Temperature dependence of the electrical conductivity and Hall effect of thallium gallium disulphide single crystals

S. E. Al Garni*

*Physics Department, Sciences Faculty for Girls, King Abdulaziz University, KSA.

ABSTRACT. Single crystal of the layered compound $TlGaS_2$ were grown by direct synthesis of their constituents. Their electrical conductivity and Hall effect was studied as a function of the temperature, perpendicularly and parallel to the layer planes and it proved to be highly anisotropic. The Hall effect measurements revealed the extrinsic p-type conduction with an acceptor impurity level located at 0.586eV for $\sigma_{\perp}$ and 0.43eV for $\sigma_{//}$ above the valence band maximum. The variation of the Hall mobility as well as the carrier concentration with temperature was investigated. The scattering mechanism of the carrier in the whole temperature range of investigation was checked. The anisotropic factor was also estimated and its temperature dependence was illustrated.

1-Introduction

For many years, the properties of layered crystal have constituted a major research area in solid-state physics. Layered crystal were often used to test some of the most advanced techniques in modern photoemission [1].This has not been applied on a large scale to ternary chalcogenides containing thallium. The interest in these materials is stimulated not only by their fundamental properties but also by possible practical applications. The ternary semiconduction $TlGaS_2$ single crystal, which is a wide-gap material, has a layered monoclinic structure [2]. The optical properties of $TlGaS_2$ is reported [3-7]. Photoluminescence spectra of $TlGaS_2$ layered crystal were studied [8]. Thermally stimulated current analysis of $TlGaS_2$ single crystal were measured [9,10].Thermal expansion of $TlGaS_2$ are investigated [11,12]. The crystal structure of the ternary semiconductor compound $TlGaS_2$ was determined [13]. Roman scattaring measausements under pressure were performed in a single crystal of $TlGaS_2$ [14,15].

Photoconductivity of $TlGaS_2$ single crystal was investigated [16-18]. $TlGaS_2$ single crystal doped by paramagnetic Fe^{3+} ions has been studied by electron paramagnetic resonance (EPR) technique [19]. The deformation effects in electronic spectra of $TlGaS_2$ are studied [20]. Low-temperature phase transition in $TlGaS_2$ layer crystal was observed [21]. Infrared reflectivity spectra of $TlGaS_2$ was reported [22].

Investigation of dc hopping conduction in $TlGaS_2$ is established [23].

Recently crystal data collection for $TlGaS_2$ is represented [24].

In spite of all the above reported studies, literature still lacks of the information about the Hall properties, the impurity level and concentration, and the dominant scattering mechanisms in $TlGaS_2$ crystal. Thus, the aim of this work is to report these properties through the electrical conductivity and Hall effect measurements and analysis.

In the present work we describe for the first time the electrical conductivity and Hall effect in two crystallographic direction for $TlGaS_2$.

2-Experimental procedure

$TlGaSe_2$ monocrystals were grown by using a modified Bridgman method, from a stoichiometric melt of starting materials sealed in evacuated (≈10-6 m ber) and carbon coated quartz ampoules with a tip at the bottom, in our crystal growth laboratory. The growth and the experimental apparatus have been described in detail elsewhere [25]. The grown single crystal exhibit good optical quality and have a light yellow color.

The x-ray diffraction patterns show that these crystals have monoclinic structure with the lattice parameters a=10.35 ºA, b=10.34 ºA, c=15.10 ºA and β=100º.

These single crystals can rather easily be cleaved into plates perpendicular to the c-axis. Samples with suitable for measurements used in this work were freshly and gently cleaved along the cleavage plane with a razor blade from the ingot and no further polishing and cleaving treatments were required because of the natural mirror-like cleaving faces for studying electrical conductivity and Hall effect, the samples were prepared in a rectangular parallelepiped shape with the required dimensions. Silver paste contact was used as ohmic contact. The ohmic nature of the contact was verified by recording the current-voltage characteristics. The conductivity and Hall coefficient were measured by a compensation method in a special cryostat with a conventional dc type measurement system.

