Conversion of subnanosecond laser pulses into electric current by multijunction photoconverters: the roleof tunnel diodes

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Using numerical simulation, the role of counterconnected tunnel diodes in multijunction monolithic photoconverters is investigated when they are illuminated by subnanosecond powerful laser pulses. It is shown that in this case, unlike stationary laser radiation, tunnel diodes are no longer key elements of a multijunction photoconverter, without which its operation is impossible, since tunnel currents are replaced by displacement currents. For the first time, using the example of two-, three- and six-junction $p-i-n$ photoconverters operating in a pulsed mode, the possibility of their operation either without tunnel diodes or with a significant reduction in the requirements for their parameters is shown.

Keywords: counterconnected tunnel diodes, displacement currents, multijunction monolithic photoconverters, subnanosecond powerful laser pulses.

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Monolithic multijunction photoconverters (MPC) of laser radiation, consisting of several epitaxially grown photoactive layers with a single $p-n$-junction (subconverters), which are located on top of each other and connected in series by counter-connected tunnel diodes (TD), allow in the photovoltaic mode to multiply the compared with single-junction PC, the output voltage at the load and ensure high efficiency in converting optical power into electrical power. It is believed that it is the TD that provides this advantage, since if the current through the MPC remains less than the peak current of the tunnel diodes, then the voltage drop across the TD or, in other words, on the barrier between adjacent subconverters turns out to be small and practically does not affect the magnitude of the voltage drop across the load. Otherwise, if there are no TD or the intensity of the laser radiation is so high that the current exceeds the peak currents of the tunnel diodes, then the voltage drops at the boundaries between adjacent subconverters increase significantly and can compensate, since they are directed in the opposite direction, for a significant proportion of the voltage drop on the photoactive $p-n$-junctions of MPC. As a result, the MPC characteristics will practically coincide with the characteristics of single-junction photoconverters. However, all this is true only if the radiation intensity does not change or changes slightly over time and the MPC practically operates in a stationary mode. This particular situation has been studied in detail in the literature (see, for example, [1]). At the same time, it turned out that in the stationary case, MPCs can, in principle, have several modes of operation, i. e., several load characteristics [2]. A completely different situation, however, arises when MPCs are supposed to be used, for example, in radiophotonics systems [3] for converting high-power laser pulses in the nanosecond range. It is natural to expect that in this case, the current flow in the MPCs should be significantly influenced by capacitive effects and, in particular, TD barrier capacitances. As far as we know, this aspect of the problem has not been considered in the literature with respect to MPC. It is possible to indicate only works devoted to the response of a separate photodetector, to which a reverse bias is applied, to excitation by a short laser pulse (see, for example, [4]). Therefore, the purpose of this work is to numerically study the features of converting high-power subnanosecond laser pulses into electric current in the photovoltaic mode by multijunction photoconverters connected to an external load. The ohmic resistance of 50 Ohms was chosen as the last one. The choice of load was explained by the fact that the specified load is used in microwave technology, as well as multijunction photoconverters, are expected to find effective use in solving these problems. Given the complexities of modeling structures with several TD [2], the main attention was paid to the consideration of two- and three-junction PC. At the same time, the issues of matching MPC with load were not considered, since with a small number of photoactive transitions, the load of 50 Ohms would not be optimal. This side of the problem is solved by increasing either the number of junctions in MPC or the number of MPC connected in series. The interband tunneling process was considered, which was taken into account by introducing an additional recombination term in the diffusion-drift equations using the nonlocal model [5,6]. The tunnel effective masses were taken to be $m_{\mathrm{e.tun}} = 0.044$, $m_{\mathrm{h.tun}} = 0.44$. Radiation with a wavelength of 830 nm was introduced from the left through the p-region. The parameters of the structures of the modeled PC are presented in Table 1 and 2. The structures had an area of $0.00049\,\mathrm{cm}^2$ and consisted of a wide-

