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# Collapsing Field Domains in Avalanche GaAs Transistors: Peculiar Phenomenon and Prospective Applications

Sergey Vainshtein, Valentin Yuferev, Juha Kostamovaara, and Vassil Palankovski

*Abstract* – **High-current avalanche switching in a bipolar transistor structure in combination with negative differential mobility at extreme (~1 MV/cm) electric fields (e.g. in GaAs) causes generation of ultra-narrow, powerfully avalanching ("collapsing") multiple field domains moving in a dense electron-hole plasma, which those domains form. Electrical switching with unique speed and high-power-density emission in sub-THz frequency range open impressive prospective applications of the phenomenon.**

*Keywords* – **Avalanche multiplication, Negative differential mobility, Electrical switching, Terahertz emission, Gunn effect, Electron-hole plasma**

## I. INTRODUCTION

Avalanche switching [1, 2] of bipolar junction transistors (BJT's) caused by feedback between impact ionization at the collector-base junction and carrier injection from the emitter to the base has been well known since the 1950s [3]. This relatively slow (~ $10^{-7}$-$10^{-8}$ s), low-current (~1 A) switching of Si transistors may change to a much faster (~a few nanoseconds), high-current (~10-100 A) mode with a moderate residual voltage (<100V, so-called "secondary breakdown"), a phenomenon that caused intensive debates in the 60s and 1970s (see [4] and the references therein). Despite the excellent intuition and foresight of the authors of [4], the problem could not be solved correctly at that time because high-current nanosecond switching is *determined by details of the field dependence of the electron and hole velocities* which cannot be included in analytical consideration of the problem. Indeed, our numerical simulations carried out 30 years later [5] have shown that the high-current mode with relatively low residual voltage across the transistor is due to *the difference between the electron and hole velocities,* and not due to the differences in *ionization rates between the electrons and holes*, as was believed for many years. (One important consequence, for example, is that high-current switching cannot be observed in p-n-p Si transistors at all [6].)

First realization of high-current avalanche switching in a GaAs BJT led to much more exotic results than in Si (and more important ones for laser diode applications [7]). Picosecond-range switching was found in a GaAs BJT [8] which was not simply faster than that in Si, but created a kind of shock: *the switching time was shorter than it takes for a carrier to cross the voltage-blocking layer* at the maximum possible (saturated) velocity! This phenomenon, termed "superfast switching", was first observed for GaAs *thyristor* structures [9, 10] a couple of decades ago, and was shown for a GaAs BJT much later [8]. The phenomenon remained unexplained until the numerical simulations and experimental data of Ref. [11] pointed to very powerful carrier generation over the entire switching volume caused by multiple, powerfully avalanching field domains, termed later "collapsing" [12] because of their drastic shrinkage during the transient. These domains travel across the structure, increase in amplitude to well above the ionization threshold (by a factor of 2 to 3!), and create an explosion-like growth in carrier density in the *switching channels*, as switching does *not* occur homogeneously along the emitter-base interface but is accompanied by current filamentation (see [8, 11, 13, 14]). An additional, but apparently highly convincing experimental argument in favor of the existence of such collapsing domains consists of the observation of copious broad-band THz emission during the switching transient in a GaAs BJT [12].

Good agreement between experimental and simulated voltage and current waveforms during the superfast switching transient was achieved in a structure of *moderate* [13] and *large* [14] *emitter area*, when the numerical model [11] was supplemented with a consideration of the currents circulating inside the transistor structure, which are the result of discharging of the collector-base barrier capacitance across the switching channels. The role of the circulating currents, which is not self-evident, but creates conditions for much more effective, stable, and reliable switching was shown in [13, 14].

A fundamental necessary condition for collapsing domains to appear is an existence of *negative differential mobility* (NDM) at an electric field exceeding ionization threshold. The effect of superfast switching and THz emission caused by collapsing domains was demonstrated so far only for GaAs, for which we have proved an existence of NDM till at least 600 kV/cm [15].

Let us illustrate now the most important features of the phenomenon and give two examples of the devices in which unique properties of collapsing domains could be applied for practical needs.

