Formation and evolution of spatial dissipate structures in GaAs n-i-n structures

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Abstract

On the basis of two-dimensional numerical simulation the formation, evolution and kinetics of spatial dissipative structures (DS) under breakdown of GaAs n-i-n structure are studied. It is found, that at some critical length of the n-GaAs layer the instability of spatial distribution of the current along contacts results in the formation of spatial periodic structures as multiple current filaments. With current increase the spatial period of DS decreases down to some minimum value. It is revealed that physically DS formation is the result of a distinction between a small spatial parameter of instability (due to avalanche-injection modulation of i-region conductivity) and a large spatial parameter of current damping (due to current spreading in the lengthy n-contact region).

Introduction

One of the striking phenomena arising in semiconductor structures, as well as in a number of physical, biological, chemical active media is the spontaneous generation of spatial temporally inhomogeneous, dissipative structures (DS). In distributed semiconductor structures DS were observed experimentally as multifilament states at impurity breakdown of n-Ge and n-GaAs at helium temperatures [1], in Si p-n-p-n diodes structures [2], at avalanche breakdown of Si on sapphire p-i-n structures [3] and in 6H-SiC p-n structures [4]. Formation of DS in these structures has been analyzed on the basis of phenomenological reaction-diffusion equations [5,6]. According to [5,6] spatial pattern formation is the result of an interaction of two processes with different spatial parameters: cumulative current increase due to current instability in the active region of the structure and suppression of current (for example due to spreading of current in the distributed quasi-neutral region of the structure [2-4]).

Recently formation of multifilament states was observed experimentally under the condition of drain-source breakdown in GaAs HEMT's and MESFET's structures [7]. Current filamentation in these structures was the result of a spatial current instability in the semi-insulating i-layer, which forms together with the source and drain n^+-contact regions a "built-in" n-i-n structure [8,9]. In addition to fundamental interest, the understanding of the DS formation phenomenon is important for the reliability of power MESFET's and HEMT's, owing to the fact that current filamentation limits the maximum drain-source voltage and results in instantaneous burnout [7-9]. For the evaluation of the DS properties and the possible design of new electronic devices the GaAs microstructures have a number of advantages. DS's of 1-10 μm dimension can be realized in these structures at room temperature. They have a high speed, high light emission efficiency and the possibility of integration with advanced GaAs IC technology.

The purpose of this study is (1) to demonstrate by help of two-dimensional numerical simulation that the spatial current distribution in a GaAs n-i-n structure under breakdown condition is unstable and results in the formation of a stable spatially periodic DS; (2) to study the evolution of DS in dependence of current magnitude and structural parameters.

Calculation procedure

For numerical simulation the two-dimensional quasi hydrodynamic model [8] was used. The calculations were performed for GaAs n-i-n structure (Fig.1(a)). The lengths of contact regions were L_A = 0.04 μm L_C=9 μm. The lengths of i-regions was L_I = 1 μm. The donor concentration in the anode and cathode contact regions was 10^{18} cm^{-3}. The calculation was performed for models of 2-D n-i-n structures with wide W = 60 μm and narrow W = 0.5 μm contacts. The later was treated as one-dimensional model. Points of I-V characteristic were calculated up to a stationary voltage value for a given current step. Spatial instability was simulated on the basis of quasi hydrodynamic equations [8] without any additional fluctuation source terms. Numerical noise in the finite-difference scheme was the only source of model fluctuations.

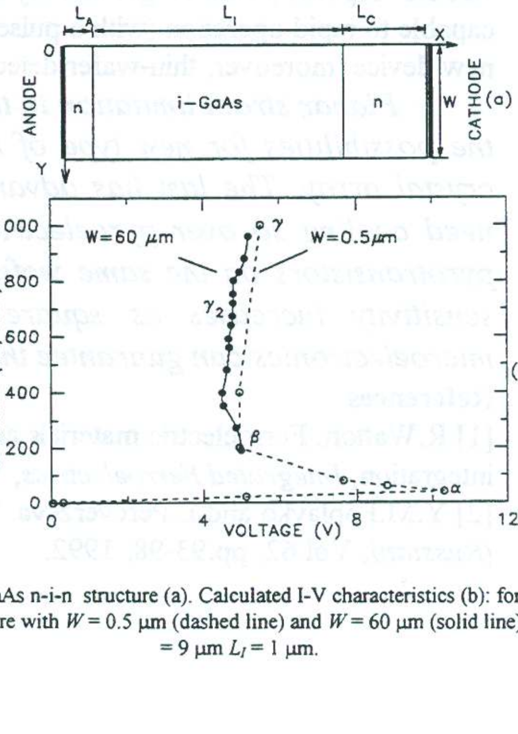

Fig.1. GaAs n-i-n structure (a). Calculated I-V characteristics (b): for n-i-n structure with W = 0.5 μm (dashed line) and W = 60 μm (solid line), L_C = 9 μm L_I = 1 μm.