Table 1. Structure of a two-junction subconverter

Material	Concentration of donors N_D, cm^{-3}	Concentration of acceptors N_A, cm^{-3}	Thickness of layers 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_0-GaAs	$1 \cdot 10^{15}$	–	0.368
n-GaAs	$1 \cdot 10^{18}$	–	0.12
n^{++}-GaAs	$2 \cdot 10^{19}$	–	0.02
p^{++}-GaAs	–	$6 \cdot 10^{19}$	0.02
p-GaAs	–	$2 \cdot 10^{18}$	0.4
n_0-GaAs	$1 \cdot 10^{15}$	–	0.9
n-GaAs	$1 \cdot 10^{18}$	–	1.93
n-Al$_x$Ga$_{1-x}$As, $x = 0.3$	$3 \cdot 10^{18}$	–	0.2
n-GaAs	$6 \cdot 10^{18}$	–	0.25
n-GaAs	$2 \cdot 10^{18}$	–	0.3

Table 2. Structure of a three-junction subconverter

Material	Concentration of donors N_D, cm^{-3}	Concentration of acceptors N_A, cm^{-3}	Thickness of layers h, μm
p-Al$_x$Ga$_{1-x}$As, $x = 0.3$	–	$5 \cdot 10^{19}$	0.3
p-GaAs	–	$1 \cdot 10^{18}$	0.08
n_0-GaAs	$1 \cdot 10^{15}$	–	0.25
n-GaAs	$1 \cdot 10^{18}$	–	0.07
n^{++}-GaAs	$1 \cdot 10^{19}$	–	0.01
p^{++}-GaAs	–	$1 \cdot 10^{19}$	0.01
p-GaAs	–	$1 \cdot 10^{18}$	0.11
n_0-GaAs	$1 \cdot 10^{15}$	–	0.43
n-GaAs	$1 \cdot 10^{18}$	–	0.11
n^{++}-C	$1 \cdot 10^{19}$	–	0.01
p^{++}-GaAs	–	$1 \cdot 10^{19}$	0.01
p-GaAs	–	$1 \cdot 10^{18}$	0.77
n_0-GaAs	$1 \cdot 10^{15}$	–	0.9
n-GaAs	$1 \cdot 10^{18}$	–	0.78
n-Al$_x$Ga$_{1-x}$As, $x = 0.3$	$3 \cdot 10^{18}$	–	0.2
n-GaAs	$6 \cdot 10^{18}$	–	0.25
n-GaAs	$2 \cdot 10^{18}$	–	0.3

area window, two or three subconverters, a rear barrier, and a buffer. Each subconverter was a $p{-}i{-}n$-diode to improve the separation of photo-carriers. The subconverter thicknesses were determined from the condition of equality of the number of photons absorbed in each subconverter. The absorption coefficients depended on the concentration of the alloying impurity and according to the data given in Ref. [7], they were taken equal to 0.87 in a p-layer, to 0.8 in a n-layer and to 1.0 reverse microns in a n_0-layer. Shockley-Reed recombination and radiative recombination were taken into account. The lifetimes of electrons and holes were considered to be the same and were equal to 10 ns in the n_0 layers and 3 ns in the remaining layers of the structure. The mobilities of electrons and holes were described by standard dependences on the concentration of an alloying impurity and the electric field. The negative differential mobility of electrons was not taken into account. The processes of photon reabsorption were not considered. In all calculations, the duration of the laser pulse was the same FWHM = 140 ps. Figure 1, a shows the photoresponse of the 2-junction photoconverter to optical pulses shown in the inset to this figure. It can be seen that even at a peak optical power density greater than 1500 W/cm^2, the maximum voltage on the load practically ceases to increase, saturation occurs when the electric field in the subconverter ceases to effectively separate charge carriers and the response time (voltage pulse) begins to increase. The maximum current density is 88 A/cm^2, and the maximum efficiency is ~ 10 %. Figure 1, b shows the distributions of the various current density components in the tunnel diode region at the time when the load voltage in the pulse reaches a maximum. It can be seen that the conduction current is close to zero, and the bias current exceeds the tunnel current by 30 %. This means that only a smaller part of the charge carriers