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## II. COLLAPSING DOMAINS

The new phenomenon discussed here is somewhat relative to the Gunn effect [16], but differs from it drastically. For clear understanding the main idea let us recall first, what is the classical Gunn effect (see Fig. 1). If a bias $V_0$ of several volts is applied to a slab of III-V semiconductor so that the average electric field $E_0$ is comparable to the *critical field* ($E_{cr}$~4 kV/cm for GaAs) at which negative differential mobility (NDM) takes place and an electron velocity starts reducing (see Fig.1), any random fluctuation of the electric field will grow since the electrons slow-down near this fluctuation and their accumulation in the region A-B causes increase in the electric field and formation of a Gunn domain. S*ingle* domain appears at the cathode, drifts to the anode, annihilates there and appears at the cathode again. Its amplitude may be an order of magnitude higher than $E_{cr}$, but it never approaches in "classical" Gunn effect the *ionization threshold* ($E_i$ ~200-300 kV/cm for GaAs).

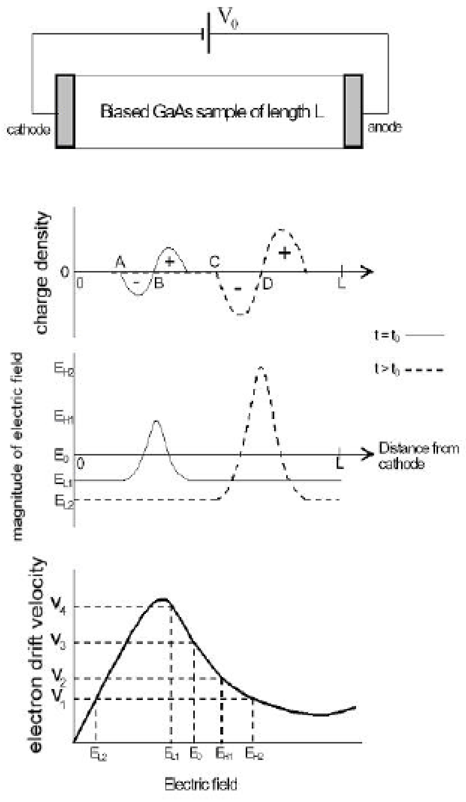


Fig.1

What will happen if we decide to increase the bias voltage from a few to >100 V, so that an average field across the sample is increased from $E_{cr}$ to $E_i$? The sample will just burn. Well, it is still possible to apply this high voltage if the semiconductor is depleted with carriers: for example to reverse biased p-n junction. *No field domains can appear* in this case, however, as their formation needs sufficiently high carrier density. Keeping in mind our goal to achieve Gunn domains at high-field (~$E_i$) biasing, let's consider first an *avalanche switching*.

Let us take now a bipolar junction transistor (BJT) structure $n^+$-p-$n_0$-$n^+$, apply positive biasing to the collector, and *inject* the electrons from $n^+$ emitter through p-base to reverse biased p-$n_0$ junction. We have shown [5, 6] not long ago that in this case high-current avalanche switching happens even in a Si transistor (Fig. 2a), which forms dense electron-hole plasma (Fig. 2b and 2c). During the switching transient we have in $n_0$-collector an average field comparable with the ionization threshold $E_i$ (Fig. 2b) and *electron-hole (e-h) plasma* (not only electrons as in Gunn effect!) with a density of ~$10^{17}$-$10^{18}$ cm$^{-3}$ (Fig. 2c). Imagine now that similar conditions were realized not in Si, but in GaAs. We can expect formation of Gunn domains. What happens in reality, however, is much more complicated and unusual phenomenon. Before discussing this we should emphasise one additional important requirement for new phenomenon to appear: *negative differential mobility* should take place not only at several kV/cm, *but also at extreme electric fields* [15], exceeding significantly ionization threshold ($E_i$ ~250 kV/cm): see Fig.3).