The measurements were performed under vacuum condition in a cryostat especially designed for mounting between the polar expansions of an electromagnet. The deigned cryostat allow measurements in a wide range of temperature.

To avoid Hall voltage drop when the length-to-width ration of the sample is less than three, according to Isenberg [26], the specimen dimensions were chosen as ($5\times1.5\times1 mm^3$) specimen with mirror surfaces was placed in its holder to avoid mechanical stress either from clamping or from differential expansion if measurements were to be made at temperature different from room temperature. The Hall contacts were to be infinitely small so that they do not distort the current flow. The temperature of the specimen was measured with the aid of a copper-constantan thermocouple. The electrical conductivity $\sigma_{\perp}$ was measured when the current was oriented at right angles to the c-axis, and $\sigma_{//}$ when its flow was parallel to the c-axis. Also the Hall coefficient was measured with the magnetic field oriented along the c-axis and the current flowing at right angles to this axis ($J \perp C // H$) $R_{H//}$. In case of transposition of the direction of current and magnetic field ($J // C \perp H$), $R_{H\perp}$ was obtained.

3-Results and discussion

The investigated temperature range was 388 K -663 K. Fig.1 shows typical behavior of the electrical conductivity as a function of temperature for a particular sample. The curves show the typical semiconductor behavior.

In general $\sigma_{\perp}$ is much higher then $\sigma_{//}$. For instance, at room temperature $\sigma_{//} = 1.244\times10^{-7}$ $Ohm^{-1}cm^{-1}$ and $\sigma_{\perp}=1.855\times10^{-7}$ $Ohm^{-1}cm^{-1}$. At low temperature (the extrinsic region), the carrier concentration may be determined by the number of ionized acceptors, since the main part will be played by free carrier transition from the impurity level, and consequently the conductivity increases slowly.

The impurity ionization energy ΔE_a, could be calculated, and, was found to be 0.586eV for $\sigma_{\perp}$ and 0.43eV for $\sigma_{//}$. When the temperature rises, the conductivity rises very rapidly due to the rapid increase in total carrier density (electron p lus holes). This means that the intrinsic conduction because more favourable at high temperature. The energy gap width was determined to be 2.24eV for $\sigma_{\perp}$ and 3.62eV for $\sigma_{//}$.

From fig.1, it is also noticed that the presence of intermediate region is seen between 438K and 593K for $\sigma_{\perp}$, while this region for $\sigma_{//}$ lies between 498 and 588K. The conductivity with this portion falls off since the mobility decreases with temperature due to lattice thermal vibration.

The transition temperature from impurity to intrinsic conductivity depends on the concentration of impurity in the specific semiconductor, and on the forbidden bandwidth for a fixed impurity concentration.

The electrical conductivity is highly anisotropic the value in the direction perpendicular to the c-axis exceeds that in the direction parallel to it by almost an order of magnitude in the low temperature region while in the high temperature by little orders of magnitude.

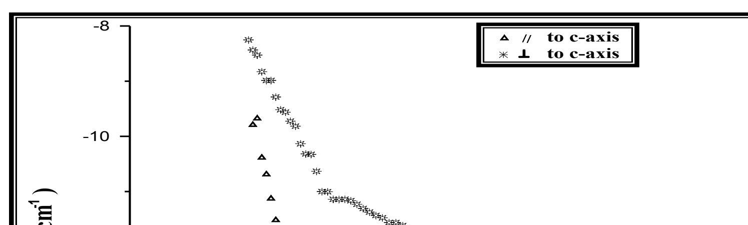

Fig. 1. Plot showing the behavior of electrical conductivity (σ) of $TlGaS_2$ with temperature

Fig.2 represents the variation of anisotropic factor with temperature. The high value of the electrical conductivity across the layers many be due to the presence of "two dimensional" defects located between the layers in real semiconductor and responsible for the carrier motion across the layers. Fig.2 shows the ratio of the electrical conductivity $\sigma_{//}/\ \sigma_{\perp}$ as a function of reciprocal temperature in the same investigated temperature range according to Maschke and Shmid equation[28]

$$\sigma_{//}/\sigma_{\perp} = Ae^{-\Delta E/KT}$$

which verify this relation.

