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Experimental Investigation of Electrical Conductivity and Hall Effect in $GaInTe_2$ Single Crystals

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Abstract: $GaInTe_2$ single crystal has been grown by a modified Bridgman technique. Conductivity type, carrier concentration and carrier mobility of $GaInTe_2$ sample were determined by Hall Effect and electrical conductivity measurements. Our study was performed in the temperature range 173-473 *k*. The sample under test was *P*-Type conducting. The Hall coefficient was found to be 9.7×10^9 cm^3/c yielding room temperature hole concentrations 6.44×10^9 cm^{-3}. The Hall mobilities of $GaInTe_2$ calculated to be 6850.99 $cm^2/v.sec$ at room temperature. The band gap of $GaInTe_2$ has determined to be 1.7 *eV*, whereas the ionization energy has the value 0.2 *eV*. The scattering mechanism of the carrier in the whole temperature range of investigation was checked.

Key words: Crystal Growth, GaInTe2, Electrical Conductivity, Hall Effect.

INTRODUCTION

Amorphous and crystalline chalcogenide semiconductors have been studied for many years because of their interesting physical properties and many potential applications (Wu, C.C., *et al*, 2005). Chalcogenide materials have the potential abilities to be applied in IR optical devices, optical fiber, optical storage and solar cells, etc. There is increasing interests in ternary compound semiconductors with the general formula 111-111-VI2 owing to their attractive physical properties: anisotropic, quasi-two dimensional structure and unusual optical and photoelectric characteristics. Since the 1990s, telleurium-based chalcogenide materials have been extensively studied for the applications to semiconductor memories. Among them $GaTe_2$ and $GaInTe_2$ are two interesting subjects of the numerous studies. The compound $GaInTe_2$ has not yet been studied in sufficient detail (Gojaev, E.M., *et al.*, 2010). Like the other ternary compound semiconductors of the family in question, this material has many applications from solar cells to nonlinear optical technologies (Gojaev, E.M., *et al*, 2011). Moreover, it can readily be intercalated with foreign ions, atoms and molecules, which suggest the possibility designing tunable super lattices based on this compound. Nevertheless to our best knowledge relatively good data exist for this semiconductor compound. In view of the scarcity of the data on the properties of gallium indium ditelluride the aim of this proper is to throw some light on the actual behavior of this compound and to reveal the contradictions of the previous results. The objective of this work is to grow $GaInTe_2$ single crystals and to study the conductivity and Hall Effect in the crystal.

Crystal Growth:

$GaInTe_2$ single crystals were grown by a modification of the Bridgman technique by using the Travelling Solvent Method (TSM). Details of the three –zones furnace and the new hydrolic pulling system have been previously published (Gojaev, E.M., *et al*, 2010). The samples used in this work were prepared by this technique from stoichiometric amounts of pure (*8N*) elements (Aldrich Mark) in an evacuated (10^{-6} *Torrs*) and sealed silica tube. In the present research the elements were 13.055 *g* of In (representing 26.1109% of the compound), 7.9274 *g* of Ga (representing 15.8548% of the compound) and 29.0175 *g* of Te (representing 58.0343% of the compound). The mixture was melted and then homogenized at 1240 *k* for 24 *h*. In this process, the ampoule was shaken at short intervals to improve intermixing of the constituents. The temperature was then reduced to 970 *k* which corresponding to the crystallization temperature by lowering the ampoule at a rate of 1.4 *mm/h*, followed by 10 *h* holds. After cooling to room temperature, the product ingot had a black color with metallic luster which in accordance with published data (Gojaev, E.M., *et al*, 2010). The crystal was characterized by XRD and DTA. Analysis of its XRD pattern and DTA showed that it was phase pure and had a tetragonal structure with the unit cell parameters a=8.361 *Å*, C= 7.33 *Å*.