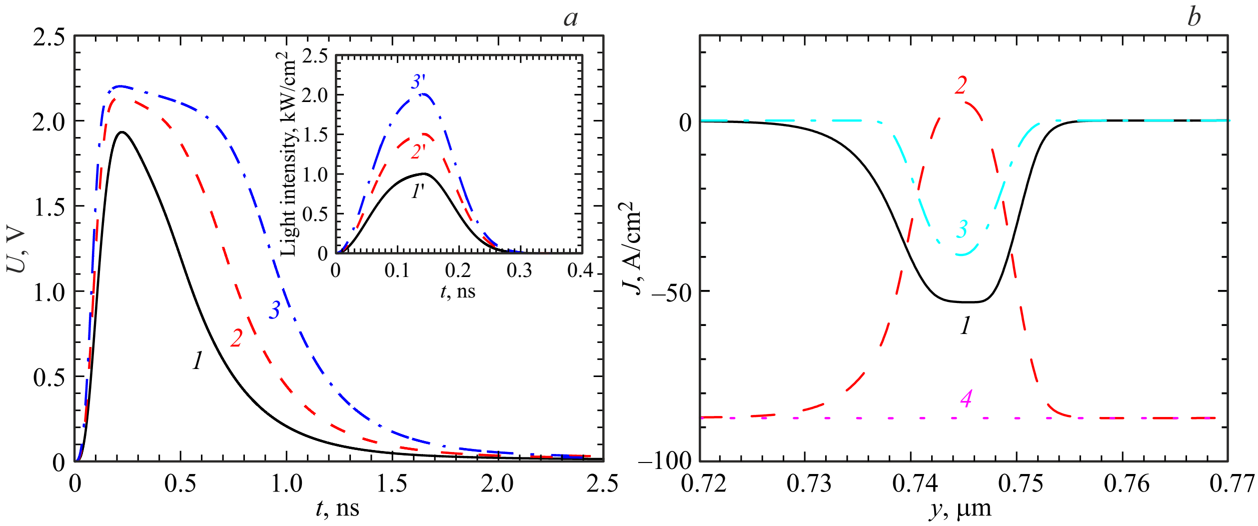

Figure 1. *a* — photoresponse of a two-junction photoconverter to laser pulses with peak power density $P_{peak} = 1020$ (*1*), 1530 (*2*), 2040 W/cm^2 (*3*). The insert shows corresponding laser pulses with a duration of 140 ps and at a wavelength of 830 nm. *b* — distributions of the density of the bias current (*1*), the conduction current (*2*), the tunnel current (*3*) and the total current (*4*) in the area of the PC TD at time 217 ps at $P_{peak} = 1530$ W/cm^2.

approaching the tunnel diode tunnel through the barrier, and the rest cannot overcome it, creating a dipole that lowers the field in TD and thereby causes the appearance of a bias current, which makes a major contribution to the flow of current between adjacent subconverters. It should be noted that in this case, the bias currents in the p–n-junctions of subconverter turn out to be more than 5, times less than the bias currents in TD. However, this is quite natural, since these transitions, unlike the p–n-junctions at the boundary between the subconverters, are not an obstacle to the flow of current. Accordingly, the resulting dipole will be weaker and will cause a smaller change in the electric field strength and a smaller bias current.

