Semiconductor Physics, Quantum Electronics & Optoelectronics. 2003. V. 6, N 4. P. 458-460.

PACS: 73.40.-c

Mechanisms of forward current transport in *p*-GaSe-*n*-InSe heterojunctions

Z.D. Kovalyuk, V.P. Makhniy*, O.I. Yanchuk

Chernivtsi Department of Institute of Materials Sciences Problems National Academy of Sciences of Ukraine, 5, Iryna Vilde str., 58001 Chernivtsi, Ukraine, E-mail: chimsp&unicom.cv.ua, yanchuka@mail.ru,
** Chernivtsi National University by Yuriy Fedkovich, 2, Kotsyubinsky str., 58012 Chernivtsi, Ukraine*

Abstract. Voltage-current characteristics forwardly biased heterojunctions *p*-GaSe-*n*-InSe made by the method of optical contact are analyzed. Asit was ascertained, the forward current is determined by tunnel-recombination processes at low voltages and overbarrier emission. The experimental characteristics are defined by the known theoretical expressions for anisotipical heterojunctions with the energy diagram by Andersen.

Keywords: heterijunction, voltage-current characteristic, current transport, gallium and indium monoselenides.

Paper received 17.07.03; accepted for publication 11.12.03.

Heterojunctions are the basis of an overwhelming majority of the modern solid-state devices and aparature [1]. The development of this perspective direction proposes carrying out of complex investigations in engineering and physics of semiconductor materials and the diode structures on their basis. The layered semiconductors, possessing a lot of the important properties from practical point of view have the particular interest for this purposes. The present paper is devoted to clearing of basic formation processes of the forward current, which are feebly explored with this point of view, heterojunctions on based gallium and indium monoselenides.

Heterostructures were produced by the original method, namely: the optical contact of thin *p*-GaSe layer with a substrate produced of *n*-InSe [2]. Concentrations of main carriers in them were $n_0 \approx 2 \cdot 10^{16}$ cm^{-3} and $p_0 \approx 6 \cdot 10^{15}$ cm^{-3} at 300 K, and their mobility's were $\mu_n \approx 800$ cm^2/V·s and $\mu_p \approx 20$ cm^2/V·s. The technology of structures creation excludes using high temperatures, therefore electrophysical properties of heterojunction components were the same as those of initial semiconductors. Besides characteristic peculiarity of layer materials is low concentration of surface defects. This fact and method of optical contact (excluding interdiffusion of atoms components), result in creation of sharp heterojunctions with still perfect interface, described by the Andersen model [3].

It is worth to note, that the analysis of experimental results becomes considerably simpler when using the band energy diagram of the heterojunction, bu it is unknown for the explored structures. A main reason of it is lack of values of the electron affinity θ of contacting materials. The available data of magnitude of work functions Φ concerns to monoselenides with unknown degree of doping [4], i.e. with uncertain depth of the Fermi level F. To determine the energy bands profile, criteria mentioned in the paper [3] can be used. The probable band energy diagram shown in Fig.1 corresponds to the system of inequalities

$$\left.\begin{array}{c} E_{g_p} > E_{g_n} \\ \Phi_n > \Phi_{p-E_{g_p}+F_n+F_p} \\ \Phi_n > \Phi_p - E_{g_n} + F_n + F_p \end{array}\right\} \qquad (1)$$

here E_g is the band gap, and indexes n and p concerns to materials with electronic and hole conductivities. If $E_{g_n} \cong 1.2$ eV and $E_{g_p} \cong 2.0$ eV [5], $F_n \cong 4.8$ eV and $F_p \cong 5.3$ eV [4], and $F_n + F_p \leq 0.3$ eV at 300 K than the system (1) is well executed for investigated heterojunctions. Peculiarity of the obtained band energy diagram is the absence of any spike near the interface. Here arrows show the most probable transmission of carriers at direct bias heterostructure.

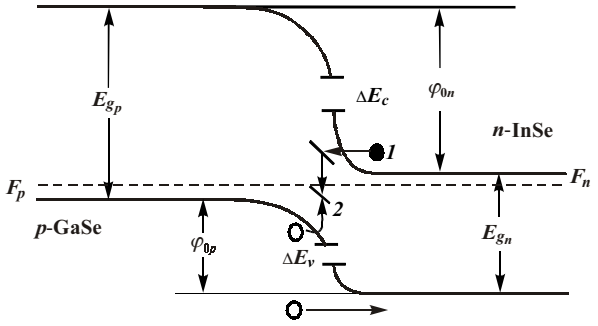

Fig. 1. Possible band energy diagram of heterojunction *p*-GaSe-*n*-InSe and the scheme of transmission of charge carriers.