Experimental Measurements:

For studying electrical conductivity and Hall Effect, the sample was prepared in a rectangular shape. After polishing processes, the sample dimension was 10.3x3.4x2.6 mm^3. In this way, the length of the sample was

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three times of its width to avoid Hall voltage drop. The *DC* Hall measurements were carried out as recommended in ASTM-F67 and quite similar to those described earlier (Gojaev, E.M., *et al*, 2007). Electrical conductivity and Hall Effect were measured under vacuum ≈of 10^{-3} *Torr*. Measurements above room temperatures were performed with the help of an electrical insulated heater, which was supplied with required voltage, gradually and slowly, from a variable transformer. Liquid Nitrogen was used for achieving the low temperature measurements. Calibrated thermocouple, made of copper constantan was used for measuring the temperature of the sample. GMW electromagnet model 5403, with digital Tesla-meter DTM-133 was employed to supply an intermediate magnetic field≈ 0.55 *Tesla*. The conductivity and Hall coefficient were measured by compensation method in a special cryostat with a conventional dc type measurement system. The Hall voltage was measured by reversing the current and magnetic field directions and taking the appropriate averages. The designed cryostat allows measurements in a wide range of temperature. Silver paste contact was used as ohmic contact. The ohmic nature of the contacts was verified by recording the current-voltage characteristics.

RESULTS AND DISCUSSIONS

Measurement of the effect of temperature on electric conductivity σ was done from 173 to 473 *k* in $GaInTe_2$ crystals as shown in Fig. 1. The curve shows a typical semiconductor behavior

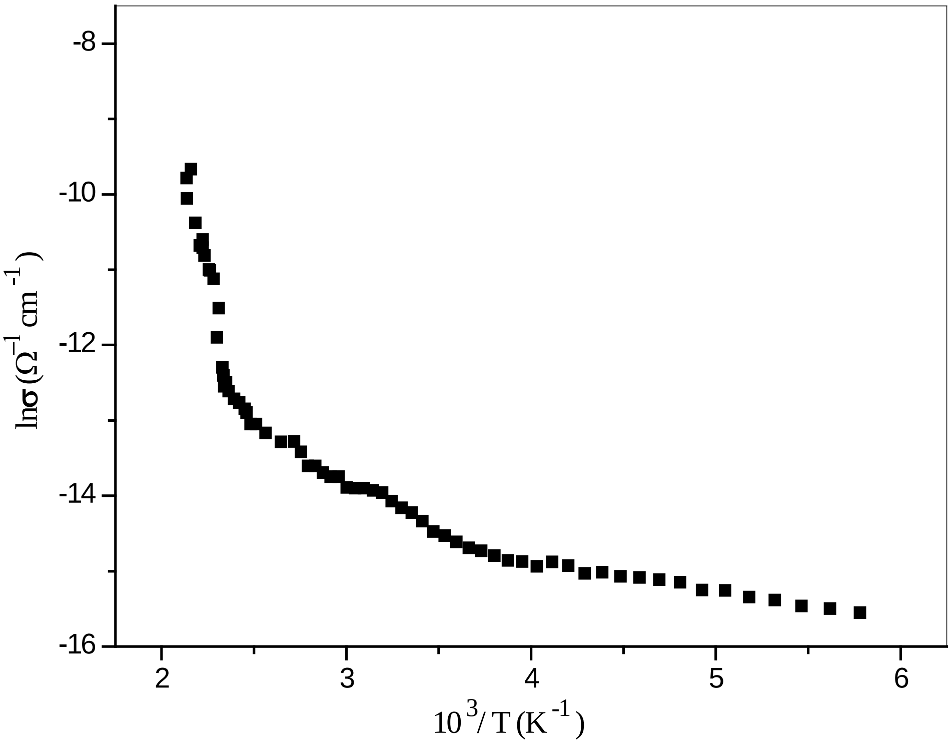

Fig. 1: Temperature dependence of the electrical conductivity for $GaInTe_2$ single Crystal.

In Fig. 1. σ increases slowly in the low temperature range (the extrinsic region) as a result of libration of the ionized acceptors and their transition from the impurity level. In the low temperature part the relation between the temperature and electric conductivity can be given as

$$\sigma = \sigma_0 \exp(-\Delta\, E_a/2KT) \qquad (1)$$

Where σ_0 is the pre-exponential factor and ΔE_a is the ionization energy of acceptors. This is observed in the temperature interval 173-250 *k* and ΔE_a was found to be 0.1 *eV*. The second region represents the transition region where the behavior of σ is governed by the behavior of both the charge carrier concentration and their mobilities. The exhausting region extended from 250 up to 400 *k*, which is characterized by exponentially increases of electrical conductivity with a relatively speed rate. A rapid increase in the conductivity with linearity is observed in the high temperature range above 400 *k*. This reveals that both electrons and holes contribute in the conduction at this high-temperature range. The dependence of this temperature range follows the relation:

