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Laser – induced donor centers in *p*-InSb

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Abstract. The laser – induced donor centers in *p*-Insb have been studied by magneto-concentration effect (MCE). The distribution of donor centers in the nonequilibrium temperature field in InSb was obtained by redistribution of the interstitial In atoms (I_{In}) and vacanciens V_{In} under laser action. Comparison of the theoretical calculation and experimental data showed that depth δ of the position of *p-n* junction increased with temperature, and that relatively large value of δ at used value of laser intensity ($P \sim 3.5$ MW/cm^2) is connected with presence of liquid phase during laser annealing process. Obtained results correlate with Atomic Force Microscopy (AFM) measurements. Experiments were performed on *p*-InSb samples in the temperature range 180–290 K. Temperature gradient was provided by YAG: Nd laser illumination ($\lambda = 0.53$ µm, $\tau = 15$ ns). The laser donor centers (LDC) of two kinds were found: one is nonstable and annealed at room temperature with relaxation constant ~ 5 s, and the other is stable, annealed at temperature 670 K. The threshold of LDC formation is 1.5 MW/cm^2.

The activation energy of the stable donor centers is 1,1 eV. Investigation of the surface morphology by AFM in dependence on the intensity of laser radiation showed a good agreement with obtained results.

Keywords: donor center, InSb, laser, Welker effect, interstitial atom, vacancy, temperature gradient.

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1. Introduction

Modification of the electrical and optical parameters of a semiconductors by laser radiation is utilized in micro- and optoelectronics production to create an irregular structure *p-n* junction [1], buried insulating [2] and conducting layers and also electric contacts [3,4] as well as technological origination of the centers of precipitation [5]. It is known that the energy dissipation process occurs in the framework of the thermal model [6]. However, the results are different in dependence on experimental conditions, namely: wavelength (λ), pulse duration (t_p) and power density (P) of the laser radiation. For example, concentration of the defects can be increased or decreased, the surface can be smoothed or destroyed (as usual, changes are started at the surface). Therefore, study of the mechanism of the laser radiation defects is of fundamental importance.

Improvements of the *p*-InSb surface by a high-energy ruby laser was found in [7]. Similar results were obtained in cases when YAG:Nd [8] and weakly absorbed CO$_2$ laser radiation [9] were used . The explanations of the observed phenomena given by authors were quite different. Vasiliev et al. [9] related it to the melting and successive oxidation of the surface of InSb while Bogatyrev and Kachurin [8] explained the phenomenon in terms of structural modification, but the kind of modification is not specified.

The purpose of this research is further investigation of the nature of LDC in InSb as well as properties of LDC itself.

Our explanation of the nature of LDC is based on the following model. High concentration of interstitial In and Sb atoms (I_{In}, I_{Sb}) and vacancies (V_{In} , V_{Sb}) are generated in *p*-InSb because of heating of the surface layer caused by laser radiation. This defects drift in the bulk with different velocities in conditions of strong non-eqiulibrium thermal processes, because the forces applied to defects is proportional to a gradient of temperature [2]. I_{In}, I_{Sb} and the vacancies V_{In}, V_{Sb} have different diffusion coefficients [10], that disturbs the equilibrium distribution of I_{In} and vacancies V_{In} near the surface of a semiconductor. In terms of that I_{In} is a donor and V_{In} is an acceptor [11], and of the fact that the movement of interstitial In is directed against the temperature front [12], redistribution in space of I_{In} takes place, forming the *n*-layer.

2. Theory

Our calculation of I_{In} distribution by depth of were performed using the non-stationary diffusion equation:

$$\frac{\partial N}{\partial t}=\frac{\partial}{\partial x}\left[D_0\exp\left(\frac{-E_a}{kT}\right)\left(\frac{\partial N}{\partial x}-NF\right)\right] \qquad (1)$$

