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HELIOTECHNICAL MATERIALS SCIENCE

Study of GaSb Doped with Te as a Material for Photovoltaic Systems

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Abstract—The article reports the results of study of *n*-GaSb⟨Te⟩ specimens with plain ohmic contacts and demonstrates that at $T > 50°C$ the studied structure generates current (up to 0.4 nA at $T = 200°C$) and voltage (up to 0.4 mV at $T = 210°C$). These phenomena are attributed to thermally stimulated decomposition of "shallow donor + vacancy" complexes with subsequent formation of periodic distribution of concentration of vacancies and shallow donors over the specimen length.

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GaSb semiconductors in recent years have become known as promising materials for photovoltaic systems. In particular, works [1, 2] demonstrate their promising character for the production of solar cells. The aim of the current work is study of the thermal voltaic properties of GaSb. The main attention is paid to the effects running in semiconductors under the influence of uniform heating. Such phenomena have been observed in certain semiconductors of the $A^{III}B^{V}$ family: GaAs doped with Sn [3, 4], GaAs doped with Te [3], and InP doped with Te [5]. In all these works the occurrence of current and/or voltage was observed in specimens with plain ohmic contacts under the action of uniform heating; the current and voltage also occurred at rather moderate temperatures, slightly exceeding the ambient temperature ($T > 50°C$, 60°C). It is important to note that these effects were observed only in semiconductors of the $A^{III}B^{V}$ family grown by the Czochralski method and possessing *n*-type conductivity. Explanation of these phenomena is based on the fact that during growing of such materials they actually have no free vacancies because they are combined into complexes with shallow donors. As demonstrated by EPR analysis, such complexes are not observed in the materials of the $A^{III}B^{V}$ family, possessing *p*-type conductivity [6]. Work [3] provides an explanation of the thermal voltaic phenomena in the materials of the $A^{III}B^{V}$ family, grown by the Czochralski method and possessing *n*-type conductivity, on the basis of the following model. All these materials initially do not contain free vacancies because they are combined into the "shallow donor + vacancy" complexes. During uniform heating of a homogeneous specimen, these complexes are decomposed under the action of temperature and if their decomposition is more intensive than the formation of the complexes, the processes of self-arrangement are initiated and periodical distribution of vacancies along the specimen length can occur. At the same time, shallow donors are also released with the consequence that their distribution along the length also becomes periodical. Therefore, isotype potential barriers of the n–n^+ type are formed along the specimen. Free carriers, generated under the action of heating, are separated on these potential barriers, and this leads to generation of current and/or voltage, which are synergetic in their essence.

If this qualitative model is valid, then similar phenomena should occur in the GaSb semiconductor doped with tellurium, since it belongs to the $A^{III}B^{V}$ family, possessing *n*-type conductivity and grown by the Czochralski method. If in a homogeneous specimen of such material under the action of heating the "shallow donor + vacancy" complexes are decomposed, then, as described in detail in [3], the progress of self-arrangement can cause a periodic distribution of the concentration of vacancies along the specimen length.

$$V = V_0 + V^* \sin \omega x, \tag{1}$$

where V_0 is the average concentration of vacancies, V^* is the amplitude of their variation, and ω is the frequency of their distribution along the length; at the same time,

$$\omega = \sqrt{\frac{K(Q)}{D_V}}, \tag{2}$$

where $K(Q)$ is the temperature-dependent coefficient of decomposition of "shallow donor + vacancy" complexes and D_V is the diffusion coefficient of vacancies.

Since each complex is comprised of one shallow donor + one vacancy, the same amount of shallow donors is released in the given process, and as a conse-

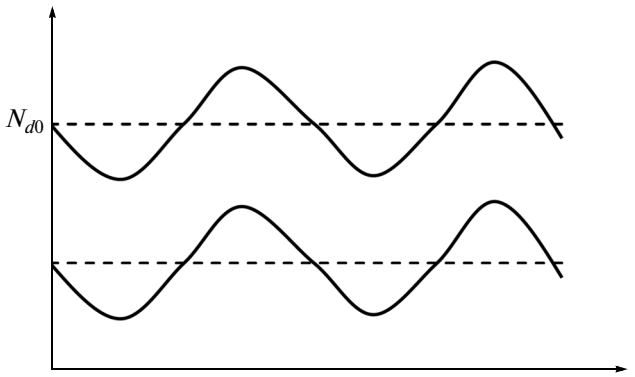

Fig. 1. Qualitative course of concentration curve of vacancies V and donors N_d along the specimen length.

