A Numerical Study of Amplification of Space Charge Waves in n-GaN Films

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Abstract— **A Numerical study of amplification of space charge waves (SCW) due to the negative differential conductivity in n-GaN films placed onto a semi-infinite substrate is investigated. A case of transverse non-uniform film is considered. The set of balance equations for concentration, drift velocity, and the averaged energy to describe the dynamics of space charge waves were used jointly with the Poisson equation for the electric field. It is possible to observe an amplification of SCW in n-GaN films of submicron thicknesses at essentially higher frequencies f >100 GHz, when compared with n-GaAs. Two-dimensional simulation of spatial distribution of the alternative part of the electric field of space charge wave in 2D is presented.**

Keywords; space charge, negative differential conductivity, n-GaN films.

I. Introduction

Amplification of traveling space charge waves (SCW) in the microwave range in n-GaAs films due to negative differential conductivity (NDC) has been under investigations for many years [1]. But the frequency range of amplification of SCW in GaAs films is $f < 44$ GHz [4, 5 and 10]. It is better to use new materials possessing NDC at higher frequencies $f = 100\ldots500$ GHz, like gallium nitride GaN or InP [9]. GaN compound semiconductor has become interested for use in many semiconductor device structures. It has potential to develop optical devices and high power electronics, because of its large direct band gap, and high frequency devices due to its expected high peak velocity. All these characteristics become GaN into an important candidate for high power, temperature, and frequency electronic applications. A comparison of GaAs and GaN shows that NDC occurs in GaAs when the occupancy of higher valleys (*L*, *X* ones) is 30% and more [2]. In GaN compound semiconductor the occupancy of higher valleys is essentially lower, of about 10%. Therefore, in GaAs it is impossible to describe the amplification of SCW by means of the simplest nonlocal hydrodynamic model, where the unified electron concentration, average electron velocity, and energy are considered [3, 7]. For GaN, it is possible to apply the simplest nonlocal model; there are evidences that in the zinc blende n-GaN the mechanism of NDC is different from the intervalley transfer, but is due to the inflection of the electron dispersion.

In the present paper the spatial increment of amplification of space charge waves due to NDC has been calculated. The influence of nonlocal dependence of the drift velocity on the average electron energy is investigated. The momentum and energy relaxation frequencies are computed. Two-dimensional simulation of spatial distribution of the alternative part of the electric field of space charge wave is presented too.

II. Equations for Space Charge Waves

Consider n-GaN film placed onto i-GaN substrate without an acoustic contact. It is assumed that the electron gas is localized in the center of film. The thickness n-GaN film is 2h < 1 μm, see Fig. 1.

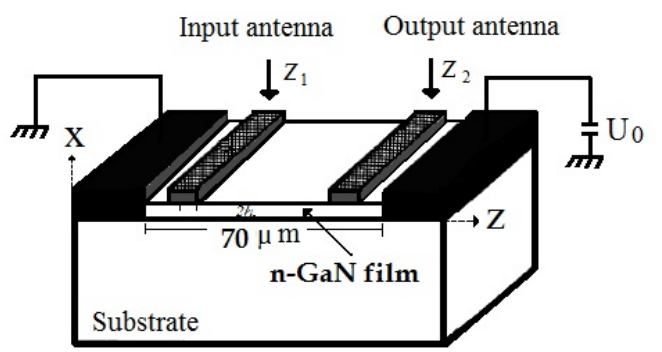


Fig. 1. The structure of the n-GaN traveling-wave amplifier fabricated with an epitaxial layer

