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Subnanosecond kinetics of recombination radiation of a high-voltage gallium arsenide diode in impact-ionization switching

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Time-correlated single photon counting is used to examine the kinetics of recombination radiation of a high-voltage gallium arsenide diode in subnanosecond switching initiated by a rapid increase in reverse voltage. Switching proceeds along local current channels. It is demonstrated that the radiation intensity reaches its maximum within less than 80 ps, providing an upper estimate for the time of diode switching into the conducting state. The fall time of radiation intensity after switching is anomalously short (250–700 ps). A subnanosecond fall time of radiation intensity indicates that the concentration of non-equilibrium carriers in conducting channels is high and the threshold of stimulated emission is reached. The stimulated nature of radiation is verified by narrowing of the recombination spectrum.

Keywords: high-voltage GaAs-diodes, recombination radiation.

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The phenomenon of subnanosecond switching of reverse-biased diode structures initiated by a rapid increase in reverse voltage is known as delayed impact-ionization breakdown and had been observed in silicon [1], gallium arsenide [2], and silicon carbide [3] structures. Devices utilizing this operation principle have the capacity to form kilovolt pulses in load with a rise time of about 100 ps. The area distribution of current has been examined experimentally only for GaAs- structures, which allow one to observe recombination radiation directly [4–6]. It was established that ultrafast switching of gallium arsenide peaking diodes proceeds along narrow local channels [4,6]. The spatiotemporal dynamics of switching of gallium arsenide diodes has been examined with the use of an electron-optical transducer (streak camera) in an attempt at fabrication of impact-ionization laser diodes [5]. Small-area diodes with a glqq cubic" shape (lateral dimensions of $100 \times 100\,\mu$m and a structure thickness of $100\,\mu$m) were studied for this purpose at an ultrahigh reverse voltage rise rate (~ 50 kV/ns). An increase in switched current (excitation level) led to a jump-like reduction in radiation fall time, which dropped from nanoseconds to 100 ps. This is indicative of the transition from spontaneous radiation to stimulated emission [5]. In contrast to [4,6], the authors of [5] have observed radiation from the entire volume of the structure. In the present study, the kinetics of recombination radiation accompanying subnanosecond switching of a gallium arsenide peaking diode is examined for the first time by time-correlated single photon counting (TCSPC).

GaAs $p^+-p^0-n^0-n^+$ structures with a base p^0-n^0 region of thickness $W \sim 100\,\mu$m fabricated by liquid-phase epitaxy on a p^+-substrate doped with zinc were studied. Their steady breakdown voltage was $U_b = 500$ V, and diameter $d = 1$ mm. The diagram of the experiment is shown in Fig. 1, *a*. Switching was initiated by a pulse of reverse voltage $U_1(t)$ that was shaped by a generator utilizing GaAs step-recovery diodes [7] and supplied to the examined diode via a coaxial line. The pulse amplitude was varied within 350–550 V at a rise time of 0.65–0.83 ns (see the inset in Fig. 1, *b*). Owing to voltage doubling due to the reflection of a generator pulse from a non-conducting diode [8], these amplitudes of an actuating pulse are sufcient for the reverse voltage across the diode to always remain above U_b, thus inducing structure „overvoltage". Reverse bias $U_2 < U_b$ was also applied to the diode. The maximum pulse repetition rate was 10 kHz. Time dependences of current $I(t)$ flowing through the structure upon switching were obtained via direct measurements of voltage across a load of 50 Ω (Fig. 1, *b*) performed with the use of high-voltage attenuators and a stroboscopic oscilloscope with a 4 GHz band.

At time point $t \approx 2.8$ ns, the voltage across the load increases to 350–500 V, which corresponds to a current increase to 7–10 A. The switching time determined at the level of 0.1–0.9 of the amplitude of a rapidly rising section of dependence $U_R(t)$, $I(t)$ is 120 ps. The accuracy of determination of this switching time is limited by the intrinsic rise time of the measurement circuit. Therefore, an independent estimate of the switching time relying on the kinetics of recombination radiation of non-equilibrium carriers (NECs) is of substantial interest.