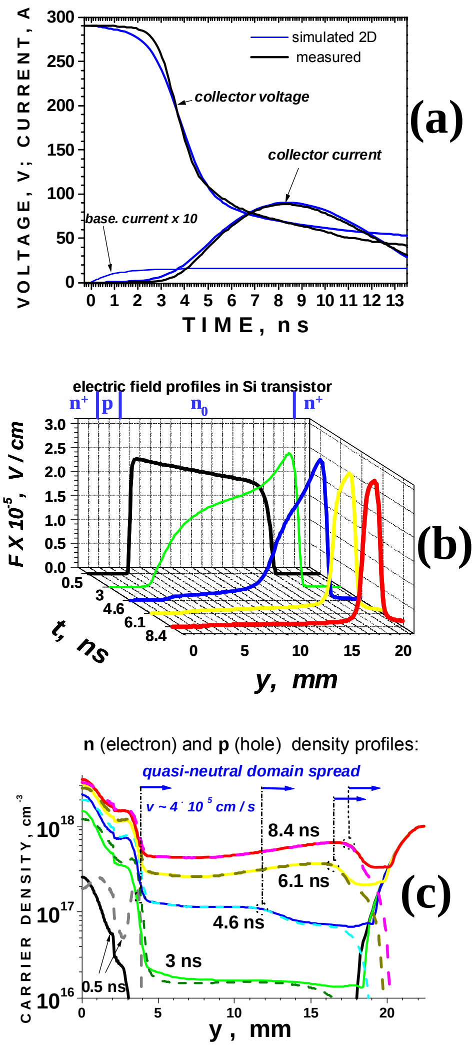


Fig.2. Measured and simulated collector voltage and collector current waveforms (a); simulated electric field (b) and carrier density profiles (c) during switching of a Si avalanche transistor at high current densities.

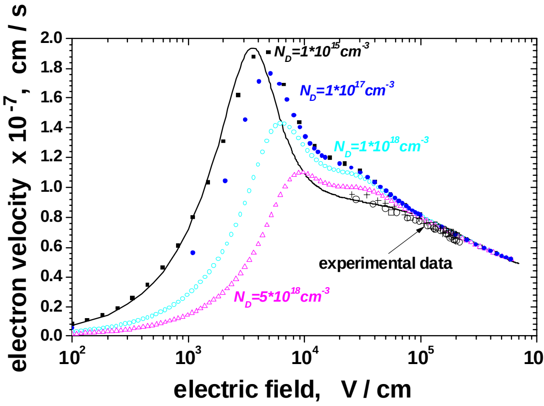
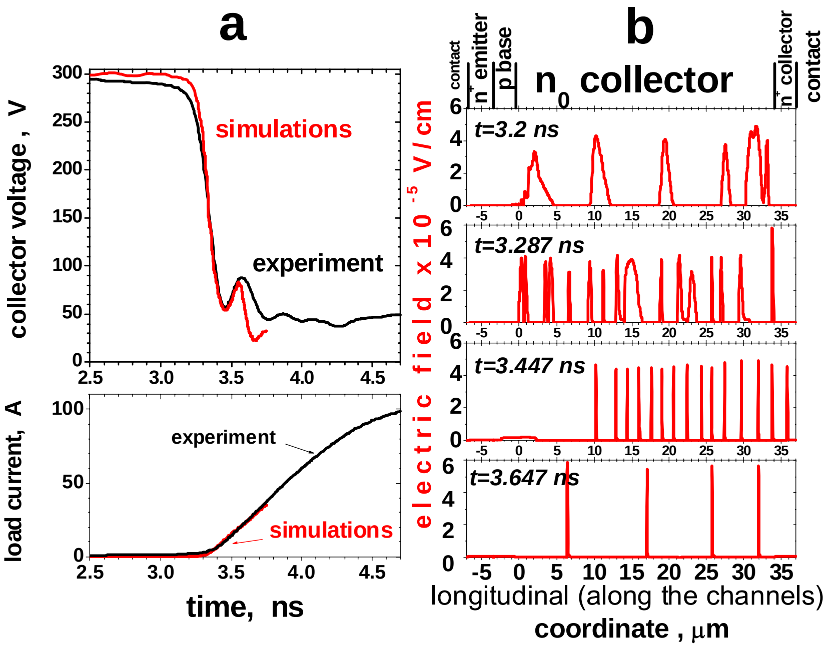


Fig.3. Dependence of the electron velocity in GaAs on electric field in excess of the ionization threshold obtained from Monte Carlo simulations and confirmed experimentally [15]. NDM up to at least 600 kV/cm is proved for the first time as a replacement for an existing believe that the differential mobility becomes constant or positive at around 350 kV/cm.