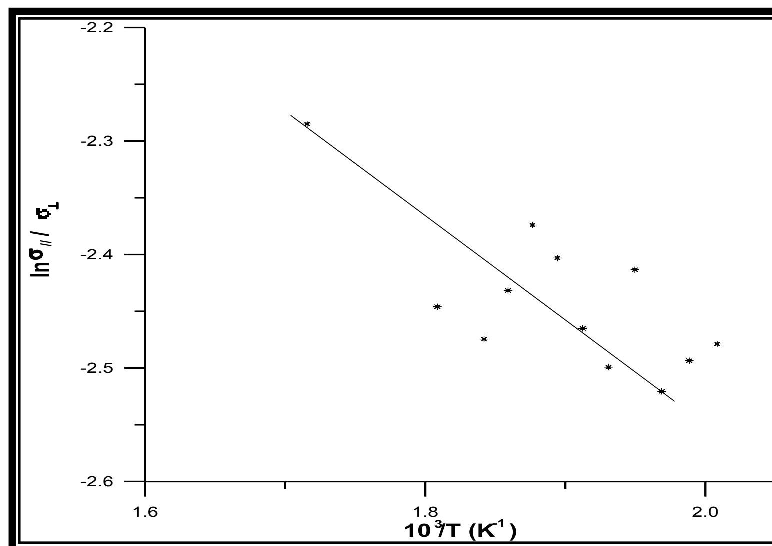

Fig. 2. Variation of anisotropic factor of $TlGaS_2$ with temperature

The temperature dependence of Hall coefficient was measured in two directions of magnetic field, one when the magnetic field is parallel to the c-axis and allowing the current to flow at right angle to this axis ($J \perp C$ // H) denoted by $R_{H//}$ and the other corresponding to the case of transposition of the direction of current and magnetic field compared with $R_{H//}$ (J // C $\perp$ H) and denoted by $R_{H\perp}$.

From the results of the experimental measurements we sea that Hall coefficient of $TlGaS_2$ has a positive sign, which indicates a p-type conductivity for our investigated $TlGaS_2$ sample.

Fig.3 represents the relation between Hall coefficient and temperature, from which can distinguish three regions. The intrinsic region in which the Hall coefficient varies linearly and

rapidly with temperature, while in the impurity region it varies slowly with temperature. An intermediate region is observed between these two region. At room temperature the values of $R_{H//}$ =1.187x10^{11}cm^3/c and $R_{H\perp}$=1.074x10^{11}cm^3/c. The results of Hall effect give evidence for the values of ionization energy of acceptor atoms and the energy gap width obtained from electrical conductivity curves, As calculated from the relation between $\ln R_H T^{3/2}$ and 10^3/T as seen in fig.4.

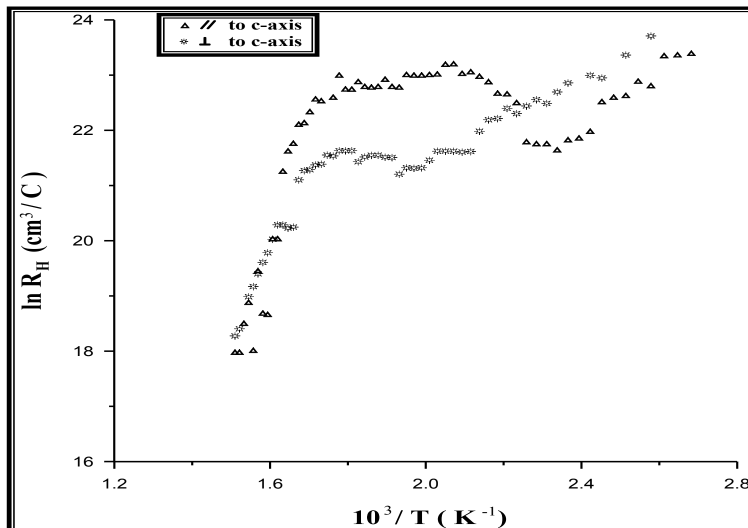

Fig. 3. Plot showing relationship between Hall coefficient and temperature for $TlGaS_2$