It could be assumed that the effect of replacing the tunnel current with a bias current in TD is associated with an excess of the current density over the peak current of the TD and the resulting transition from the tunnel branch of the TD VAC to the injection branch. To verify this, we performed similar calculations for significantly lower optical power densities, when it was certainly possible to expect that carriers would prefer to tunnel through the barrier and the bias current would be negligible. The results are shown in Figure 2. It is apparent that this did not happen, and the bias current is still significantly higher than the tunnel current everywhere. This fact can be commented on as follows. For a tunnel current to occur, the Fermi quasi-levels in the n- and p-layers of the TD must shift relative to each other, and this means the occurrence of a potential difference, an electric dipole that will support it, and, consequently, a bias current. Thus, it turns out that tunnel diodes are no longer critically important for converting short laser pulses using MPC, unlike in the case of stationary radiation conversion. Moreover, for the options presented

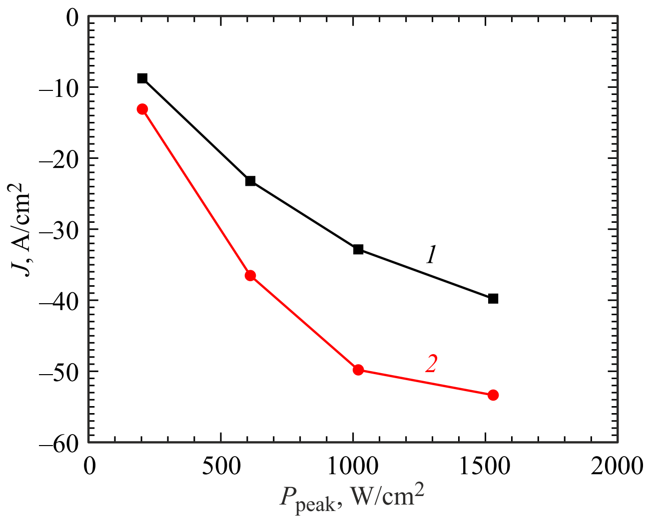

Figure 2. Dependence of the current density in the region of the tunnel diode on the peak laser radiation power for a two-junction photoconverter: *1* — tunnel current density, *2* — bias current density.

in Figure 1, *a*, calculations were performed with the tunnel effect disabled. It turned out that the voltage curves had not changed much. This suggests that, from the point of view of the price-quality ratio, it makes little sense to achieve a high level of perfection of tunnel diodes or even use them at all to connect adjacent subconverters, limiting ourselves to structures consisting only of photoactive junctions of the n–p-n–p-type. To verify this conclusion, we performed calculations at different levels of doping of p- and n-layers, etc. The results are shown in Figure 3, *a*. It can be seen

