Terahertz Emission from Collapsing Field Domains during Switching of a Gallium Arsenide Bipolar Transistor

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Broadband pulsed THz emission with peak power in the sub-mW range has been observed experimentally during avalanche switching in a gallium arsenide bipolar junction transistor at room temperature, while significantly higher total generated power is predicted in simulations. The emission is attributed to very fast oscillations in the conductivity current across the switching channels, which appear as a result of temporal evolution of the field domains generated in highly dense electron-hole plasma. This plasma is formed in turn by powerful impact ionization in multiple field domains of ultrahigh amplitude.

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Background.—A single field domain of moderate amplitude and relatively large width is typical of the Gunn effect [1]. Relatively weak impact ionization in Gunn domains may complicate the effect due to presence of holes, and cause current filamentation [2,3]. Powerfully ionizing multiple domains with very unusual parameters and temporal evolution were recently predicted in transient simulations of superfast switching in an n^+-p-n_0-n^+ transistor structure in which copious electron injection takes place into a high-voltage biased (depleted) layer of n-type gallium arsenide [4,5]. Current filamentation is intrinsic to this regime [4]. To differentiate these domains from the ''classical'' Gunn effect they are termed here ''collapsing'', meaning that the ionization within the domains forms an electron-hole plasma, the density of which grows in time and causes drastic (nanometer-scale) domain narrowing (collapsing) with a simultaneous increase in the domain amplitude to $\sim 10^6$ V/cm. A necessary condition for the formation of collapsing domains is the existence of negative differential mobility (NDM) *at extremely high fields*, (significantly) exceeding the ionization threshold [4], while in the Gunn effect an existence of NDM at only moderate fields is sufficient. Experimentally, the collapsing domains can be formed by applying an average electric field to the active region that is comparable with the ionization threshold ($\sim$200 kV/cm in GaAs), while the classical Gunn effect occurs at fields that are $\sim$2 orders of magnitude lower. A high (ionizing) electric field can be applied only to a depleted layer of a semiconductor, while *domain formation requires a sufficiently high carrier density in the active layer.* In a bipolar junction transistor (BJT) structure the emitter supplies the electrons to the depleted n_0 region thus triggering the domain nucleation and supporting self-sustaining avalanche switching. One might assume that similar domains also form in photoconductive semiconductor switches (PCSS) based on $A_{III}B_V$ materials, in which very fast switching, a lock-on state and current filamentation have been observed [6], as also in a GaAs BJT. This proposition has not yet been formulated and tested, however. Furthermore, the possible formation of collapsing domains in systems with NDM may be of interest not only in a solid-state context but also for experts working with charge particle transport in gases and liquids, in which NDM can take place above the ionization threshold under certain conditions (see Refs. [7,8]).

Only one item of experimental evidence for the existence of collapsing domains has been found so far, namely, a good fit [5] between simulated and measured voltage and current waveforms during the switching transient in a GaAs BJT. We present here some additional arguments, namely, experimentally observed terahertz emission and ''hot'' photon emission during the switching of a GaAs BJT. A numerical study is also made of the characteristics of terahertz emission and physical reasons of its appearance are analyzed.

THz current oscillations in switching channels of a GaAs bipolar transistor.—Measured and simulated transient profiles of the collector voltage (curves 1, 1′) and the current across the collector contact (2, 2′) are shown in Fig. 1(a). A GaAs transistor structure analogous to that described in Ref. [4] was used, but increased donor density in the n_0 collector layer and reduction in its thickness caused a lower blocking voltage ($\sim$100 V instead of $\sim$300 V in Ref. [4]). The part of the numerical model describing carrier transport and impact ionization was analogous to that in Refs. [4,5]; the switching current passed across several channels (total area $\sim 3.7 \times 10^{-6}$ cm^2) and fast growth in carrier density in the channels was brought about by powerful impact ionization in multiple (collapsing) field domains spreading along the filaments. The simulated current in the channels [curve 3′ in the inset to Fig. 1(a)] demonstrated powerful picosecond-range oscillations, which did not penetrate to the external circuit (curve 2′) but became locked within the barrier capacitance of the nonswitched part of the transistor structure [5].