$$\sigma = \sigma_0 \exp(-\Delta E_g / 2KT) \qquad (2)$$

Using this formula, the energy gap $\Delta E_g = 2.4$ *eV*. This value contrasts with the data of other author (Gojaev, E.M., *et al*, 2005).The calculated energy gap width from the relation between $\ln \sigma$ and $10^3/T$ is larger than that in the literature. We may attribute the discrepancy between the value of ΔE_g due to the presence of large number of intrinsic defects that affect strongly the motion of scattering of current carriers and phonons. This effect disappears when we used the Hall coefficient for the determination of ΔE_g from Hall Effect. the electrical conductivity at room temperature was measured to be about$7.063\times10^{-7}\Omega^{-1}\text{cm}^{-1}$ Since Hall effect is important and helpful for the determination of many physical parameters, this work was extended to cover the effect of temperature on the Hall coefficient R_H as shown in Fig. 2.

Fig. 2. show relationship between Hall coefficient and temperature for $GaInTe_2$ single crystal

This was done in a wide range of temperature (173-473 *k*). From the measurements of Hall coefficient, it is evident that the sign of the Hall coefficient of $GaInTe_2$ is positive in the entire temperature range of investigation. This indicates the compound is *P*-type semiconductor, which is in reasonable agreement with the results of other published data (Hussein, S.A., *et al*, 1989).

The Hall coefficient at room temperature was evaluated as 9.7×10^9 cm^3/c. Determination of the energy gap and Ionization energy from Hall data is possible by plotting the relation between $\ln R_H\, T^{3/2}$ and $10^3/T$ as shown in Fig. 3 on the basis of the following relationship:

$$R_H\, T^{3/2} \propto \exp(-\Delta E_g / 2KT) \qquad (3)$$

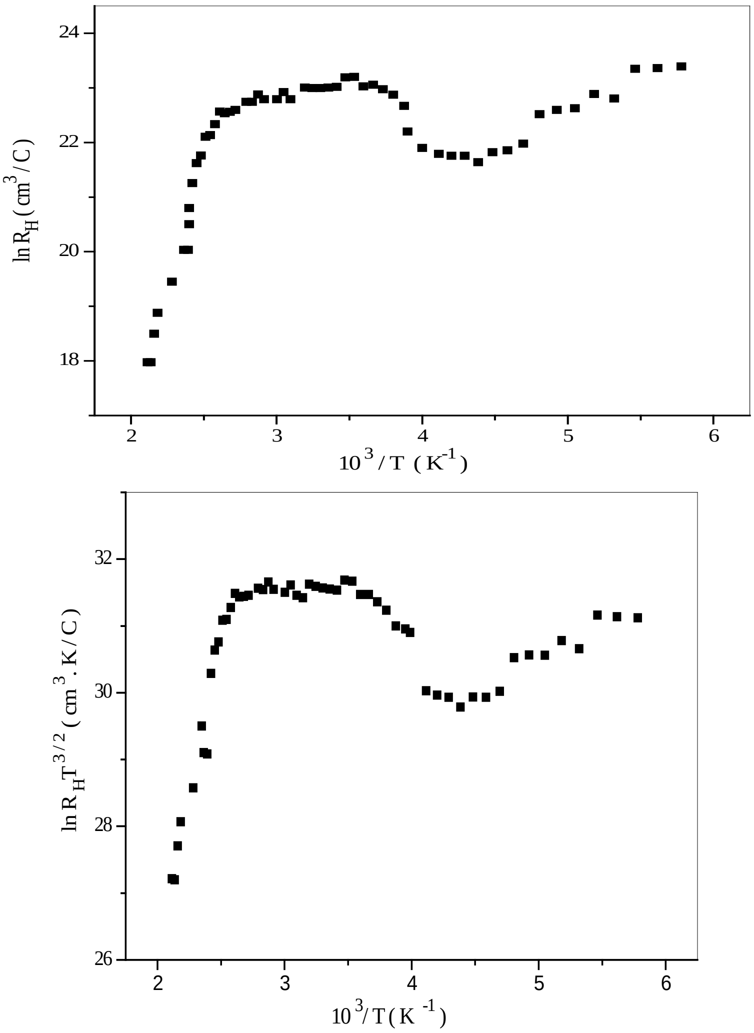

Fig. 3: Relation between $R_H T^{3/2}$ and $10^3/T$ for $GaInTe_2$ single crystal.