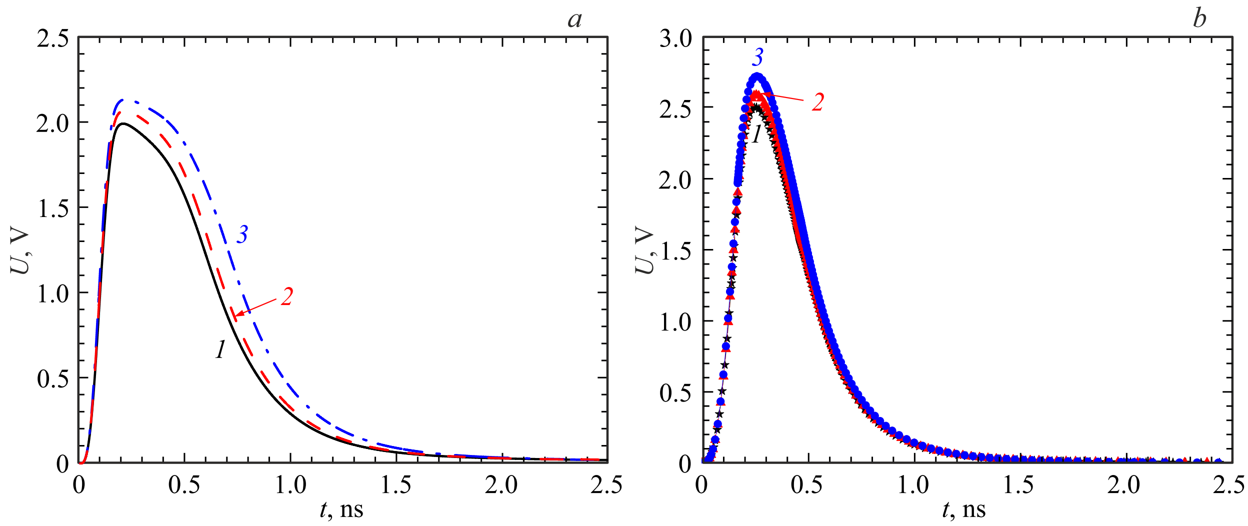

Figure 3. Photoresponses of photoconverters at different concentrations of dopants in tunnel diode layers: *a* — two-junction photoconverter at $P_{\text{peak}} = 1530\,\text{W/cm}^2$: *1* — $N_D = 1 \cdot 10^{18}\,\text{cm}^{-3}$, $N_A = 3 \cdot 10^{18}\,\text{cm}^{-3}$; *2* —$N_D = 5 \cdot 10^{18}\,\text{cm}^{-3}$, $N_A = 1.5 \cdot 10^{19}\,\text{cm}^{-3}$; *3* — $N_D = 2 \cdot 10^{19}\,\text{cm}^{-3}$, $N_A = 6 \cdot 10^{19}\,\text{cm}^{-3}$. *b* — three-junction photoconverter at $P_{\text{total}} = 2040\,\text{W/cm}^2$: *1* —$N_D = 1 \cdot 10^{18}\,\text{cm}^{-3}$, $N_A = 1 \cdot 10^{18}\,\text{cm}^{-3}$; *2* — $N_D = 5 \cdot 10^{18}\,\text{cm}^{-3}$, $N_A = 5 \cdot 10^{18}\,\text{cm}^{-3}$; *3* —$N_D = 1 \cdot 10^{19}\,\text{cm}^{-3}$, $N_A = 1 \cdot 10^{19}\,\text{cm}^{-3}$.

