A temperature-dependent pre-exponential factor in Efros-Shklovskii variable range hopping conduction in p-type $CuInTe_2$

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Abstract

We report on the temperature dependence of the electrical resistivity down to 0.4 K in single crystal sample of $CuInTe_2$ with a hole concentration at room temperature of 2.32x10^{18} cm^{-3}. Mott type variable range hopping (VRH) conduction is observed in the temperature range from 90 to 53 K. A crossover to Efros-Shklovskii (ES) type VRH conduction with a temperature-dependent pre-exponential factor, i.e. $\rho = \rho_0 T^\alpha \exp(\frac{T_0}{T})^{0.5}$ with $\alpha = 0.18$, is seen below 25 K. This is the first time that a crossover from Mott to ES VRH with a pre-exponential factor has been reported.

Key words: Mott; Efros-Shklovskii; variable range hopping; pre-exponential factor; resistivity

1. Introduction

The temperature dependence of the electrical resistivity of insulating materials that have constant density of states around the Fermi surface has been predicted to follow Mott law, $\rho = \rho_0 T^\alpha \exp(\frac{T_0}{T})^s$ with s and α equal to 0.25, at low temperatures. When the Coulomb gap appears in the density of states due to the Coulomb repulsion, the resistivity is expected to show ES type VRH with s and α equal to 0.5 [1]. Crossover from Mott to ES type conduction can be observed either by lowering the temperature or the carrier concentration.

However, when analyzing experimental data the exponent α is taken usually to be zero both for Mott and ES type of conduction. On the other hand, it is found experimentally that $\alpha \approx 0$ when the carrier concentration is very near the critical concentration $p_c(n_c)$ that defines the metal-insulator transition in p- or n-type materials [2]. In the case of ES type of conduction α becomes different from zero when the carrier concentration departs from p_c to lower values.

$CuInTe_2$ belongs to the I-III-VI_2 family of semiconductors. Its electrical and optical properties have been reported in detail earlier [3,4]. Measurements made down to 4 K shows a crossover from Mott to ES type of conduction with α=0 in a sample of this material with a carrier concentration of 10^{16} cm^{-3} [4], which is far away from p_c=3.4x10^{19} cm^{-3}. In this paper we report on the temperature dependence of the electrical resistivity down to 0.4 K in a sample with a carrier concentration of 2.3x10^{18} cm^{-3}. In addition to the crossover from Mott to ES type conduction, the exponent α of the preexponential factor in the ES VRH conduction is found to be different from zero.

2. Experiment

The single crystal of $CuInTe_2$ was grown with a technique explained elsewhere[5]. For the measurements we used a 182 Keithley nanovoltmeter and a 220 Keithley current source. A standard four probe technique was employed. The temperature was measured by a LakeShore calibrated cernox thermometer.

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3. Results and discussion

The main body of Fig. 1 shows the variation of $\ln(\rho)$ against $T^{-1/4}$ between 108 and 43 K. Linear behavior is observed in the temperature range 90 to 53 K, which is indicative of Mott type VRH conduction with $\alpha = 0$. The zero temperature resistivity $\rho_0 = 0.035$ Ωcm and the Mott characteristic temperature $T_M = 29670$ K. The inset to this figure shows resistivity versus temperature in the whole temperature range. Fig. 2 displays $\ln(\rho/T^{0.18})$ versus $T^{-1/2}$ between 25 and 4 K. The linear dependence between 19 and 5 K on this plot implies ES type VRH conduction with a temperature-dependent preexponential factor with $\alpha = 0.18$. The ES temperature $T_{ES} = 0.63$ K and $\rho_0 = 3.64$ Ωcm.

Different types of analysis of the data such as the plot of $\ln(\frac{dln\rho}{dlnT})$ versus ln$T$ and percentage deviation yielded no significant change in the values of these parameters. It is noteworthy that it was not possible to fit the data for ES conduction with $\alpha = 0$. To our knowledge, this is the first time that a temperature dependent preexponential factor has been observed in ternary compounds.