The coordinate system is chosen as follows: X-axis is directed perpendicularly to the film, the electric field E0 is applied along the Z-axis, exciting and receiving antennas are parallel to the Y-axis. 2D model of electron gas in the n-GaN film is used. Thus, the 2D electron concentration is presented only in the plane $x = 0$. The space charge waves possessing phase velocity equal to the electron drift velocity $v_0 = v(E_0)$, $E_0 = U_0/L_z$, are considered, where U_0 is bias voltage, L_z is the length of the film. Generally, a non-local dependence of the electron drift velocity v_d on the electric field takes place. In our simulations, an approximation of two-dimensional electron gas is used in device of Fig. 1. This device contained an n-GaN film on the dielectric substrate, and a couple of source and drain ohmic contacts [4,5]. A microwave signal applied to the input electrode modulates the electron density under this electrode. These modulations are drifted to the drain and amplified due to the negative resistance effect. The amplified signal is taken from the output electrode placed near the drain. Obviously, the output signal is maximal when all the waves reach the output electrodes with the same phase. The set of balance equations for concentration, drift velocity, and the averaged energy to describe the dynamics of space charge waves in a thin GaN film takes following form:

$$\frac{\partial n}{\partial t} + div(n\vec{v}) = 0$$

$$\frac{d\vec{v}}{dt} = \frac{\partial \vec{v}}{\partial t} + (\vec{v}\nabla)\vec{v} = \frac{e\vec{E}}{m^*(w)} - \frac{1}{nm^*(w)}\nabla(nT) - \vec{v}\gamma_p(w);$$

$$\frac{dw}{dt} = e\vec{E}\vec{v} - \frac{1}{n}\nabla\left((n\vec{v} - k\nabla)T\right) - (w - w_{00})\gamma_w(w) \qquad (1)$$

$$T = \frac{2}{3}\left(w - \frac{m^*(w)v^2}{2}\right); k = \frac{5nT}{2m^*\gamma_p(w)}$$

Here n, v, and w are electron concentration, average velocity, and average electron energy; γ_p, γ_w are momentum and energy relaxation frequencies; m^* is the effective mass, T is the electron temperature in energetic units, κ is the thermoconductivity coefficient; w_{00} = 0.039 eV is the electron energy at 300 K; γ_p, γ_w, m^* are functions of the average electron energy w. Thermoconductivity is not essential up till the frequencies 2..3 THz. From stationary dependencies $v = v(E)$, see fig. 2, where are experimental and Monte Carlo simulations, and $w = w(E)$, it is possible to get the relations $E = E(w)$, $v=v(w)$, $\mu= v(w)/E(w) =\mu(w)$, then the relaxation frequencies can be calculated as:

$$\gamma_p(w) = \frac{e}{m^*(w)\mu(w)}; \ \gamma_w(w) = \frac{e\mu(w)E^2(w)}{(w-w_{00})} \qquad (2)$$

The calculated dependencies are given in Fig, 3. One can see that the momentum relaxation frequency is $\gamma_p >> \gamma_w$, therefore, for the frequencies of SCW f << 1 THz is possible to neglect by the inertia of electrons.

The Eqs. (1) are added by boundary conditions (the sizes of the film are L_z, L_y):

$$\varphi(x, y; z = 0) = \varphi(x, y; z = L_z) = 0;$$
$$n(y; z = 0) = n(y; z = L_z) = n_0; \qquad (3)$$
$$E_y(x, y = 0; z) = E_y(x, y = L_z; z) = 0;$$
$$\frac{\partial n}{\partial y}(y = 0, z) = \frac{\partial n}{\partial y}(y = L_z, z) = 0.$$

Here φ is the varying part of potential, $n = n_0 + \tilde{n}$ where n_0 is the constant equilibrium electron concentration, $\tilde{n}$ is the varying part. Below we investigate the linear amplification of SCW in GaN films on the dielectric substrate. The zinc blend n-GaN is considered. The following representation is used:

$$w = w_0 + \tilde{w}, n = n_0 + \tilde{n}, v_z = v_0 + \tilde{v}_z \qquad (4)$$
$$v_x = \tilde{v}_z, E_z = E_0 + \tilde{E}_z, E_x = \tilde{E}_z$$

A small microwave electric signal $E_{ext} = E_m \cdot \sin(\omega t) \cdot \exp(-((z-z_1)/z_0)^2-((y-y_1)/y_0)^2)$ is applied to the input antenna. Here z_1 and y_1 are the position of the input antenna; z_0 and y_0 are its half-width. When this small microwave signal is applied to the input antenna, the excitation of space charge waves in 2D electron gas takes place. These waves are subject to amplification, due to the negative differential conductivity.

