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ABSTRACT

A simple miniature source generating pulse trains with a central frequency of ~100 GHz and a duration of 50–100 ps has been demonstrated recently. The source is based on nanometer-scale collapsing field domains (CFDs) generated in the collector of an avalanching bipolar GaAs transistor. The central frequency is determined by the domain transient time across the collector, and thus, a routine increase in the oscillation frequency from 0.1 to 0.3–0.5 THz would require a reduction in the collector thickness by a factor of 3–5. This is not acceptable, however, since it would reduce the maximum blocking voltage affecting the achievable peak current across the avalanche switch. We suggest here a solution to this challenging problem by reducing the CFD travel distance while keeping the collector thickness unchanged. Here, the discovered and interpreted phenomenon of CFD collapse when entering a dense carrier plasma zone made it possible by means of bandgap engineering. A CFD emitter generating ~200 GHz wavetrains of ~100 ps in duration is demonstrated. This finding opens an avenue for the increase in the oscillation frequency without any reduction in the emitted power, by using a smart structure design.

Multiple field domains of ~0.5 MV/cm in amplitude, shrinking down to ~50 nm and then collapsing, have been found in physics-based numerical modeling of the avalanche-switching transient in GaAs bipolar-junction transistors (BJTs). Later termed "collapsing field domains" (CFDs), these provided an interpretation of the puzzle of superfast switching in high-voltage GaAs BJTs and were later adopted to interpret superfast switching in photoconductive GaAs switches (PCSS) and GaAs avalanche S-diodes. These CFDs were confirmed in various experiments employing the comparison of the measured and simulated voltage and current waveforms, temporal profiles of band-to-band emission from the switching channels, and "hot" photon and subterahertz emission. It was found that the principal condition for the existence of CFDs is negative differential mobility (NDM) "at extreme electric fields" at least up to 0.6 MV/cm, a point proven so far only for GaAs. Eventually, the CFD concept was confirmed by means of measurements and modeling of pulsed millimeter-wave emitters based on a low-voltage BJT avalanche switch. In these micrometer lateral sized, resonator-free emitters combined with a submillimeter on-chip antenna, a nanometer-scale CFD will circulate across the n0-collector layer, resulting in free space emission of a wavetrain of duration ~50–100 ps. The central frequency of ~110–130 GHz reported so far is determined by the travel of the CFD across a ~700 nm n0-layer with a velocity of ~100 nm/ps. At first glance, the frequency can be increased by simply reducing the n0-collector thickness, but the problem is complicated by two factors. (i) The emission requires an extreme current density of ~10 MA/cm² in the switching channels, which corresponds to a peak current of ~200 mA in a pulse of duration ~100–150 ps. This current amplitude requires relatively a high initial transistor biasing of ~20 V on account of the voltage drop across the switched-on structure, contact resistance, and LCR circuit impedance. Attaining necessary peak current is problematic at a much lower initial biasing of ~10 V when using an n0 collector layer thickness of only 350 nm in the 200 GHz source. (ii) A technological limitation of ~4 × 10¹⁸ cm⁻³ on the maximum possible doping in the n⁺ GaAs subcollector results in "conical" spreading of the CFD into the subcollector when the electron-hole (e-h) plasma...
density in the channels reaches \( \sim 10^{19} \text{cm}^{-3} \). Then, \( \sim 200-300 \text{nm} \) CFD penetration into the subcollector will add \( \sim 2-3 \text{ps} \) to the CFD circulating period, reducing the oscillation frequency accordingly.

Our way of resolving this problem consists of reducing the travel length of the CFD below the thickness of the voltage-blocking \( n_0 \)-collector layer. The collapsing of the CFD when it enters the zone of increased carrier plasma density made this possible: a phenomenon found, interpreted, and employed here.

Before considering the phenomenon, which is critically important for this work, let us first discuss quasi-steady-state CFD motion as illustrated in Fig. 1(a). Quasi-steady-state motion is possible only in the presence of (i) both electrons and holes, (ii) impact ionization, and (iii) NDM above the ionization threshold. No analytical theory for CFD exists as yet, but some of the domain properties can be understood qualitatively on account of the dependence of the electron velocity \( v_e \) on the electric field \( E \) of Fig. 1(b). The CFD [Fig. 1(a)] surrounded by e-h plasma moves to the right at a velocity \( v_D \approx 100 \text{nm/ps} \), see Fig. 1(b), and the front CFD wall is determined by the positive charge \( (p + N_D - n) \times q \), where \( n, N_D, p \) are the electron, donor, and hole densities and \( q \) is the electron charge. The plasma splits [Fig. 1(d)] thanks to the electrons moving ahead of the domain front with a velocity exceeding that of the domain \( [v_e > v_D] \) at 1.2 kV/cm \(< E < 16 \text{kV/cm} \), Fig. 1(b)] and leaving behind a noncompensated charge of the holes.