Results

Calculated I-V characteristics of the n-i-n structures are presented in Fig. 1(b). One can divide the I-V characteristics into the following regions: region of linear current increase, negative differential conductivity (NDC) region and high conductivity region of positive differential resistance. Processes, resulting in formation of these regions can be understand from the analysis of the electric field, electron and hole density distributions in narrow n-i-n structure [8]. In Fig.2 these distributions are presented for the narrow n-i-n structure (W = 0.5 μm) for the three states: avalanche breakdown (α), NDC (β) and high conductivity (γ) (Fig.1 (b)). With current increase field near the anode n-i junction is increased and avalanche impact ionization begins (state (α)). Generated holes arising to cathode enhance injection of electrons from this region. Space charge of the injected electrons increases the electric field and avalanche ionization near anode. This positive feedback results in formation of the quasineutral region near cathode n-i junction (Fig.2 (b,c)). With current increase the quasineutral region expands in the anode direction, thus decreases voltage drop across i-region (Fig.2(a)) and provides NDC of the structure. In the high conductivity state (γ) the voltage drop on lengthy cathode n-region provides small positive differential conductivity.

Calculated I-V characteristic of the wide n-i-n structure (W = 60 μm) is presented in Fig.1(b) by dashed line. The shape of NDC region of the I-V characteristic of this structure differs from that for the narrow n-i-n structure (W = 0.5 μm) (Fig.1(b)). For current steps exceeding critical current for NDC formation a quasistationary state with uniform current distribution along contacts is observed at first after fast transition process. In this quasistationary uniform state the voltage value, field and carrier density distributions coincide with voltage and distributions for a narrow structure under the same current density. Then a new stationary nonuniform stable state with numerous current filaments forms during the time interval of 300-500 ps. Two-dimensional distribution of the field, electron and hole density is presented in Fig.3 for the current I = 690 kA/cm^2. Regions of the high current density can be identified as filaments. In the filament regions the field and carrier density distribution along current lines corresponds to the distributions in the high conductivity state (γ) of the narrow structure (Fig.2).

With current increase the period and the current density inside the filaments decrease (Fig.4(a)) up to a certain minimum values. Then the current density inside the filament increases at fixed spatial period up to saturation current density value in n-regions. Kinetics of spatial period decrease with step current increase consists in the splitting of filaments in the initial state (Fig.4(b)). Kinetics of spatial period increase with step current decrease

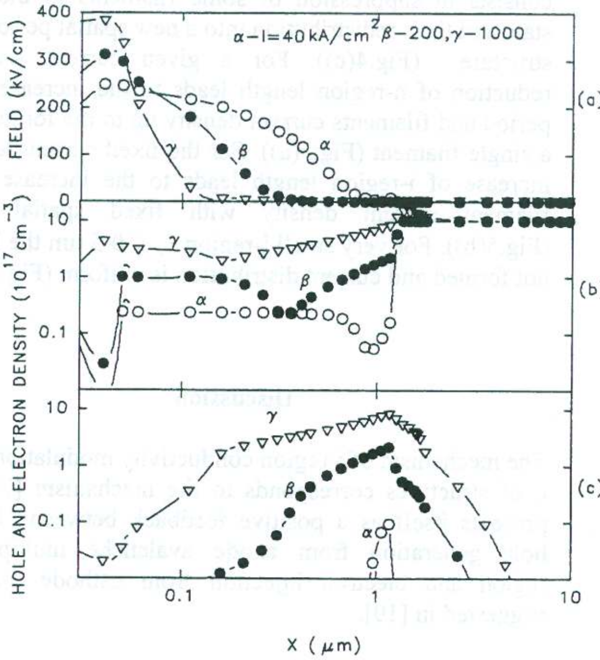

Fig. 2. The field (a), electron (b) and hole (c) density distribution in GaAs n-i-n structure with W= 0.5 μm, L_C = 9 μm, L_I = 1 μm for: avalanche breakdown state (α), NDC state (β) and high conductivity state (γ), marked by points "α", "β", "γ" in Fig.1(b), respectively.