In the temperature region in which the conductivity is predominantly intrinsic, the forbidden band width was estimated to be ΔE_g=1.7*eV*. The depth of the acceptor center was determined from the region in which the conductivity is predominantly due to impurity atoms and was found to be 0.2eV. These values are in good agreement with the published values (Nagat, A.T., 1989).

The curve shows the following facts:

The three regions of the curve support that extrinsic conduction appears from 173-250 *k* and intrinsic one begins from 400 to 473 *k*, while the transition region lies between 250 and 400 *k* as observed in Fig. 1.

As for the importance of the mobility data in the field of solids, especially semiconductors, the present work has dealt with the investigation of the effect of temperature on the free carrier mobility. The reason for this is to spot some light on the scattering mechanism of the charge carrier.

A combination of the hall measurements and the electrical conductivity data was used to study the temperature dependence of the Hall mobility of the charge carriers. Fig. 4 depicts the variation of μ as a function of temperature

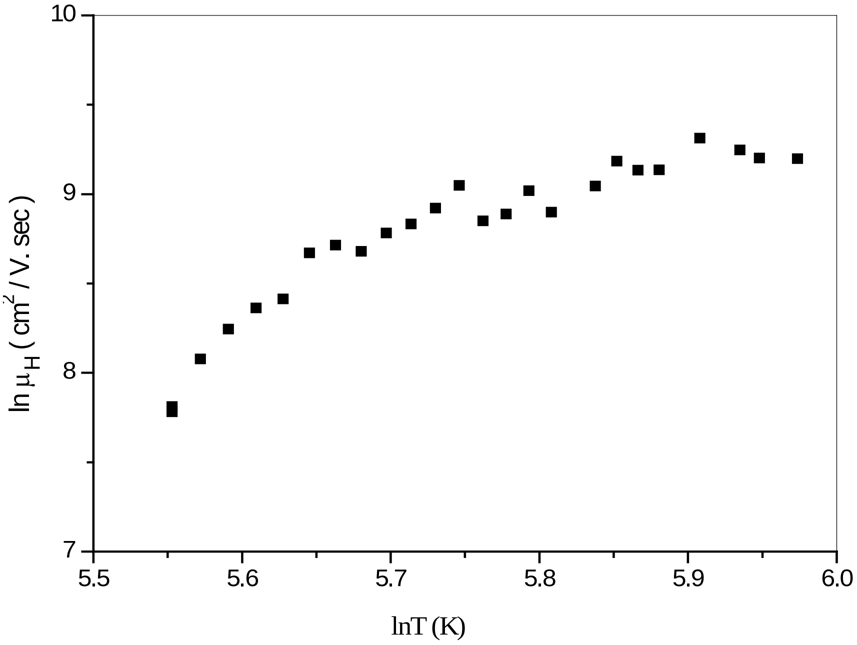

Fig. 4: The behavior of Hall mobility as a function of temperature for $GaInTe_2$ single crystal.

From the graph one may conclude that, the general behavior of μ against T can be divided in to two parts.

1) The low temperature part, which corresponds to the extrinsic conduction and the mobility, seems to increase as the temperature increases reaching maximum value at 11.083x10^3 *cm²/v.sec*. Corresponding to 368 *k* and obeys a power low $\mu \approx T^{4.4}$. Such behavior is unusual compared with those obtained in other semiconductors, but this behavior is noticed in other ternary chalcogenide semiconductor $TIGaTe_2$ (Mobark, M., *et al*, 1998). More efforts are needed to throw a clear light upon this behavior.

2) The high temperature part, is the intrinsic conductivity part, in which the mobility decreases with increasing temperature. In this region the mobility decreases according to the law $\mu \approx T^{-1.9}$ indicates that stoichiometric vacancies and certain defects are responsible for scattering processes. This usually occurs in defect-semiconductor at high temperature.

