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Generation of microwave pulses by zero-bias monolithic triple-junction AlGaAs/GaAs $p-i-n$ photoconverters and modules

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The possibility of microwave pulses generation in the photovoltaic mode by monolithic triple-junction AlGaAs/GaAs photoconverters of laser radiation grown by molecular beam epitaxy has been demonstrated. In monolithic triple-junction $p-i-n$ AlGaAs/GaAs photoconverters, a significant increase in output peak pulse power and fast performance in the subnanosecond range has been achieved compared to single-junction $p-i-n$ photoconverters. When pulsed laser radiation at a wavelength of 850 nm with a peak power of < 5 W and full width at half maximum (FWHM) of $\tau_{0.5} = 140$ ps was injected from the optical fiber, photoresponse pulses with amplitude $U_{\max} = 2.7$ V, peak power $P_{peak} = 21.6$ dBm, and $\tau_{0.5} \leqslant 750$ ps were obtained. A module of two series-connected photoconverters provided output pulses with an amplitude of $U_{\max} = 3.4$ V, power $P_{peak} = 23.7$ dBm and $\tau_{0.5} \leqslant 420$ ps. It is shown that the module of four monolithic triple-junction photoconverters is capable of forming a bipolar microwave pulse with parameters $U_{\max} = 6.4$ V, $P_{peak} = 29.1$ dBm, $\tau_{0.5} \leqslant 1$ ns, bandwidth up to 1.4 GHz and the main carrier frequency of ~ 0.8 GHz. The numerical modeling showed a fairly good agreement between the measured and calculated photoresponse pulses shapes of photoconverters.

Keywords: monolithic triple-junction photoconverter, $p-i-n$ AlGaAs/GaAs photoconverter, microwave pulse generation, molecular beam epitaxy, pulsed laser radiation, full width at half maximum, optical fiber, peak power

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Currently the conventional radioelectronics is being replaced with a new radio-photonic component base, where some of the most important elements, for example, in radio-photonic active phased antenna arrays (ROFAR) [1] are the powerful pulse photo converters (PC). ROFAR efficiency is to a large extent determined by the output electric power of PC, fast response, agreement with the load (antenna), and energy self-sufficiency, providing for complete galvanic isolation between the antenna array and the main generating equipment. For this purpose PCs must generate microwave-pulses of maximum power in photovoltaic mode, i. e. without supply of the back voltage bias. Small (up to 1 km) length of fiberoptic communication lines in radio-photonic systems makes it possible to work without considerable losses in the spectral range 700–900 nm, where GaAs/AlGaAs PCs have high efficiency ratio.

In various types of PC structures, such as $p-i-n$ PCs [2], PCs with a partially depleted absorber (PD) [3], unidirectional PCs (UTC) [4], modified unidirectional PCs (MUTC) [5], the key feature is the presence of non-doped ($p-i-n$, PD and UTC PC) or lightly doped (MUTC) i-layer of micron thickness. The main array of the research and developments is dedicated to the photodiodes operating in diode mode (at back voltage bias), and is oriented at conversion of laser radiation at wavelength $\lambda = 1550$ nm. In paper [6] it is shown that in MUTC InGaAsP/InP PC with diameter of photoactive surface $\leq 50\,\mu$m at voltage biases ≤ 44 V ($\lambda = 1550$ nm), the values of the output peak power ≤ 44.2 dBm are achieved with amplitude $U_{\max} \leq 38$ V and duration at half maximum of amplitude $\tau_{0.5} \sim 30$ ps. In [6] the characteristics are provided for quick-acting MUTC GaAs/AlGaAs PCs with sensitivity ~ 0.5 A/W and quantum efficiency up to 73 % in the gigahertz range at wavelength 850 nm with zero shift, which ensured the output electric pulses with milliwatt (< 10 dBm) peak power.

This paper is dedicated to development and research of characteristics of the subnanosecond powerful monolithic triple-junction $p-i-n$ AlGaAs/GaAs PCs (TJ PC) of laser radiation (830–860 nm), operating in photovoltaic mode.