At low voltage V, current I should be determined by tunnel-recombination processes, transmission 1–2 in Fig. 1, corresponding. Since these transmissions are sequential, then the total flow of carriers is limited by the less probable process: tunnelling – 1 or a recombination – 2. Therefore, initial regions of direct branches of voltage-current characteristics are described by the expression [3,5]

$$I = I_{gr} + I_t = I_{gr}\left[\exp\left(\frac{eV}{2kT}\right)-1\right] + I_{t0}\exp(\alpha V + \beta T). \quad (2)$$

Here α and β are parameters, dependent on the voltage and temperature; I^0_{gr} is the current of the cut-off at $V = 0$, and I_{t_0} is the tunnel current at $V = 0$ and $T = 0$. From Fig. 2 the experimental voltage-current characteristics in semilogarithmic coordinates indeed contain two regions with various slopes. The more sharp dependence $I(V)$ corresponds to the recombination process in the spatial charge area of the heterojunction I_{gr}, and the parameter I^0_{gr} is determined by the expression [3,6]

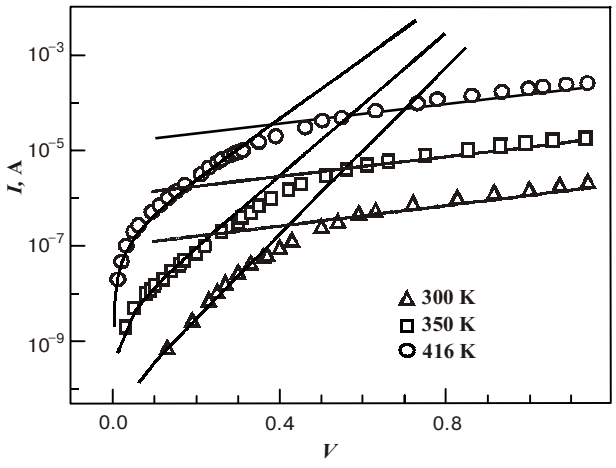

Fig. 2. Initial sites of direct branches of voltage-current characteristics at various temperatures. Points corresponds to experiment, solid lines – to calculation.

$$I^0_{gr} \cong S\frac{en_i d}{\tau_i} = A(T)\exp(-E_g/2kT), \quad (3)$$

where S is the area of the diode, d is width of spatial charge area, t_i is lifetime of nonequilibrium carriers in the spatial charge region, n_i is concentration of intrinsic carriers in the material with band gap E_g, remaining labels are wellknown. Due to the fact that in these materials $E_g > 1.2$ eV, and coefficient $A(T) \sim T^{3/2}$, one can propose that temperature changes of recombination current of the cut-off are caused by the exponential factor. Since in given temperature range in the first approximation it is possible to neglect the dependence of the factor $A(T)$ and to consider it is equal to its value at 300 K. Magnitude $A(300) \approx 6.4\cdot10^{-5}$ is easily determined from (2) at the known experimental value I^0_{gr} and the calculated exponential. At calculation $E_g(T) = E_g(0)-\gamma T$, and parameters: $E_g(0) \cong 1.31$ eV and $\gamma \cong 3.7\cdot10^{-4}$ eV/K [5] were considered. From Fig. 2, experimental dependencies $I_{gr}(V,T)$ are in perfect agreement with calculated in area of voltages at which recombination processes dominate.

At high V, the weaker linear relation $I(V)$ caused by change current transmission mechanisms is observed. In this area of voltages, as mentioned above, the forward current is controlled by tunnelling of carriers (transmission 1 in Fig.1) and described by the second form of expression (2). Parameters included in it at 300 K for the given sample appeared to be equal: $\alpha \cong 2.1$ В$^{-1}$, $\beta \cong 4.6\cdot10^{-2}$ K^{-1} and $I_{t_0} \cong 1.5\cdot10^{-5}$ A. Substitution of these parameters in the expression for I_t also has a possibility of tunnel current persence at other temperatures in the explored range. The good coincidence of experimental and theoretical values $I_t(V,T)$ means of agreement the exact select of model for the current transport.