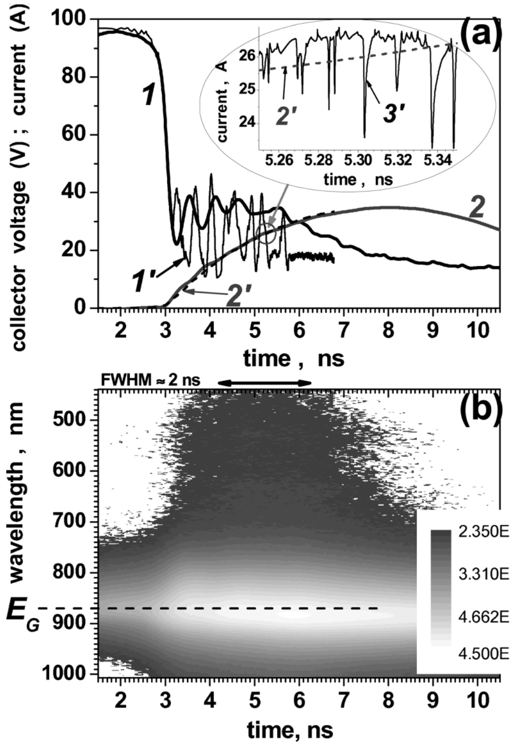

FIG. 1. (a) measured (curves 1,2) and simulated ($1'$, $2'$) voltage and current waveforms across the collector contact, and current across the switching channels (curve $3'$ in the inset); (b) time-resolved spectrum of near-infrared (*optical*) emission from the switching channels recorded from *the gap in the emitter and base metallization* using a spectrograph-equipped streak camera.

Time interval for THz current oscillations.—As will be shown below, the picosecond current oscillations (curve $3'$) cause THz-range emission. This emission starts at the fast switching instant ($t \approx 3$ ns) and continues "forever" in 1D modeling (if the current continues). In reality, however, the field domains exist for only a few nanoseconds after the fast switching occurs (in the transient range ~3–7.5 ns). This statement is based on the following experiment. The time-resolved spectra of *optical* emission measured from the end face of the switching filaments is shown in Fig. 1(b). An increase in the carrier density in the channels caused not only growth in radiative recombination (around the photon energy of the band gap E_G), but also a noticeable intensity at much higher photon energies (up to $\sim 1.6 E_G$). These hot photons appeared immediately after the beginning of switching and disappeared gradually as the voltage across the transistor declined [compare curve 1 in Fig. 1(a) and 1(b)]. We ascribe this emission to the recombination of hot electrons and holes, which gained their energy in the field domains (see Fig. 2). Hot photons will be emitted for as long as the field domains (and picosecond current oscillations) exist. We attribute the quenching of the domain (and THz emission) mode to nanosecond-range broadening of the switching channels [9], which causes a reduction in the current density. The FWHM temporal width of the hot photon emission was found to be ~2 ns [Fig. 1(b)], and this is the value which we ascribe to the duration of THz emission and use below to estimate terahertz peak power.

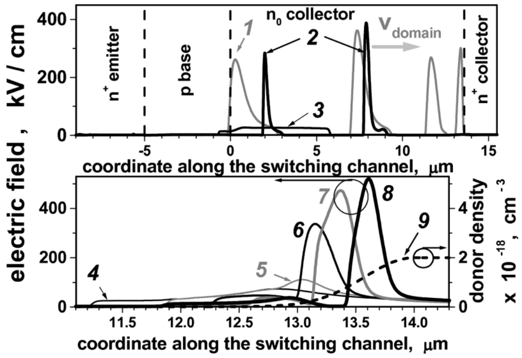

FIG. 2. Electric field (curves 1–8) and donor density (9) profiles along the switching channels. The field profiles correspond to transient instants in Fig. 1: 1–2.78 ns, 2–3.179, 3–3.579, 4–3.979, 5–3.980, 6–3.981, 7–3.982, 8–3.983.