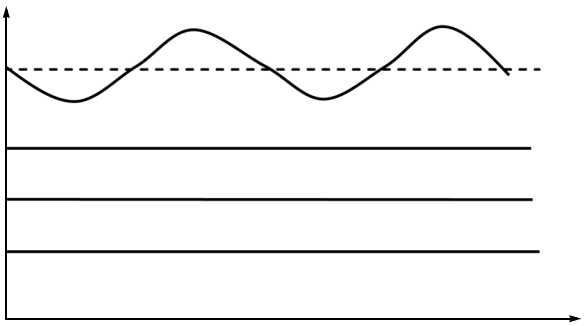

Fig. 2. Qualitative course of concentration curve of electrons in semiconductor during heating: curve *1*—initial state (with initial concentration n_n); curves *2* and *3*—uniform increase in electron concentration with temperature $n(\tau_1) = n_n + \tau_n Q(\tau_1)$, $n(\tau_2) = n_n + \tau_n Q(\tau_2)$; curve *4*—variation of electron concentration stipulated by periodic distribution of shallow donors occurring upon decomposition of "shallow donor + vacancy" complexes as a consequence of uniform heating.

quence the concentration of doping shallow donors ceases to be constant and acquires a periodic nature (Fig. 1):

$$N_d = N_{d0} + V^* \sin \omega x, \tag{3}$$

where N_d is the total concentration of donors and N_{d0} is the initial concentration of donors.

The second term in Eq. (3) describes the number of donors released as a consequence of decompositions of the complexes.

Therefore, a series of potential barriers with diffusion potential is generated in the material along the specimen:

$$V_{n-n^+} = \frac{kT}{q} \ln \frac{N_d}{N_{d0}}, \tag{4}$$

where $N_{d0} = n_n$ is the concentration of electrons in the initial material.

Usually during heating free carriers are nucleated, a portion of them are recombined, and then a new equilibrium concentration is established; i.e., initially the process is described as follows:

$$\frac{dn}{dt} = U - Q(T), \tag{5}$$

where $U = \dfrac{n - n_n}{\tau_n}$ is the recombination of free carriers, $Q(T)$ is the heat generation, and τ_n is the lifetime. Under stationary conditions ($dn/dt = 0$) $U = Q$, and the established new concentration is

$$n = n_n + \tau_n Q, \tag{6}$$

where $\tau_n Q = \Delta n$ is the additional concentration of electrons occurring as a consequence of heating, whereas Δn will increase with temperature. In a conventional material without decomposition of complexes and periodical variation of the concentration of donors the concentration of electrons will increase with temperature (Fig. 2).

However, in our case, when the concentration of dopant becomes periodical along the length, the concentration of free electrons also becomes periodical, or at least acquires a periodic component:

$$n = n_n + \tau_n Q + V^* \sin \omega x. \tag{7}$$

Using boundary conditions, conventional for study of synergetic processes, and without excitation at the specimen edges we have

$$n|_{x=0} = n_n + \tau_n Q(T), \tag{7a}$$

which evidences the progress of self-arrangement exclusively in the specimen itself, without any effects of contacts. When the concentration of electrons starts to obey Eq. (3), its view can be qualitatively illustrated in Fig. 2 (curve *4*). Since the semiconductor has isotype potential barriers, internal electric field E_D is formed here. Correspondingly, at the boundaries of opened specimen there is formed a dynamic difference of potentials $V_Q = \int_0^d E_D dx$, which should be reasonably considered as synergetic thermal EMF:

$$V_Q = -\frac{kT}{q} \frac{(b-1)}{(b+1)} \ln \frac{n(d)}{n(0)}. \tag{8}$$

This EMF is determined by the drop of the concentrations of free carriers, spontaneously occurring in a homogeneous semiconductor under the action of uniform heating. Such synergetic thermal EMF differs in principle from the conventional Dember EMF, which is known to be formed as a consequence of external (caused, for instance, by injection) variation of the concentration of carriers. The only common property of these two EMFs is their equal dependence on the difference of mobility of electron and holes.

