouachi A, El Idrissi H. Electrical properties of 70Ge:Ga near the metal—insulator transition. Journal of Semiconductors, 2015, 36(6): 062001

[11] Narjis A, El Kaaouachi A, Limouny L, et al. Study of insulating electrical conductivity in hydrogenated amorphous silicon–nickel alloys at very low temperature. Physica B, 2011, 406: 4155

[12] Vekilov Y K, Mukovskii Y M. Variable range hopping conductivity in manganites. Solid State Commun, 2012, 152: 1139

[13] Adkins C J. Conduction in granular metals-variable-range hopping in a Coulomb gap. Phys Condens Matter, 1989, 1: 1253

[14] Zabrodskii A G, Zinoveva K N. Low-temperature conductivity and metal–insulator transition in compensate n-Ge. Soviet Physics-JETP, 1984, 59: 425

[15] Friedman J R, Zhang Y, Dai P, et al. Magnetic-field-induced crossover from Mott variable-range hopping to weakly insulating behavior. Phys Rev B, 1996, 53: 9528

[16] Waller D. Operations management: a supply chain approach. Cengage Learning Business Press, 2003

[17] Khan A, Hildreth W B. Case studies in public budgeting and financial management. New York, NY: Marcel Dekker, 2003

[18] Rosenbaum R, Murphy T, Palm E, et al. Magnetoresistance of insulating amorphous Ni_xSi_{1-x} films exhibiting Mott variable-range hopping. Phys Rev B, 2001, 63: 094426

[19] Makise K, Hidaka K, Ezaki S, et al. Metal-insulator transitions in IZO, IGZO, and ITZO films. J Appl Phys, 2014, 116: 153703

[20] Vaziri M. Low-temperature conductivity of epitaxial ZnSe in the impurity band regime. Appl Phys Lett, 1994, 65: 2568

[21] Shekhar S, Prasad V, Subramanyam S V. Anomalous Efros–Shklovskii variable range hopping conduction in composites of polymer and iron carbide nanoparticles embedded in carbon. Phys Lett A, 2006, 360: 390

[22] Mitin V F, Kholevchuk V V, Kolodych B P. Ge-on-GaAs film resistance thermometers: low-temperature conduction and magnetoresistance. Cryogenics, 2011, 51(1): 68