Recombination radiation in the cathode–anode direction was observed from the part of the diode n^+-layer clear of the contact (Fig. 1, *a*). The TCSPC technique was used to record optical signals [9]. The temporal resolution of the setup (~ 40 ps) was specified by the detector (silicon single-photon avalanche photodiode) operation rate. The circuit of synchronization between the single-photon detector and an electrical pulse propagating within the coaxial measurement channel had a temporal stability (jitter) no worse than 20 ps. At an actuating pulse repetition rate of 10 kHz, the dynamic range of the detector was on the order of 3 kHz. This provided an opportunity to accumulate statistical data with a high temporal resolution within an accumulation time of 20 min ($\sim 10^7$ pulses) and achieve the needed processing accuracy. Optical radiation spectra were recorded with a spectrograph and a CCD array.

The spatial pattern of recombination radiation (see the inset in Fig. 2) is qualitatively similar to the data from [4,6]: switching proceeds along multiple local channels with a characteristic diameter around 10 μm. Integrated recombination radiation spectra obtained by accumulating the signal over 1000 pulses differ from one channel to the other. Three spectra of this kind are shown in Fig. 2. The first two of them may be called typical. The spectrum for a channel of the first type (curve *1*) is qualitatively similar to the spontaneous radiation spectrum: with the maximum of the spectral line positioned at 870 nm, its FWHM is 25–30 nm. In the case of channels of the second type (curve *2*), the FWHM of the spectral line with its maximum at 875 nm is 11 nm; i.e., significant narrowing of the radiation spectrum was observed. The third spectrum (curve *3*) is characterized by a lower radiation intensity. In terms of width, this spectrum falls in between the first two types of spectra. Its reduced intensity may be attributed both to a lower intensity of an individual pulse and to the reason that not every pulse actuates the channel. The results of detailed examination of spontaneous and stimulated emission spectra of GaAs-diodes will be reported in a separate study.