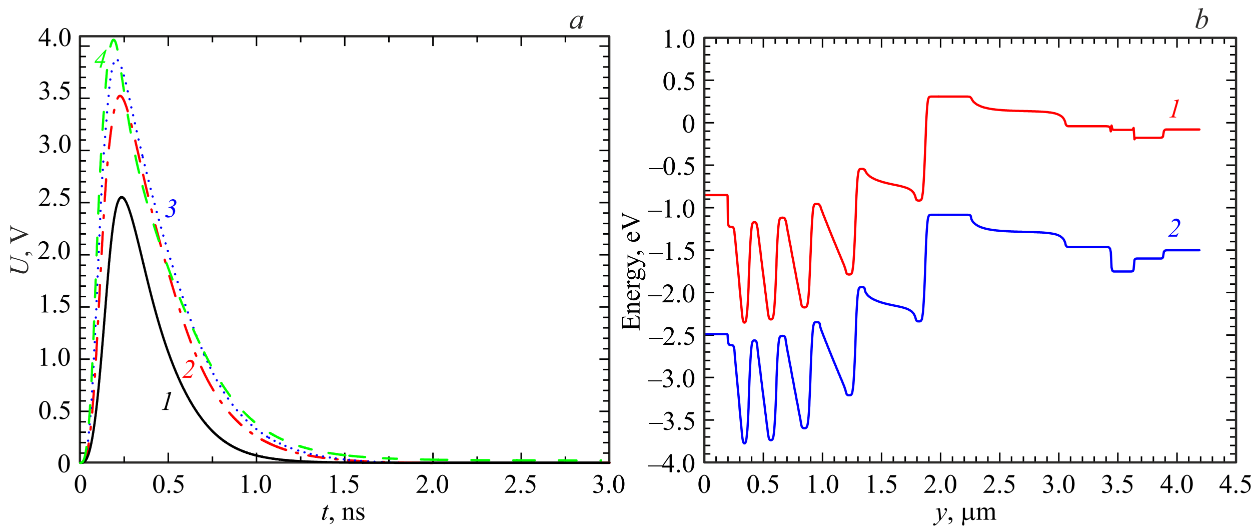

Figure 4. *a* — photoresponse of a six-junction photoconverter at different peak laser radiation power, when doped in TD layers $1 \cdot 10^{18}\,\text{cm}^{-3}$: *1* — 4081, *2* — 8163, *3* — 12244, *4* — $16326\,\text{W/cm}^2$. *b* — zone diagram of a six-junction photoconverter at time $t = 236$ ps at peak laser power $4081\,\text{W/cm}^2$: *1* — conduction band, *2* — valence band.

that the maximum difference between the curves is 8%. Thus, the abandonment of the tunnel diode (curve *1*) leads only to a relatively small decrease in the amplitude of the voltage at the load, but it significantly simplifies the photoconverter growing technology. Similar results are obtained for three-junction photoconverter (Figure 3, *b*). The relatively smaller increase in the amplitude of the voltage pulse, which is visible in the figures, during the transition from a two- to a three-junction photoconverter is associated with a lower optical power per sub-pulse in a three-junctionphotoconverter. At the same time, the conversion efficiency at the maximum of the voltage pulse in the three-junction photoconverter is higher and amounts to 13–15%.

As noted above, modeling of MPCs with the number of TD greater than 2 faces very great difficulties due to the poor convergence of iterative processes and the need for a sharp increase in the amount of computational memory. The results obtained make it possible to use simplified models in which the effect of quantum tunneling is disabled to study the functioning of MPCs in the pulse mode. This approach was used in this paper to numerically study the characteristics of a six-junction photoconverters. The structure of the latter was similar to the structure of two- and three-junction photoconverter, and the optical thicknesses of subconverters were 0.172, 0.208, 0.283, 0.359, 0.565, and 1.427, respectively. Tunnel diodes were still part of the photoconverter, but their role was limited to an increase in the thickness of the subconverters adjacent to them, as well as a change in the volume charge layer near the boundary between subconverters. Figure 4, *a* shows a photoresponse of a six-junction photoconverter at different peak power of an optical pulse in the case when the doping of the TD was $1 \cdot 10^{18}\,\mathrm{cm}^{-3}$. It can be seen that the peak voltage limit value turns out to be only slightly higher than 4 V, i.e. ~ 0.7 V per a subconverter, while for two- and three-junction photoconverters this value was close to 1. Thus, it turned out that a further increase in the number of photoactive $p-n$-junctions leads to a new problem, namely, a decrease in the efficiency of the photoconverters. A hint of the cause of this phenomenon can be seen in Figure 4, *b*, which shows the zone diagram of the six-junction photoconverter at time $t = 236$ ps, when the voltage reaches its maximum value. It can be seen that the main part of the voltage falling on the structure falls on the last three subconverters At the same time, the potential changes in the volume charge layers at the boundaries between the subconverters turn out to be almost the same, but the bias of the $p-n$-junctions inside the subconverters significantly differ: in the first three subconverters, they are, firstly, significantly less than in the last three subconverters, and secondly, they are close in absolute magnitude to potential changes near the boundaries of the subconverters, which leads to a relatively small voltage drop at the first subconverters. We assumed that the reason is that the first subconverters turned out to be too thin and it was necessary to increase their thickness. However, this requires a reduction of the absorption coefficient in them. As a trial version, GaAs was replaced with AlGaAs in the first three subconverters. The calculation results are not given here, we only point out that the assumption turned out to be correct and in this way we were able to increase the amplitude of the voltage pulse by ~ 1.5 times.

Thus, for structures with at least two- and three-junction photoconverter designed to convert subnanosecond high-power laser pulses into a load voltage pulse, it is possible to either remove the TD altogether or significantly weaken the requirements for their parameters with virtually no loss of efficiency.

Conflict of interest

The authors declare that they have no conflict of interest.

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