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The problem of nonuniqueness of the laser radiation conversion into electric current in multijunction monolithic photoconverters

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We study the multiplicity of solutions for a monolithic two-junction photoconverter of laser radiation, the structure of which has a window and a rear barrier, as well as traps in a tunnel diode (TD). The existence of two solutions is shown, one of which corresponds to the tunnel branch of the current-voltage characteristic of the TD, and the second to the diffuse branch. It is also shown that in the presence of traps, the transfer of charge carriers through the TD barrier occurs through tunneling in both solutions. Moreover, in the second solution, tunneling occurs even in the mode of the open-circuit voltage, when charge carriers move in one direction. A method for implementing the second solution in practice is proposed.

Keywords: Photovoltaics, laser radiation, multi-junction photoconverter, tunnel diod, traps.

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1. Introduction

The multijunction photoconverters (MPC) of laser radiation, comprising several single-junction PC (sub-converters or conversion cascades) located above each other and serial connected by back-to-back tunnel diodes (TD), are rather attractive for use in optical systems of wireless transmission of energy and information signals, and in various radiophotonic devices (see, for example, [1]), as they ensure output voltage increasing by several times as compared to single-junction PC upon keeping high efficiency of optical power conversion into electrical power. In particular, for normal operating MPC the open-circuit voltage U_{oc} is practically equal to sum U_{oc} of all single-junction PCs being part of MPC. Foreign publications contain results of numerical and experimental studies of MPC, comprising 2 to 20 $p{-}n$-transitions [2–7]. On other hand, the tunnel diodes being part of MPC have N-like current-voltage curve (CVC). So, if current through TD is lower the peak current, the tunnel diode has two stable equilibrium states. Naturally we expect that at this condition for same MPC existence of several options of radiation conversion into electric current is possible. In principle, maximum number of such options can reach 2^{M}, where M — number of tunnel diodes. At that, only in one option (let's call it the first one) the mode of current flow corresponds to tunnel branch of CVC in all TDs. For all other cases, minimum in one TD the current will correspond to the diffusion branch of CVC, and, hence, voltage on it is significantly higher (for system AlGaAs $\sim 1\,\mathrm{V}$), this will lead to the conversion efficiency decreasing. Generally, in practice the first option is implemented. Perhaps this is why this issue has not yet received due attention in the literature. Note that MPC modeling with number of TDs exceeding one faces to significant calculation difficulties. This, obviously, is directly associated with specified ambiguity of MPC operation modes. Due to this in such cases TDs are generally replaced by ohmic coupling. But at such approach we can successfully model only the first mode, at that all other solutions are excluded from the discussion. Apparently, this problem was first considered in the paper [8] using the example of the simplest structure ($p{-}n{-}\mathrm{TD}{-}p{-}n$) of two-cascade PC based on gallium arsenide. It was shown that besides known loading characteristic corresponding to the tunneling of charge carriers through TD barrier, there is second loading characteristic associated with injection of charge carriers through this barrier as result of its significant decreasing. However, the question arises whether the appearance of the second solution is associated with the simplicity of the considered PC structure, which did not contain neither window, nor rear barrier, or traps, i. e., factors that are characteristic of actual PCs.

So, this paper objective is study of effect of said factors on the problem of nonuniqueness of the laser radiation conversion in MPC. The problem setting is similar to that in paper [8].

2. Two-junction PC

Again, the two-junction PC is considered, but its structure is much closer to the actual one: there is wide-band window, rear barrier and traps in the tunnel diode. Parameters of the structure are listed in the Table. Interband tunneling was amended by the tunneling through traps, which energy is $0.4\,\mathrm{eV}$ relative to E_c or E_v. The tunneling process itself is considered by introduction of additional recombination term into diffusion-drift equations as per non-local model [9]. Effective masses of electrons and holes for tunneling were practically equal to standard values of the appropriate

Structure of two-cascade photoconverter with wide-band window and rear potential barrier

Material	Concentration of donor N_D, cm^{-3}	Concentration of acceptors N_A, cm^{-3}	Thickness of layer h, μm
p-Al$_x$Ga$_{1-x}$As, $x = 0.3$	–	$2 \cdot 10^{19}$	0.04
p-GaAs	–	$2 \cdot 10^{18}$	0.2
n-GaAs	$5 \cdot 10^{17}$	–	0.42
n^{++}-GaAs	$2 \cdot 10^{19}$	–	0.025
p^{++}-GaAs	–	$6 \cdot 10^{19}$	0.025
p-GaAs	–	$2 \cdot 10^{18}$	0.4
n-GaAs	$5 \cdot 10^{17}$	–	1.926
n-Al$_x$Ga$_{1-x}$As, x=0.3	$3 \cdot 10^{18}$	–	0.025
n-GaAs	$3 \cdot 10^{18}$	–	0.05

masses, as result the density of peak current of TD was limited to 32 A/cm^2. Radiation was introduced from left, and number of photons adsorbed in each subconverter (SUBC), was same.

