TECHNICAL PHYSICS LETTERS

Founded by Ioffe Institute

Published since January 1975, 12 issues annyally

ISSN: 1063-7850 (print), 1090-6533 (online)

TECHNICAL PHYSICS LETTERS is the English translation of ПИСЬМА В ЖУРНАЛ ТЕХНИЧЕСКОЙ ФИЗИКИ (PIS'MA V ZHURNAL TEKHNICHESKOI FIZIKI)

Published by Ioffe Institute

Saint Petersburg
Ioffe Institute

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High-power subnanosecond module based on $p-i-n$ AlGaAs/GaAs photodiodes

V.M. Andreev, V.S. Kalinovskii, N.A. Kalyuzhnyy, E.V. Kontrosh, A.V. Malevskaya, S.A. Mintairov, M.Z. Shvarts

Ioffe Institute, St. Petersburg, Russia
E-mail: vmandreev@mail.ioffe.ru, kontrosh@mail.ioffe.ru

Received April 16, 2024
Revised May 28, 2024
Accepted June 2, 2024

The results of the development and research of a photodetector module based on AlGaAs/GaAs $p-i-n$ photodiodes at conversion of laser radiation in photovoltaic (without reverse bias) and photodiode (with reverse bias up to 120 V) operating modes are presented. Photodiodes grown by MOVPE epitaxy in the photovoltaic mode under excitation by laser radiation at a wavelength of 810 nm with a power density of $\sim 500\,\text{W/cm}^2$ provided efficiency $\sim 54\%$. The maximum output pulsed electrical power of the photodetector module when excited by pulsed laser radiation with a peak power of ~ 13 W and a duration of ~ 1.0 ns was 2.5 W in the photovoltaic mode and 8.0 W in the photodiode mode, with a reverse bias of 120 V.

Keywords: photodetector module, AlGaAs/GaAs $p-i-n$ photodiodes, laser radiation, photovoltaic and photodiode operating modes, MOVPE epitaxy, reverse bias

DOI: 10.61011/TPL.2024.10.59683.19957

Photovoltaic conversion of laser radiation is used widely in fiber-optic communication lines (FOCLs) and atmospheric optic communication lines (AOCLs). Photodiodes (PDs) based on InGaAs/InP heterostructures are normally used in such systems. These diodes cover the $1.3-1.55\,\mu$m spectral range of laser radiation and ensure long-distance transmission of data in transparency windows within this spectral range with minimal losses, which is necessary for efficient operation of FOCLs and AOCLs.

The use of lasers and PDs based on heterojunctions in the AlGaAs/GaAs system is promising for radio photonics devices with transceiver channels based on short FOCLs [1–8] and AOCL systems [9]. These PDs provide increased efficiency and power within the $800-860$ nm spectral range for systems for energy and data transmission over an optical channel. The maximum theoretical values of efficiency of photovoltaic converters of laser radiation within the $800-860$ nm wavelength range reach 85% at a radiation power density above $100\,\text{W/cm}^2$ [10]. The experimentally observed efficiency levels are 54% at laser radiation power density $p_{laser} = 1.4\ \text{kW/cm}^2$ [11], 62% at $p_{laser} = 100\,\text{W/cm}^2$ [12], and 68.9% at $p_{laser} = 11\,\text{W/cm}^2$ [13]. The conversion efficiency is increased in heterostructure PDs by their back wide-bandgap barrier for minority carriers and due to the return of transmitted, unabsorbed, and optical radiation produced in recombination of electron-hole pairs left unseparated by the $p-n$-junction field [12,13] back to the active region. In radio photonics and other information and energy systems, the problem of improving the efficiency of photovoltaic converters is coupled with the need to increase the response speed with an increase in the output power of photovoltaic converters of laser radiation [1–8].

In the present study, we report the results of examination of fiber-optic photodetector modules based on an assembly of high-power and high-speed AlGaAs/GaAs $p-i-n$ PDs that provide highly efficient photovoltaic conversion of high-power subnanosecond pulses of monochromatic radiation ($810-850$ nm). Photodiodes for photodetector modules were fabricated based on of AlGaAs/GaAs heterostructures grown by metalorganic vapor-phase epitaxy (MOS hydride epitaxy). The structures featured an n-GaAs substrate ($N_D = 2 \cdot 10^{18}\,\text{cm}^{-3}$), an n-$Al_{0.2}Ga_{0.8}As$ back potential barrier $0.2\,\mu$m in thickness, photoactive n- and p-GaAs (N_D, $N_A = 1 \cdot 10^{18}\,\text{cm}^{-3}$) layers with an overall thickness of $1.3\,\mu$m, and an undoped „drift" i-layer of GaAs $1.5\,\mu$m in thickness sandwiched between them. A frontal wide-bandgap p-$Al_{0.13}Ga_{0.87}As$ layer $3\,\mu$m in thickness with an acceptor density raised to $N_A \sim 10^{19}\,\text{cm}^{-3}$ helped reduce ohmic losses. PD chips with a photosensitive area $250-1000\,\mu$m in diameter were then formed. The ohmic resistance per unit PD area was on the order of $10^{-4}\,\Omega\cdot\text{cm}^2$.