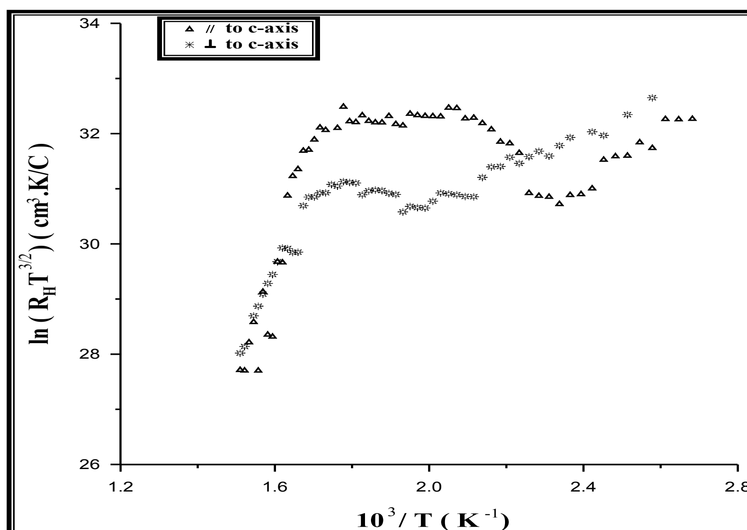

Fig. 4. Shows the relation between $R_H T^{3/2}$and 10^3/T of $TlGaS_2$

The mobilities of charge carriers moving in the large plane and perpendicular to it depend on temperature. This dependence is shown in fig.5. Two region can be distinguished, low-temperature region in which the mobility seems to increase slowly with increasing temperature. In this range of temperature all the mobilities exhibit approximately the temperature dependence $T^{1.6}$ law which can be attributed to the impurity scattering.

At high temperature both $\mu_\perp$ and $\mu_{//}$ follow α $T^{-1.3}$ dependence. This leads to the assumption lattice scattering dominates and impurity concentration has little effect on the mobility. In this region the mobility seems to decrease with increasing temperature lattice scattering which is due to thermal vibration of the atoms in the crystal, disrupts the periodicity of the lattice and thereby impedes the motion of free carriers. The variation in the value of $\mu_{//}$ and $\mu_\perp$ can be attributed to strong anisotropy of carrier motion and normal to the layer plane and the position

of macroscopic defects which are responsible for the carrier motion. At room temperature $\mu_{//}$ and $\mu_{\perp}$ are estimated as 1.079×10^3 and 1.2×10^4cm/V.sec., respectively.

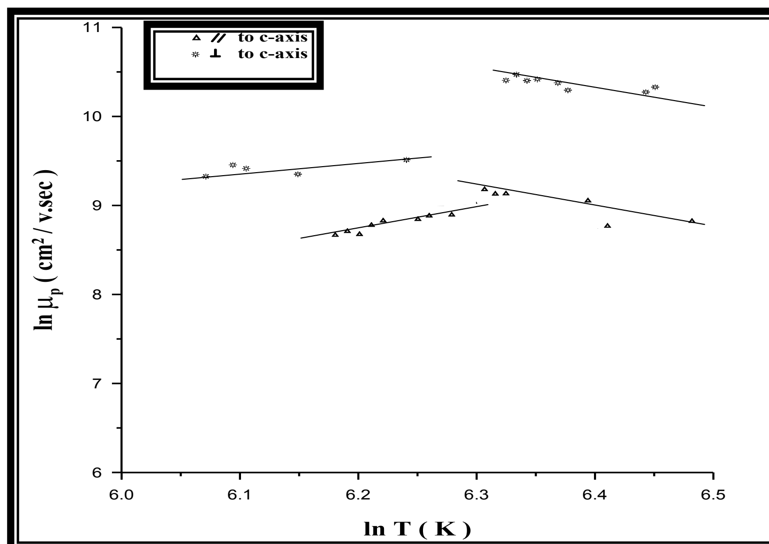

Fig. 5. Dependence of mobillities of charge carriers with temperature for $TlGaS_2$