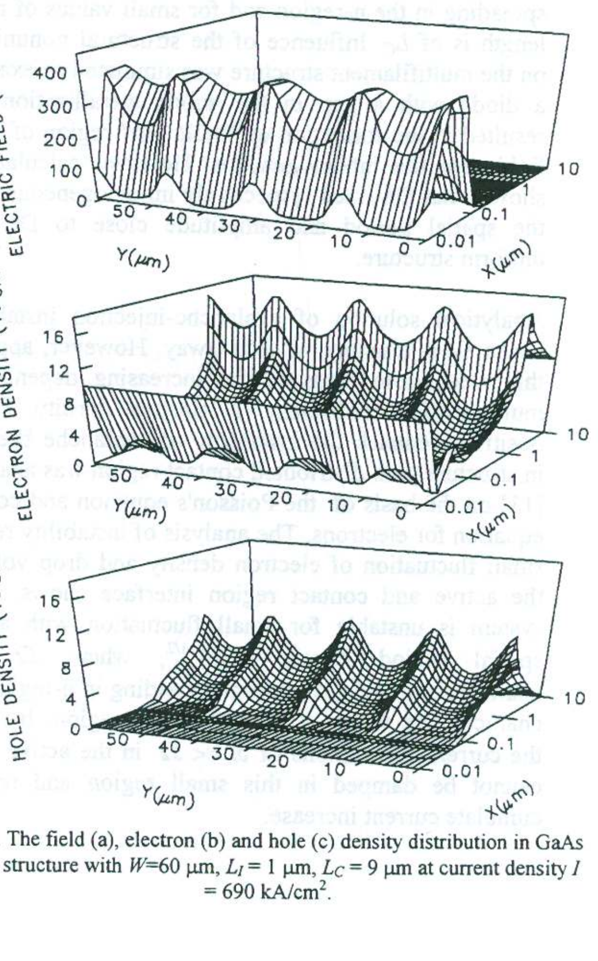

Fig.3. The field (a), electron (b) and hole (c) density distribution in GaAs n-i-n structure with W=60 μm, L_I = 1 μm, L_C = 9 μm at current density I = 690 kA/cm^2.

consists in suppression of some filaments in the initial state and their redistribution into a new spatial periodic structure (Fig.4(c)). For a given current level the reduction of n-region length leads to the increase of the period and filaments current density up to the formation of a single filament (Fig.5(a)). For the fixed current level the increase of i-region length leads to the increase of the filament current density with fixed spatial period (Fig.5(b)). For very small i-region $L_I \leq 0.5$ μm the NDC is not formed and current distribution is uniform (Fig.5(b)).

Discussion

The mechanism of i-region conductivity modulation of n-i-n of structures corresponds to the mechanism [7-9] and presents itself as a positive feedback between level of hole generation from anode avalanche multiplication region and electron injection from cathode n-contact, suggested in [10].

Formation of the multifilament states in the 2-D structure may be explained by spatial instability of current distribution along contacts due to increase of fluctuations with allocated spatial period. In different series of calculations performed at the same given current the filaments were localized in the different part of the structure, however current density inside filament and period were the same. The spatial period of DS was determined by the characteristic length of current spreading in the n-region and for small values of n-region length is of L_C. Influence of the structural nonuniformity on the multifilament structure was simulated as example of a diode with a gap in the anode metallization, which resulted in the formation of "built - in" region of a strong field near the inhomogeneous. However calculation has shown, that DS fixed respectively inhomogeneous, but has the spatial period and amplitude close to DC in the uniform structure.

Analytical solution of avalanche-injection instability in GaAs n-i-n structure while is away. However, apparently, this mechanism leads to the increasing dependence of multiplication coefficient vs. electron density. For such positive feedback the instability of avalanche breakdown in structure with distributed contact region was analyzed in [11] on the basis of the Poisson's equation and continuity equation for electrons. The analysis of instability relatively small fluctuation of electron density and drop voltage on the active and contact region interface shows, that the system is unstable for small fluctuation with allocated spatial period equals $(\Omega\omega)^{-1/2}$, where Ω is the characteristic width of current spreading in n-region and ω characteristic width of instability in i-region. Increase of the current fluctuations of $\omega \ll \Omega$ in the active i-region cannot be damped in this small region and results in cumulate current increase.