The rear CFD wall, determined by the negative charge \( (n-p-N_D) \times q \), forms as follows: The holes penetrating the domain from the right perform the impact generation of new e-h pairs. The holes, both those captured by the domain and those generated inside it, are promptly swept out of the domain of width \( W_D \approx 50 \text{nm} \) (within a time of \( \sim W_D/(v_D + v_H) \sim 0.25 \text{ps} \)). The electrons stay in the domain much longer \( \sim W_D/(v_D - v_e) \approx 1 \text{ps} \) and make a dominant contribution to the ionization, especially on account of their higher ionization rate. This causes an accumulation of electrons inside the domain, and the negative charge will form the new position of the rear wall [see the dashed curve in Fig. 1(a)]. The “former” rear wall will turn into e-h plasma thanks to compensation of the excess electron charge by the holes that have arrived from the right. Note that the electrons cannot penetrate into the domain from the left because their velocity in a high electric field is less than that of the domain, see Fig. 1(b). Thus, the negative charge in the rear wall can exist only in the presence of impact ionization, and the CFD disappears if its amplitude is reduced below the ionization threshold. In all transient simulations, \( v_D \approx v_H \) the CFD collapsed when penetrating from the \( n_0 \) collector to the \( n^- \) subcollector, and simultaneously, a new domain formed from the left-hand side at the \( p-n_0 \) interface. That is why the frequency of the CFD-based oscillator was determined by the time required for the domain to travel across the \( n_0 \) collector. We will show below that the CFD may also collapse inside the \( n_0 \) layer, provided that a zone of increased carrier plasma density is formed before the domain front. Later in this paper, we will demonstrate experimentally that a simple means of bandgap engineering will allow the designing of a source that emits higher frequencies without any reduction in the power, thanks to this new phenomenon.

To demonstrate this phenomenon numerically and interpret it physically, we consider a simple situation in which the CFDs are obtained in a \( n^-\text{-}n_0\text{-}n^+ \) structure (free from any heterostructure or even a p-n junction) under high-current \( (\sim 1-10 \text{MA/cm}^2) \) pulsed (a few nanosecond) biasing. We selected a set of conditions at which two identical domains move monotonically across the \( n_0 \) layer and collapse only when reaching the “anode” \( n_0^-\text{-}n^+ \) interface. The e-h plasma zone induced in the other simulation run by means of local optical excitation caused the domain to collapse earlier, inside the \( n_0 \) region. See the snapshot of two domains and the position of the optically excited zone in Fig. 1(c), the carrier profile in Fig. 1(d), and the space charge (black) and displacement current (blue) profiles in Fig. 1(e). The “left” domain in Figs. 1(c)-(e) moves to the right at a constant velocity \( \sim 100 \text{nm/ps} \) without any noticeable change in its shape. The amplitude of the “right” CFD is reduced, and the domain disappears (collapses) within an \( \approx \text{ps} \) of the instant shown in Figs. 1(c)-(e) at which the front wall of the domain penetrates the plasma zone.

The displacement current density is equal to \( J_d = e_0 \partial \vec{E}/\partial t \), where \( E \) is the electric field, \( e_0 \) and \( c \) are the vacuum dielectric constant and dielectric constant in GaAs, and \( t \) is the time. The electric field is a function of only one variable \( x = x - v_D \times t \) provided that the domain velocity \( v_D \) is constant. Then, on account of the Poisson equation, the displacement current density is \( J_d = \rho = q (p - n + N_D) \times v_D \). This means that at a constant domain velocity, \( J_d \) differs from the space charge \( \rho = q (p - n + N_D) \) forming the domain only by a
factor $\eta_{\text{PD}}$, see the identical blue and black curves for the left domain in Fig. 1(e), which is witness to the monotonic nature of the domain movement.