The set of equations (1) are solved numerically. Stable implicit difference schemes are used. A transverse inhomogeneity of the structure in the plane of the film along Y-axis is taken into account. The following parameters are chosen: 2D concentration of electrons in the film is $n_0 = 10^{17}$ cm^{-3}, the initial uniform drift velocity of electrons is $v_0 = 1.8\text{x}10^7$ cm/s, the length of the film is L_z = 70 µm, the thickness of the film is $2h$ = 0.1 - 1 µm.

III. Simulations and Results

Amplification of space charge waves is investigated by dispersion relation, where the unperturbed (stationary) values of E_0, v_0 are chosen in the regime of negative differential conductivity ($dv/dE < 0$). With some mathematical transformations of (1) the following equation is obtained.

$$\frac{\partial \tilde{n}}{\partial t} + n_0\frac{\partial \tilde{v}}{\partial z} + v_0\frac{\partial \tilde{n}}{\partial z} - D\frac{\partial^2 \tilde{n}}{\partial z^2} = 0 \qquad (5)$$

Assuming that $\tilde{n}$ obeys the law ~exp($i\omega t$ - ikz) , Eq. (6) gives the dispersion relation:

$$\left[i(\omega - kv_0) + Dk^2\right]\tilde{n} - ikn_0\tilde{v} = 0 \qquad (6)$$

The results of direct simulations of $k(\omega)$, ($\omega=2\pi f$ is frequency and $k = k'+ik''$ is complex) of set linearized equations (1) is showed in Fig. 4, with different film thickness, Curve 1 is for E_0 = 150 kV/cm, $n_0 = 1.5 \text{ x}10^{17}$ cm^{-3}. Curve 2 is for E_0 = 150 kV/cm, $n_0 = 1 \text{ x } 10^{17}$ cm^{-3}. Curve 3 is for E_0 = 160 kV/cm, $n_0 = 1.5\text{x}10^{17}$ cm^{-3}. Curve 4 is for E_0 = 150 kV/cm, $n_0 = 1.5\text{x } 10^{17}$ cm^{-3}. The typical output spectrum of the electromagnetic signal is given in Fig. 5a for one input signal. In fig. 5b, the input carrier frequencies are f_1 = 33 and f_2 = 44 GHz. The amplitude of the input electric microwave signal is E_{m1} = 0.0015 kV/cm and E_{m2} = 0.04 kV/cm. In figure 4b, one can see the amplification of the input signals, the generation of the second harmonics ($2f_1$ and $2f_2$), and the sum of frequencies ($f_1 + f_2$). In addition, is possible to see in the spectrum that the amplitude of the output signal with frequency f_1 is smaller compared with the amplitude of the output signal with frequency f_2, since the amplitude of the input signal f_1 is smaller in comparison of the input signal amplitude f_2. Although the growth rate decreases as the RF frequency increases, for our case an amplification of 15 dB is obtained. The duration of the input pulse is $2t_0$ = 2.5 ns. The maximum of the input pulse occurs at t_1 = 2.5 ns. Both, the amplified signal at the first and the second harmonic of the input signals, which are generated due to the nonlinearity of the space charge waves. When one increases the amplitude of input signal, the noise increases too, it can be seen in fig. 5c.

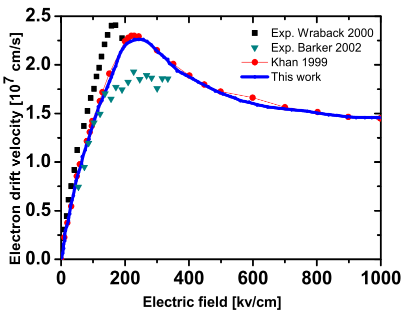


Fig. 2. Electron drift velocity as a function of electric field. Experimental and MC simulation results.