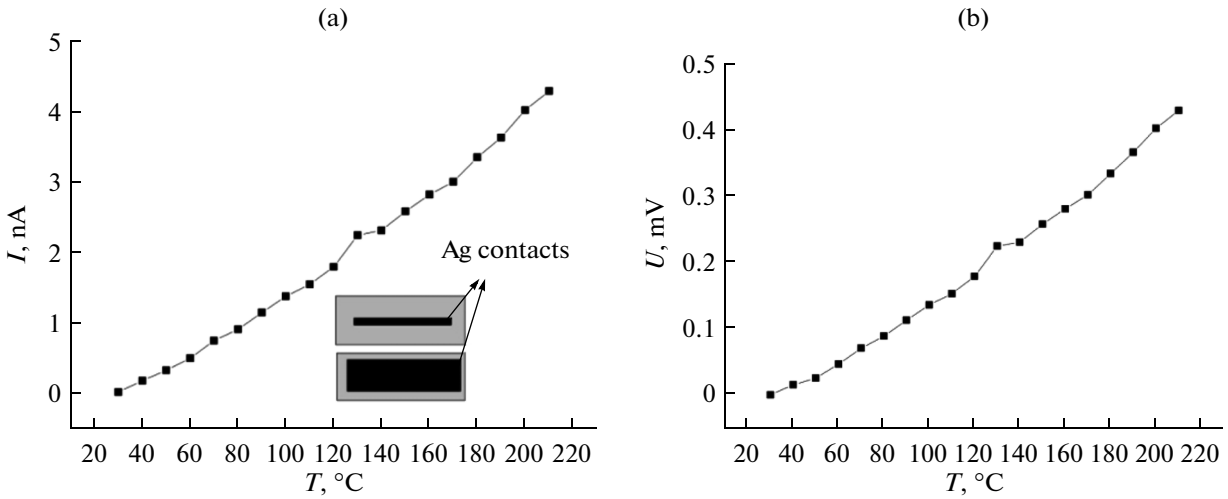

Fig. 3. Current (a) and voltage (b) as functions of temperature for *n*-type GaSb⟨Te⟩ specimen with ohmic contacts. Schematic view of a specimen is illustrated in Fig. 3a.

Total voltage drop on specimens is determined as follows:

$$V = \frac{J}{q\mu_p(b+1)}\int_0^d \frac{dx}{n} - \frac{kT}{q}\frac{(b-1)}{(b+1)}\int_0^d \frac{dn}{n}. \quad (9)$$

Using Eq. (7) for the concentration of electrons, we obtain the final dependence of current on voltage:

$$J = J_Q \frac{q}{kT}(V - V_{oc}), \quad (10)$$

where

$$J_Q = \frac{qD_p(b+1)(n_n + \tau_n Q(T))^2}{d\left(n_n + \tau_n Q(T) + \frac{V^*}{\omega}(\cos\omega d - 1)\right)}, \quad (11)$$

and

$$V_{oc} = V|_{J=0} = -\frac{kT}{q}\frac{(b-1)}{(b+1)}\ln\left(1 + \frac{V^*\sin\omega d}{n_n + \tau_n Q(T)}\right) \quad (12)$$

can be considered as the synergetic Dember thermal EMF.

In order to experimentally verify the validity of this model, specimens of GaSb doped with Te were used, possessing *n*-type conductivity with initial concentration $n_n = 2 \times 10^{17}$ cm^{-3}. The thickness of the specimens was d = 530 μm and the cross-section surface area was $S = 63$ mm^2. They were equipped with ohmic contacts made of Ag, solid on one side and in the form of a strip on the other side. The measured results of the current and voltage dependences are illustrated in Figs. 3a and 3b. In the depicted curves of $J(T)$ and $V(T)$ it can be seen that under the influence of uniform heating the specimens with plain ohmic contacts generate current and/or voltage.

Therefore, the performed study demonstrates that the GaSb⟨Te⟩ semiconductor, as well as other materials of the $A^{III}B^{V}$ family with *n*-type conductivity grown by the Czochralski method, possess thermal voltaic properties. Under the influence of heating at $T > 60$°C the self arrangement of vacancies and shallow donors initiates, which leads to the generation of synergetic in character current and voltage in a specimen with plain ohmic contacts.

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