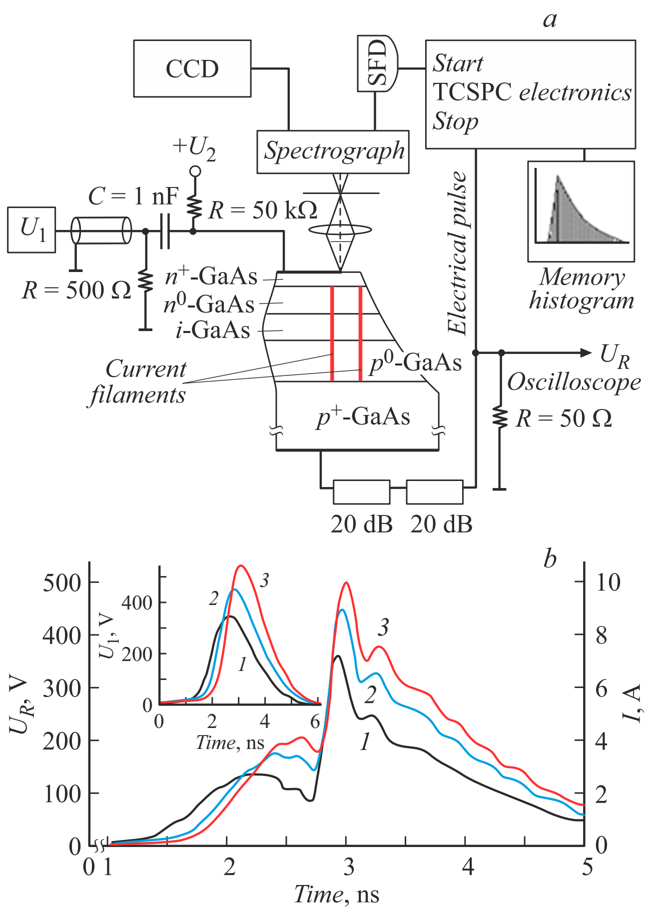

Figure 1. *a* — Diagram of the experimental setup; *b* — U_R pulse at a 50 Ω load and current flowing through the diode. Actuating generator pulse $U_1(t)$ is shown in the inset. The maximum U_1 amplitude, rise time t_r, and FWHM Δt of actuating pulses shown in the inset are $U_1 = 360$ V, $t_r = 0.83$ ns, and $\Delta t = 1.7$ ns for curve *1*; $U_1 = 450$ V, $t_r = 0.69$ ns, and $\Delta t = 1.65$ ns for curve *2*; and $U_1 = 540$ V, $t_r = 0.65$ ns, and $\Delta t = 1.5$ ns for curve *3*.

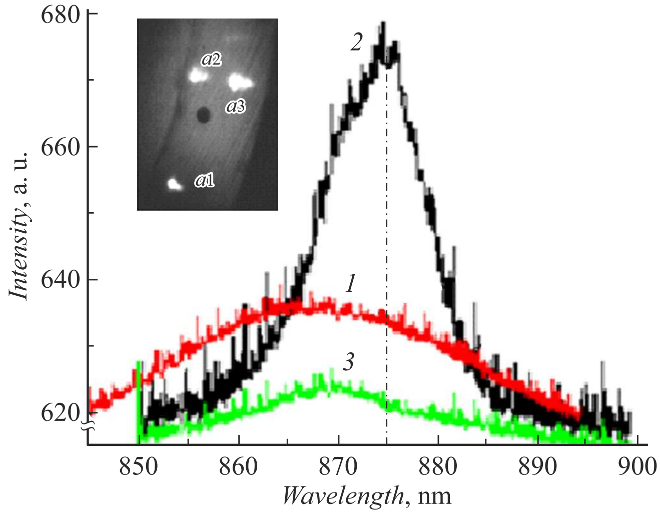

Figure 2. Emission spectra of current channels obtained by averaging over 1000 accumulated pulses. The curves correspond to channels $a1$ (*1*), $a2$ (*2*), and $a3$ (*3*). A photographic image of recombination radiation of the diode in the cathode–anode direction in shown in the inset. Measurements were performed under initial reverse bias $U_2 = 50$ V and actuating pulse amplitude $U_1 = 540$ V.

The kinetics of recombination radiation was examined by TCSPC for each channel separately (Fig. 3). A shift of approximately 30 ns between optical and electrical measurements was introduced owing to certain technical features of the setup. In view of this, the time scales in Figs. 1, *b* and 3 have different reference points. Different channels have different radiation intensities, which agree in general with the integrated spectra in Fig. 2. However, all channels have similar time dependences. Let us examine two key features of radiation kinetics.

First, the radiation intensity rise time (at the 0.1–0.9 level) is 80 ps for each channel. Note that an increase in NEC concentration precedes a decrease in diode voltage, since the latter is associated with the discharge of the passive device part (barrier capacitance) via switching channels; in addition, the concentration continues to rise up to the end of switching [10]. Therefore, 80 ps is an upper estimate of