3) At room temperature μ_H = 6850.9 *cm²/v.sec.*

The typical behavior of the carrier concentration as a function of temperature is illustrated in Fig. 5.

Now, it is well established, in the text, that within the intrinsic region of conduction the following relation can be applied to describe the temperature dependence of the charge carrier concentration.

$$p_i = c\ \exp(-\Delta E_g / 2\,KT) \tag{4}$$

This relation facilitates calculation of the energy gap. The value of ΔE_g Agrees with that obtained from Fig. 3 and the published value.Furthermore, at room temperature carrier concentration calculated to be 6.44x10^9 cm^{-3}. Calculation of the diffusion coefficient for holes gave a value of 171.7 *cm²/sec*.

Assuming that the effective mass for holes is equal to the rest mass and using the value for the hole mobility at room temperature, the mean free time could be determined and its value was equal to 3.939X10^{-12} *sec*. Also the diffusion length of holes in $GaInTe_2$ specimen was evaluated as 2.597X10^{-5} *cm*.

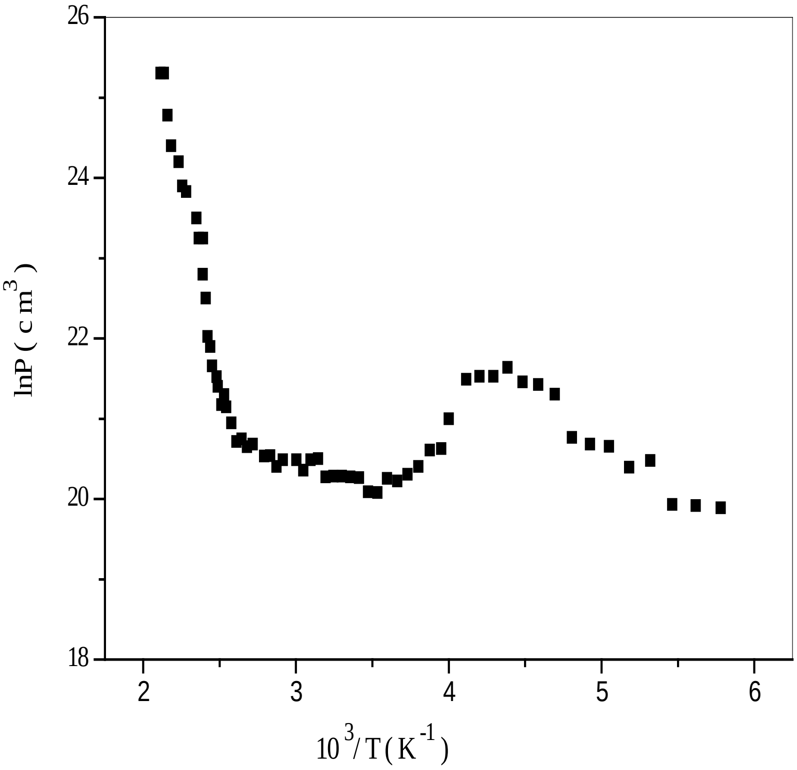

Fig. 5: Variation of Holes concentration with temperature for $GaInTe_2$ single crystal.

Conclusion:

Measurement of the electrical conductivity and Hall Effect were carried out in a wide range of temperature (173-473 *k*) for gallium indium ditelluride monocrystals. The crystals were grown in single crystal form by a modified Bridgman technique. High pure starting materials were used for the preparation of $GaInTe_2$ in the form of large cylindrical ingots of dark metallic luster and were identified by XRD and DTA analysis. All measurements were taken under vacuum conditions in a special cryostat designed for this purpose. Results of measurements on the Hall coefficient indicate a *P*-type conductivity. The energy gap was found to be 1.7 *eV* and the depth of the acceptor level was found to be 0.2 *eV*. The hole concentration at room temperature 6.44 x 10^9 cm^{-3} conductivity and Hall mobility at 300 *k* was evaluated as 7.063x10^{-7} $(\Omega\ cm\ )^{-1}$ And 6850.9 9 $cm^2/v.sec$ respectively. Other important parameters such as diffusion coefficient, diffusion length and the relaxation time for holes were estimated.

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