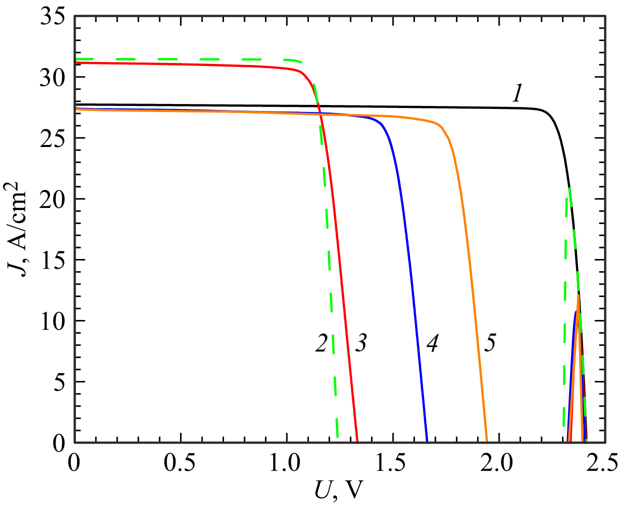

Figure 1. Loading curves for different solutions (operation modes of PC). *1* — first solution, *2–5* — second solution at different concentrations of traps: $N_{\text{trap}} = 0$ (*2*), 10^{14} (*3*), 10^{15} (*4*), 10^{16} cm^{-3} (*5*). (A color version of the figure is provided in the online version of the paper).

3. Results and discussion

Figure 1 presents loading curves at radiation power 100 W/cm^2 (when current is below the peak current of TD) and at different concentrations of traps. We see that in spite of structure complexity as compared to [8], in all cases there are two solutions. The first solution, described by curve *1*, is not affected by traps, and second solution already significantly depends on their concentration. Short circuit current J_{sc} in second solution is somewhat higher than in the first solution, and open circuit voltage U_{oc} is significantly lower. At that U_{oc} increases with N_{trap} rise, but this is accompanied by form factor decreasing, so the conversion efficiency does not change significantly and stays much lower that in the first solution. Note that in area of the open circuit voltage for the fist solution (curve *1*) the second solution appears again and completely coincides with the first solution. But maximum current of the second solution is much lower the current of the first solution, so in this section also the conversion efficiency of the second solution is lower. Note that in initial state (without radiation and applied voltage) the contact differences of potentials on p-n-transitions were 1.35 V for both SUBCs and 1.9 V for TD. When PC is illuminated, the redistribution of potential occurs through the thickness of the structure due to mismatch of currents as a result of the difference in the thickness of the cascades (Figure 2). In short circuit mode in the first solution the first SUBC (closest to the illuminated surface) is forward biased by 1.05 V, the second one is reverse biased by 1.03 V, at the same time TD bias is +0.02 V only, which corresponds the tunnel branch of its CVC. In the second solution the picture changes dramatically, and the tunnel diode is strongly forward biased, shifting to the diffuse branch of CVC. Note that TD bias value insignificantly decreases (in range 3–10%) with voltage rise on PC up to voltage U_{oc}. At $N_{\text{trap}} = 0$ such bias is 1.24 V and is practically completely compensated by the positive bias of p–n junction in the second cascade at all values of voltage on PC up to U_{oc}. The later means [8], that charge carriers generated in the second SUBC do not contribute to the electric current, this is explains half the value U_{oc} in Figure 1 (curve *2*). With increase in traps concentration TD bias decreases (for example, for $N_{\text{trap}} = 10^{15}$ cm^{-3} in short circuit mode it is 0.86 V), and zone diagram becomes qualitatively more similar to the zone diagram of the first solution (Figure 2, *a*–*c*). Figure 3 shows distributions of electron and hole currents through thickness of structure for the second solution at $N_{\text{trap}} = 10^{15}$ cm^{-3}. We see, that charge carriers transfer through TD barrier is still performed by the tunneling (but through traps) at all voltages, for which the photovoltaic mode exists, although on TD significant voltage drops ~ 0.8 V. The electron and hole currents in the open circuit mode (Figure 3, *b*) are of special interest, they are rather significant, although full current is equal to zero. As said currents have different signs the electrons and holes move in same direction to the left towards illuminated surface. At that in TD jump-like drop of these currents to zero occurs, similar, for example, to short circuit mode (Figure 3, *a*). The unusual situation arises when charge carriers tunneling through the TD barrier move in one direction. This can be explained as follows. For electrons, moving from right to left, p–n-transition in TD is not barrier, and they roll from p-are of TD into n-area, and from here they tunnel towards holes that also approach the barrier from the right. Note that at $N_{\text{trap}} = 0$ carriers in the second solution, like in paper [8], are transferred through the TD barrier by injection.

