SCATTERING MECHANISMS OF CHARGE CARRIERS IN GALLIUM ANTIMONIDE DOPED WITH IRON

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Abstract

Obtaining, homogenizing, and purifying technologic conditions for gallium antimonide doped with iron and simultaneously doped with iron and tellurium are described. According to the research of galvanometric features of nondoped gallium antimonide and gallium antimonide doped with 3 at % iron concentration for the temperature range of 4.2÷300 K, the mechanisms of charge carrier scattering are analyzed. It is demonstrated that for explanation of experimental data obtained for the U = U(T) function it is necessary to involve an additional mechanism of charge carrier scattering specific to the inclusions formed in gallium antimonide – clusters. Using the physical conceptions of this mechanism, the basic characteristics of scattering of the charge carriers determined by clusters are determined.

1. Introduction

Gallium antimonide stands out chemical combinations of $A^{III}B^{V}$ family with strong properties of semiconductors. The scientific and applicative interest in gallium antimonide (E_g = 0.7 eV) is determined by the following: it is the only material from the great family of $A^{III}B^{V}$ semiconductors in the structure of power bands; the energy gap band is approximately identical to the spin-orbit splitting; the crystalline lattice constant is correlative (within Vegard law) with the crystalline lattice periods of a great number of alloys of $A^{III}B^{V}$ combinations. It can be used as a substrate in various microelectronic structure technologies; it can be successfully presented in technologic processes as passive and active material within heterostructures; on the basis of these heterostructures, optoelectronic systems for a spectral range of 0.8÷4.1 μm may be constructed [1]. Non-doped gallium antimonide obtained by different technologic methods is a material with type-p conductivity. The acceptors that determine physical features of non-doped gallium antimonide are the vacancies in gallium or stibium sublattices or impurity structures of GaSb type [2]. The problem of behavior of dopant from transition element group, for instance, Fe, Ni, Cr, and Mn in gallium antimonide is urgent and disputable. Only two works are known in which the physical properties of gallium antimonide doped with iron [3] and with manganese [3] have been analyzed. In work [4] it is proved that manganese in gallium antimonide forms some inclusions oriented along the direction of melting zone displacement, which modifies the mechanisms of charge carrier scattering. The modifications of charge carrier scattering mechanisms in gallium antimonide doped with iron have not been studied.

In the present work the mechanisms of charge carrier scattering in gallium antimonide doped with iron within a concentration range of 0.01÷2.0 at %, in a temperature interval of 4.2÷300 K are studied. The results of scattering mechanism modification in gallium antimonide with double doping – iron + tellurium - are presented.

2. Results and discussion

Doped and non-doped gallium antimonide studied in this work was obtained using the technological process with the following components: the synthesis of gallium antimonide from pure elements (gallium, stibium) and iron and tellurium dopants in set concentrations in evacuated optic quartz test-tubes; the container with respective components was installed in the electric furnace in which a temperature of 900°C was maintained; it was connected with a mechanic vibrator with a 50 Hz frequency. In the above mentioned technologic conditions the synthesis process lasted for 24 hours, after that the electric furnace with the container in which the synthesis took place was freely cooled. The next stage of the technologic process of gallium antimonide obtaining is homogenization and growing of single crystals in the zone melting installation. The main components of this installation are the following: an additional furnace with a temperature of 400°C was and a mobile electric furnace with a width of 5 cm, in the center of which a temperature of 720°C was maintained. In terms of construction, the installation allows us to vary the rate of melting zone displacement, as well as the displacement direction. The homogenization process contains 20 cycles of the melting zone displacement with a rate of 5mm/hour (the cycle consists of the melting zone displacement in one direction and in the opposite one); the last procedure of single crystal growth is the melting zone displacement in one direction with a rate of 1 mm/hour. The crystallization melting zone is displaced in electric field of a certain orientation. The technologic installation diagram used in this work is presented in Fig. 1.