On the other hand, $I_d = I_{\text{tot}} - I_{\text{cond}}$, where $I_{\text{tot}}$ and $I_{\text{cond}}$ are the total and conduction current densities. Imagine that the e-h plasma density before the front of the domain experiences noticeable growth within a distance comparable to the domain width. In this case, $I_{\text{tot}}$ at the domain front wall must grow as well, thus reducing $I_d$ in order to keep $I_{\text{tot}}$ constant along the structure for the 1-D model. [See the fragment of the blue curve in Fig. 1(e) corresponding to the front wall of the right domain.] Thus, the electric field $E$ (and the module of its spatial derivation $dE/dx$) will grow in the range of 0.385–0.41 $\mu$m less significantly than would be the case in the presence of quasi-steady-state domain movement. This means that the positive charge in the front wall will be smaller than in a quasi-steady-state. On the other hand, the domain is a dipole, which requires a charge balance, and thus, the negative charge in the rear wall must also be reduced. Accordingly, both $dE/dx$ and $E$ are reduced faster than in a quasi-steady-state, which means an increase in $I_d$ as seen from the simulation results presented by the blue curve in Fig. 1(e) at the position 0.36–0.39 $\mu$m.

Looking at the curves in Figs. 1(c) and 1(e), one can say that the front wall of the right domain tends to slow down, while the electric field in the rear wall experiences rapid reduction, which results in domain shrinkage from the back and eventual collapse. (This is a typical scenario for the external appearance of the dynamics of CFD collapse at the n$_0$-n$^+$ interface as well, as was occasionally observed in various earlier GaAs avalanching BJT simulations).

All in all, the current redistribution between the conductive and displacement current components at the border of the plasma zone is the physical reason for domain collapse.

The first subterahertz pulsed emitter prototype making use of CFD and based on a submicrometer GaAs BJT structure was described in Ref. 11, and the structure of a source using exactly the same construction is shown in Fig. 2(a). The only difference of the used structure here from that described in Ref. 11 concerns the implementation of the heteroemitter (as in HBT transistors). The advantage of using the HBT structure lies in the increased efficiency of electron injection (making easier avalanche triggering), but there is also a disadvantage due to higher residual voltage, apparently associated with a static domain formed in the N layer of the heteroemitter. (The properties of this static domain and its effect on the operation of the device require a further detailed study).

The simulations show that the circulating domain forms near the p$^+$-n$_0$ interface at a sufficiently high plasma density ($>10^{17}$ cm$^{-3}$) and is annihilated (collapses) in the n$^+$ subcollector at the boundary where the donor density becomes equal to the e-h plasma density in the switching channel (within the range of $\sim$10$^{18}$–10$^{19}$ cm$^{-3}$ typical of subterahertz emitters). Due to technological limitations on the maximum subcollector doping ($\sim$4 x 10$^{18}$ cm$^{-3}$), the condition for domain collapse is satisfied only at a certain distance $\Delta$ from the n$_0$-n$^+$ interface [see Fig. 2(a)], thanks to the conical form of the current spread. This adds $\Delta/\eta_{\text{PD}} \sim$ 2 ps to the initially expected $t_{\text{pulse}} = 7 ps$ period of the CFD oscillations for both BJT$^{11}$ and HBT [Fig. 2(a)] with a $W_{\text{PD}} = 700 nm$ n$_0$-collector layer. [As already mentioned, a relatively thick collector withstanding an initial biasing of $\sim$22–25 V is needed to reach the peak current $>200 mA$ across the device which is necessary for the emission of sufficient power ($\sim 1 mW$).]

One should also account for the $\sim 30 \Omega$ impedance of the external circuit exhibiting a storage capacitor of $\sim 1 pF$ and a parasitic inductance of storage capacitor, a contact resistance of $\sim 10\Omega$ for the $\sim 2 \mu m^2$ channel area, a 10 $\Omega$ load resistor, and a residual $\sim 10 V$ voltage across all the high-field domains: a delicate matter to be discussed in detail elsewhere.

The design of the emitter structure suggested here, which is capable of withstanding the same initial biasing (22–25 V) but emits at practically twice the frequency ($\sim 200 GHz$) given the same peak power ($\sim 1 mW$), is shown in Fig. 2(b). This is essentially the same emitter as for $\sim 100 GHz$, except that GaAs at coordinates >660 nm is replaced with Al$_{0.08}$Ga$_{0.92}$As, resulting in the formation of an abrupt isotope heterojunction [Fig. 2(c)]. The doping profile and the collector-base breakdown voltage remain unchanged since electrons are practically absent in the space charge region independent of the varying bandgap. During the avalanche switching, however, the carrier plasma accumulates on the left of the heterojunction [ <660 nm, Fig. 2(c)] which creates the zone of dense electron-hole plasma between the coordinates 500 and 660 nm. This results in CFD collapse at the left-hand boundary of the zone.