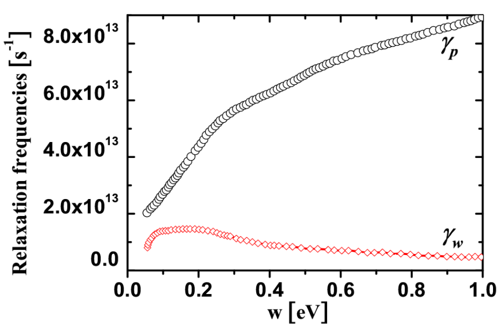


Fig. 3. The calculated relaxation frequencies for zinc blend case.

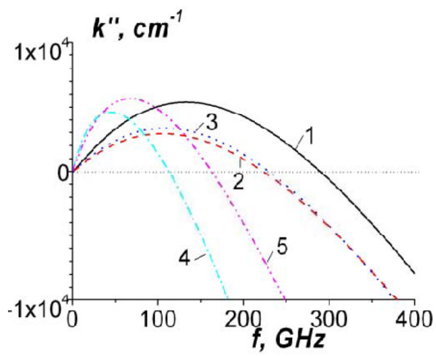
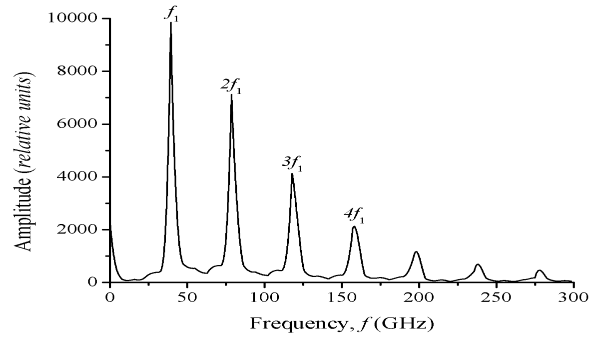
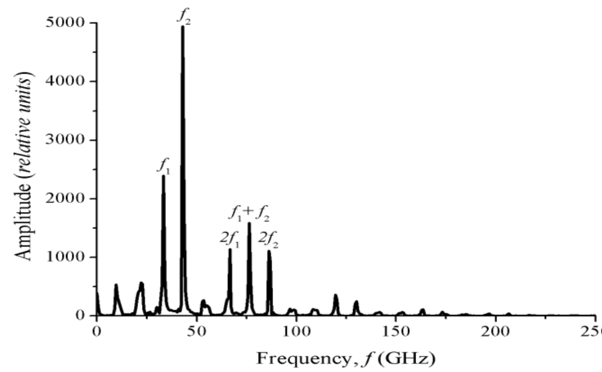


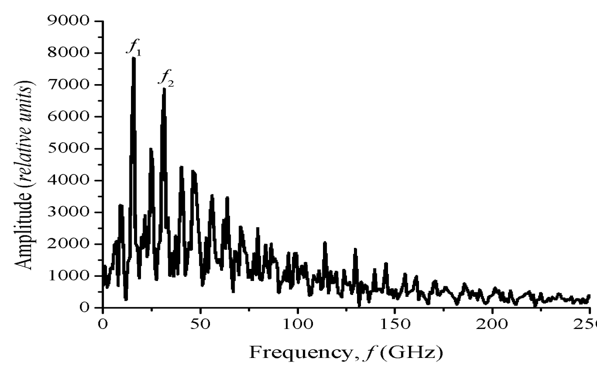
Fig.4. The spatial increments k''(f). Curve 1 is for E_0 = 150 kV/cm, n_0 = 1.5 x10^{17} cm^{-3}; Curve 2 is for E_0 = 150 kV/cm, n_0 = 1 x 10^{17} cm^{-3}; Curve 3 is for E_0 = 160 kV/cm, n_0 = 1.5x10^{17} cm^{-3}; Curve 4 is for E_0 = 150 kV/cm, n_0 = 1.5x 10^{17} cm^{-3}, x_0 = 0.05 μm (reduced mobility at the boundaries); Curve 5 is the same as 4, but with nonuniform doping, x_d = 0.02 μm.