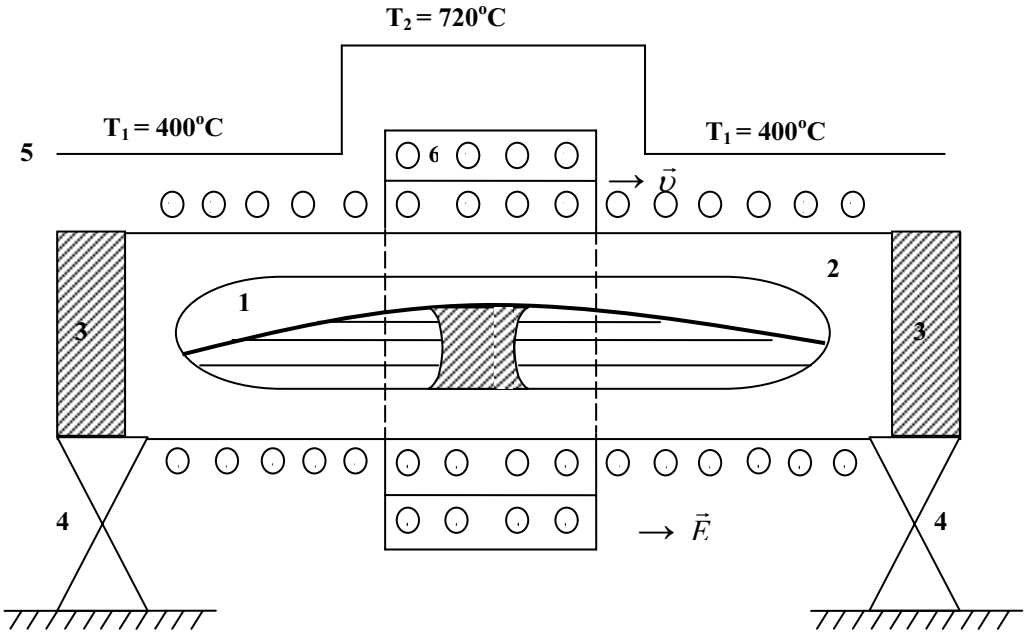

Fig. 1. Technologic installation diagram. 1 – the evacuated test tube with the obtained ingot as a result of the synthesis process; 2 – the additional electric furnace mounted on the quartz tube; 3 – porous brick plugs; 4 – installation prop; 5 – temperature diagram; 6 – the mobile melting zone; E – electric field intensity; υ – melting zone displacement rate.

For the galvanometric measurement, parallelepiped-shaped samples were prepared and preliminary chemically processed. They had 6 contacts welded within the conceptions of the known experiment. During the experiment the electric conductivity and the Hall effect were measured. Using these experimental data the mobility of charge carriers was calculated. All

the studied samples of gallium antimonide both non-doped and doped with different iron and tellurium concentrations had the p-type conductivity.

Fig. 2 presents, for instance, the dependence of charge carrier mobilities on temperature for three samples: non-doped gallium antimonide (conventionally marked F – 0); gallium antimonide doped with 0.01 at % iron concentration (F – 2 sample); gallium antimonide doped with 0.01 at % iron concentration and with 0.01 at % tellurium concentration (FT – 9 sample). The temperature range is 4.2÷300 K.

While comparing the mobility spectra for A and B samples we can emphasize that GaSb doping with iron leads to a considerable modification of the mobility dependence on temperature within the low temperature range (to ~50 K) and to an insignificant modification within the high temperature range. And vice versa, the simultaneous doping of gallium antimonide with iron and tellurium does not essentially modify the mobility spectrum within low temperature range, but causes an appreciable modification at high temperatures.