The specified PCs were grown by molecular-beam epitaxy (MBE) method on n-GaAs substrate ($N_D \sim 3 \cdot 10^{18}\,\mathrm{cm}^{-3}$). The structure of TJ PC (fig. 1, a) included three $p-i-n$ GaAs subelements with thicknesses of upper, medium and lower junctions, selected on the basis of the condition of equality between photocurrents generated in the subelements [7]. Doping levers for p-layers were $N_A \geq 1 \cdot 10^{18}\,\mathrm{cm}^{-3}$, for n-layers - $N_D \leq 1 \cdot 10^{18}\,\mathrm{cm}^{-3}$ and for i-layers $N_D \sim 1 \cdot 10^{15}\,\mathrm{cm}^{-3}$. The connecting elements between the photoactive $p-i-n$-junctions were back-to-back nanoscale GaAs $p^{++}-n^{++}$ tunnel diodes, each with total thickness of ≤ 30 nm. The structure also included a wide-band window p-$Al_{0.2}Ga_{0.8}As$ ($N_A \sim 5 \cdot 10^{19}\,\mathrm{cm}^{-3}$ — $0.3\,\mu$m) and a rear potential barrier n-$Al_{0.2}Ga_{0.8}As$ ($N_D \sim 3 \cdot 10^{18}\,\mathrm{cm}^{-3}$ — $0.2\,\mu$m). PC chips with a photosensitive surface $250\,\mu$m in diameter, a ring meshed front contact (Ag(Mn)/Ni/Au) with thickness

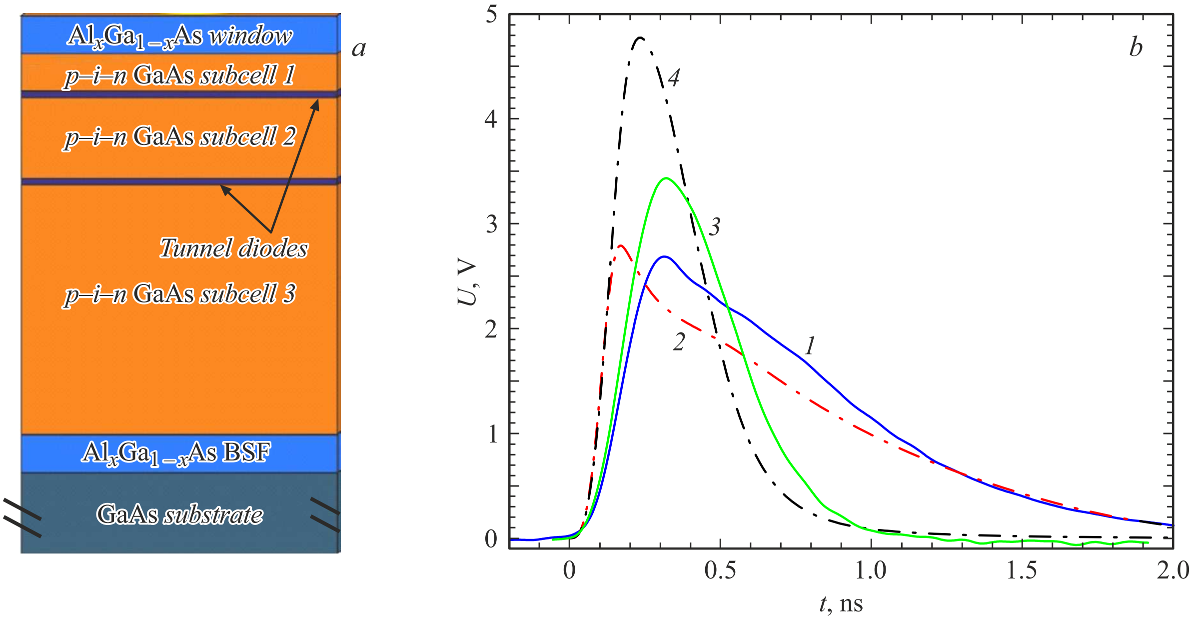

Figure 1. *a* — structure of monolithic triple-junction $p-i-n$ AlGaAs/GaAs PC. Digits indicate upper (*1*), medium (*2*) and lower (*3*) $p-i-n$ GaAs subelements, connected by $n^{++}-p^{++}$ GaAs tunnel diodes; *b* — pulses of photo response of monolithic $p-i-n$ TJ PC (*1* — experiment, *2* — estimate) and module of two series-connected TJ PCs (*3* — experiment, *4* — estimate) at laser radiation power of 4.7 W and duration of 140 ps.

