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Electrical Characterization of GaTe and GaTe:Cu Semiconductor Compounds

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Abstract

Electrical properties of GaTe and GaTe:Cu binary compound semiconductors were investigated by Hall effect and resistivity measurements in the 77-320 K temperature range. Donor and acceptor densities, compensation ratios, acceptor ionization energies, valence band effective mass of holes and effective density of states in valence band were determined for the undoped and Cu doped samples using the single donor-single acceptor analysis of the hole concentration. Temperature coefficient of the hole mobility was determined and compared with related theories.

Key Words: Electrical characterization; layered semiconductors; GaTe.

1. Introduction

Gallium compounds such as GaTe, GaSe and GaS crystallizes in a layer structure characterized by perfect cleavage planes, as they have weak Van der Waals forces between the layers, but with strong covalent bonds in the layer plane [1]. The crystal structure of GaTe is more complicated than the others. It presents a monoclinic structure consisting of four-layer Te-Ga-Ga-Te packets joined together by Ga-Ga bonds, which lie approximately at right angels to the interlayer Ga-Ga bonds [2] while the others have hexagonal structures. The new Ga-Ga bonds that appeared in monoclinic GaTe structure are thought to present the strong anisotropy to its physical properties [3]. The anisotropic properties is attractive to investigators in that it may help them to acquire a better insight GaTe.

2. Experimental Procedure

For the present work, high quality GaTe and GaTe:Cu (0.5 wt.% Cu) single crystals were grown by Bridgman-Stockbarger method. The crystals were examined by Energy Dispersive X-ray analysis (EDAX) with a Rigaku X-ray diffractometer. Surface and stoichiometry analysis of samples were performed by Electron Microprobe Analysis (EMPA) with a JEOL JSM-6400 Scanning Electron Microscope. They were found to be nearly stoichiometric.

The samples for the electrical measurements were cleaved from the grown ingots with a razor blade. No further mechanical and chemical treatment were required because of the natural mirror-like surfaces of samples. Ohmic contacts were made by In evaporation of 6Ns purity on bar-shaped samples under $\sim 10^{-5}$ mbar pressure, followed by an annealing at 250°C in nitrogen atmosphere for 20 minutes. Hall effect and resistivity measurements were carried out along the layers using direct current applied perpendicular to the sample and field between 77 and 320 K, at a magnetic field of 0.9 T.

A detailed analysis of the electrical data was carried out by fitting the experimental results with the relation given by the single donor-single acceptor model. This model is able to give the following information for a p-type material: a) the concentration of acceptors; b) the ionization energy of acceptor levels; c) the compensation ratio; d) the value of effective mass; and e) the effective density of states in the valence band.

3. Analysis of the Results and Discussion

All of the samples used in this work were determined as p-type conduction by thermal electromagnetic force (emf) and Hall effect measurements. The hole concentration was evaluated by using $p = r/(eR_H)$relation where e is the electronic charge, R_H is the Hall coefficient and r is the mobility ratio, which was taken to be $r = 1$. Assuming that the crystals contain a single set of acceptor levels of concentration N_A with an ionization energy E_A and a single set of compensating donors of density N_D, in the single donor-single acceptor model the carrier concentration p is given by the expression [4]

$$\frac{p(p+N_D)}{(N_A-N_D-p)N_v'} = \frac{1}{\beta}\left(\frac{m_h^*}{m_0}\right)^{3/2}\exp\left(-\frac{E_A}{k_BT}\right). \tag{1}$$

where, β is the impurity-spin degeneracy factor, k_B is the Boltzman constant, T is the absolute temperature, $N_v' = 2\left(2\pi k_BT/h^2\right)^{3/2}$ and m_h^* is the valance band effective mass of holes. We first theoretically reproduced the left hand side of Eq. (1) using experimental p values to determine the values of N_A and N_D. Then the logarithm of the left side of Eq. (1) was plotted against $(1/k_BT)$. This plot results in a straight line only for the correct values of N_A and N_D. In the low temperature range, the plot of the right hand side of the Eq. (1) against $(1/k_BT)$ can be well fitted in order to give the values of β, m_h^* and E_A. The parameters evaluated from the fitting procedure of Eq. (1) to the experimental data with the $\beta = 2$, $m_h^* = 0.6m_0$ and $N_v = 1.16 \times 10^{19}\text{cm}^{-3}$ values for GaTe and GaTe:Cu

samples are listed in Table 1. The plots corresponding to this fitting procedure for the two samples have been shown in Figure 1(a) and (b).

Table 1. Best fit parameters for the single donor-single acceptor model.

