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Self-excitation of the microwave-range auto-oscillations in avalanche GaAs diodes

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Self-excitation of microwave current oscillations has been observed experimentally in GaAs avalanche diodes connected in series with an ohmic load. The oscillation frequency varied from 5.3 to 8.2 GHz depending on the breakdown voltage (100 to 220 V), diameter (100 to 200 μm) and doping profile of the $p^+-p-i-n-n^+$-structure under study. The voltage and current amplitudes amounted to tens of volts and units of amperes. Numerical simulations have revealed that in the diode there occurs a self-oscillation process of generation and subsequent extraction of the non-equilibrium electron-hole package, which is accompanied by electric field screening by non-equilibrium carries. Stationary state of the diode with avalanche current is unstable on the positive differential resistance branch of the reverse current-voltage characteristic in the absence of external resonator.

Keywords: high-voltage GaAs diodes, microwave oscillations, self-oscillations.

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Avalanche multiplication of carriers in semiconductor structures with a reverse-biased $p-n$-junction can lead to spatial and temporal current instabilities and is exploited in creating devices of both the switch and generator types [1]. The widest known microwave generation device based on a reverse-biased diode is an impact ionization avalanche transit-time diode (IMPATT diode) [1,2]. The IMPATT current oscillations require matching the modulating voltage with flight time and are typically actualized when IMPATT diode is placed in a specially designed resonator [1,2]. However, IMPATT diode research pioneer A.S. Tager [2] pointed out the possibility of self-excitation of avalanche oscillations [2]. In the 2000s, it was found out that high-frequency self-oscillations of avalanche current may be observed in highpower Si and GaAs diodes in the absence of external resonators [3–5]. This work reports on experimental observation of self-excitation of high-power microwave current oscillations in GaAs avalanche diodes with a stationary avalanche breakdown voltage of $100-200$ V. Numerical simulation was accomplished, and the self-oscillation mechanism was explained. The study has shown that spontaneous occurrence of self-oscillations is associated with the „soft“ oscillatory instability of the stationary state of the I-V curve reverse branch with positive differential resistance.

The experimental procedure was almost the same as that in the experiment for observing the lock-on effect described in detail in [6]. A quasi-rectangular voltage pulse about 20 ns in length, which was formed by a coaxial line, was applied to a diode connected in series with a 50-Ω load (Fig. 1). The triggering pulse amplitude was chosen higher than the stationary avalanche breakdown voltage but lower than the threshold necessary to switch the device within 100 ps to the high-conductivity state in the pulse sharpener mode [1,6,7]. Duration of the triggering pulse front edge was several nanoseconds. Pulse repetition rate was 1 kHz. The measurements were performed within the frequency band $\leqslant 8$ GHz where the amplitude of the input sinusoidal signal was attenuated by the oscilloscope maximum to 70%.

Self-oscillations were detected in seven batches of GaAs $p^+-p-i-n-n^+$ structures fabricated by liquid-phase epitaxy (see the Table). The diodes had different diameters d (100 to 200 μm). Fig. 1, a presents the time dependence of voltage $U_R(t)$ at the series 50 Ω load for one of the batch 6 diodes. Peak-to-peak amplitudes of voltage (ΔU) and current were about 80 V and 1.6 A, respectively, the oscillation frequency was $f = 6$ GHz. The maximum detected oscillation peak-to-peak amplitude was greater than 120 V and 2.4 A (batch 7 in the Table). The presence of an initial phase of gradual amplitude growth and a nanosecond delay are observed. The discovered phenomenon was similar to self-oscillations studied in [3,5] for silicon diode structures. The possibility of high-frequency oscillations in the GaAs structure was previously demonstrated in [4]. In [6] we have observed ~ 1.5 GHz self-oscillations studying the lock-on effect in GaAs diodes with $U_b = 500$ V and $d = 500\,\mu$m. In that paper we emphasized that the discovered phenomenon needs separate investigation.

Optical radiation on the diode structure facet and metallization-free area was detected at the pulse length of 20 to 300 ns and repetition rate of 1 kHz. Localization of current in narrow current filaments, which is characteristic of microplasma breakdown and 100 ps long switching of GaAs avalanche sharpeners [1,6], was not detected. This allows assuming the avalanche processes to be homogeneous over the structure area.