The reason for fast current oscillations [curve $3'$ in Fig. 1(a)] lay in the temporal evolution of the field distribution, as presented in Fig. 2. Curves 1 (four gray-colored field domains) and 2 (two domains) in the upper panel show the field profiles (collapsing domains) at the beginning and end of the fast switching edge. By $t > 3.2$ ns a dense electron-hole plasma had been formed in the switching channels and the moving collapsing domains had disappeared, giving way to two new types of domain instability. These two instabilities alternated (or even overlapped) in time, and caused the generation of THz emission at $t > 3.2$ ns (see below). One of these was a very broad (~5.7 μm) nonionizing (~26 kV/cm) domain (see curve 3) moving towards the collector contact at a very high velocity of $\sim 4 \times 10^8$ cm/s. (The velocity of the *collapsing* domains is lower by a factor of 20 to 40 [4]). The parameters of the broad, fast-moving domain are in fairly good agreement with the analytical theory of the Gunn effect with two kinds of carriers [10], and analogous (very fast) domains might have been observed experimentally in a high-gain photoconductive switch [11]. (This kind of instability could rather be termed a "plasma wave", due to its high velocity, but we use the terminology of Ref. [10]). The generation/annihilation time for this "broad" domain was as small as $5.7\ \mu\text{m}/4 \times 10^8\ \text{cm/s} \approx 1.4$ ps, and the voltage across the domain was about 15 V, which caused considerable picosecond oscillations in the conductivity current across the channels. The second process was generation and annihilation of a single "anode" domain, which was similar in amplitude and width to the collapsing domains but it did not spread across the n_0 layer and was confined within the n_0-n^+ collector interface (see lower panel in Fig. 2). This domain periodically disappeared (curve 4) and then grew (curves 5–8) to a maximum voltage of ~15 V across the domain within a time of ~3 ps. Both instabilities became possible due to the fast formation of a dense ($\sim 10^{18}$–10^{19} cm^{-3}) electron-hole plasma by ionization in the collapsing domains. In a steady-state situation, very high carrier density and strong fields would have caused prompt sample destruction, but durable and reliable operation became possible in the presence of superfast (picosecond-range) switching and nanosecond filament broadening [9]. The fast current oscillations observed in the simulations provide an obvious hint to measure THz emission generated in the switching channels.

THz emission.—The transistor chip was placed close to a Si bolometer window with different band-pass filters inserted between the emitter and the receiver [Fig. 3(a)]. The evaluated duration of the THz-range emitted pulse was about 2 ns [see Fig. 1(b) and comments], while the bolometer response was as slow as ~1 ms. Consequently, a "burst" mode was used in the experimental setup in which a train of ~40 pulses was emitted by the transistor with a repetition period of 70 μs. The oscillograms of the bolometer response are shown in Fig. 3(b). After the characteristic time for a bolometer response (~1 ms) the signal became saturated [curves 1 and 2 in Fig. 3(b)] at a level corresponding to the average power recorded by the bolometer. Multiplication of this power by the duty cycle of $\sim 70\ \mu\text{s}/2\ \text{ns} = 35\,000$ gives a value for the *peak power*. A peak power of ~150 μW was obtained in the spectral band 25 GHz–0.3 THz, and 245 μW in the 25 GHz–1 THz band [see experimental points 1 and 2 in Fig. 3(c)]. No notable difference was recorded between the emission in the $f < 3$ THz band and that in the $f < 1$ THz band (curve 2), which means that the signal in the $1 < f < 3$ THz band was lower than the noise. We attribute an additional signal (average power in excess of ~7 nW) recorded in the bands $f < 9$ THz and $f < 25$ THz [curves 3 and 4 in Fig. 3(b)] to black body (thermal) radiation. Indeed, this signal grows linearly in time throughout the duration of the pulse train (burst). The estimates for black body radiation confirmed this proposition, and one particularly convincing piece of evidence being the fact that the spectral integral in Planck's formula provided exactly the same ratio for the "excess" (above 7 nW) emission at $f < 9$ THz and at $f < 25$ THz, as was observed in Fig. 3(b), while the estimated black body signal at $f < 3$ THz was negligible in absolute terms. All in all, the signal presented by curves 1 and 2 in Fig. 3(b) certainly corresponds to nonthermal emission generated by the switching channels in the sample.