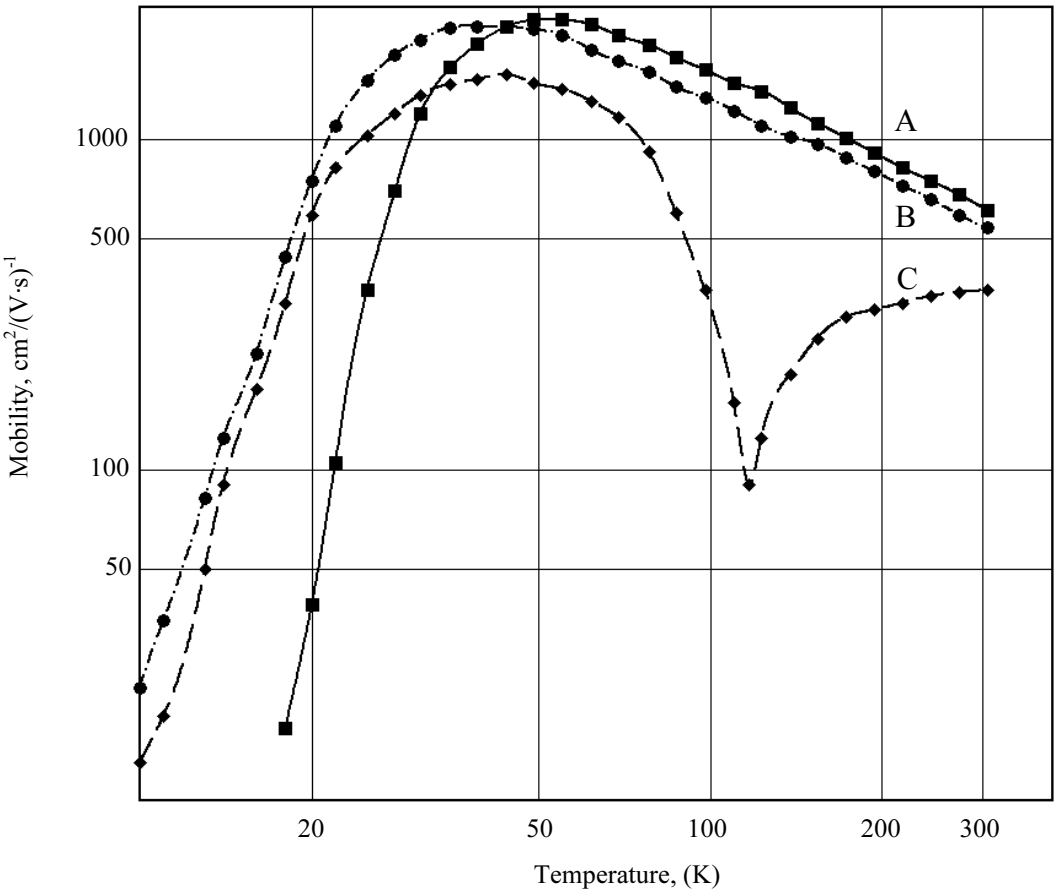

Fig. 2. Charge carrier mobility dependence on temperature for the following samples: A) GaSb; B) GaSb doped with Fe (0.01 at %); C) GaSb doped with Fe (0.01 at %) and Te (0.01 at %).

In addition, within the (100÷150 K) temperature range a sudden fall of mobility is registered, which gets to a stressed minimum of mobility at T = 120 K. Such an unusual feature was not observed in non-doped gallium antimonide and in gallium antimonide doped with iron. So, the presence of tellurium together with the iron as dopers leads to scattering mechanism variation within the mentioned temperature interval based on donor-acceptor interaction.

It is well known [5] that charge carrier mobility is influenced by different scattering mechanisms. At low temperatures, scattering by the ionized impurities prevails; at higher temperatures scattering by the crystalline lattice oscillations (acoustic and optic phonons) prevails.

The metallographic studies of the obtained samples register several inclusions oriented along the melting zone displacement, which, according to the structure, can be combinations of iron with oxygen.

Analysis of the mobility dependence on temperature for different samples has shown that these mechanisms do not suffice to explain this dependence. It is known that in GaSb there is the tendency of forming clusters (regions of spatial charge concentration). Thus, the mobility is influenced by the following scattering mechanisms: 1) acoustic oscillations of the lattice; 2) optic oscillations of the lattice; 3) clusters (an additional mechanism specific for gallium antimonide doped with iron).

The mobility conditioned by charge carrier scattering on ionized impurities is calculated as follows

$$U_i = \frac{3{,}69 \cdot 10^{20} cm^{-3}}{N_i} \cdot \frac{1}{Z^2} \cdot \left(\frac{\varepsilon}{16}\right)^2 \cdot \left(\frac{T}{100}\right)^{3/2} \cdot \frac{1}{\sqrt{\frac{m^*}{m_0}} \ln(1+\beta^2)}, \quad (1)$$

where

$$\beta = \frac{1}{Z} \cdot \frac{\varepsilon}{16} \cdot \frac{T}{100} \cdot \left(\frac{2{,}35 \cdot 10^{19} cm^{-3}}{N_i}\right)^{1/3}, \quad (2)$$

where N_i is the ionized impurity concentration; ε is the static dielectric permeability; T is the absolute temperature; m^* is the he effective gap weight; m_0 is the electron rest weight; Z is the impurity charge number.

The mobility conditioned by the scattering on acoustic oscillations of the crystalline lattice is calculated as follows

$$U_A = \frac{3{,}6 \cdot 10^4}{\left(\frac{m^*}{m_0}\right)^{5/2} \cdot \left(\frac{T}{100}\right)^{3/2} \cdot E^2{}_A} \cdot \frac{C_L}{10^{12}} \quad (3)$$

where E_A is the acoustic oscillations energy; C_L is the longitudinal coefficient of resilience.

The mobility conditioned by the scattering of optic oscillations of the crystalline lattice is calculated as follows

$$U_0 = \frac{2{,}6 \cdot 10^5 \cdot \exp(\theta / T)}{\left(\frac{m^*}{m_0}\right) \cdot \sqrt{\theta} \cdot 397{,}4 \left(\frac{1}{\varepsilon_{op}} + \frac{1}{\varepsilon}\right)}^{3/2}, \quad (4)$$

where θ is the Debye temperature; ε_{op} is the optic dielectric permeability.