The value $\alpha = 0.18$ is far from the theoretical value of 0.5 in ES type of conduction. Such a departure from 0.5 has been reported previously for compensated Ge:Sb in the dilute regime[6], which is consistent with the present result. On the other hand, data from several samples of uncompensated Si:As in the critical regime were fitted reasonably well with values of α ranging from near 0 to 0.4, which the value nearest to zero corresponding to the sample with the concentration closest to p_c[2]. Thus, it is not obvious how α depends on the concentration. The value of α reported here suggests a small fluctuating short ranged potential producing a departure from strictly hydrogenic wave functions[7], for the cation-cation vacancies and antisites structural defects that provide charge carriers in the present sample.

In summary we report for the first time the presence of temperature dependence of the pre-exponential factor in ES VRH conduction in ternary compound semiconductors.

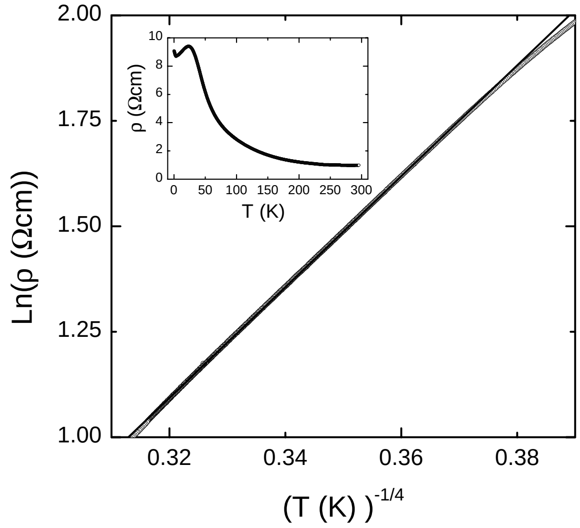

Fig. 1. Resistivity against $T^{-1/4}$ between 108 and 43 K. The solid line is a fit to the data. The inset displays the resistivity data in the entire temperature range.

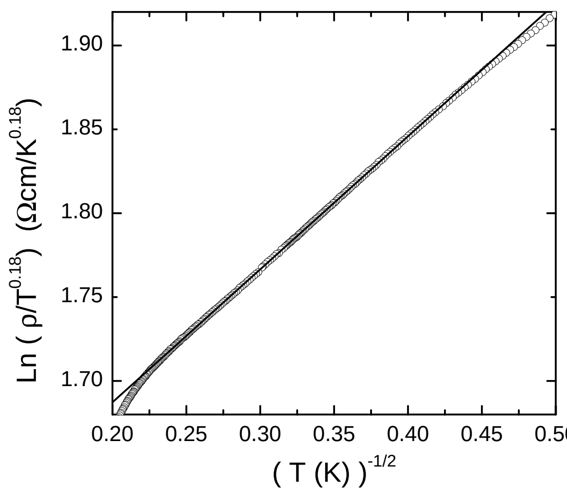

Fig. 2. $\ln(\rho/T^{0.18})$ versus $T^{-1/2}$ between 25 and 4 K K. The solid line is a fit to the data.

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References

[1] T. G. Castner, in *Hopping Transport in Solids*, edited by M. Pollak and B. I. Shklovskii (Elsevier/North-Holland, Amsterdam, 1990), p. 1.

[2] W. N. Shafarman and T. G. Castner, Phys. Rev. B **33**, (1986) 3570.

[3] S. M. Wasim, C. Rincón, G. Marín, P. Bocaranda, E. Hernández, I. Bonalde, and E. Medina, Phys. Rev. B **64**, (2001) 1951011.

[4] M. Iqbal, J. Galibert, S. M. Wasim, E. Hernández, P. Bocaranda, and J. Leotin, Phys. Stat. Sol. (b) **219**, (2000) 351.

[5] G. Marín, S. M. Wasim, G. S. Perez, P. Bocaranda, and A. E. Mora, J. Electron. Mater. **27**, (1998) 1351.

[6] F. R. Allen and C. J. Adkins, Philos. Mag. **26**, (1972) 1027.

[7] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer-Verlag, Berlin, 1984).