Simulation of the total THz power generated.—The emission caused by the currents in the channels and nonswitched part [5] of the structure in different spectral bands and at different transient instants is shown by curves 3–5 in Fig. 3(c). The simulated emission exceeds the measured one by a very significant margin. The simulated time-averaged spectra are presented in Fig. 3(d). The total *far-field emission* caused by conductivity current oscillations was calculated in the model using the formula

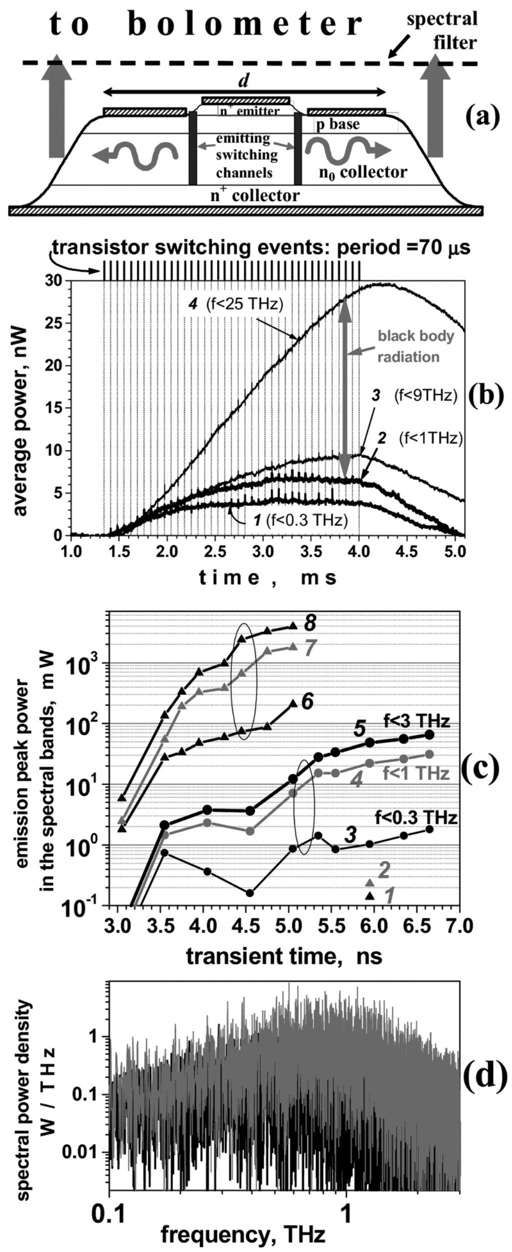

FIG. 3. Measured and simulated peak power in the THz range. (a) schematic presentation of the transistor chip and experimental setup; the emitter and base metal contacts of size ***d*** provide undesirable shielding of the emission source from the bolometer. (b)-oscillograms of Si bolometer responses scaled by the known bolometer responsivity (4.4 nW/mV); the curves correspond to different bands of the band-pass filters used in the experiment: 1–25 GHz $< f <$ 0.3 THz; 2–25 GHz $< f <$ 1 THz; 3–25 GHz $< f <$ 9 THz; 4–25 GHz $< f <$ 25 THz. (c) measured (1,2) and simulated (3–5) peak power for a "low voltage" transistor: (1) and (3) correspond to the spectral band $f <$ 0.3 THz, (2) and (4) to $f <$ 1 THz, and (5) to $f <$ 3 THz. Curves 6–7 show the simulated emission power in different spectral bands for a "high-voltage" (300 V) transistor analogous to that in Refs. [4,5]: (6) corresponds to band $f <$ 0.3 THz, (7) to $f <$ 1 THz and (8) to $f <$ 3 THz. (d) simulated spectra for a "low voltage" transistor (black) averaged over the transient time interval 3.1–6.3 ns and for a "high-voltage" transistor (gray) averaged over the interval 3–5.1 ns.