The mobility conditioned by clusters scattering is calculated as follows

$$U_c = \frac{e}{N_c \cdot A \cdot \sqrt{2m \cdot k_B \cdot T}}, \quad (5)$$

where e is the elementary charge; k_B is the Boltzmann constant; N_c is the cluster concentration; A is the cluster effective section.

This formula cannot be directly used, because the parameters N_c and A (the section depends on temperature) are not known. For the calculations an empiric approximate formula can be used

$$U_c = \frac{\beta}{T^\alpha}, \quad (6)$$

where the parameters β and α can be determined by numerical methods.

When several mechanisms act the mobility is calculated as follows

$$\frac{1}{U} = \frac{1}{f}\left(\frac{1}{U_1} + \frac{1}{U_A} + \frac{1}{U_0} + \frac{1}{U_c}\right), \tag{7}$$

where, *f* is a factor that characterizes the part of the space occupied by the clusters.

The values α, β, and *f* were determined through regression analysis numeric methods so that the theoretical mobility calculated by formula (7) would better coincide with the experimental one. During the calculations the following parameter values for GaSb were used: Z = 1; ε = 15,6; ε_{op} = 14,44; $m^* = 0.55 \cdot m_0$; E_A = 4 eV; θ = 340 K; $C_L = 0.64 \cdot 10^{12}$ *dyn/cm*^{2}.

Figure 3 presents the results obtained for the F-0 sample (non-doped gallium antimonide). The experimental results are shown by squares; the dependences $U_I(T)$, $U_A(T)$, $U_0(T)$, and $U_S(T)$ are shown by discrete lines. The continuous line depicts the resulting dependence $U_S(T)$ calculated by formula (7).

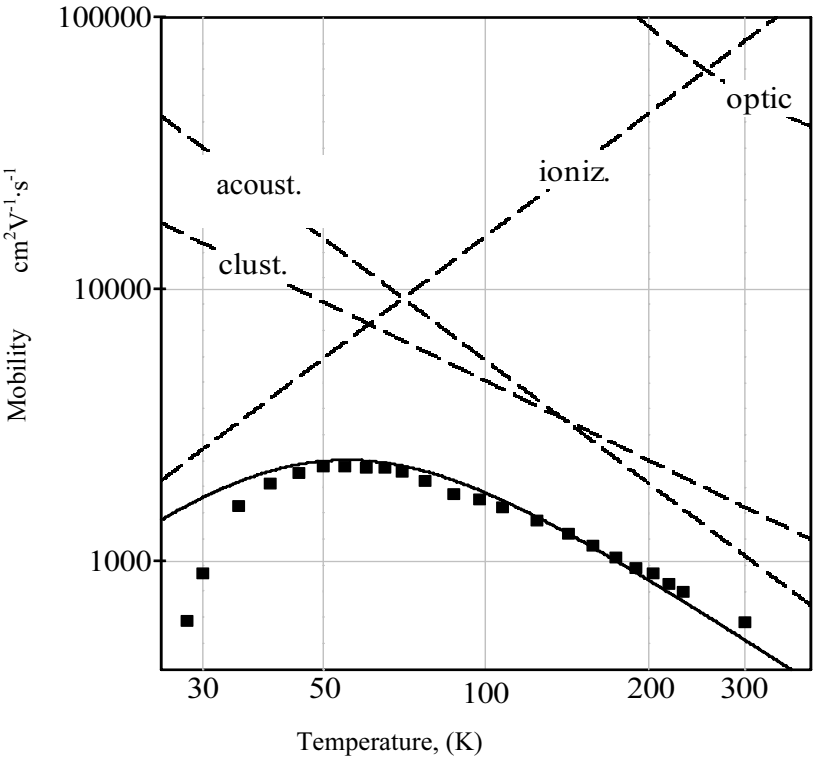

Fig. 3. The dependence of mobility (expressed in cm^2 / (V·s)) on temperature for non-doped GaSb. Dashed lines show theoretical calculations using formulas (1)-(5); squares depict the experimental data; continuous line shows theoretical calculations using formula (7).

Figure 4 presents mobility spectra for F-3 sample (gallium antimonide doped with 0.03 at % iron). The theoretical calculations for the integral mobility correspond to formula (7). Using the conceptions of work [3] and the experimental results for gallium antimonide clusters, main parameters were estimated: V_S is the volume; R_S is the radius; N_S is the cluster concentration.