(a)



(b)



(c)

Fig. 5. Spectral components of the electric field of space charge waves at the output antenna using signals with the following parameters: (a) Amplitude Em1 = 15 kV/cm and frequency f1 = 40 GHz, (b) Amplitudes Em1 = 0.0015 kV/cm and Em2 = 0.04 kV/cm and frequencies f1 = 33 GHz and f2 = 44 GHz, respectively. (c) Amplitudes Em1 = 0.5 kV/cm and Em2 = 0.4 kV/cm and frequencies f1 = 12 GHz and f2 = 27 GHz, respectively.

The spatial distributions of the alternate components of the electric field $E^{\sim}_z$ in 1D is presented in fig. 6, with different electron concentrations values. In fig. 7 one can see the spatial distribution of the alternative part of the electric field of space charge wave in 2D, for $E^{\sim}_z$ and $E^{\sim}_y$. The length of the film is 70 μm. The transverse width of the film along Y-axis is 500 μm. The maximum variation occurs in the output antenna.

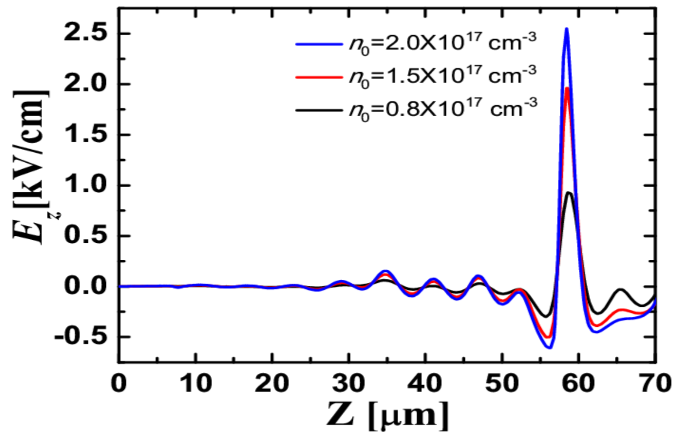
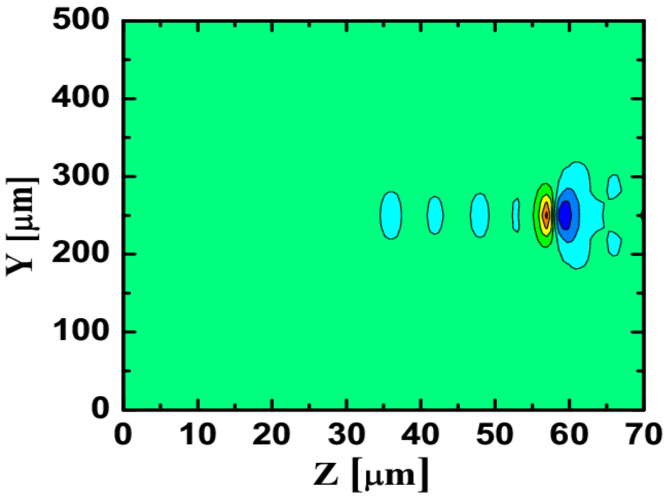
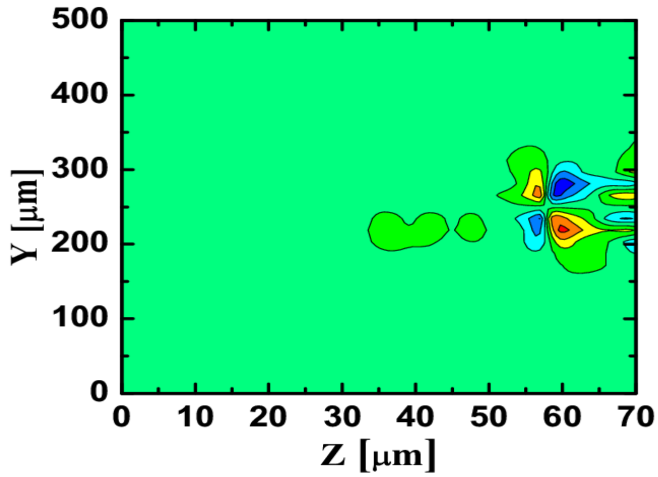


Fig. 6. Spatial distribution of the alternative part of the electric field of space charge waves in 1D along the n-GaN film in Z direction, Ez.