$h \sim 3600$ Å and a back contact (Au(Ge)/Ni/Au) with thickness $h \sim 2000$ Å were formed by post-growth planar processing. The side surface of the mesa-structure was passivated with a Si_3N_4 dielectric layer.

The studied TJ PCs had maxima of the external quantum efficiency $Q_{ext} \geq 21\,\%$ at wavelengths 850–860 nm (without the shadowing with the front contact mesh and the reflectance ratio $< 10\,\%$).

To agree with the $50\,\Omega$ load and improve heat removal, PCs were installed using vacuum soldering method onto a symmetrical microstrip line based on AlN. The contacts were flanged by $50\,\mu$m golden wire with minimization of the inductance value. Microwave modules were made, which consist of two and four TJ PCs mounted on the microstrip heat-removing AlN bases. Pulse laser excitation of both individual TJ PCs and in the module was carried out accordingly with multi-mode optic fiber and optic fiber splitter (1/2) with output diameters $50\,\mu$m.

The characteristics of fast response for some monolithic TJ PCs and modules on their basis were studied when excited by a pulse laser at wavelength 850 nm with duration at half maximum of amplitude $\tau_{0.5} = 140$ ps, repetition rate of 1 kHz and output peak power of up to 5 W. To estimate the PC photoresponse, non-stationary drift-diffusion equations of charge carrier transfer were used together with the Poisson equation for the potential. The process of interband tunneling was considered, which was taken into account by introducing an additional recombination term in the transfer equations using a nonlocal model [7]. Shockley–Reed–Hall recombination and radiative recombination were taken into account. The processes of photon re-absorption were not considered. The estimate of the shapes of output electric pulses (curves *2* and *4* in fig. 1, *b*) was done for the condition of ideal inclusion of PC in the electric circuit.

Fig. 1, *b* presents the results of the measurement and estimation of the photoresponse pulses for an individual $p-i-n$ TJ PC and a module of two such TJ PCs connected in series. Curves *1* (experiment) and *2* (estimate) are related to $p-i-n$ TJ PC, and curves *3* and *4* (experiment and estimate, accordingly) — to the module of two TJ PCs at pulse power of the laser radiation of 4.7 W. The estimate was done in accordance with the quality of photo-generated currents in each of the photoactive $p-i-n$-junctions [8]. All measurements were made at the load $50\,\Omega$ with oscilloscope TDS7704B (Tektronix). For $p-i-n$ TJ PC a good agreement was obtained between the shaped of experimental and estimated curves of the photoresponse pulses. Differences in time parameters and amplitude of the pulse (fig. 1, *b*) for the module of two series-connected TJ PCs may be explained by heterogeneity of the laser radiation density on the front surface of TJ PC, and also parasite inductances and capacitances of $p-i-n$ TJ PC installation on the microstrip line.

According to the obtained results, the maximum amplitude of photoresponse ($U_{\max}$), rise time (τ_{rise}) and fall time (τ_{fall}) at levels from 0.1 to 0.9 of the amplitude and duration of electric pulse at half maximum of amplitude ($\tau_{0,5}$) were accordingly: $U_{\max} = 2.7$ V, $\tau_{rise} = 173$ ps, $\tau_{fall} = 1.28$ ns, $\tau_{0.5} = 750$ ps for a single TJ PC and $U_{\max} = 3.4$ V, $\tau_{rise} = 179$ ps, $\tau_{fall} = 430$ ps, $\tau_{0.5} = 420$ ps for a module of two series-connected TJ PCs.