The further increasing of direct voltage leads to reducing of height of potential barriers for electrons φ_{0_n} and holes φ_{0_p} (fig.1). It promotes propagation of a long overbarrier transport of carriers I_d, which finally (major V) should become dominating. As $\varphi_{0_n} > \varphi_{0_p}$ that overbarrier current is hole, passages 3 on Fig.1. According to the theory [3,6] at $eV >> kT$

$$I \cong I_d = I_s\exp(eV_0/kT) = I_s\exp\left(\frac{eV - eIR_0}{kT}\right) \quad (4)$$

here V_0 is voltage in the barrier, which at large currents through the diode may distinct from affixed V by magnitude $\Delta V = IR_0$, R_0 is resistance of components heterojunction and ohmic contacts. Expression (4) is easily conversed

$$\ln I - \frac{eV}{kT} = LnI_s - \frac{eR_0}{kT}I, \quad (5)$$

and the experimental voltage-current characteristics are convenient to be built in coordinates $\ln I - eV/kT$ by I. As

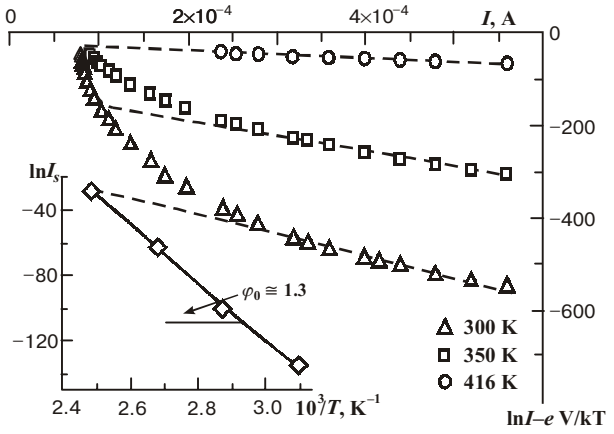

Fig. 3. Comparison of direct voltage-current characteristics at the large currents values from expression (5). In insertion shown istemperature dependence of the cut-off current I_s.

follows from Fig. 3, experimental dependencies $I(V)$ is not bad approximated by lines in the chosen coordinates at large currents. The deviation of the experimental points from lines is caused by the forward current tunnel-recombination component contribution above. The reducing of the lines scope with T increasing is that had discussed with magnification of concentration of main carriers in components of heterojunction that reduces in the magnitude R_0. From (5) it follows that the cut-off on axis of ordinates at $I = 0$ corresponds to the saturation current I_s, that is $\ln I_s$. Dependence $I_s(T)$ is determined, by the exponential factor [3,5]

$$I_s \sim \exp(\varphi_0 / kT), \qquad (6)$$

where φ_0 is the height of the potential barrier, in our case it is equal φ_{0_p}. The experimental dependence $I_s(T)$ is well approximated by the line in coordinates $\ln I_s$ vs $10^3/T$, and its energy slope is ~ 1.39 eV. This value is close to magnitude E_g of InSe at 0°K, that does not contradict chosen band diagram for heterojunction *p*-GaSe-*n*-InSe (Fig. 1). Calculation of absolute values I_s, unfortunately, is hampered due to the absence of the data of the magnitude diffuse lengths of minority carriers. There is also the open problem of the nature and parameters of local centers that take place in formation of tunnel-recombination currents. We think, that this problem demands additional researches and makes a subject of separate operation.

At the same time, the discussed result convincingly testify the benefit of applicability for heterojunction of the Andersen model investigated in the paper. The forward current of these structures is adequately described within the framework of known tunnel-recombination and overbarrier current transport mechanism theories.

Reference

1. Alferov J.I. History and future of semiconductor heterojunctions // *Physics and techniques of semiconductors* . **32**(1), pp.3-18 (1998).
2. Bakumenko V.L., Chishko V.F // Electrical properties of optical contact of layered semiconductors // *Physics and techniques of semiconductors*. **11**(10), pp. 2000-2002 (1977).
3. L.Sharma, R.K.Purohit. *Semiconductor heterojunctions*. Pergamon Press (1974).
4. Bakumenko V.L., Kovaljuk Z.D., Tishin E.A., Chishko V.F. // Influence of surface "aging" on indium and gallium monoselenides work function and photoelectrical properties // *Physical electronics*. 19, pp.123-126 (1979).
5. Landolt-Boernstein. *Numerical Data and Functional Relationships in Science and Technology. New Ser. Group III: Crystal and Solid State Physics.* Vol. **17**, sv. f [Ed. by O. Madelung.– (Berline. A.: Springer.-562 (1983)].
6. Fahrenbrunch A.L., Bube R.H. *Fundamentals of Solar cells / Photovoltaic solar energy conversion*. New York, (1983).