One-dimensional numerical simulation was performed for the experimental conditions in the drift-diffusion approxi-

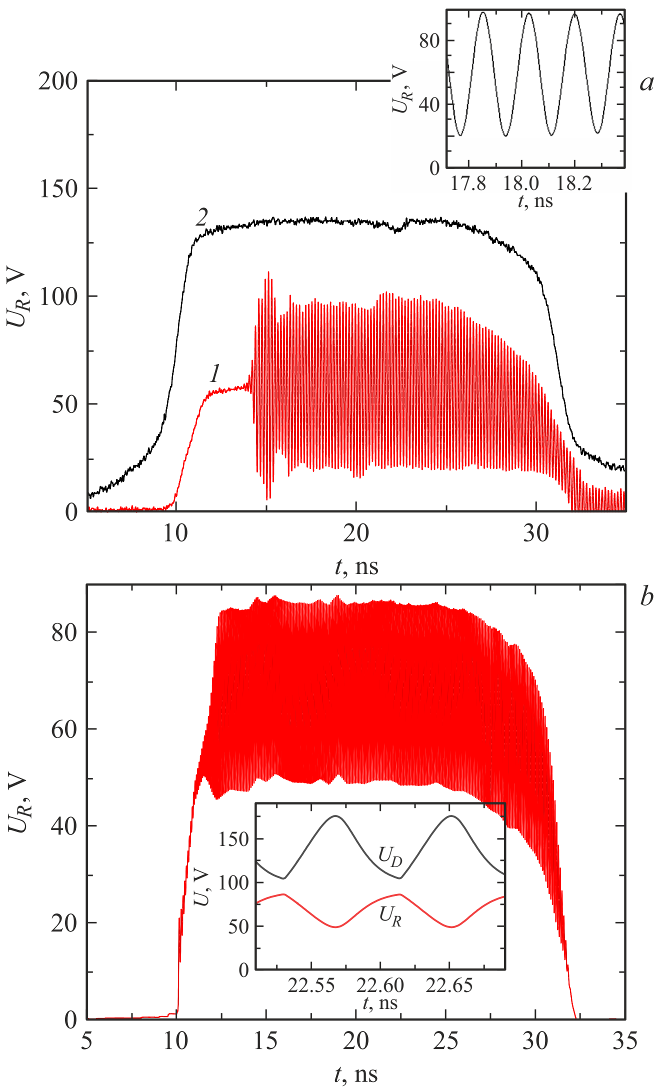

Figure 1. *a* — experimental data: voltage $U_R(t)$ at the series 50 Ω load upon the occurrence of oscillations (*1*) and triggering voltage pulse measured on the matched 50 Ω load (*2*). The inset presents experimental dependence $U_R(t)$ on a larger scale. *b* — dependence of voltage across the load simulated by one-dimensional numerical simulation in the drift-diffusion approximation. The inset presents the simulated dependences of voltage across the $U_R(t)$ load and diode voltage $U_D(t)$.

mation consistent with the external circuit equations. The results of simulation are presented in Fig. 2, *b*. Their agreement with experiment was only qualitative: the calculated self-oscillation frequency was 12 GHz, voltage peak-to-peak amplitude at the load was about 35 V. The simulations were performed by using a model $p^+{-}p{-}i{-}n{-}n^+$ structure doping profile consistent with the fabrication procedure and ensuring matching by stationary breakdown voltage U_b. The oscillations were assumed to be homogeneous over the entire structure area S. The simulated amplitude decreased with decreasing active area S_a and total area S

Parameters of diodes and microwave oscillations (U_b is the stationary breakdown voltage, d is the diode structure diameter, f is the microwave oscillation frequency, ΔU is the voltage oscillation peak-to-peak amplitude at the 50 Ω load conneted in series)

Batch	Structure parameters		Microwave oscillation parameters	
	U_b, V	d, μm	f, GHz	ΔU, V
1	180–220	200	6.0–6.4	66–70
2	120–180	100	6.1–7.0	16–70
3	140–160	100	6.6–6.9	26–33
4	120–130	100	7.2–8.2	3–15
5	120–130	100	6.3–6.9	25–31
6	100–120	150	5.9–6.3	35–80
7	100–160	150	5.3–5.4	50–120

remaining the same. The oscillations vanished completely at $S/S_a = 1.2$.

Analysis of the electric field and carrier concentration dynamics has shown (Fig. 2) that the oscillation mechanism is similar to that for Si diodes described in [3,5]. In the structure $p{-}i{-}n$-region, periodic emergence and sweeping-out of a package of nonequilibrium carriers takes place. Thereat, the carrier concentration at the $p{-}n$-junction varies from $5 \cdot 10^{14}$ to $10^{16}\,\mathrm{cm}^{-3}$, while the electric field ranges from 180 to 350 kV/cm. The oscillation mechanism is associated with the avalanche multiplication, electric field screening by free carriers, and drift removal of carriers. When concentration of $10^{16}\,\mathrm{cm}^{-3}$ is reached, the electric field begins to be displaced from the region occupied by nonequilibrium electrons and holes (Fig. 2, *a*, $t = 22.58$ ns). The field profile takes a double-humped shape, and intensity becomes insufficient for further impact ionization (Fig. 2, *a*, $t = 22.60$ ns). The nonequilibrium carrier concentration at the $p{-}n$-junction decreases to $\sim 5 \cdot 10^{14}\,\mathrm{cm}^{-3}$. The electric field increases again to the breakdown value, and the oscillation cycle repeats.