The relation between carrier concentration and temperature is illustrated in fig.6. In the intrinsic region the following relation is considered

$$P_i = (N_C N_V)^{\frac{1}{2}}\, e^{-(\Delta E_g/2KT)}$$

From this relation the forbidden gap width and the ionization energy are calculated, and these values show good agreement with our obtained values.

From fig.6 one can notice that the concentration of carrier in the intrinsic region increases rapidly with temperature, while it increases slowly with temperature in the impurity region.

At room temperature the concentration of free carrier lies between 1.30×10^7cm^{-3} and 6.57×10^7cm^{-3}.

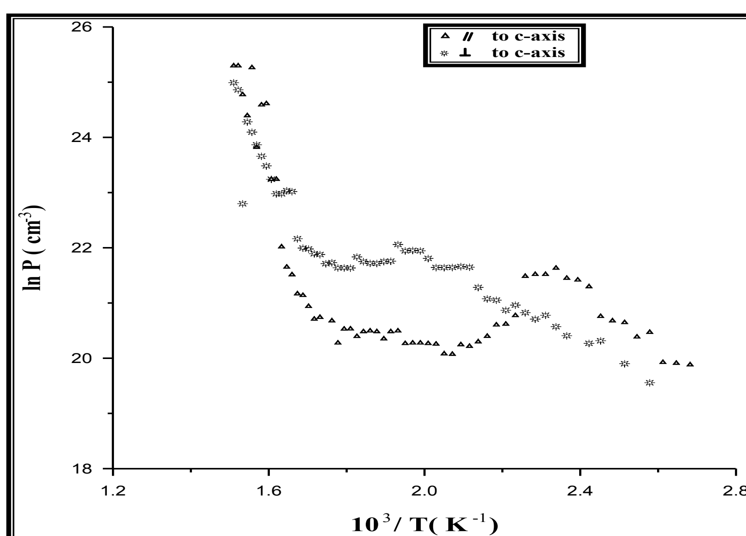

Fig. 6. Plot showing the relationship between carrier concentration and temperature for $TlGaS_2$

4-Conclusion

High pure starting materials were used for the preparation of $TlGaS_2$crystals by Bridgman technique. The resulting ingots were identified by x-ray analysis. All measurements were

taken under vacuum condition in a special crystal designed for this purpose. The measurements were made over a wide range of temperature. Results of measurements of the Hall coefficient indicate a p-type conductivity for our investigated samples, The variation in the mobilities parallel and perpendicular to c-axis were attributed to strong anisotropy of carrier motion along and normal to the layer plane and the position of the macroscopic defects which are responsible for the carrier motion. The scattering mechanism as well as the anisotripic factor was checked. The electrical conductivity and carrier concentration are observed to decrease while the Hall coefficient increases with decreasing temperature.