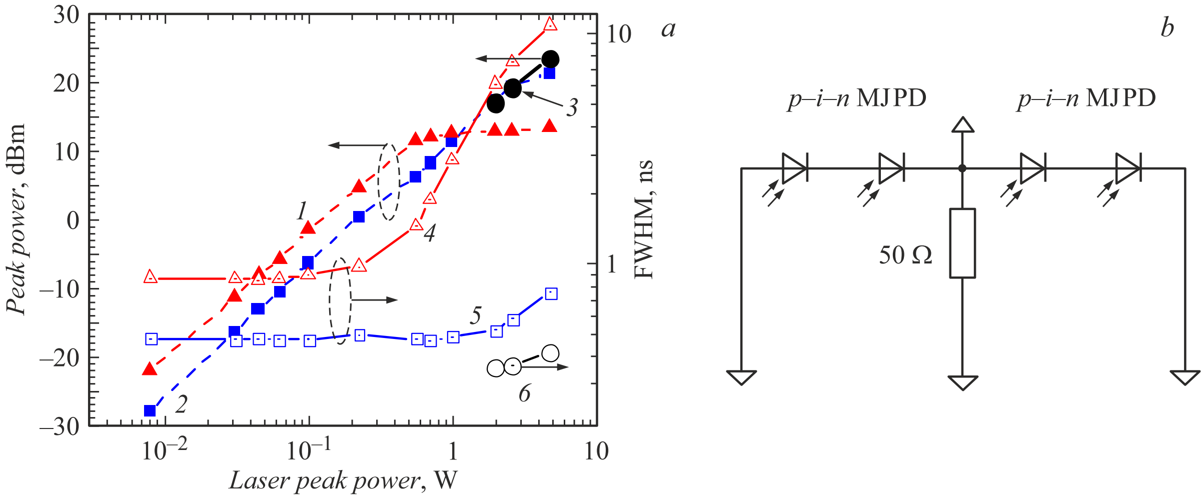

Figure 2. *a* — dependences of the output peak pulse power (*1–3*) and pulse durations at half maximum of amplitude (*4–6*) for a single-junction $p-i-n$ PC (*1, 4*), monolithic $p-i-n$ TJ PC (*2, 5*) and module of two $p-i-n$ TJ PCs (*3, 6*) on the pulse power of the laser radiation ($\lambda = 850$ nm); *b* — electric circuit diagram of the module of four $p-i-n$ TJ PCs.