Combination of three factors (high-voltage biasing, dense e-h plasma and NDM at extreme fields) provides the results shown in Fig.4. First of all, we observe both in the experiment and in the simulations ~200 ps switching: see collector voltage in Fig. 4a. We call it “superfast” as switching from non-conductive to highly conductive state (many orders increase in the conductivity) occurs within a time which is *shorter* than it takes *even for a single carrier* to cross the structure at saturated (maximum possible) velocity, while switching should require very many such acts. This puzzle is resolved by looking at the field profiles at various instants along the direction of the current flux (see Fig. 4b). Amazing are *multiple* field domains, which *amplitude exceeds the ionization threshold by a factor of 2 to 3*. During the transient monstrous impact ionization rate in the domains creates promptly high density of e-h plasma; increased plasma density shrinks the domains; this results in further increase in the domain amplitude and rise in the ionization rate, etc. This positive feedback provides very fast carrier generation (dense plasma formation), domain shrinkage and hence voltage reduction across the structure. We termed these domains “collapsing” [12] as the ionization in the domains causes their drastic (nanometre scale) shrinkage in time. Properties of the collapsing domains tend to current filamentation [11] which supports in turn even faster domain narrowing [13] resulting in enhanced device stability, reliability, and durability [14]. An existence of the switching filaments is experimentally confirmed by band-to-band radiation (see Fig. 5) and simulations predict very powerful picosecond current oscillations [12] in these channels with amplitude up to ~10 MA/cm$^2$ (see Fig.6): oscillations occur due to formation and annihilation of collapsing domains.



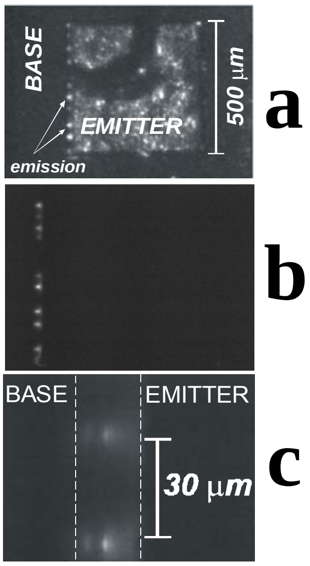


Fig.4. Superfast avalanche switching in a GaAs BJT (a) and electric field profiles (b) across the structure at different instants (“collapsing” domains).

Fig.5 *Band-band emission patterns corresponding to a single switching of GaAs avalanche transistor:* (a) upper view with external lighting, (b) and (c) emission from the switching channels at different magnifications; the light is emitted from the gap between the emitter and the base contacts to the structure.

## III. TERAHERTZ EMISSION

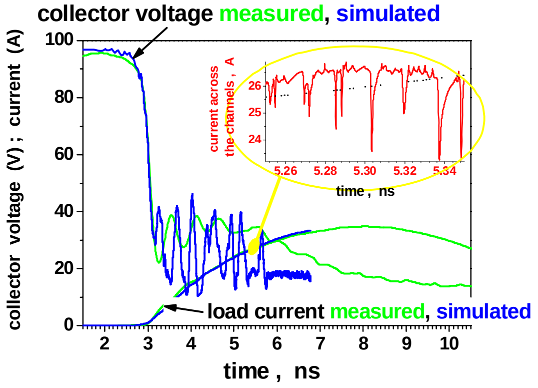


Fig.6. Measured and simulated collector voltage and current [12]; *in the insert*: simulated *ps current oscillations in the channels* caused by collapsing domain formation and annihilation.

These oscillations allow calculation to be made of far-field THz power generated in the channels [12]. The simulation results predicted multi-milliwatt emission with a broad 0.1-2 THz emission spectrum critically dependent, however, on the transistor structure, chip size and layout, etc. The modeling of THz generation is a delicate matter, indeed, as the emission generated in the switching channel depends critically on the impedance of the "passive" part of the structure surrounding the channels as this impedance affects the amplitude of the current oscillations [13, 14].