References

[1] **Ashraf, I. M., Abdel-Rahman, M. M.,** and **Badr, A. M.,** *J. Phy. D. Appl. Phys.* **36**;109 (2003).
[2] **Song, Ho-jun, Yun, Sang-Hyun,** and **Kim,** *J. Phys. Chem.. Sol.* **56**;787 (1995).
[3] **Guseinov, B. G., Guseinov, G. D., Guseinov, N. Z.,** and **Kyazinov, S. B.,** *Phys. Stat. Sol.* (b) **133**,25 1986).
[4] **Hanis, M. P., Anagnostopuls, A. N., Kambasand,K., Spyridelis, *J.,*** *Mat. Res. Bull.,* **27**;25 (1992).
[5] **Gürbulak, B.,** *Phys. Stat. sol.* (a) **184**, 349 (2001).
[6] **Abay, B., Güder, Efeoglu, H., Yogurtcu, Y. K.,** *Phys. Stat. Sol.* (b) **227**, 469 (2001).
[7] **Kato, A., Nishigaki, M., Mamedov, N., Yamazaki, M., Abdullayeva, S., Kerimova, E., Kato, H. A.,** and S. lida, *J. Phys. Chem. Sol.* **64,** 1713(2003).
[8] **Yuksek, N. S., Gasanly, N. M., Aydinli, A., Ozkan, H.,** and **Acikgoz, M.,** *Cryst. Res. Technol.* **39**;800 (2004).
[9] **Mikailov, F. A., Kuzan, S., Rameev, B. Z., Kulibekov, A. M., Keaimova, E.,** and **Aktas, B.,** *Sol. Stat. Commum. 138, 239 (2006).*
[10] **Yuksek, N. S., Gasanly, N. M., Ozkan, H.,** *Semicond. Scien. Technol.* **18**;834 (2003).
[11] **Belenkü, G. L., Abdullayeva, S. G., Solodukhin A. V., and Suleymanov, R. A.,** *Sol. State. Commun.* **44;**1613 (1982).
[12] **Kurbanov, M. M.,** *Inorganic Material* **39;**916 (2003).
[13] **Delgado, G. E., Mora, A. J., Perez, F. V.,** and **Gonzalez, J.,** *Physica B:Cond. Matter* **391:**385 (2007).
[14] **Henkel, W., Hochheimer, H. D., Carlone, C., Wener, A., Ves. S.,** and **Schering, H. G.,** *Phys. Rev. B.**26;**3211 (1982).*
[15] **Perez, F. V., Cadenas, R., Power, C., Gonzalez, j.,** and **Chervin, C. J., Applied, J.,** *Phys.* **101;**63534 (2007).
[16] **Kalkan, N., Kalomiros, J. A., Hanias, M.,** and **Anagnostopoulos, A. N.,** *Sol. Stat. Commum.* **99;**375 (1996).
[17] **Ashraf, I. M.,** *J. Phys. Chem.* B., **108;** 10765 (2004).
[18] **Qasraili, A. F., Gasanly, N. M.,** *Semicond. Scien. and Technol.* **20;**446 (2005).
[19] **Mikailov, F. A., Kazan, S., Rameev, B. Z., Kulibekov, Kerimova, E., Aktas, B.,** *Sol. Stat. Commum.* **138;**239 (2006).
[20] **Allakherdiev, K. R., Mammedov, T. G., Syleymanov, R. A.,** and **Gassanov, N.Z.,** *J. Phys. Condens. Matter* **15;**1291 (2003).
[21] **Aydinli, A., Elliatiogluk, R. Allakhverdiev, R., Ellialtioglu, S.,** and **Gasanly, N. M.,** *Sol. Stat. Commun.* **88;**387 (1993).
[22] **Gasanly, N. M., Dzhavadov, B. M., Ragimov, A. S., Tagirov, V. I.,** and **Guseinov, R.E.,** *Physica* B+C,**112**;78 (1982).
[23] **Mustafaeva, S. N., Aliev, V. A.,** and **Asadov, M. M.,** *Phys. Semicond.* **40;**561 (1998).
[24] **P**anich, A. M., and **Kashida, S.,** *J. Phys. Cond. Matter* **20;**39521 (2008).
[25] **Hussein, S. A.,** and **Nagat, A. T.,** *Ctyst. Res. Technol.* **24;**283 (1989).
[26] **Isenberg, j., Russel, B. R.,** and **Green, R. F.,** *Phys. Rev.* **79;**286 (1950).
[27] **Maschke, K.** and **Shmid, P.,** *Phys. Rev.* (B)**12;**4312 (1975).