The mechanisms discussed above are illustrated by the numerical and experimental results presented in Fig. 3. The measured and simulated voltage and current temporal profiles [Fig. 3(a)] fit each other very well until the instant $\sim 0.08 ns$. We are inclined to attribute the violation of this agreement at later instants to a limitation in the 1-D modeling approach, which does not account for the possible turn-on spread (switching channel temporal broadening) found earlier in Si avalanche BJTs. 3

Simulated and measured temporal profiles of the emission, obtained using zero-bias Schottky detectors (VDI, Inc.) built into waveguides and designed for different spectral bands, are shown in

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FIG. 2. Schematic diagram of the AlGaAs/GaAs HBT structures of the pulsed avalanching sources with CFD collapsing at different spatial positions. (a) “Basic” $\sim 130 \pm 20 GHz$ source, (b) “special” $\sim 210 \pm 20 GHz$ source with added isotope heterojunction, (c) e-h density profile formed during the avalanche switching ahead of the heterobarrier (8% Al), and (d) the “external” on-chip circuit, and the bow-tie on-chip antenna used in both sources.
Fig. 3(b). The 100 GHz structure emits in the ~110–150 GHz “low-frequency band” (LFB, black curves) and the 200 GHz structure in the ~190–230 GHz “high-frequency band” (HFB, red curves). The emission bands were characterized experimentally using a set of bandpass spectral filters. The agreement of the simulations with the detector in time.

The field profiles shown in Figs. 3(c) and 3(d) allow an interpretation to be given for the data shown in Figs. 3(a) and 3(b). During the delay stage of the avalanche switching transient (0–23 ps), the electron injection from the emitter provides a reconstruction of the electric field in the collector [see 0 ps and 22.8 ps profiles in Fig. 3(c)]. The impact generation of holes near the n−-subcollector and the electron injection from the emitter then together create e-h plasma in the channel with a density sufficient for CFD formation. Then, the ionization in the CFDs causes a rapid increase in the plasma density increasing the current and shrinking the domains, while the latter reduces the collector voltage [see interval 30–100 ps in Fig. 3(a)]. Simultaneously, domain circulations [Figs. 3(c) and 3(d)] cause current oscillations in the antenna [see Fig. 2(d)] and the emission represented by the black and red curves in Fig. 3(b).

A certain difference exists in the mechanisms of plasma formation and subterahertz oscillations particular to the 100 and 200 GHz structures. In both cases, the electron injection from the left combines one from the n+ n− heterobarrier with the avalanche injection from the static high-field domain in the N-region between −0.1 and −0.2 μm [see Figs. 3(c) and 3(d)]. The avalanche injection of the holes from the right in the 100 GHz structure [Fig. 3(c)] is always due to ionization in the CFDs during their travel and collapsing stages. In the 200 GHz structure, the avalanche injection of the holes in the static field domain at 0.7–0.85 μm [Fig. 3(d)] predominates, while the ionization in the moving field domains makes a smaller contribution. The most important difference for subterahertz emission concerns the position of the CFD collapse. In the basic structure [Fig. 2(a)], the CFD penetrates onto the n+ subcollector, so that the domain travel length is about 0.8–0.9 μm and the central oscillation frequency is close to 100 GHz. In the special structure [Fig. 2(b)], the CFD collapses at the boundary of the plasma zone [see Figs. 3(d) and 3(e)], which is located between 0.5 and 0.7 μm. The reason for this zone is hole accumulation in the narrow-band material near the heterobarrier (0.7 μm), with simultaneous compensation of the charge of holes by the electrons. (What concerns the left-hand side carrier profile of the plasma zone, its shape obtained numerically is determined by the mechanisms of the carrier transport under complicated time-dependent carrier avalanche injection and can scarcely be interpreted briefly or in simple qualitative terms.)

To summarize, the phenomenon of CFD collapse when entering the e-h plasma zone, as introduced and interpreted here, allows simple methods of bandgap engineering to be applied to overcome the fundamental frequency limitations of our unique subterahertz wavetrain source. The method verified here for ~200 GHz is applicable to higher frequencies as well.

A number of promising applications can be foreseen for a family of sources utilizing plasma-controlled oscillation frequency. One is the replacement of traditional, but bulky and costly femtosecond-laser-based sources in time-domain imaging (TDI). Especially advantageous is the subpicosecond temporal resolution obtainable in this way, which is comparable to that of the optoelectronic approach, thanks to the Interferometric Enhancement (IE) effect in the CFD-based source. The other subterahertz applications include security systems, biomedicine, and short-range communications.

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