where N is the concentration of interstitial In, F is the force exerted on I_{In} in presence of temperature gradient $F = -(Q^*/T)\cdot\partial T/\partial x$, where Q^* is the transport heat, E_a is the activation energy, x is the coordinate directed from the surface to the bulk of the semiconductor. From the microscopic theory for vacancies we can obtain formula $Q^*_{=} = akT$, where $a \approx 3.5$ [2]. The calculations are made for the semiconductor samples placed in the temperature field $T = \Delta T e^{-x/x_0} + T_0$. Let's introduce undimensional variable coordinate $\xi = x/x_0$ and time $\tau = tD_0/x_0^2$. Then equation (1) becomes

$$\frac{\partial N}{\partial \tau}=\frac{\partial}{\partial \xi}\left[D_0\exp\left(\frac{-E_a}{kT}\right)\left(\frac{\partial N}{\partial N}+\frac{N_a}{T}\cdot\frac{\partial T}{\partial \xi}\right)\right] \qquad (2)$$

with $T = \Delta T e^{-\xi} + T_0$. In our calculations we take $T_0 = 300$ K, $E_a = 1.2$ eV, $\Delta T = 500$ K (Fig. 1a) and $\Delta T = 400$ K (Fig. 1b). Boundary condition $\left(\frac{\partial N}{\partial \xi}+\frac{N_a}{T}\cdot\frac{\partial T}{\partial \xi}\right)_{\xi=0}=0$ conserves the total number of I_{In}, I_{Sb}. As initial condition we take interstitial In distributed at the vicinity of surface. As it is shown in Fig.1, the depth (δ) of I_{In} distribution increases with the lattice temperature, and is characterised by the maximum $N(\delta)_{|\xi=\delta} = N_{max}$ in the volume of a semiconductor. The calculation of δ at maximum value of intensity of the laser radiation $I_{max} = 10$ MW/cm^2 gives the value of 0.5 μm.

3. Experimental

Experiments were performed for *p*-InSb sample with concentration of noncompensated acceptors about 10^{12} cm^{-3}. Typical size of the samples 5.0×2.0×0.04 mm^3 were chosen based on the following speculation: length, to provide uniform illumination of the sample, and appropriate thickness d are a little more than bipolar diffusion length of nonequilibrium charge carriers (L), $L \approx 30$ mm at 200 K) to determine the depth at which the *p-n* junction is located using the Welker effect [13]. Illuminated surface of the sample was chemically treated using etching with CP-4A to obtain the minimal surface recombination velocity $S_{min} \approx 10^3$ cm/s, while opposite surface was mechanically polished to obtain $S_{max} \approx 10^5$ cm/s. The samples with surfaces treated asymmetrically were chosen to increase method sensitivity connected with thickness of bipolar part of the sample. According to [14], the maximum of the dependence of conductivity on thickness of the sample d takes place at $d = 1.4\ L$.

The technique of current – voltage characteristics (CVC) in both transversal magnetic field ($B_z = 0.1$ T) and electric field (up to $E_x = 200$ V/cm) was used to study kinetics of the annealing of LDC. The depth of the *p-n* junction was estimated from gauss-ampere characteristics (GAC) in transversal magnetic field up to 0.3T. As a light source YAG:Nd laser working in Q-switch regime ($\lambda = 1.06$ μm, $t_p = 15$ ns, $W = 0.1$ J) was used. InSb samples were irradiated at the air. Changes of the surface morphology were investigated by Atomic Force Microscope. The investigation of the LDC start point P_{thc} and surface melting start point P_{ml} are situated about 1.5 MW/cm^2 and 3.5 MW/cm^2, accordingly.