Sample	ϱ (300K) (Ω-cm)	p(300K) (cm^{-3})	N_A (cm^{-3})	N_D (cm^{-3})	E_A (meV)	K
GaTe	13	8.85×10^{15}	1.78×10^{17}	8.4×10^{16}	128	0.47
GaTe:Cu	9	3.59×10^{16}	2.60×10^{17}	1.1×10^{17}	63	0.42

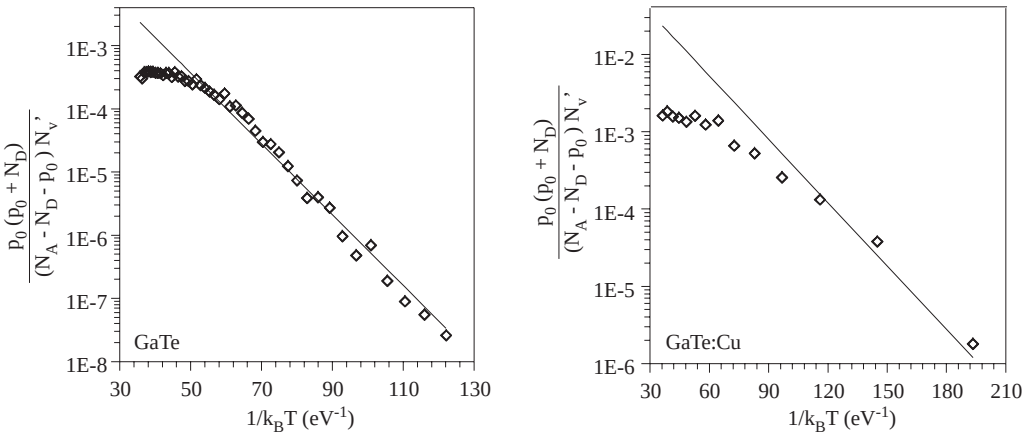

Figure 1. Results of single donor-single acceptor analysis for (a) GaTe and (b) GaTe:Cu samples.

According to Table 1, resistivity, compensation ratio (K) and the ionization energy decreases while the hole concentration increases with the impurity (Cu) content. The value of E_A is in agreement with previously published data in literature for GaTe [5,6]. When calculated theoretically by the hydrogenic impurity model, considering the dielectric constant value ($\varepsilon = 7.3$) of GaTe, one can obtain a value of $E_A = 153$ meV for the acceptor ionization energy. Thus, ionization energy values obtained in this work imply that impurity levels observed in GaTe are hydrogenic levels. Decreasing of the ionization energy for the Cu doped sample may be due to the compensation of existing levels by Cu atoms occuring new impurity levels.

Temperature dependent Hall mobility data were evaluated from the $\mu_H = \sigma R_H$ equation, from which we plotted the logarithm of μ_H against $(\ln T)$ for the two samples. This plot results in a straight line and its slope gives the temperature exponent (n) of the $\mu_H \propto T^{-n}$ relation. We determined the temperature exponents from Figure 2 as $n = 1.99$ for GaTe and $n = 2.1$ for GaTe:Cu samples. Figure 3 represents the expected n values for

different electron (hole) -lattice interactions, which can exist in layered structures, as a function of optical phonon energy $\hbar\omega$ for various semiconductors. In this figure, curve (a) refers to the scattering by acoustical modes which produces a mobility proportional to T^{-1} in the two-dimensional limit since the density of states is constant in this limit, curve (b) represents the polar case which can be of importance in compounds having elements of different electronegativities and results from the variational calculation of the mobility in the two-dimensional limit and curve (c) describes the scattering effects of homopolar optical modes [7].

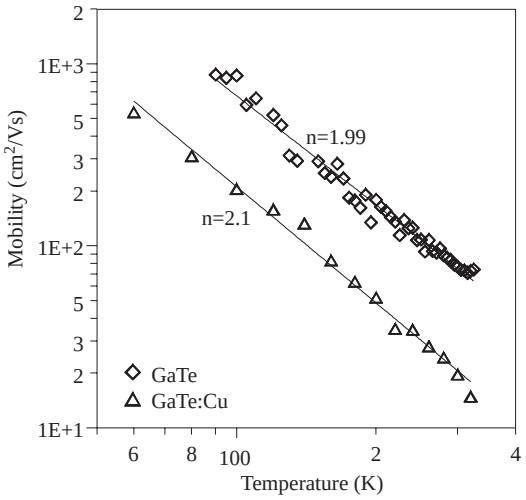

Figure 2. Mobility vs. temperature for GaTe and GaTe:Cu samples.

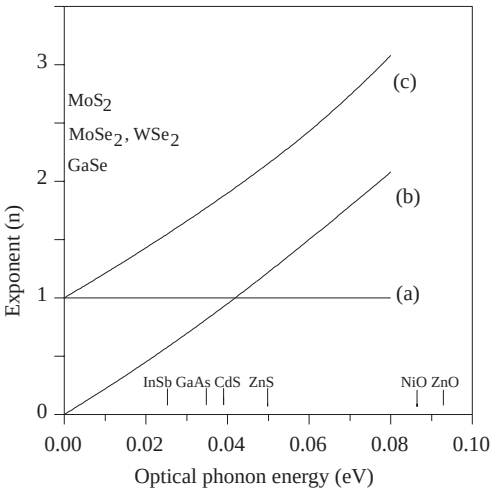

Figure 3. n exponent values as a function of optical phonon energy ($\hbar\omega$) [7].

Inspection of Figure 3 readily shows that a dominant scattering by homopolar optical phonons is the best hypothesis one can make to interpret the experimentally obtained exponents. None of the exponents obtained in this work is indeed close to the expected values for acoustical or polar scattering. It can be seen from Figure 3 that these values of n lies in the homopolar optical phonon scattering range. Therefore, on the basis of these measurements, we can safely say that these results of n imply that the main scattering process controlling the carrier transport in GaTe is the homopolar optical phonon scattering.

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