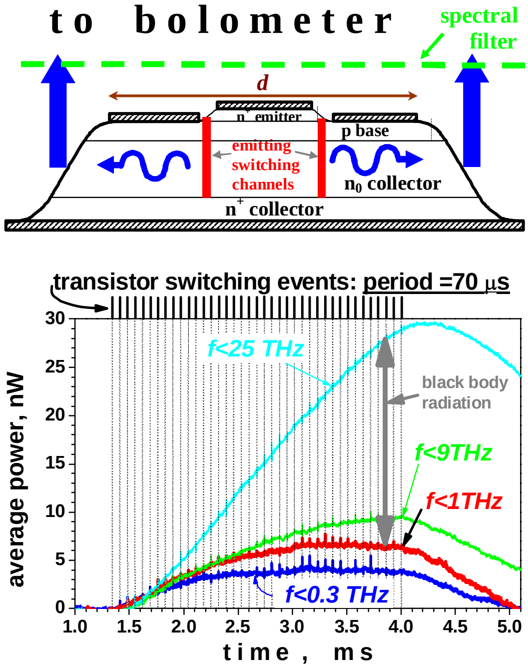


Fig.7. Si bolometer response to the burst of nanosecond pulses emitted by the transistor chip and filtered by several low-pass THz filters. The fraction of the response cased by black-body radiation grows in time and can be easily separated from nanosecond emission of the switching channels [12].

Rigorously speaking, the model used for simulation of THz waves *generated in the channels* so far is too rough and requires radical revision. Besides, we did not model THz emission *radiated to the space* at all. There are many theoretical problems to be solved, and mathematical approaches to be developed. The prediction of copious THz emission is apparently correct, but the simulation of the emission power and spectrum, depending on the transistor structure and chip geometry, requires very significant efforts and extended experimental verification. First experimental data were obtained [12] using a Si bolometer. These were indirect measurements which should be considered as preliminary ones. The point is that we expected emission of THz pulses of a few nanoseconds in duration (during the transistor switching transient), while the Si bolometer is very slow (~1 ms), and we had to use "burst" operation mode of the transistor (see Fig.7), recording an average power emitted by the train of nanosecond pulses and multiplying it on the duty cycle for obtaining the peak power. (In doing so we needed the value of the THz pulse duration, which was not known. We assumed in Ref. [12] that it coincides with the duration of "hot" near-infrared emission from the channels measured with spectrograph-equipped streak-camera.)

The measurements resulted in the conclusion that 100 V transistor with chip size of about 300x300 µm emitted 2-3 ns pulses of ~150 µW peak power in 25-300 GHz band and about ~100 µW in 0.3-1 THz band. The average power is fairly low (nW range), due to large duty cycle: 70µs/3ns ~3×$10^4$, which does not mean, however, that this emission is of no practical interest. Opposite, selection of a nanosecond detector makes ~100 µW pulsed emission apparently more attractive for many applications than CW emission of the same (100 µW) power. This is because Flicker noise can be neglected in the nanosecond range, also a disturbance from black-body radiation is absent as this emission is not registered by nanosecond detector. Then, fairly high responsivity in the nanosecond range of not only NbN (or MoRe) superconductive bolometers, but even Schottky diodes allows us to expect possible replacement for the bolometers by room temperature receiver. The results achieved so far [12] may be considered as only a "hint" for the beginning of development and characterization of various avalanching GaAs (and other III-V) bipolar THz emitters.

Very lately we have performed first measurements of sub-THz pulses emitted by different laboratory prototypes of avalanching GaAs-based BJT's using high-speed NbN and MoRe superconductive bolometers (custom designed for us by Scontel, Moscow), and quasi-optical detector (QOD) based on a Schottky diode and purchased from Virginia Diode Inc. (VDI). Fig. 8 shows test results characterizing temporal response of NbN and MoRe bolometers, using a near-infrared pulsed laser diode as a reference source. NbN bolometer response on ~3 ns in duration sub-THz pulse for relatively high-voltage GaAs BJT is shown in Fig. 9. Reliable spectral and power characterization of the emitted pulse is a matter of future, while certain preliminary guesses can be made from pulse observation through different metal meshes (see Fig. 9).