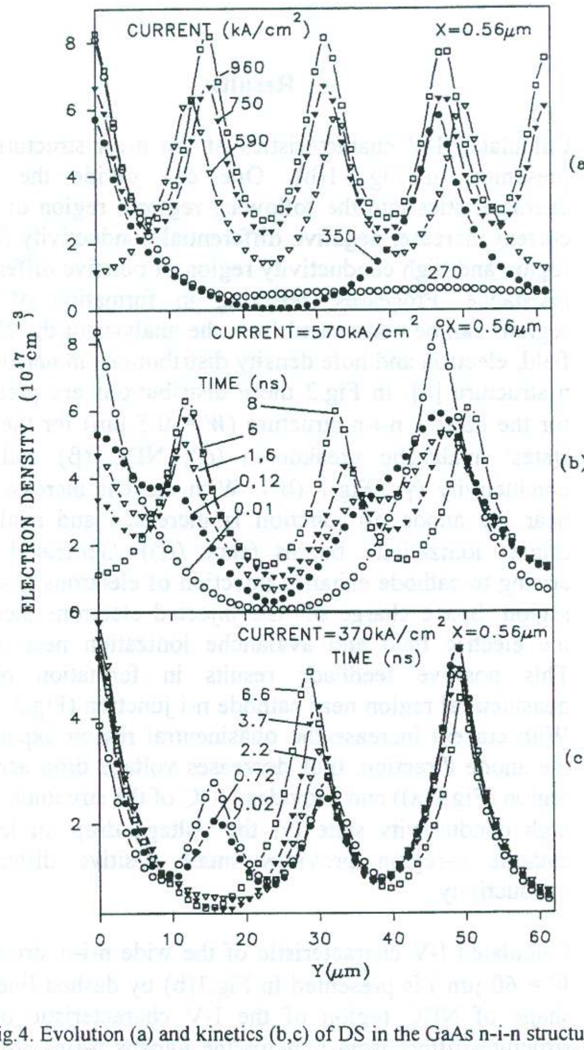

Fig.4. Evolution (a) and kinetics (b,c) of DS in the GaAs n-i-n structure with $W = 60$ μm, $L_I = 1$ μm, $L_C = 9$ μm. Stationary distributions of the electron density in the X=0.56 μm plane for the given current values (a). Distribution of electron density after a step wise current density increase from 320 up to 570 kA/cm^2 (b) and after a step wise current density decrease from 570 up to 370 kA/cm^2 (c).

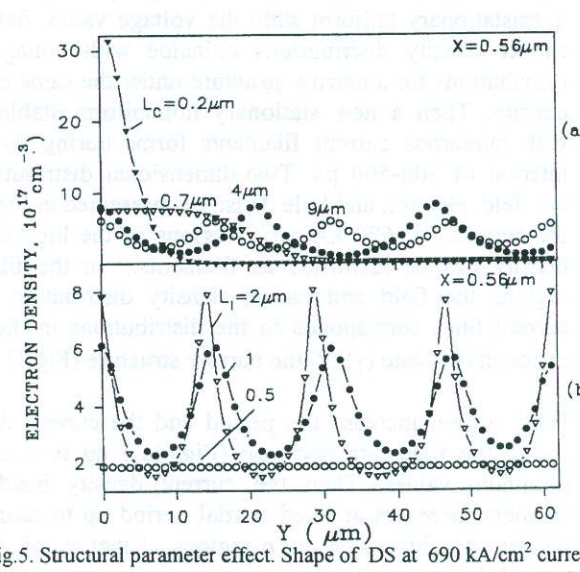

Fig.5. Structural parameter effect. Shape of DS at 690 kA/cm^2 current density for $W = 60$ μm and varying cathode n-region length L_C with fixed $L_I = 1$ μm (a); and for different i-region length L_I with fixed $L_C = 9$ μm (b);

Conclusion

Using 2D numerical simulation the current instability and the formation of stationary multifilament states (or DS's) have been investigated in a GaAs n-i-n structure under breakdown condition. The kinetics, DS evolution and structural parameter influence have been studied. The following results were obtained. In breakdown condition at some critical length of the quasineutral n-region of the GaAs n-i-n structure the spatial current instability results in the spontaneous formation of spatial periodic DS's. The DS period has about the n-region length, and the dimension about the i-region length. With current increase the spatial period and amplitude of DS decrease down to some minimum value. The presence of nonuniformity at edge of contact does not change the general picture of DS formation (period, amplitude, evolution), but determines a DS localization relatively nonuniformity. The formation and properties of multifilament states in GaAs n-i-n structures correspond to the theory of DS in distributed media [6] and experimental results of the formation of multifilament states at MESFET and HEMT breakdown [7,9]. The formation of high current density filaments allows to explain the picture of numerous local meltings of the active region, which is observed after instantaneous burnout of MESFET and HEMT structures.

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