(a)



(b)

Fig. 7. Spatial distribution of the alternative part of the electric field of space charge wave in 2D, (a) $E^{\sim}_z$ and (b) $E^{\sim}_y$.

IV. Conclusion

The nonlinear interaction of space charge waves in n-GaN films possessing negative differential mobility has been presented. A microwave frequency conversion using the negative differential conductivity phenomenon is carried out when the harmonics of the input signal are generated. An increment in the amplification is observed in *n*-GaN films at essentially higher frequencies $f > 100$ GHz. The maximum amplification of the space charge waves in the *n*-GaN film (gain of 20 dB) is obtained at the frequency $f \approx 110$ GHz, using a distance between the input and output antennas of about 70 μm. The nonlinear effects can be technologically profiteers for the design and fabrication of new kind of semiconductor devices that operate in the microwaves and millimeter waves range. The effective application of these devices in communication, radar, meteorology and spectroscopy systems will have a positive effect in the efficiency and speed of data transfer.

Acknowledgment

This project has been partially funded by the CONACyT-Mexico grant CB-169062 and by the ECEST-SEP (Espacio Común de Educación Superior Tecnológica) Program under the mobility program for professors.

References

[1] A.Barybin, “*Waves in Thin-Film Semiconductor Structures with Hot Electrons*”, Nauka, Moscow, 1986.

[2] S. Pearton, J. Zolpere.a., “GaN: Processing, Defects, and Devices“, *J. Appl. Phys*., Vol.86, No 1, pp.1-79, 1999.

[3] M.Levinshtein, S.Rumyantsev, and M.Shur, “*Properties of Advanced Semiconductor Materials: GaN, AlN, InN*”, Wiley, N.Y., 2001

[4] Z.F. Krasil'nik and V.P. Reutov, Nonlinear Theory of Space-Charge Wave Amplification in n-GaAs Thin Films, *Radiophysics and Quantum Electron. J.,* vol. 19, no. 7, 756 - 761, 1976.

[5] A.I. Mikhailov and S.A. Sergeev, Efficiency of Excitation of Space Charge Waves in a Thin-film Semiconductor Structure with a Single Strip Schottky Barrier, *Tech. Phys.,* vol. 44, no. 1, 117–119, 1999.

[6] M. Wraback, H. Shen, J. Carrano, T. Li, J. Campbell, M.J. Schurman, and I. Ferguson, Time- Resolved Electroabsortion Measurement of the Electron Velocity – Field Characteristic in GaN, *Appl. Phys. Let*., 76, no. 9, 1154-1157, 2000.

[7] J. Barker, R. Akis, D. Ferry, S. Goodnick, T. Thornton, D. Kolesk, A. Wickenden, and R. Henry, High-Field Transport Studies of GaN, *Physica B*, 314, no. 1-4, 39-41,2002.

[8] M. A. Khan, Q. Chen, M. S. Sure, B. T. Dermott, J. A. Higgins, J. Burm, W. J. Scha and L. F. Eastman, GaN based heterostructure for high power devices**,** *Solid-State Electron*. 41, no. 10, 1555-1559, 1999.

[9] A. Garcia-Barrientos, V. Palankovski, "Numerical Simulations of Space Charge Waves in InP Films and Microwave Frequency Conversion under Negative Differential Conductivity", *Applied Physics Letters*, 98, 072110-1 - 072110-3, 2011.

[10] A. Garcia-Barrientos, V. Grimalsky, E. Gutierrez-Dominguez, V. Palankovski, "Nonstationary Effects of the Space Charge in Semiconductor Structures", *Journal of Applied Physics*, vol. 105, 074501-1 - 074501-6, 2009.