The capacitance–voltage characteristics (C–V characteristics) of PDs with different photoactive areas were measured (curves *1, 2* in Fig. 1, *a*). The capacitance was determined using an *LCR*- meter at a signal frequency of 100 kHz. According to the results of calculations based on the experimental C–V characteristics of PDs with a photosensitive surface diameter of $300\,\mu$m (curve *3* in Fig. 1, *a*), the background dopant density in the i-layer near the interface with the p-layer was $N_A \sim 4 \cdot 10^{15}\,\text{cm}^{-3}$.

AlGaAs/GaAs $p-i-n$ PDs designed with account for impurity density $N_A \sim 4 \cdot 10^{15}\,\text{cm}^{-3}$ in the depletion i-layer

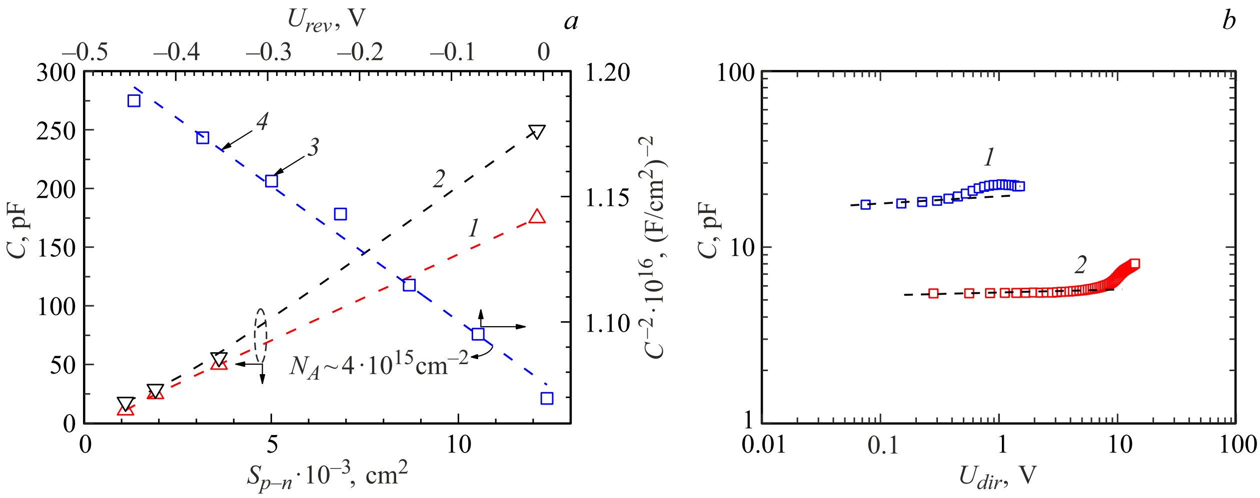

Figure 1. *a* — Dependences of capacitances of $p-i-n$ PDs ($\varnothing$ 250–1000 μm) on the photoactive area: under zero bias (*1*) and under a forward bias of 0.8 V (*2*); dependence $C^{-2}(U)$ for $p-i-n$ AlGaAs/GaAs PDs ($\varnothing$ 300 μm) (*3*) and its linear approximation (*4*). *b* — Dependences of capacitances on forward bias for a $p-i-n$ PD ($\varnothing$ 300 μm) (*1*) and a photodetector module of 16 PDs (*2*).

were used in photovoltaic modules. The studied photodetector modules included 16 series-connected $p-i-n$ PD chips with a photoactive surface diameter of 300 μm mounted on a heat-dissipating insulating microstrip ceramic board. These modules were excited by laser radiation pulses transmitted via multimode optical fibers with a core diameter of 200 μm. Regardless of the diameter of multimode optical fibers, the optical signal was introduced completely into the studied $p-i-n$ PDs in all measurements. The space between the fiber ends and the photosensitive PD surfaces in the photovoltaic module was filled with an immersion liquid that had the same refraction index as the optical fiber.