Within the calculations it was supposed that the clusters are identical and have charges determined by Z = 35 and the following formulas were used

$$V_S = \frac{Z}{N_A - N_D} \qquad (8)$$

$$R_S = \left(\frac{3}{4}V_S\right)^{\frac{1}{3}} \qquad (9)$$

$$N_S = \frac{f}{V_S} \qquad (10)$$

$$\mu = e\left[N_S A\sqrt{2mkT}\right]^{-1} \qquad (11)$$

The last formula corresponds to the theory of clusters.

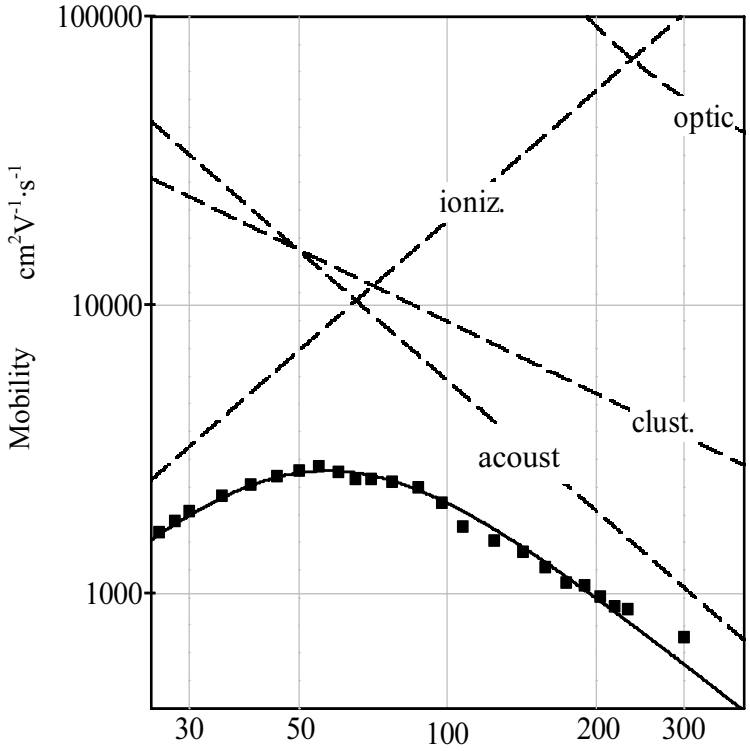

Fig. 4. The dependence of mobility (expressed in $cm^2/(V \cdot s)$) on temperature for GaSb doped with Fe (F-0 sample). Dashed lines show theoretical calculations using formulas (1)-(5); squares depict the experimental data; continuous line shows theoretical calculations using formula (7).

The calculation results for the cluster parameter samples studied in this work using the conception of experimental data correlation with the theoretic ones are presented in the table.

Basic characteristics of clusters in gallium antimonide

Sample	Dopant (Fe), at %	f	N_A-N_D, $10^{17}cm^{-3}$	R_S, Å	V_S, $10^{-16}\,cm^3$	N_S, $10^{15}cm^{-3}$
F-0	0	0.83	1.7	536	2.1	4.0
F-1	0.005	0.81	1.9	517	1.8	4.4
F-2	0.01	0.72	2.2	492	1.6	4.5
F-3	0.03	0.56	2.1	500	1.7	3.4
F-4	0.10	0.67	3.1	439	1.1	5.9
F-5	0.30	0.72	2.5	472	1.4	5.1
F-6	1.00	0.55	3.6	418	1.0	5.7
F-7	2.00	0.62	4.2	397	0.8	7.4
F-8	3.00	0.81	6.3	347	0.6	14.6
FT-9	0.01+0.10Te	0.69	2.2	492	1.6	4.3

Conclusions

The above discussed results allow formulating the following conclusions:

1. The technology of obtaining, homogenizing, purifying, and doping of gallium antimonide with iron in a concentration up to 3% and the technology of simultaneous doping with iron and tellurium were modified.
2. There were studied the galvanometric properties of gallium antimonide doped with iron within the temperature interval (4.2÷300 K), as well as the peculiarities of galvanometric effect of simultaneous doping with iron and tellurium samples.
3. There were analyzed the mechanisms of charge carrier scattering for non-doped gallium antimonide. The experimental results of the U = U(T) dependence were explained with the implication of an additional mechanism of dispersion determined by the formation of some inclusions called clusters.
4. Using the conceptions presented in work [3], all the basic characteristics of the clusters were determined: V_S (the volume occupied by the clusters), R_S (the radius), and N_S (the concentration) from a supposition that the clusters are identical and possess charges determined by Z = 35.

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