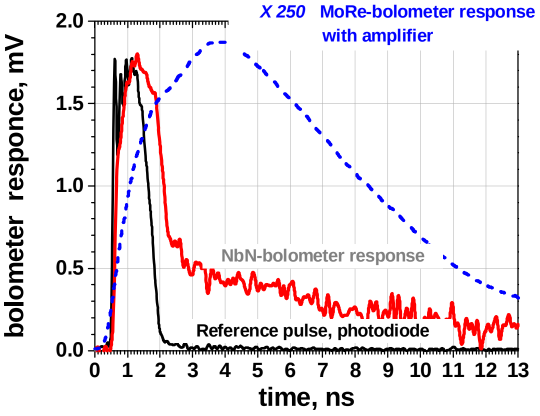


Fig.8. Response of high-speed bolometers developed by Scontel (Moscow) on a reference pulse from 1.3µm laser diode. NbN bolometer is directly connected to the oscilloscope, while output of MoRe bolometer is amplified by a “cold” amplifier (gain 27 db): MoRe bolometer is slower, but more sensitive and has lower NEP.

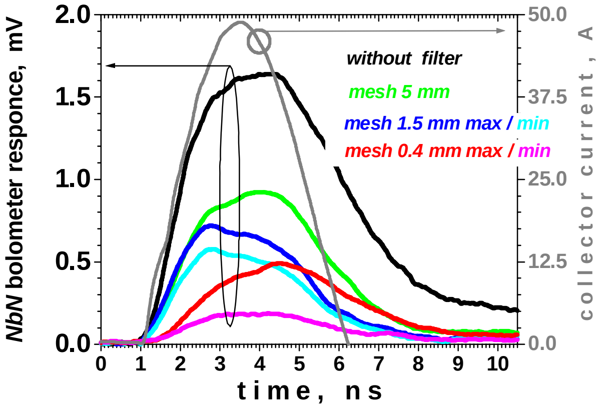


Fig.9. First tests of a GaAs avalanching BJT response using NbN bolometer. The bolometer is directly connected to the oscilloscope. Distance between the transistor and bolometer is about 10 cm. No collimator of THz emission is used. A rough idea on the emission spectrum can be obtained from comparison of the waveforms passed through metal meshes with the cell sizes of 5, 1.5 and 0.4 mm. The filter rotation causes remarkable change in the signal, which speaks apparently in favour of the emission polarization. ***At further research steps reliable filters (under fabrication and characterization) will be used instead of meshes presented here only as an example.***

Next, an even more impressive example shown in Fig. 10 is ~1 ns in duration pulse of sub-THz emission generated using relatively low-voltage transistor and detected by *room temperature* (!) detector based on a Schottky diode. The combination of miniature, low-cost room-temperature emitter and detector opens very interesting prospective for active 2-D and 3-D sub-THz imaging in different systems. Any analogue of a THz emitter comparable with a GaAs BJT accounting for a combination of the parameters is apparently absent. It is worth noting that a characterization of THz emission from avalanching GaAs-based BJT laboratory prototypes has just started and the pioneer results presented here are of preliminary character and are shown for illustration purposes. A work on accurate specification of possible future applications of avalanching THz pulsed emitters is ahead.

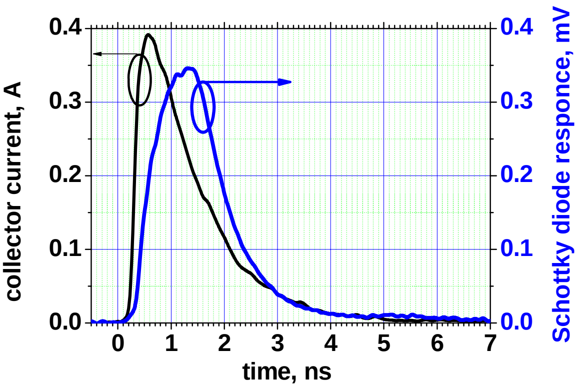


Fig.10. Current pulse across a GaAs-based transistor and sub-THz pulse emitted by the transistor and detected by a Schottky diode (QOD manufactured by VDI).