In contrast to the small-signal IMPATT operation mode [1,2], the central role in the above-described mechanism is played by the electric field screening by free carriers. However, due to a small thickness of the nonequilibrium carrier package and moderate carrier concentration, the electric field gets displaced from the package incompletely as in the case of a greater applied pulse amplitude [1,6,7]. Apparently, the strongly nonlinear mode considered here is borderline between the classical operating mode and trapped plasma mode of IMPATT diodes (trapped plasma avalanche transit-time diode or TRAPATT diode [1]).

Fig. 3, *a* presents the stationary reverse I-V characteristic of the diode under study, which corresponds to the numerical simulations shown in Figs. 1, *b* and 2. The I-V curve quasi-stationary operating point corresponds to the current of 1.1 A. In this state, the maximum carrier concentration in the vicinity of the $p{-}n$ transition is $\sim 5 \cdot 10^{15}\,\mathrm{cm}^{-3}$. The operating point relates to the I-V curve region with

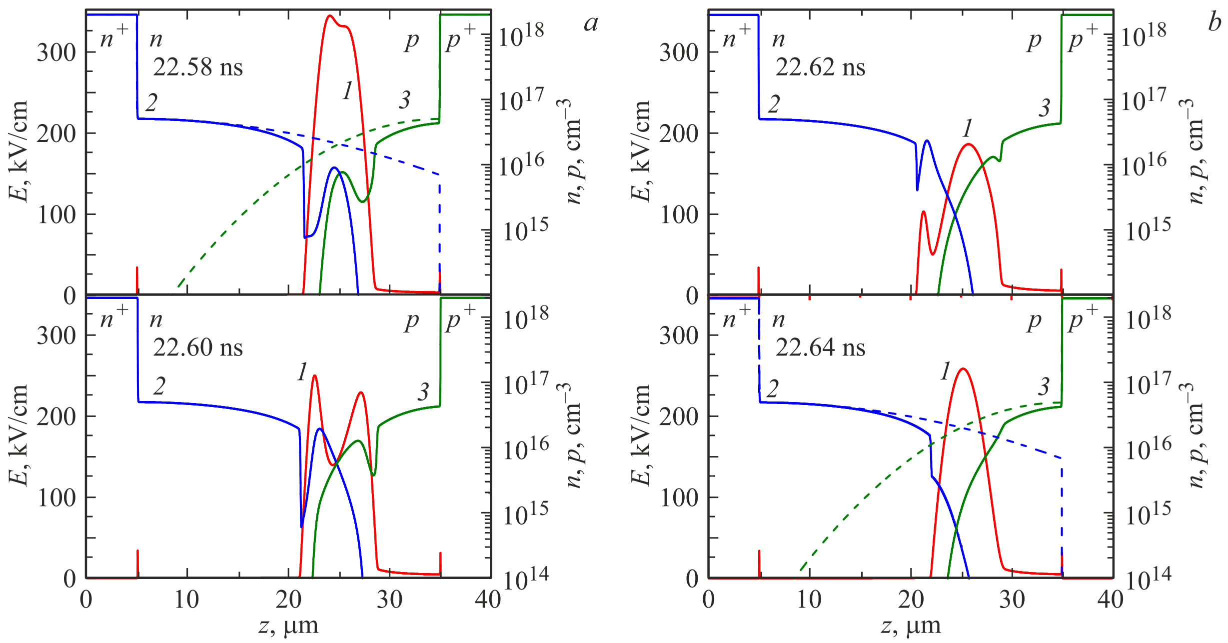

Figure 2. Dynamics of electric field $E(z,t)$ and carrier concentrations $n, p(z,t)$ in the process of the 12 GHz avalanche current oscillations: distributions of electric field (*1*), and electron (*2*) and hole (*3*) concentrations corresponding to a single oscillation period at successive time moments $t = 22.58$, 22.60 ns at the stage of electric field decrease (*a*) and $t = 22.62$, 22.64 ns at the stage of electric field growth (*b*). Dashed lines represent the structure's doping profile.

positive differential resistance at zero frequency. The I-V curve region with negative differential resistance related to the double avalanche injection mode [1] corresponds to a current exceeding 10 A. Under the conditions of our experiment, transition to the self-oscillation mode is initiated by a strong excitation of the system far from the stationary point (curve *3* in Fig. 3, *b*). However, numerical simulation shows that the stationary state with positive differential resistance is unstable with respect to small perturbations (oscillatory supercritical Andronov–Hopf instability [8]). Oscillations arise in the „soft" mode when, first, an unstable stationary state with the required current density is achieved „quasi-statically" (with the voltage rise time of 20 ns), and, second, oscillations are self-excited (curve *4* in Fig. 3, *b*).