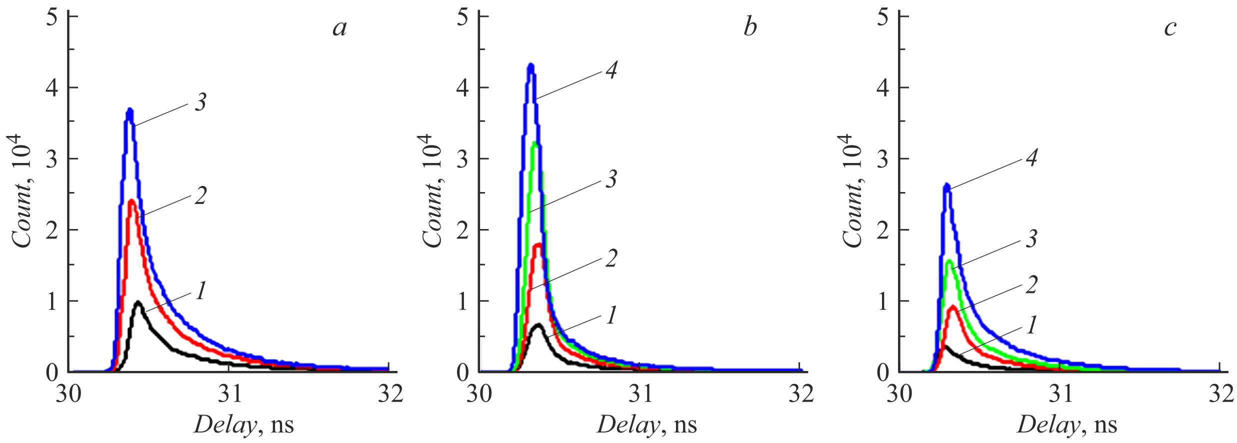

Figure 3. Histograms of optical pulses measured by time-correlated single photon counting. The initial reverse bias of the diode is $U_2 = 50$ V. Reverse voltage pulse amplitude U_1 was 390 (*1*), 420 (*2*), and 480 V (*3*) for current channel $a1$ in the left panel; 360 (*1*), 390 (*2*), 420 (*3*), and 480 V (*4*) for channel $a2$ in the center panel; and 360 (*1*), 390 (*2*), 420 (*3*), and 510 V (*4*) for channel $a3$ in the right panel.

the current rise time in the circuit and the diode switching time.

Second, the radiation intensity is characterized by a rapid subnanosecond drop immediately after switching (Fig. 3). The intensity fall time determined at the level of 0.9–0.1 of the maximum value is 710, 240, and 600 ps for channels $a1$, $a2$, and $a3$, respectively. These times are much shorter than the NEC lifetime: the time of spontaneous radiative recombination is several nanoseconds, and the Shockley–Read recombination time in the studied structures may reach 100 ns. Thus, a subnanosecond intensity fall time is indicative of stimulated emission. Note that the current flowing through the diode after switching decreases in proportion to pulse amplitude $U_1(t)$ (Fig. 1, *b*); i.e., the diode conductivity remains high throughout the entire pulse.

The spectrum narrowing (curve *2* in Fig. 2) observed for certain channels also indicates that radiation is of a stimulated nature. The radiation intensity fall time (~ 250 ps) for current channel $a2$ with spectrum narrowing is shorter than the one for channel $a1$ (~ 700 ps). However, fall times for all channels are anomalously short. It may be assumed that stimulated emission is common to all channels, but the spectrum gets narrower only in some of them due to the random nature of mode selection in a semiconductor structure without an optical cavity.

The observed spectrum narrowing and subnanosecond radiation intensity fall times provide experimental confirmation of the fact that the NEC concentration in current channels exceeds the stimulated emission threshold (according to the estimate given in [11], $1.4 \cdot 10^{17}\,\mathrm{cm}^{-3}$) as a result of switching. This value agrees with the results of numerical modeling of switching of GaAs-diodes where the NEC concentration after switching reached $10^{18}\,\mathrm{cm}^{-3}$ [12]. The mechanism of production of NEC concentrations this high in a GaAs-diode involves the emergence of bipolar ionizing Gunn domains [12].

Our experiments demonstrate that the threshold of stimulated emission is reached not only in extreme experimental conditions [5], but also in routine operation regimes of GaAs-diodes upon formation of rapidly rising current pulses. However, substantial differences between the characteristics of radiation of individual channels raise difficulties on the way toward the practical application of impact-ionization breakdown in engineering of coherent radiation sources. The causes of these differences warrant further study.

Thus, recombination radiation of ultrafast avalanche switching of a GaAs-diode detected by time-correlated single photon counting reveals that the switching time in the delayed impact-ionization breakdown regime does not exceed 80 ps. The observed spectrum narrowing and a subnanosecond recombination radiation intensity fall time suggest that the NEC concentration in current channels exceeds the threshold required for stimulated emission ($1.4 \cdot 10^{17}\,\mathrm{cm}^{-3}$).

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Conflict of interest

The authors declare that they have no conflict of interest.

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