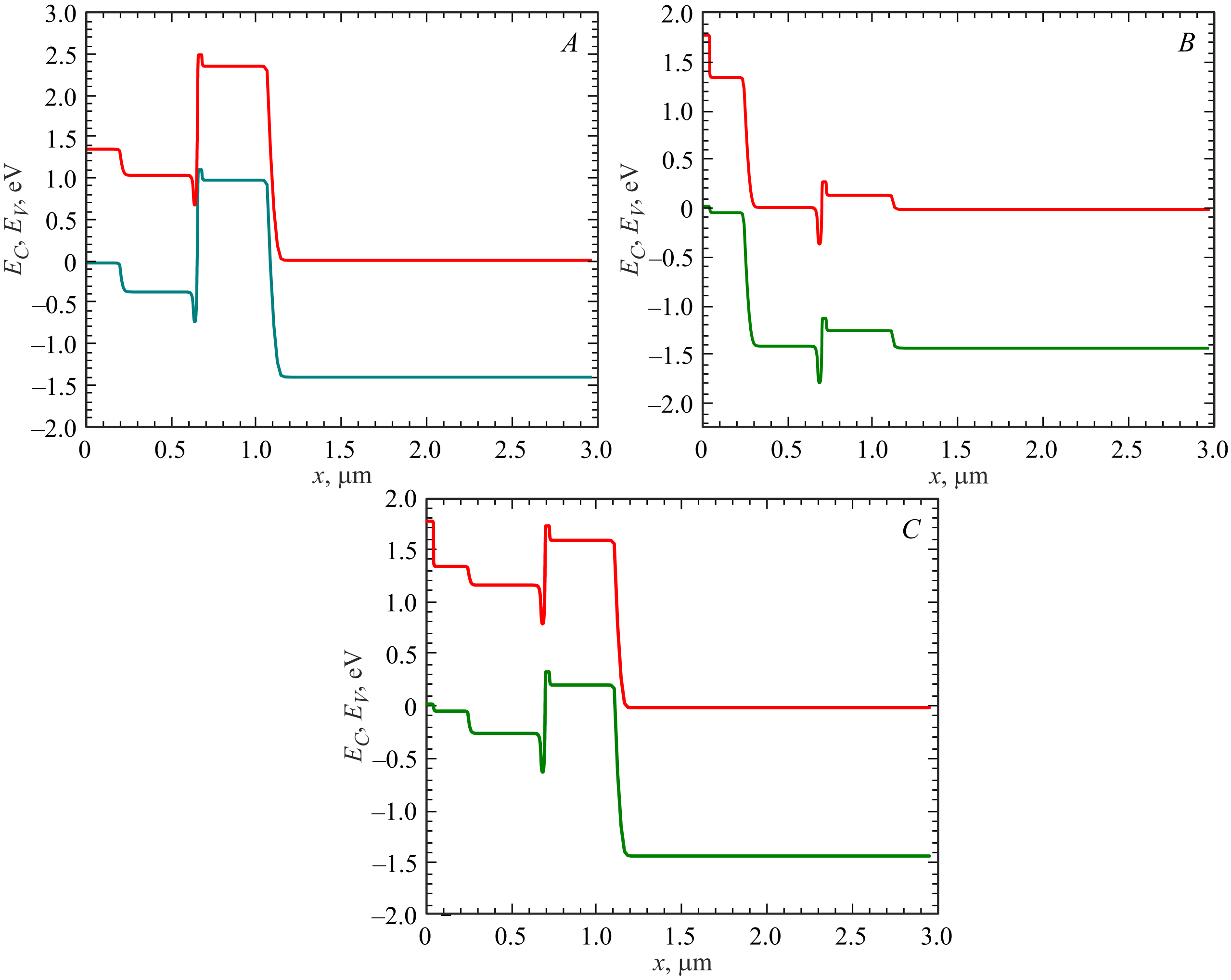

Figure 2. Zone diagrams of two-junction PC in short circuit mode. A — first solution, B and C — second solution at $N_{\text{trap}} = 0$ and $N_{\text{trap}} = 10^{15}\,\text{cm}^{-3}$ respectively.