## IV. PICOSECOND VOLTAGE SWITCH

The same physical processes which cause THz emission are responsible for *picosecond electrical switching in GaAs BJTs*. At the moment, there are no commercially available *single active switching components*, which are able to provide high current (1-10 A) and high voltage (100-400 V) pulses in the picosecond range. Only two types of high-speed *pulse generators* operating in ps range can be found: one (http://www.kentech.co.uk/pulser_summary.html) is based on a long chain of Si avalanche transistors (because a single Si transistor can operate only in a ns mode), and the other one (http://www.fidtechnology.com/Products/fpg5-10.htm) is based on drift-step recovery bipolar Si diodes and transistors in combination with the silicon avalanche sharpers (SAS). There, picosecond switching is realized in a *passive* component. These generators require sophisticated smart circuit framing and kV-biasing, which puts also significant limitation on the pulse repetition rate, and increase the size and price. Thus, all currently available picosecond generators cannot compete with *suggested here* GaAs BJT, which has a chip size of ~1 mm$^2$ and requires very moderate power supplies (which should only charge small capacitance of 1-200 pF to 300-400 V or less). Our recent results [14] show possibility of achieving extremely low residual voltage (down to ~2 to 10 V), keeping the switching time shorter than 200 ps (see Fig. 11) simply by appropriate increase in the emitter area of the transistor chip. One important application of picosecond GaAs switch is for pumping of high-power, high-speed gain-switched [7] and Q-switched [17-20] laser diodes. Other applications may include development of unique high-current picosecond generators, sweep generators for streak-cameras, fast image intensifiers, electrical and optical modulators, etc.

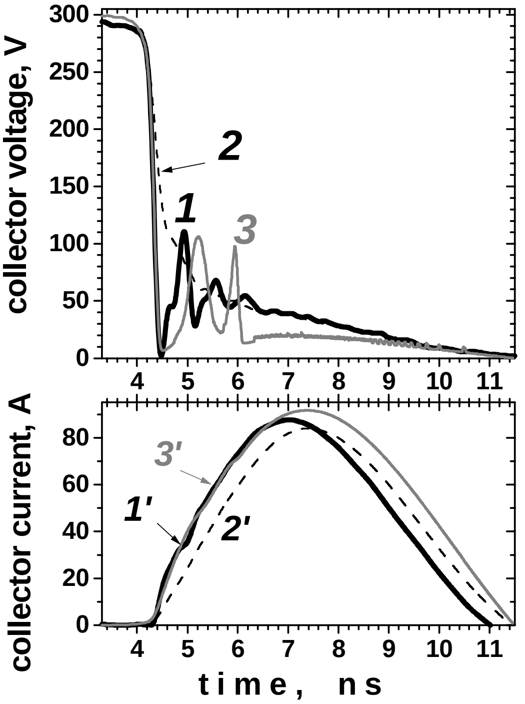


Fig.11. Measured collector voltage and current (curves *1,1'*) in the transistor chip of "large" emitter area $A_0 \approx 2.6\times10^{-2}$ cm$^2$, and comparisons with the experimental data (*2,2'*) for the transistor of "small" emitter area and with simulation results for $A_0 \approx 2.6\times10^{-2}$ cm$^2$ (*3,3'*) [14].

## V. CONCLUSION

A peculiar phenomenon of the collapsing domain formation in avalanching GaAs BJT determine unique parameters of THz emitters and superfast picosecond switches, which can be developed on the basis of a GaAs BJT structure. Ultra-high density of the emitted THz power of this broad-band nanosecond source can provide means for development of miniature, real-time, room-temperature 2-D and 3-D imagers. From the other hand GaAs-based avalanche transistor is apparently the only *active, single-component* semiconductor switch providing high-voltage picosecond pulses.

## VI. ACKNOWLEDGEMENTS

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