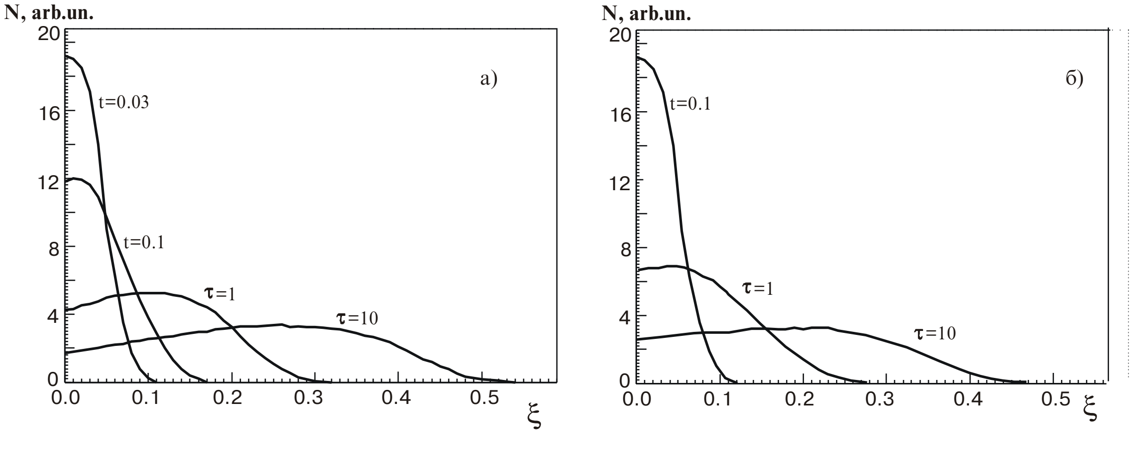

Fig.1. Distribution of I_{In} concentration as a function of the reduced coordinates: a) at $T = 800$ K; b) at $T = 700$ K.

4. Results and discussion

The illuminated surface of the InSb samples becomes of *n*-type with light intensity of the YAG:Nd-laser radiation more than 1.5 MW/cm^2 that corresponds to the activation threshold of I_{In}. We observed at least two types of centres: the first is stable up to 670 K, and the second one is non-stable at room temperature. The decay time of the non-stable centres relaxation was about 5 s. The estimation of the activation energy of the stable centres gives a value E_a = 1.1 eV that correlates well with value of energy activation of the In self-diffusion. It is known [10] that V_{In} is annealed more rapidly than V_{Sb} in the high temperature region (T = 400 K) with the result that equilibrium of I_{In}, V_{In} is broken down. These defects are separated due to the temperature gradient caused by strongly absorbed laser radiation. Due to opposite charges of these vacancies the polarized state is «frozen» in conditions of fast cooling, which makes *p-n* junction. The depth of the *p-n* junction must be dependent on the wavelength, intensity of the laser radiation of the thermal diffusion length, and of the thermal drift which is proportional to *grad T* and transport heat of In atoms Q^* [2]. We supposed that threshold character of the effect is caused by increasing of the non-uniform crystal heat up to value of the *grad T* sufficient for migration of the I_{In}.

An estimation of the *p-n* junction depth is carried out using GAC from the deviation of the sample conductivity (Fig. 2, points A).

The accumulation effect (repeated irradiation by the laser pulses) is caused by formation of potential barrier of *p-n* junction. The availability of the *p-n* junction close to surface in the conditions of the Welker effect is equal to absence of the surface recombination S = 0. In this case the change of the crystal conductivity is caused by its effective thickness d_i (thickness of *i*-layer), consequently, by the depth of *p-n* junction. Because of some exceeding of the thickness d of the using InSb crystal comparing to L, the shift of the *p-n* junction in the volume was observed with increasing of the laser intensity (Fig. 2, points A). This leads to increasing of the sample conductivity with following saturation of this dependence (Fig. 3). According to [13] the maximum deviation of the conductivity take place at $d_i \cong 1.4$ L that allows to estimate the depth value of *p-n* junction that is about $\delta \cong 8$ µm at initial thickness d ~ 50 µm.

Morphologic investigation of the surface of *p*-InSb samples by AFM depending on the intensity of laser radiation showed that the changes in the morphology of the surface appearing in drops which were observed by Vasiliev et al [9] at the irradiation of the surface of InSb by CO$_2$ laser (λ = 10.6 µm, t_p = 150 ns), and the increase of roughness of the surface, appears at the intensity more than 3.5 MW/cm^2.

