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Changes in the characteristics of semiconductor structures of microwave amplifiers under the action of pulsed laser radiation

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The effect of pulsed laser radiation on the change in the parameters of semiconductor structures of field-effect transistors with a Schottky gate with an operating frequency range of 1.5−8 GHz and integrated amplifiers with an operating frequency range of 0.4−6 GHz is studied. Laser radiation with 25 ns pulse duration, incident on the transistor crystal, creates a pulsed photocurrent. It is shown that the amplitude of the pulsed photocurrent is three times higher than the operating transistor current. The current-voltage characteristics of the field-effect transistor were measured in the mode of pulsed laser radiation. The amplitude dependence of the pulsed photocurrent in semiconductor structures on the power of laser radiation for various wavelengths of 1.06 μm and 0.53 μm is studied. It is shown that as a result of the action of pulsed laser radiation on semiconductor structures, a short disappearance of the amplification of the high-frequency signal at the amplifier output occurs.

Keywords: laser radiation, transistor, microwave amplifier, photocurrent, current-voltage characteristic.

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Introduction

A high energy electromagnetic and charged particle flux in cosmic space dropping on a spacecraft can cause electronic modules to malfunction or trigger a short-term loss of their functions during the ionizing radiation flow-through time [1,2]. The electron-hole pairs [3,4] are formed under the action of gamma ray photons, charged and neutral particles passing through the semiconductor. Their amount depends on the energy absorbed in the semiconductor rather than on the type of radiation. A similar effect of electron-hole pair formation occurs under the action of laser radiation dropping directly on semiconductor structures. Electronic equipment is tested by various types of ionizing radiation. For this purpose, ionizing radiation sources are used: electron and ion accelerators, sources of powerful braking electron radiation, radioisotope sources placed in protection shields and nuclear reactors.

Pulsed ionizing laser radiation is also used for on-line testing of electronic equipment as when it is absorbed in semiconductor structures, a photocurrent pulse occurs generated as a result of electron-hole pairs formation. Testing can be held of both manufactured semiconductor devices with no upper part of the casing over the crystal, and waffer pattern structures using probe methods at the earliest stages of electronic device fabrication [5,6].

To establish the relationship between ionization by emitting laser radiation and high-energy X-rays, a calculation method can be applied and a method of calibration by braking radiation generated by pulsed electron accelerator with particle energies of hundreds keV. In the computational method it is necessary to take into account the zone structure of the compound semiconductor, the reflection of laser radiation from the surface, its homogeneity and absorption depth, the efficiency of electron-hole pair production at a given energy of laser quanta [5–7]. In this paper the computational method is complicated by the necessity to consider the two-photon absorption mechanism of laser radiation at the wavelength of 1.06 μm in a GaAs wideband semiconductor structure. Pulsed electron accelerators can also be used for experimental studies and calibration measurements aiming at determining the coefficient of equivalence between laser intensity and high-energy radiation dose rate.

The use of lasers in a laboratory environment simplifies the testing process significantly and reduces the labor intensity of electronic equipment testing, shortens the test period and increases the measurements accuracy through low level of pulsed interference compared to the interference of powerful pulsed electron and ion accelerators [7–9]. The purpose of this work is to experimentally study the effect of pulsed laser ionizing radiation on the performance of GaAs transistor amplifiers.

1. Experimental procedure

The range of operating frequencies of modern microwave electronics shifts to the tens of GHz range, and above. Currently, semiconductor compounds with high electron mobility are used that clearly distinguishes them from semiconductor structures based on Si, SiC, SiGe, GaN. GaAs-based structures or other semiconductor compounds of A_3B_5 are widely used to manufacture microwave amplifiers, which