Fiber transmission of energy allows for galvanic separation of transmitting and receiving energy modules, providing greater protection against electromagnetic interference. The designed PD module is intended to be used for conversion of pulsed laser radiation in photovoltaic (without bias) and photodiode modes. In the photovoltaic operation mode, a $p-i-n$ PD generates photovoltage. Therefore, the C–V characteristics of individual PDs and the module under forward bias need to be measured. The experimental C–V characteristics of both an individual $p-i-n$ PD and a photovoltaic module of 16 PDs connected in series are shown in Fig. 1, *b*. The capacitance values for individual $p-i-n$ PDs remain virtually unchanged at a forward bias up to 0.5 V. In the assembly of 16 PDs, the capacitance remains constant up to 8 V. The module of 16 PDs had the following capacitance values: $\leq$ 5 pF without bias and up to 7 pF with a forward bias of 10 V.

The current–voltage characteristics (I–V characteristics) of $p-i-n$ PDs under load were measured with laser radiation input from an optical fiber 50 μm in diameter with a pulse duration of 66 μs and a repetition rate of 200 Hz at a wavelength of 810 nm within the 0.1–1.5 kW/cm^2 power density range. Figure 2 presents the photovoltaic PD parameters as functions of the laser radiation power. The dependences of the short-circuit current (curve *1*) and the open-circuit voltage (curve *2*) are shown in Fig. 2, *a*. The maximum efficiency values ($\sim$ 54%) determined from the I–V characteristics under load were achieved within the 400–700 W/cm^2 range of laser radiation power density (curve *1* in Fig. 2, *b*).

Figure 3, *a* presents the results of measurements of electrical photoresponse pulses of the photodetector module containing 16 AlGaAs/GaAs $p-i-n$ PDs in the photovoltaic mode without reverse bias (curve *2*) and in the photodiode mode with reverse bias (curve *3*). The measurement circuit included $p-i-n$ PDs connected in series in the module, a load resistor (50 Ω), and a reverse bias source. The output pulsed on-load voltage was recorded by an oscilloscope with a bandwidth of 7 GHz and an input resistance of 50 Ω. Thus, the overall load resistance was 25 Ω, which corresponded to the optimum load point on the light I–V characteristic of the module and provided the maximum output electrical power. Figure 3, *a* shows also the shape of the laser radiation pulse with a peak power of $\sim$ 13.0 W (curve *1*). The obtained pulsed photoresponse characteristics were used to calculate the following photovoltaic parameters as functions of the applied reverse bias voltage varying within the $U_{rev} = 0-120$ V range: the half-amplitude duration of the electrical signal (curve *1* in Fig. 3, *b*) and the pulsed electrical power (curve *2* in Fig. 3, *b*). The photoresponse pulse duration decreased from $\sim$ 1 to 0.75 ns within the $U_{rev} = 0-120$ V range. The maximum output pulsed electrical power of the photodetector module at a laser excitation power of $\sim$ 13.0 W was $P_{out} = 2.5$ W in the photovoltaic operating mode and $U_{rev} = 120$ V – $P_{out} = 8.0$ W in the photodiode mode under reverse bias. The reduction in length of the photoresponse pulse of the photodetector