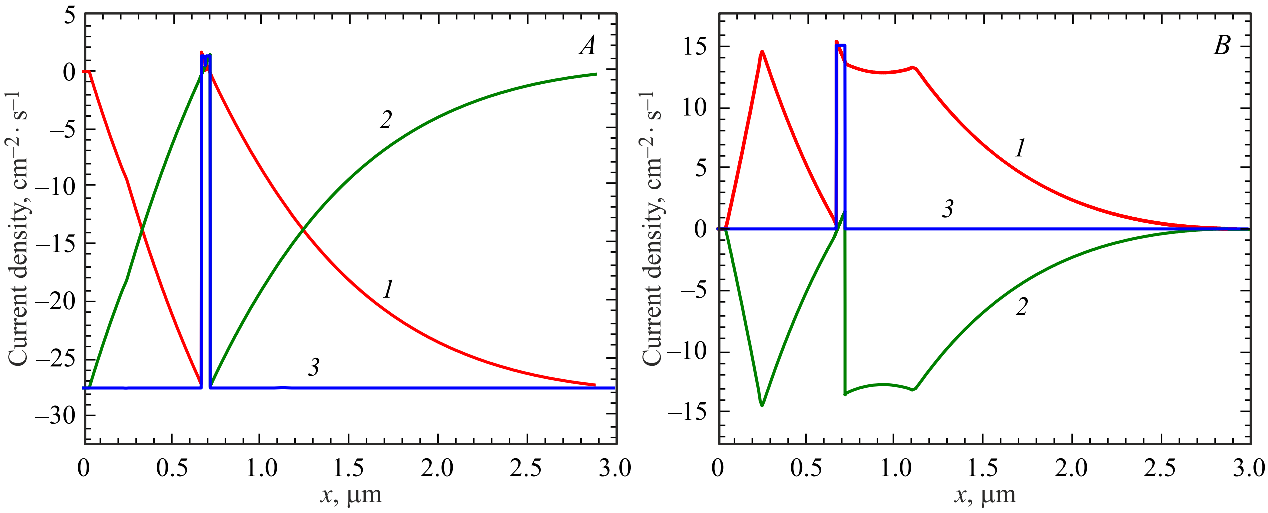

Figure 3. Density distribution of electron (1) and hole currents (2) through thickness of PC in second solutions at $N_{\text{trap}} = 10^{15}\,\text{cm}^{-3}$ in short circuit mode (A) in open circuit mode (B). Curve 3 — density of total current.

As it was shown above, in actual MPC the operation principle described by the first solution is implemented. And how it is possible to check other solutions existence in practice? Relating to two-junction PC this can be made as follows. At rather high radiation power the current exceeds the peak value of TD current, and we have the second solution only. If now the radiation power is abruptly decreased to level, when current again will be below the peak current of TD, the second solution will stay. Just by this non-stationary way the load curves *2–5* in Figure 1 were obtained, since due to the complexity of the PC structure, we were unable to obtain them using the usual iterative method from the stationary equations. This in turn explains the reason why generally in practice the first solution is implemented.

4. Conclusion

So, it was shown that complexity of structure of two-junction PC does not lead in disappearance of the problem of nonuniqueness of laser radiation converter. There are basis to suppose that this conclusion will be also true for MPC.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S. Yuferev, I.A. Tolkachev, V.S. Kalinovsky. Techn. Phys. Lett., **50** (7), 39 (2023). DOI: 10.61011/PJTF.2024.01.56925.19674
[2] D.F. Zaitsev, V.M. Andreev, I.A. Bilenko, A.A. Berezovsky, P.Yu. Vladislavsky, Yu.B. Gurfinkel, L.I. Tsvetkova, V.S. Kalinovsky, N.M. Kondratyev, V.N. Kosolobov, V.F. Kurochkin, S.O. Slipchenko, N.V. Smirnov, B.V. Yakovlev. Radiotekhnika, **85** (4), 153 (2021). DOI: 10.18127/j00338486-202104-17 (in Russian)
[3] Mark C.A. York, Simon Fafard. J. Phys. D: Appl. Phys., **50**, 173003 (2017). DOI: 10.1088/1361-6463/aa60a6
[4] E. Moon, M. Barrow, J. Lim, D. Blaauw, J.D. Phillips. IEEE J. Photovoltaics, **10**, 1721 (2020). DOI: 10.1109/JPHOTOV.2020.3025450
[5] S. Fafard, D.P. Masson. J. Appl. Phys., **130**, 160901 (2021). DOI: 10.1063/5/0070860
[6] H. Helmers, C. Armbruster, M. von Ravenstein, D. Derix, C. Schöner. IEEE Trans. Power Electron., **35**, 7904 (2020). DOI: 10.1109/TPEL.2020.2967475
[7] J. Huang, Y. Sun, Y. Zhao, S. Yu, J. Dong, J. Xue, C. Xue, J. Wang, Y. Lu, Y. Ding. J. Semicond., **39** (4), 044003 (2018). DOI: 10.1088/1674-4926/39/9/094006
[8] A. Wang, J. Yin, S. Yu, Y. Sun. Appl. Phys. Lett., **121**, 233901 (2022). DOI: 10.1063/5.0109587
[9] S. Fafard, F. Proulx, M.C.A. York, L.S. Richard, P.O. Provost, R. Ares, V. Amez, D.P. Masson. Appl. Phys. Lett., **109**, 131107 (2016). DOI: 10.1063/1.4964120

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