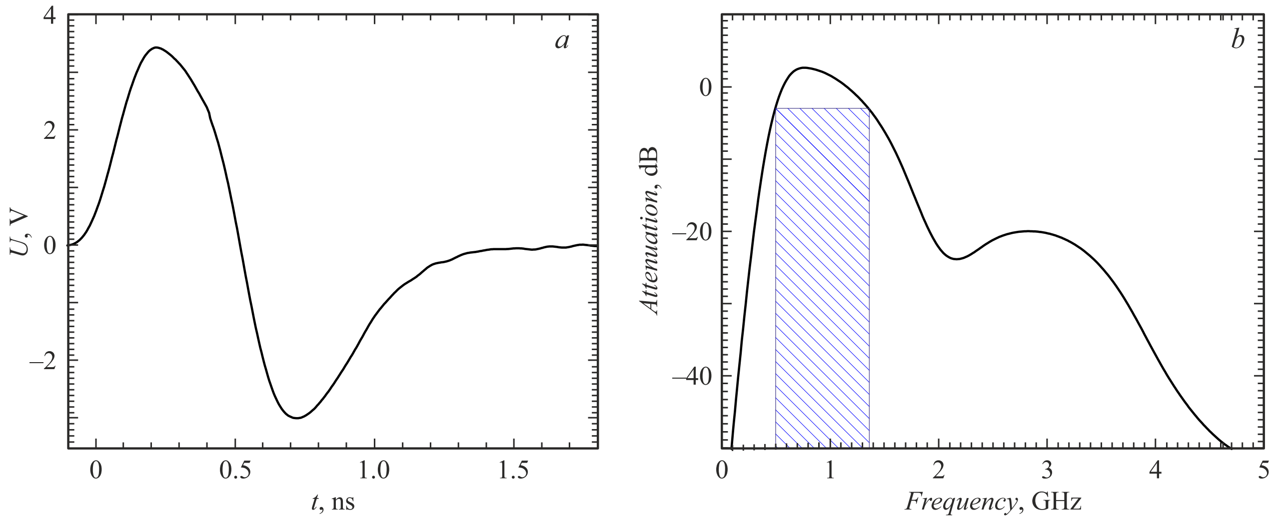

Figure 3. *a* — bipolar photoresponse pulse of optic fiber module of four $p-i-n$ TJ PCs (Ø 250 μm) at the load $R_{load} = 50\,\Omega$ when excited by pulse laser radiation ($\lambda = 850$ nm, $\tau_{0.5} \sim 140$ ps); *b* — frequency characteristic of bipolar photoresponse pulse with the dedicated frequency band at the level of -3 dB.

Fig. 2, *a* presents the experimental dependences of the output peak power (curves *1–3*) and durations of photoresponse pulse (curves *4–6*) for TJ PC (curves *2, 5*) and module of two TJ PCs (curves *3, 6*). It also provides for comparison the characteristics of single-junction PCs (SJ PCs) with mesa diameter of 250 μm, obtained in the same MBE-mode with similar post-growth processing, at identical laser excitation ($\lambda = 850$ nm) from optic fiber (curves *1, 4*). Duration of the photoresponse pulse at half maximum of amplitude of TJ PC (curve *5*) at maximum power of laser radiation is less than in SJ PC by more than an order (curve *4*). Peak power of TJ PC (curve *2*) grows linearly in the laser radiation power density range ($\lambda = 850$ nm) to 9.5 kW/cm^2, while for SJ PC already at the optical power density ≥ 1.0 kW/cm^2 the saturation occurs (curves *1*), and the value of the output peak power practically does not change. At laser radiation power of 4.7 W the values of the output maximum peak power P_{peak} were 13.4 dBm for SJ PC, 21.6 dBm for TJ PC and 23.7 dBm for a module of two serially connected TJ PCs.

For effective operation of ROFAR, it is necessary to generate powerful bipolar pulses. It is shown that a microwave module comprising four $p-i-n$ TJ PCs (fig. 2, *b*), when excited by laser radiation with peak power of up to 10 W and delay between the laser pulses ~ 500 ps [8–10] at 50 Ω load resistance provides an output bipolar pulse with amplitude 6.4 V (29.1 dBm) and duration $\tau_{0.5} \leq 1$ ns (fig. 3, *a*). Frequency characteristic of bipolar pulse by level

-3 dB has a bandwidth of up to 1.4 GHz with the main carrier frequency ~ 0.8 GHz (fig. 3, *b*).

Therefore, as a result of the conducted studies, the generation of powerful subnanosecond microwave pulses by monolithic triple-junction $p-i-n$ AlGaAs/GaAs PCs and microwave modules on their basis was demonstrated in photovoltaic mode.

It was shown that in triple-junction $p-i-n$ PCs compared to single-junction $p-i-n$ PCs the fast response was better with substantial increase of the output peak pulse power:

— photoresponse pulse of TJ PC at load 50 Ω at peak power of laser radiation 4.7 W ($\lambda = 850$ nm, $\tau_{0,5} = 140$ ps) was $U_{\max} = 2.7$ V, $\tau_{0.5} = 750$ ps, $P_{peak} = 21.6$ dBm and $U_{\max} = 3.4$ V, $\tau_{0.5} = 420$ ps, $P_{peak} = 23.7$ dBm for the module of two TJ PCs;

— module of four TJ PCs in photovoltaic mode may generate microwave pulses with amplitude 6.4 V (29.1 dBm), duration $\tau_{0.5} \leq 1$ ns, bandwidth at the level of -3 dB up to 1.4 GHz and main carrier frequency of ~ 0.8 GHz.

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Conflict of interest

The authors declare that they have no conflict of interest.

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