$$\frac{\mu \cdot \mu_0}{(4\pi)^2} \times \frac{1}{c} \times \int \left(e_R \times \int \frac{\partial j}{\partial t} dV \right)^2 d\Omega, \qquad (1)$$

where $\mu\cdot$, μ_0, and c are the magnetic permittivity and photon velocity; $\vec{e}_R$ is a unit vector; $\vec{j}$ is the conductivity current density calculated in the transient modeling, and integration is performed over the volume V of the semiconductor structure and over the total space angle $\Omega = 4\pi$. Formula (1) ignores boundary conditions for radiation scattering and reflections. The generation and annihilation of the field domains discussed above causes variation in the conductivity current j and results in the emission defined by Eq. (1).

The fact that we did not record experimentally any emission in the band at $f > 1$ THz, and that the measured emission at $f < 1$ THz was much less than the simulated value [see Fig. 3(c)] is not surprising. The chip used in the experiment [Fig. 3(a)] was designed for electrical switching operation (*not as a THz emitter*), and the top Ohmic contacts of total size $\boldsymbol{d}$ very efficiently mask the bolometer window with respect to the emission source, also the reflection at the surface of the mesastructure reduces additionally the radiation yield. Thus only small fraction of the generated power may leave the sample. Even much lower power (below the noise) at high frequencies ($f > 1$ THz) is apparently associated with very low efficiency of the wave guiding in parallel direction in the n_0 layer of $W_n \sim 12\ \mu$m in thickness ($\lambda \gg W_n$). This should explain why the emission was not observed at $\boldsymbol{\lambda} < \boldsymbol{d}$ in the experiment shown in Figs. 3(a) and 3(b), with $d \approx 300\ \mu$m, while *no radiation at all* was detected in another experiment with a "larger" chip ($d \approx 1.2$ mm).

Even much higher *internal* THz power is predicted in the high-voltage transistor simulations [see Fig. 3(c) and 3(d)], but the model prediction should be treated with supreme circumspection, since proper coupling of the emitting volume to free space given the limitations of a GaAs transistor structure is a fairly delicate matter. Also, consideration of the effect of distributed capacitance and inductance in this structure (see Ref. [5]) would require more careful adaptation of the model to THz frequencies. Otherwise, the realization of an all-electronic multi-mW pulsed source operating at room temperature could be very attractive [12], particularly for terahertz reciprocal imaging [13] and terahertz absorption spectroscopy [14].

Among various plasma instability scenarios [15] which may cause THz oscillations in electronic devices, the closest to our case appears to be the popular model of plasma waves in GaAs-based compounds [16], as confirmed experimentally in low-dimension field-effect transistors at cryogenic temperatures [17]. We would *not* attribute the results of our THz measurements to analogous plasma waves, however, as a number of very critical assumptions belonging to the model [16] are not valid in a GaAs bipolar transistor (ballistic regime, low-dimension, low/moderate carrier density, cryogenic lattice temperature, etc.).

One may express doubts regarding the validity of using a local-field ionization, drift-diffusion model in the case of very narrow ionizing domains (Fig. 2). One can see from Fig. 1(a), however, that the measured and simulated voltage waveforms fit perfectly at the beginning of the transient, when generation of the collapsing domains take place, and the prediction of THz emission is essentially based on the generation and annihilation of fast-moving broad domains (curve 3 in Fig. 2), which can hardly be considered an artefact [10,11]. A certain difference in the voltage waveforms at $t > 3.3$ ns, however, may be associated with limitations in the model.

In conclusion, the copious (sub-mW) sub-THz emission and hot photon emission observed experimentally from the switching channels of a GaAs transistor provide important arguments in favor of the existence of collapsing domains. The collapsing domains concept may be of interest in the case of objects and materials in which NDM takes place in high electric fields exceeding the ionization threshold. The simulations show qualitative/semiquantitative agreement with the experiment and predict more powerful emission, spreading into the terahertz (1–3 THz) range. One may expect the development of a pulsed (nanosecond-range), broadband THz emitter with peak power in the multi-mW range that operates at room temperature once the problem of coupling to free space can be solved.

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