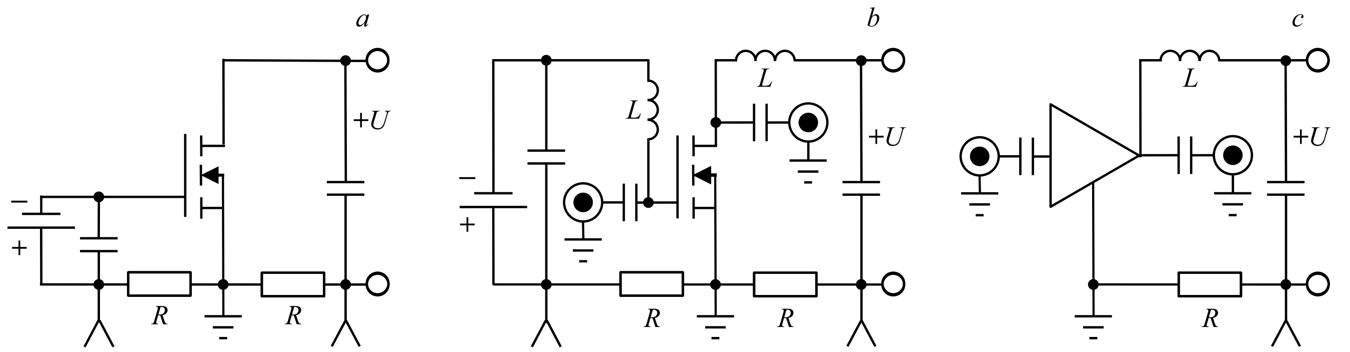

Figure 1. Photocurrent measurement circuits: *a* — field-effect transistor, *b* — photocurrent and microwave signal of a transistor amplifier, *c* — photocurrent and microwave signal of an integrated amplifier.

are of principal interest for modern electronics. For the experimental studies, GaAs MESFETs (metal−semiconductor field-effect transistor) were used, with Schottky gate and integrated amplifiers based on pseudomorphic transistors with high electron mobility (pHEMT). The field-effect transistors had the following characteristics: operating frequency range 1.5−8 GHz, gain 23 dB, gate−source voltage of −0.6 V, drain−source voltage was 5 V, drain current made 25 mA. Integral amplifiers with the operating frequency range of 0.4−6 GHz and the gain of 14 dB had a supply voltage of 5 V. In experimental studies, 1 GHz microwave signal generator was used, and oscilloscope DSO9404A. The work was performed using a „Radon-8M" laser unit operating mainly at a harmonic wavelength of $1.06\,\mu$m or at the second harmonic of $0.53\,\mu$m. The maximum energy of the laser pulse at the sample was 150 mJ, the duration of the laser pulse along the base was 25 ns.

The Nd:YAG-laser radiation was directed from above to the front side of the semiconductor crystal of a field-effect transistor or integrated amplifier. The radiation absorption was influenced by the location of the contact metallized areas on the crystal, that being a distinctive feature of that research method. With a low average power laser operating in a single-pulse mode with a long pulse spacing, no heating of the metal contacts was observed. The specifics of using a double-mode laser was that the quantum energy with a wavelength of $1.06\,\mu$m was smaller than the energy gap width of the GaAs semiconductor compound. Therefore, the formation of electron-hole pairs in the semiconductor was caused by the two-photon absorption of laser radiation. In the infrared spectrum the transparency of the semiconductor structure is higher than in the visible range, so the radiation penetration depth and absorption homogeneity in terms of depth was higher than for the radiation with a wavelength $0.53\,\mu$m. On the other hand, during the laser radiation in the visible spectrum, the quantum energy was twice as high, exceeding the energy gap width of the semiconductor compound. Those factors will affect the efficiency of electron-hole pair formation, and also, the depth and homogeneity of laser absorption in the semiconductor.

When the oscilloscope is directly connected to the transistor amplifier circuits, its low input impedance of 50 Ω will shunt the available active and reactive elements of the transistor amplifier thus changing its operating mode. Therefore, in order to measure the currents in the amplifier circuits, current-measuring resistors were used, with the resistance of 2 Ω (Fig. 1), that were connected with respect to ground into the current brake of the transistor gate and drain power sources, or into the integrated amplifier power circuit. Connecting the oscilloscope to low impedances allowed significantly reducing the error of measurement method related to the impact of low input resistance of the oscilloscope on the circuit. The use of the measuring resistor $R = 2\,\Omega$ and the activation of matched impedance 50 Ω at the oscilloscope input allow measuring the parameters of wideband microwave signals and short pulses to an accuracy of only a few percent. The circuit in Fig. 1, *a* was used to measure the pulse photocurrent in the transistor gate and drain circuits and to obtain the volt-ampere characteristics (VAC) of the transistor. Fig. 1, *b*, c shows photocurrent pulse measuring circuit and microwave signal at the amplifier output. Thus, on the oscilloscope screen we can observe the changed shape of the microwave signal under the action of laser radiation simultaneously with the photocurrent pulse. The photocurrent was measured with the oscilloscope input channel closed, the nominal operating current was metered with the laser turned off.

2. Results and discussion

2.1. The influence of pulsed laser radiation on signal amplification

The pulsed laser flux aiming directly at the surface of the semiconductor structure of the amplifier (Fig. 1, *c*), leads to the failure of the microwave signal amplification at the amplifier output. Fig. 2 shows the changed shape of the microwave signal at the output of the integrated amplifier with the increasing power of laser radiation with a wavelength of $\lambda = 0.53\,\mu$m with spacing of $P/P_0 = 0.2$. Under the action of pulsed laser radiation, the microwave

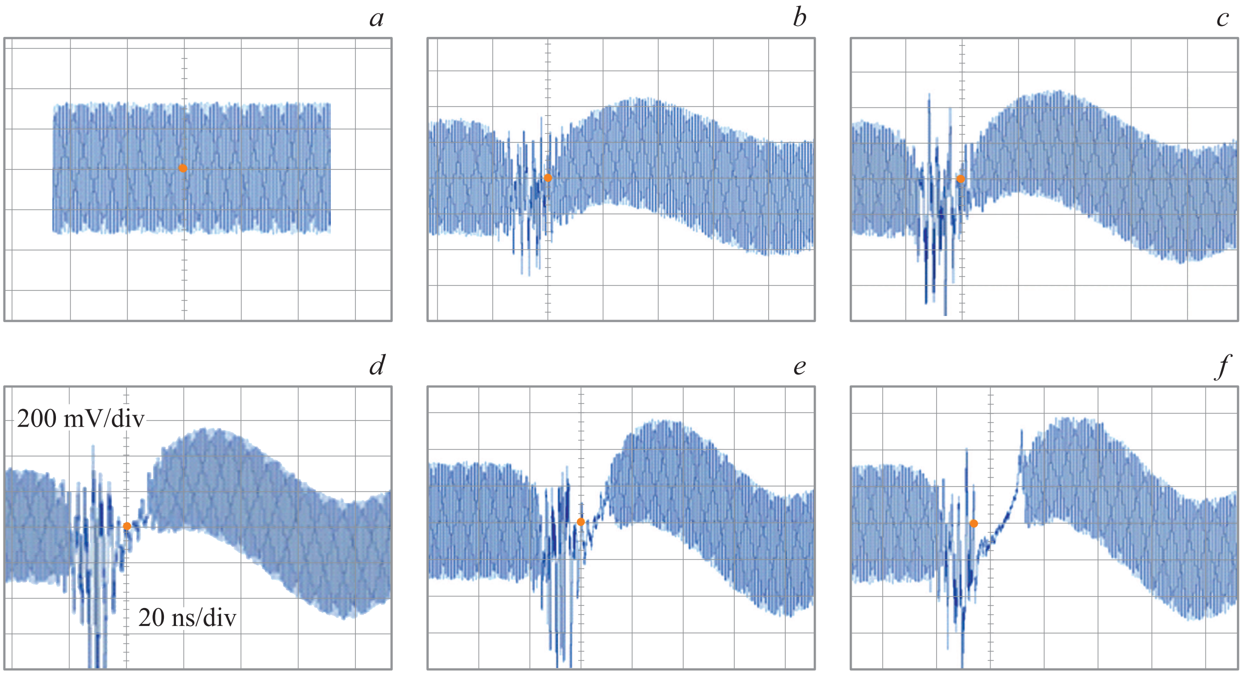

Figure 2. Change in the shape of the microwave signal with the increase of relative laser power P/P_0 at 0.2 intervals within the 0–1 range: a — $P/P_0 = 0$, b — 0.2, c — 0.4, d — 0.6, e — 0.8, f — 1.

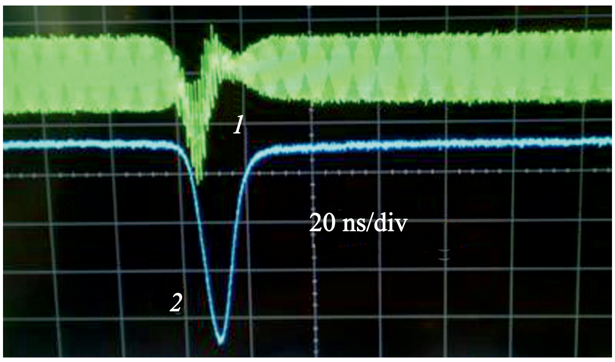

Figure 3. Oscilloscope record of GaAs MESFET amplifier signals: *1* — microwave signal (0.5 V/div), *2* — photocurrent pulse (20 mV/div).

signal is interrupted and high-frequency oscillations are observed. At the end of a laser pulse the amplitude of the microwave signal is recovered over a time exceeding the laser pulse length. The recovery of the microwave signal amplitude can be affected by the decay duration of electron-hole pairs formed as a result of GaAs compound laser ionization.

The operation of the amplifier is significantly affected by the photocurrent pulse flowing in the semiconductor structure of the transistor amplifier under the action of laser ionization. Fig. 3 shows the microwave signal at the GaAs MESFET amplifier output and the photocurrent pulse shape ($\lambda = 1.06\,\mu$m) in the amplifier power supply circuit, measured according to the scheme in Fig. 1, *b*. The microwave signal amplitude reduces sharply at the front of the photocurrent pulse, and then its brief absence follows. After the laser pulse ends, the signal is recovered to 0.8–1 amplitude. The photocurrent pulse in Fig. 3 is symmetric about the pulse middle: the front time and the pulse decay time are practically the same. The pulse photocurrent flowing in the transistor ceased at the end of ionizing laser radiation. No changes were recorded of the photocurrent pulse duration upon the change of the laser power, only the amplitude changed, this testifying of the absence of charge accumulation in the semiconductor structure under the action of laser ionization.

No threshold effect was observed of microwave signal amplification failure upon laser irradiation (Fig. 2). It appears that at different laser power levels there is always a photocurrent flowing in the transistor and affecting the operation of the transistor amplifier.

2.2. Field-effect transistor pulse photocurrent

A laser radiation pulse can change the operating mode of the transistor amplifier in various ways or not change it, if the amplitude of the pulse photocurrent is much smaller than the operating current of the transistor. Therefore, in order to assess the level of laser exposure experimental studies were carried out of the dependence of photocurrent amplitude on the relative laser power, and the photocurrent dependence on the transistor power supply voltage in pulse laser exposure mode.

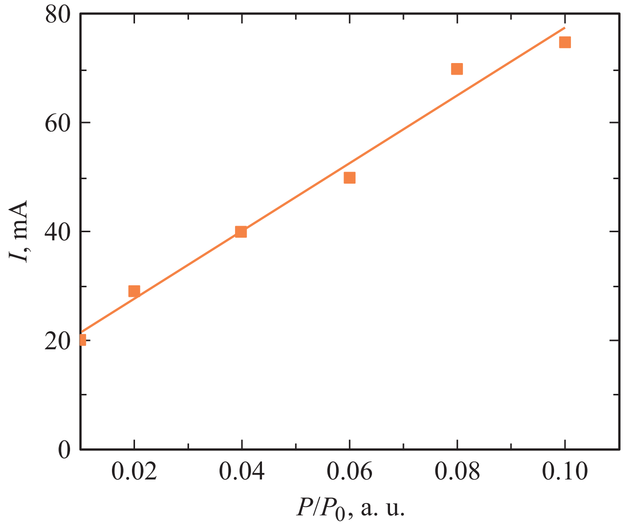

Figure 4. Dependence of transistor drain current on the relative laser power

The amplitude of the GaAs MESFET photocurrent pulse is proportional to the laser radiation power (Fig. 4). With low relative laser power ($\lambda = 1.06\,\mu$m) the amplitude of the photocurrent increases in proportion to the amount of energy absorbed. Fig. 5, *a* shows the VAC of the transistor. The amplitude of the photocurrent pulse exceeds the constant operating current of the transistor 3–4 times. With the drain voltage increase, the amplitude of the photocurrent pulse grows faster as compared to that of the operating current of the transistor if the drain voltage increases. The channel of a field-effect transistor can be represented by a resistance that is equal to the drain–source voltage-to-drain current ratio. With laser exposure of the semiconductor structure of the transistor the channel resistance reduces almost threefold. The channel resistance makes $50\,\Omega$, and it does not depend much on the transistor voltage (Fig. 5, *b*).

Apparently, the structure of GaAs transistors and the change in their conductivity under the action of laser ionization affects the photocurrent pulse amplitude and, accordingly, the failure of the microwave signal amplification. For fabrication of MOSFET- and pHEMT- amplifiers GaAs substrates are used on which a GaAs layer is MBE-grown. In pHEMT- amplifiers a thin layer of another semiconductor is grown over that layer making, together with the GaAs, a heterojunction to form a 2D electronic gas. Electrons are highly mobile, this is why the GaAs-based transistors are characterized by a high operating frequency. In the normal state of the transistor, the GaAs substrate has low conductivity because the intrinsic GaAs material has a high resistivity due to its large energy gap width. In this connection, due to the large dielectric permittivity, the capacitance of the substrate layer to the transistor case is small.

When laser radiation passes through a field-effect transistor, electron-hole pairs are generated in its semiconductor structure near the surface, in the GaAs channel of the transistor and in the massive substrate, that drift to the drain and source metal contacts under the action of the electric field. As the result, the photocurrent flows in the absorption region of laser radiation. So, two currents are flowing in parallel in the transistor: the operating current in the field-effect transistor channel and the photocurrent, which exceeds the operating current several times. As the photocurrent in the substrate is associated with ionizing laser radiation and is not affected by the control voltage at the gate of the transistor, the amplification mode of the microwave signals is disturbed. Apparently, in order to reduce the photocurrent flowing in the substrate, a GaAs transistor can be fabricated with a structure similar to that of a silicon-on-insulator (SOI) transistor. SOI transistors have a high radiation resistance. This is achieved by separating the thin channel of the transistor through which the drain current flows from the silicon substrate with the oxide layer, in order for the electron-hole pairs formed in the massive silicon substrate not to affect the transistor performance.

To reduce the effect of the photocurrent, the thickness of the GaAs channel of the field-effect transistor can be reduced to reduce the volume of the ionization region. An insulating layer can also be placed between the GaAs channel of the transistor and the GaAs substrate, similarly to the SOI transistor structure. Then the electron-hole pairs arising in the substrate by laser ionization will have little effect on the operation of the transistor. The fabrication of GaAs transistors with an intermediate insulating layer depends on the capabilities of MBE-technology that should ensure the growth of a structured GaAs layer on the insulating layer. For silicon, there is a suitable oxide SiO_2 with lattice parameters close to silicon. For a GaAs compound, it is necessary to choose an optimal composition and structure of the corresponding insulating layer.

2.3. Pulse VAC of a transistor in the laser exposure mode

The field-effect transistor VAC are shown in Fig. 6, *a*. Measurements of MESFET drain and gate currents were taken according to the diagram in Fig. 1, *a*. The positive voltage at the transistor drain is the MESFET operating polarity with *n*-channel. When the voltage polarity is reversed (negative voltages of VAC), the drain photocurrent also reverses its direction. When the voltage is positive, the amplitude of the pulsed photocurrent is several times greater than the drain operating DC. When the voltage is negative, the photocurrent is smaller than the DC drain current. At a constant gate voltage of -0.6 V the amplitude of the gate photocurrent changes insignificantly with the change of the drain–source voltage polarity.

With constant source–drain voltage of $U = 5$ V the gate voltage U_g changed (Fig. 6, *b*). A photocurrent with an amplitude of about 15 mA was flowing in the gate circuit. The amplitude of the gate photocurrent was weakly

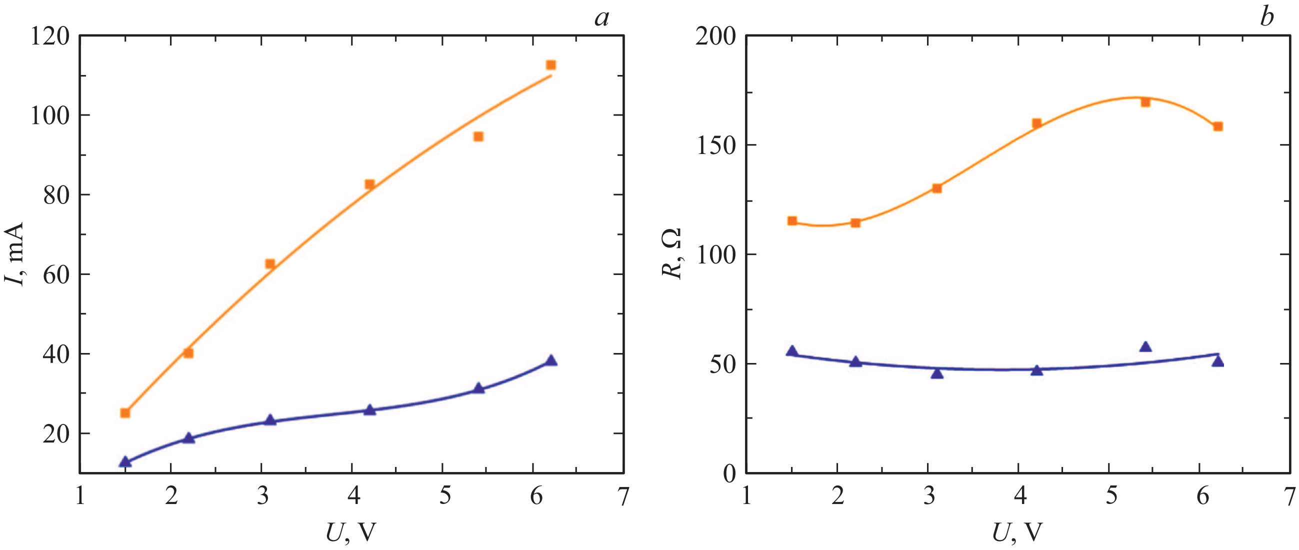

Figure 5. VAC of the transistor: *a* is the dependence of drain current on source−drain voltage (■ is drain photocurrent, ▲ is the transistor operating current); *b* is the dependence of transistor channel resistance on source−drain voltage (■ is the channel resistance in laser pulse mode, ▲ is the channel resistance in the laser pulse absence mode).

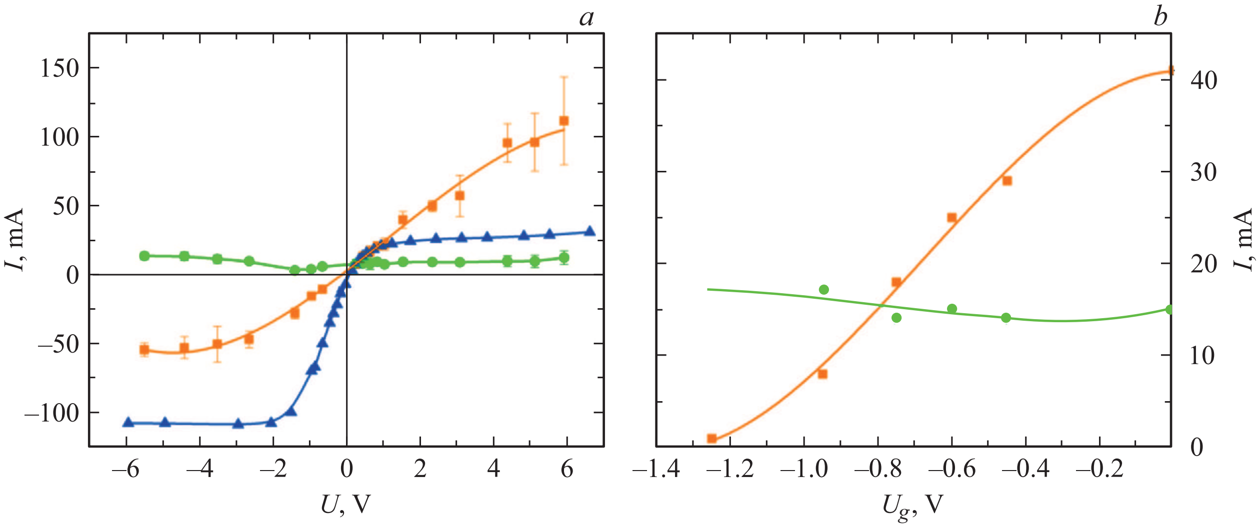

Figure 6. Transistor VAC: *a* is the dependence of drain and gate currents on source−drain voltage (■ is the drain photocurrent, ▲ is the drain operating current in the absence of pulsed laser radiation, • is the gate photocurrent); *b* is the dependence of the drain and gate photocurrents on the gate−source voltage (■ is the drain photocurrent, • is the gate photocurrent).

dependent on the gate voltage, while the drain photocurrent increases as the field-effect transistor channel opens with the voltage increase from −1.5 to 0 V.

A sharp increase in transistor current under the action of pulsed laser exposure results in a short-term absence of microwave signal at the amplifier output (Fig. 3). This is related to the fact that a current surge in the transistor channel leads to a change in the mode of operation of both the transistor and the entire amplification stage. The operating point of the transistor on the VAC shifts to the region of heavy currents exceeding several times the operating current of the transistor. At the same time, the transistor voltage drops significantly as with the sharp increase of the drain current the voltage drop across the inductance (or resistor) installed in the amplifier supply circuit (Fig. 1, *b, c*) increases resulting in a decrease of the drain voltage. Additionally, under laser action the impedance of the transistor channel reduces significantly compared to the operating mode. The transistor works similarly to an electronic switch with heavy current and low source−drain voltage, to which input the microwave signal arrives. Therefore, the amplifying stage under the action of pulsed laser radiation does not amplify the signal arriving to its input.

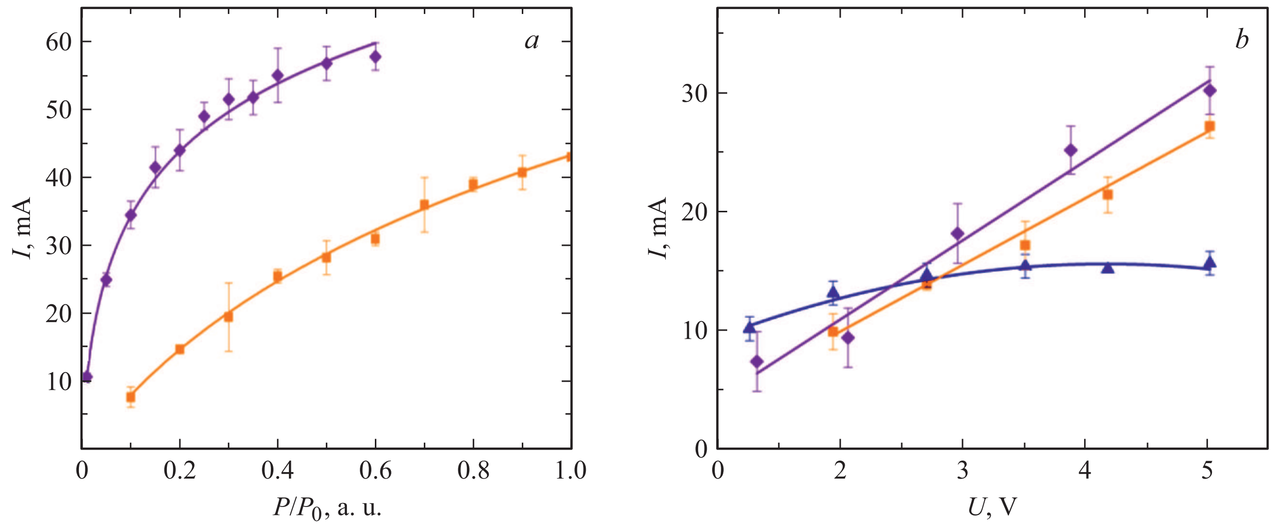

Figure 7. Photocurrent amplitude in the amplifier supply circuit: *a* — dependence of the photocurrent on the relative laser power; *b* — dependence of photocurrent on the supply voltage at different wavelengths ■ is $\lambda = 1.06\,\mu$m, ♦ is $\lambda = 0.53\,\mu$m, (▲ is the dependence of the amplifier operating DC current on the supply voltage in the absence of pulse laser radiation).

2.4. Influence of laser wavelength on the photocurrent of a GaAs pHEMT-based integrated amplifier

Photocurrent dependence on the relative laser power (Fig. 7, *a*) and VAC (Fig. 7, *b*) were determined for laser radiation with different wavelengths 1.06 and 0.53 μm. In low-power region ($P/P_0 < 0.2$) of the laser, the photocurrent amplitude increases much faster for a shorter wavelength $\lambda = 0.53\,\mu$m than when the laser operates at $\lambda = 1.06\,\mu$m (Fig. 7, *a*) wavelength. This is likely to be linked to high efficiency of electron-hole pair formation in the amplifier semiconductor structure with the twofold increase of laser radiation quantum energy when their energy is greater than the semiconductor energy gap width. This is confirmed by the amplifier VAC (Fig. 7, *b*). The dependence of the photocurrent amplitude on the amplifier supply voltage does not differ significantly for different wavelengths of laser radiation. However, the relative power of the laser operating at the wavelength $\lambda = 1.06\,\mu$m made $P/P_0 = 0.5$ and was 5 times greater than the relative power of the laser operating at $\lambda = 0.53\,\mu$m wavelength. Besides, the high absorption efficiency of laser radiation within the visible spectrum can be influenced by the heterogeneity of energy release over the thickness of the semiconductor, the semiconductor structure and the topology of microwave amplifiers.

Conclusion

Testing of amplifier semiconductor structures by powerful pulsed laser radiation allows revealing the specifics of microwave signals amplification in the laser ionization mode. A laser-induced pulsed photocurrent flows in the amplifier supply circuit, its amplitude exceeding the operating current of the amplifier multiple times. The photocurrent pulse changes the operating currents and voltages of the transistor microwave amplifier thus leading to a brief absence of the microwave output signal. The photocurrent creates an additional voltage drop across the resistors and inductors in the amplifier supply circuit that set the operating mode of the transistor. This leads to a significant voltage decay across the field-effect transistor. As a result, the transistor operating mode and VAC change significantly. Upon the end of laser pulse the signal amplitude recovers. The study of laser radiation effect on the photocurrent amplitude at different wavelengths of 1.06 and 0.53 μm showed that when the laser operates at a visible spectrum wavelength lower radiation power is required to produce the same photocurrent amplitude as in semiconductor infrared laser radiation.

Conflict of interest

The author declares that he has no conflict of interest.

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