There appears to be in interval P =1.5-3.5 MW/cm^2 the degree of dissociation of A-B pairs in a metasable state of liquid phase has not been sufficiently yet [15] to attain high level crystalline defectivity after recrystallisation, Fig.4; a) pointed tops are observed in Fig.4; b) at the intensity more than 6.0 MW/cm^2, which evaporates

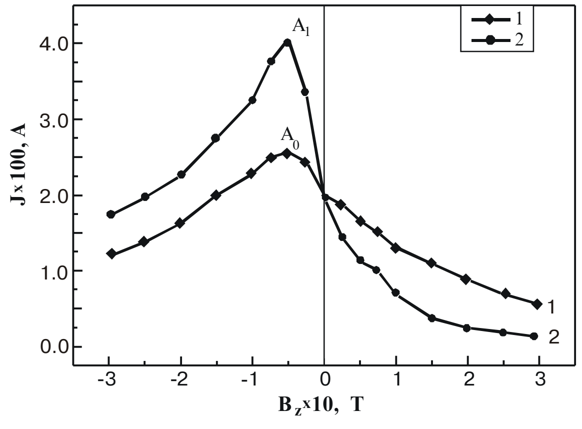

Fig.2. GAC of *p*-InSb sample: (1) before laser irradiation, (2) after laser irradiation of intensity P = 10 MW/cm^2.

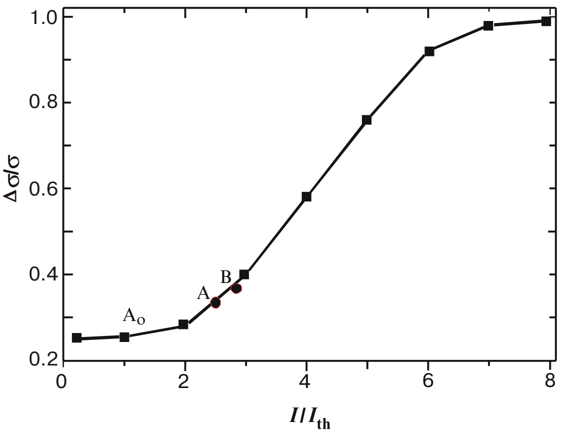

Fig.3. Change of sample conductivity as a function of laser intensity.

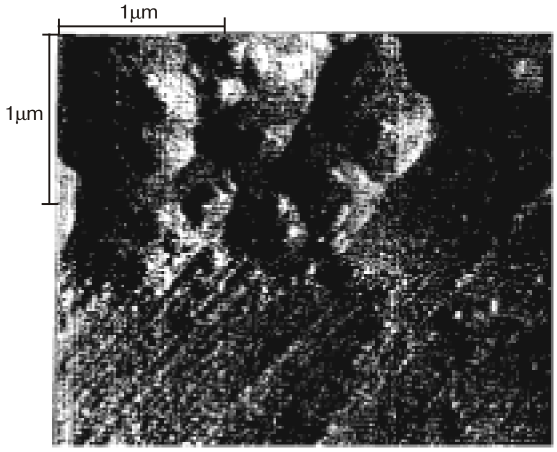

Fig.4. Morphology of the *p*-InSb surface after laser irradiation of P = 6.0 MW/cm^2.

probably at liquid InSb and with following considerable dissociation of A-B atoms of InSb [16]. The latter correlated with decrease of current on CVC at such value P in conditions of E·H fields, and carriers drift to the illuminated surface. The evaluation of the InSb melting threshold P_m which has been obtained for the case of adiabatic heating with following parameters: ρ = 5.76 g·cm^{-3}; c = 0.21 J·g^{-1}·K^{-1}; k = 10^5 cm^{-1} (ρ, c, k are specific density specific heat and absorption coefficient respectively). The results are shown in Fig. 3, points A. ρ = 5.76 g·cm^{-3}; c = 0.21 J·g^{-1}·K^{-1}; k = 10^5 cm^{-1}. In is not inconceivable the contribution of antistructural defect Sb$_{\mathrm{In}}$ in the structure of LDC.

Conclusion

A new mechanism of *p-n* junction creation in *p*-InSb, namely, redistribution of the I_{In} and V_{in} in the presence of the temperature gradient was proposed. Nonstable LDC at room temperature and stable LDS up to 670 K near the surface of *p*-InSb with decay time ~5 s were observed. The usage of the magnetoconcentration effect for estimation of the *p-n* junction depth was proposed.

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