Now let us list the main differences between our experiments and those on Si diodes described in [3,5]. First, in [3,5] a specific circuit of sequential pumping the diode in and out was applied to transit to the self-oscillation mode; the circuit is typical of step recovery diodes [9]. Our experiments show that oscillations may be initiated also in the simplest circuit with a relatively slow increase in the voltage across the diode, which is important for practical applications. Second, our analysis points to the oscillatory instability of the stationary state with avalanche current as to the universal source of microwave oscillations. Third, for some of the studied structures we have achieved a significantly higher (up to 1 MW/cm^2) generation power per unit area of the structure. Areas of the structures we have studied were orders of magnitude smaller, while current density was higher (~ 10 kA/cm^2). At the same time, the physical mechanism of oscillations detected in GaAs diodes is the same as in Si diodes [3,5]. The effect of the negative differential mobility of electrons in GaAs needs more investigation.

Due to high amplitudes of microwave oscillations (above 1 A) and simplicity of the electrical circuit, the studied diodes are of interest in view of modulating high-power semiconductor lasers and applying them in the new field of radiophotonics [10,11]. Note that the doping profile of the studied $p^+{-}p{-}i{-}n{-}n^+$ structures was not only non-optimized for microwave oscillations but also poorly technologically controllable in the i-layer region. This can explain the significant scatter in oscillation amplitudes in different structures from different batches (see the Table). To realize practical application of this effect, its optimization and further research and are necessary.

Thus, in this study there was revealed and interpreted a new nonlinear phenomenon, namely high power microwave oscillations in pulsed GaAs diodes connected to a circuit with a series ohmic load without external resonators.

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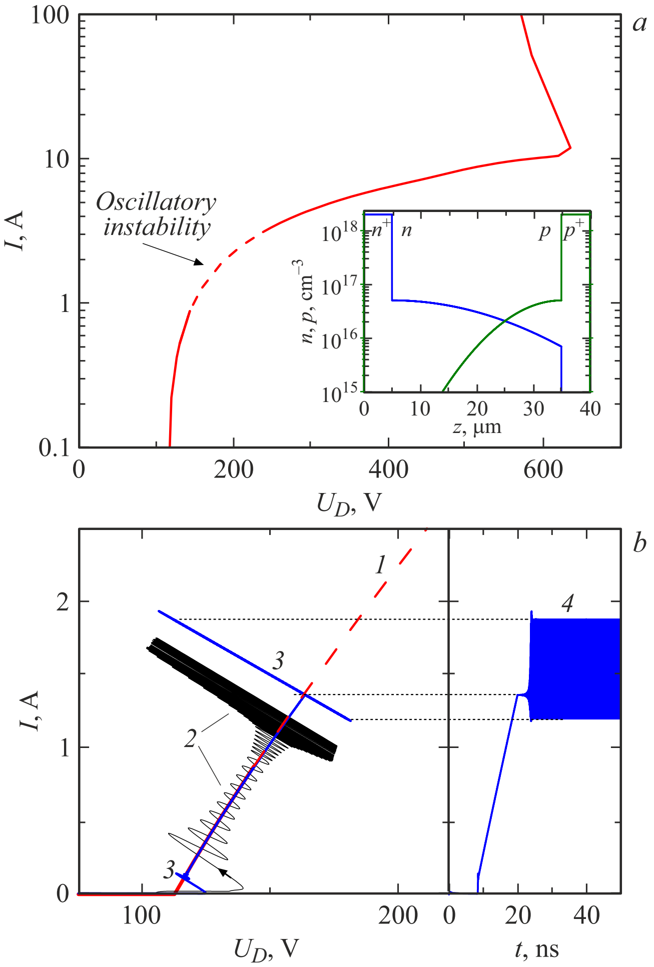

Figure 3. *a* — simulated stationary I-V characteristic of the $p^+-p-i-n-n^+$ structure under study. The unstable part of the I-V curve is represented by a dashed line. The inset presents the model doping profile. *b* — calculated I-V curve in a linear scale (1); „phase trajectory" (I, U_D) (2) constructed based on numerical calculations presented in Fig. 1, *b* (voltage growth during 2 ns); „phase trajectory" (I, U_D) (3) and corresponding time dependence of current $I(t)$ (4) — results of modeling the „soft" transition to oscillations with a slow (during 20 ns) increase in diode voltage.

Conflict of interests

The authors declare that they have no conflict of interests.

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