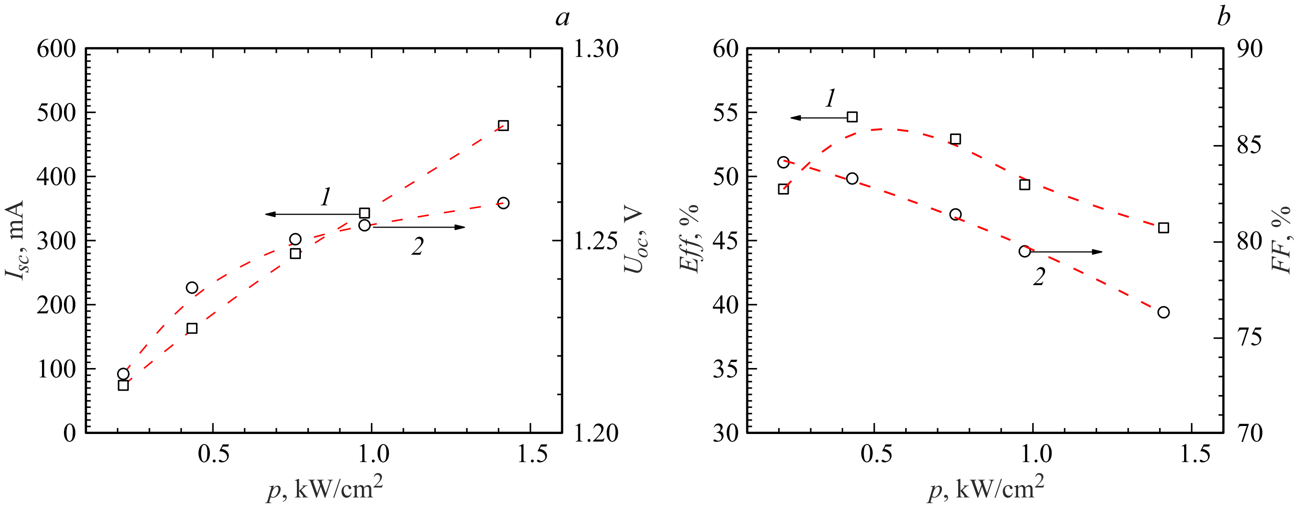

Figure 2. Dependences of the following $p-i-n$ PD parameters on the laser radiation power density ($\lambda = 810$ nm): *a* — short-circuit current I_{sc} (*1*) and open-circuit voltage U_{oc} (*2*); *b* — efficiency (*1*) and fill factor FF of the characteristic under load (*2*).

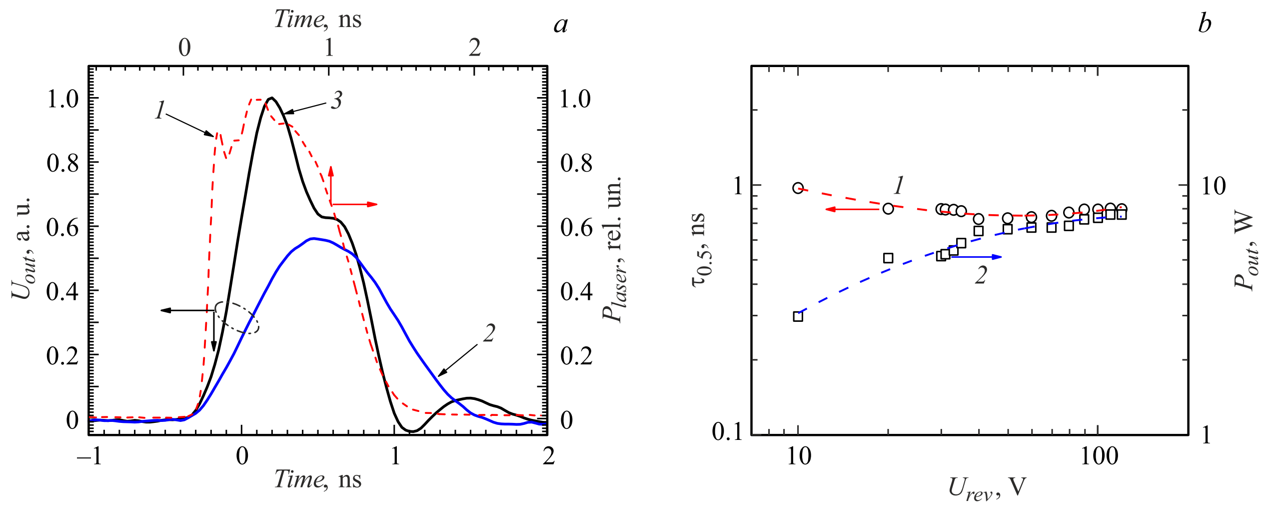

Figure 3. *a* — Normalized pulse shapes of laser radiation ($\lambda = 850$ nm, $P_{peak} = 12.87$ W) (*1*) and of the photovoltaic module of 16 $p-i-n$ PDs without bias (*2*) and with a reverse bias of 120 V (*3*). *b* — Dependence of half-amplitude duration $\tau_{0.5}$ of electrical pulses at the output of the photodetector module of 16 $p-i-n$ PDs on reverse bias (*1*) and dependence of the peak photodetector module power on reverse bias ($P_{peak} = 12.87$ W) at load resistance $R_{load} = 25\,\Omega$ (*2*).

module under reverse bias is attributable to a reduction in capacitance of $p-i-n$ PDs.

The results of examination of a fiber-optic photodetector module based on 16 series-connected AlGaAs/GaAs $p-i-n$ PDs excited by laser radiation in photovoltaic and photodiode operating modes were reported. The efficiency of photodetectors with a photosensitive surface diameter of 300 μm, which were used in the module, reached $\sim 54\%$ at a laser radiation power density of ~ 500 W/cm^2. The duration of electrical pulses at the output of the photodetector module was $\tau_{0.5} = 0.75-0.8$ ns under a reverse bias voltage varying within the $U_{rev} = 30-120$ V range. These parameters were achieved due to the use of well-designed $p-i-n$- PDs, the identity of their photovoltaic characteristics, and the sophisticated technology of diode mounting on a microstrip line with minimization of parasitic inductances and capacitances in the module and matching to an external load.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin