Amplification of Space Charge Waves at Very High Electric Fields in GaAs Films

A. Garcia-Barrientos[1,2], V. Palankovski[2], and V. Grimalsky[3]

Abstract - The nonlinear interaction of space charge waves including the amplification in microwave range at high electric fields (10 - 300 kV/cm) in *n*-GaAs films, possessing the negative differential conductance phenomenon, is presented. Both the amplified signal at the first harmonic of the input signal and the generation of second and third harmonics of the input signal, which are due to the negative differential resistance effect at very high electric fields are shown.

I. Introduction

It is widely recognized that semiconductor device modeling is one of the most critical issues in high-frequency design. In principle, the most powerful and general approach to the modeling and simulation of high-frequency semiconductor devices is to perform a detailed numerical solution of the basic semiconductor transport equations for charge carriers in several spatial dimensions and time, consistently with the Poisson equation.

The millimeter and sub-millimeter microwave range is very important for applications in communications, radar, and spectroscopy. However, the structure of semiconductor devices (transistors, diodes, etc), required for such a short wavelength, becomes very complex, which makes its fabrication difficult and expensive. One potential alternative to explore the use of such a part of the electromagnetic spectrum resides in the use of nonlinear wave interaction in active media. For example, the space charge waves in thin semiconductor films, possessing negative differential conductivity (for example n-GaAs, n-InP, n-GaN, etc.), propagate at frequencies that are higher than the frequencies of acoustic and spin waves in solids. This means, for example, that an elastic wave resonator operating at a given frequency is typically 100 000 times smaller than an electromagnetic wave resonator at the same frequency. Thus, attractively small elastic wave transmission components such as resonators, filters, and delay lines can be fabricated.

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Space charge waves have been researched since a long time ago, which can be traced back to the 1950s [1,2]. However, the early experimental work on the amplification of space charge waves with a perturbation field started in the 1970s [3], continues today. The first monolithic device using space charge waves was a two-port amplifier developed at the beginning of 1970s in the United States. This device contained an n-GaAs film on the dielectric substrate, and a couple of source and drain ohmic contacts. 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 study of amplification of space charge waves and microwave frequency conversion under negative differential conductivity will be one of the most relevant topics in microelectronics and communications in the coming years, due to its potential for high-frequency applications. In previous work [4], results were carried out using the negative differential mobility at moderate electric fields (3 - 10kV/cm). In this work, we employ the negative differential conductivity effect at very high electric fields (10 - 300 kV/cm), where the dynamic range is shorter, however this phenomenon is also present, and the generation of harmonics is guaranteed due to non-linear medium.

II. Equations for Space Charge Waves

Consider n-GaAs film placed onto i-GaAs substrate without an acoustic contact. It is assumed that the electron gas is localized in the center of film. The thickness n-GaAs film is $2h < 1$ μm, see Fig. 1. The coordinate system is chosen as follows: X-axis is directed perpendicularly to the film, the electric field E_0 is applied along the Z-axis, exciting and receiving antennas are parallel to the Y-axis. 2D model of electron gas in the n-GaAs 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.

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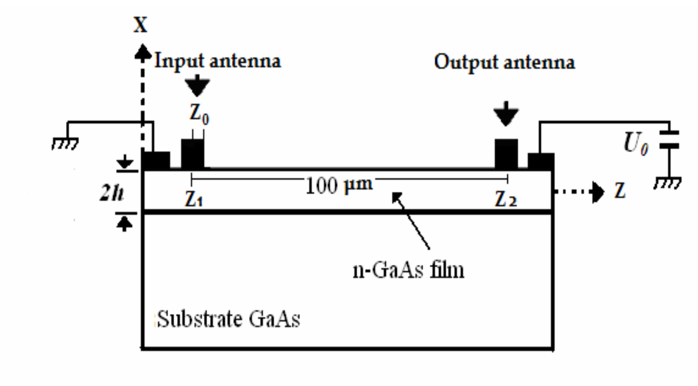


Fig. 1. The structure of the n-GaAs traveling-wave amplifier fabricated with an epitaxial layer.

In the simulations, an approximation of two-dimensional electron gas is used. The set of balance equations for concentration, drift velocity, average energy, describing the dynamics of space charge waves within the n-GaAs film takes a form [5]:

$$\frac{d(m(w)\vec{v}_d)}{dt} = -q(\vec{E} - \frac{\vec{v}_d E_s}{v_s}); \quad \frac{dw}{dt} = -q(\vec{E}\vec{v}_d - E_s v_s);$$
$$\frac{\partial \tilde{n}}{\partial t} + div(n\vec{v}_d - D\nabla\tilde{n}) = 0; \quad D(w) = \frac{2}{3}\frac{\tau_p(w)}{m(w)}\left(w - \frac{1}{2}mv^2\right); \tag{1}$$
$$\vec{E} = \vec{e}_z E_0 - \nabla\varphi + \vec{e}_z \tilde{E}_{ext}; \quad \Delta\varphi = -\frac{q}{\varepsilon_0 \varepsilon}\tilde{n};$$
$$\tilde{E}_{ext} = \sum_{j=1}^{2} E_{oj}\sin(\omega_j t)\exp\left(-\left(\frac{z-z_1}{z_0}\right)^2 - \left(\frac{y-y_1}{y_0}\right)^2\right)$$

where v_d is the drift velocity, w is the electron energy, $m(w)$ is the average electron effective mass, w_0 is the equilibrium value of w, D is the diffusion coefficient, and ε_0 is the relative dielectric permittivity of n-GaAs, $\tau_{p,w}(w)$ are the relaxation times, n_0 is the equilibrium value of the two dimensional concentration of electron gas. E_0 is a bias electric field. It is assumed that a condition of occurring negative differential conductivity is realized. Because the signal frequencies are in microwave or millimeter wave range, it is possible to separate diffusion and drift motions. For sake of simplicity, instead of relaxation times, the parameter E_s has been introduced [6]:

$$\frac{m(w)}{\tau_p(w)} = \frac{E_s}{v_s(E_s)}, \quad \frac{w - w_0}{\tau_w(w)} = qE_s v_s(E_s) \tag{2}$$

In such a representation, a direct correspondence between local field dependence and non-local effects is well seen. Because a dependence $E_s = E_s(w)$ is unique, it is possible to express the parameters w and v_s through the value of E_s. Fig. 2 shows the dependence of the electron drift velocity at very high electric fields as obtained from our Monte Carlo simulations [7] in comparison to experimental data from [8-12]. Note that a local dependence between the drift velocity and the electric field is $v_d = v_s(E)$. The effect of non-local dependence can lead to some quantitative corrections for the increment of the amplification of space charge waves of millimeter wave range in n-GaAs film.

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

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

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.

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 $n_0 = 10^{12}$ cm^{-2}, the initial uniform drift velocity of electrons is $v_0 = 8\text{x}10^6$ cm/s, the length of the film is L_z = 0.1 mm, the thickness of the film is $2h$ = 0.1 - 1 µm.

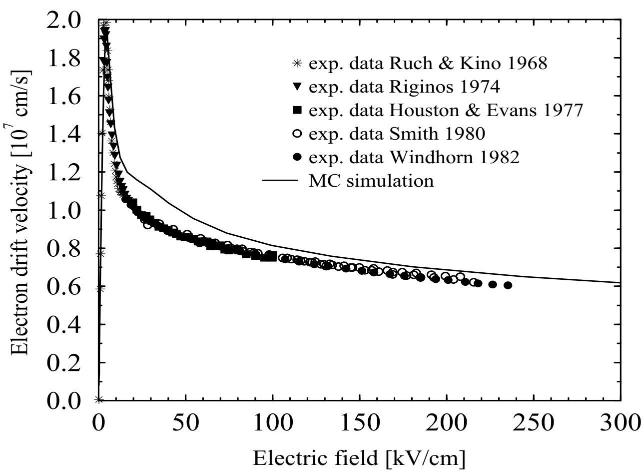


Fig. 2. Electron drift velocity as a function of electric field. The negative differential conductance is also present.

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.

$$\frac{\partial \tilde{n}}{\partial t} + n_0 \frac{\partial \tilde{v}}{\partial z} + v_0 \frac{\partial \tilde{n}}{\partial z} - D \frac{\partial^2 \tilde{n}}{\partial z^2} = 0 \quad (4)$$

Assuming that $\tilde{n}$ obeys the law ~exp($i\omega t$ - ikz) , Eq. (4) gives the dispersion relation:

$$\left[i(\omega - kv_0) + Dk^2 \right] \tilde{n} - ikn_0 \tilde{v} = 0 \quad (5)$$

where from simulations of $D(k,\omega)=0$ (angular frequency $\omega = 2\pi f$ is real and $k = k' + ik''$ is complex) the imaginary part of the longitudinal wave number k'' of the space charge waves, is obtained. Eq. (5) is the solution of the dispersion equation using averaged balance model. The case $k'' > 0$ corresponds to spatial increment (amplification), whereas the case $k''< 0$ corresponds to decrement (damping). In Fig. 3, the spatial increment for the averaged balance model is presented. It can be seen that an amplification of space charge waves in GaAs films occurs in a wide frequency range, and the maximal spatial increment is $k''= 1\text{x}10^5$ m^{-1} at the frequency f = 30 GHz. When compared with the results at moderate electric fields [4], it is possible to observe an amplification of space charge waves at essentially higher frequencies f > 40 GHz. To obtain an amplification of 15 dB, it is necessary to use a distance between the input and output antennas of about 100 μm.

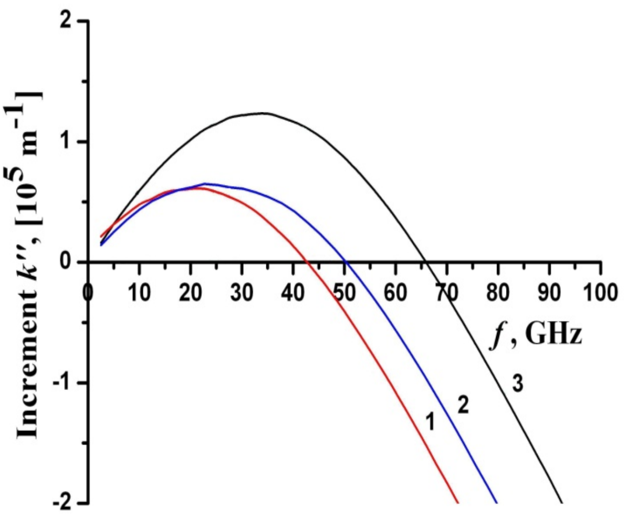


Fig. 3. Spatial increments of instability $k''(f)$ of space charge waves. Curve 1 is for E_0 = 150 kV/cm, $n_0 = 10^{12}$ cm^{-2}, and film thickness $2h$ = 0.05 μm; curve 2 is for E_0 = 150 kV/cm, $n_0 = 10^{12}$ cm^{-2}, and film thickness $2h$ = 0.1 μm; Curve 3 is for E_0 = 150 kV/cm, $n_0 = 2\text{x}10^{12}$ cm^{-2}, $2h$ = 0.1 μm.

III. Simulations and Results

A small microwave electric signal $E_{ext} = E_m \cdot \sin(t) \cdot \exp(-((t-t_1)/t_0)^2) \cdot \exp(-((z-z_1)/z_0)^2)$ is applied to the input antenna. Here z_1 is the position of the input antenna, z_0 is its half-width. Therefore, the parameter $2t_0$ determines the duration of the input electric pulse. In our simulations, this parameter is $2t_0$ = 2.5 ns. The carrier frequency ω is in the microwave range: $\omega = 3\text{x}10^{10} – 5\text{x}10^{11}$ rad/s. When a small microwave signal is applied to the input antenna, the excitation of space charge waves in the 2D electron gas takes place. The space charge waves are subject to amplification due to the negative differential conductivity.

The set of equations of the detailed model is solved numerically. A stable implicit difference scheme is used. A transverse inhomogeneity of the structure in the plane of the film along the Y-axis is taken into account. The following parameters are chosen: 2D electron concentration in the film is $n_0 = 10^{12}$ cm^{-2}, the initial uniform drift velocity of electrons is $v_0 = 8\text{x}10^6$ cm/s, the length of the film is L_z = 0.05 - 0.1 mm, the thickness of the film is $2h$ = 0.1 - 1 μm.

The typical output spectrum of the electromagnetic signal is given in Fig. 4. The input carrier frequency is $\omega = 6.2\text{x}10^{10}$ rad/s (≈10 GHz). The amplitude of the input electric microwave signal is E_m = 0.025 kV/cm. 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 harmonic of the input signal and the second harmonic of the input signal, which is generated due to the nonlinearity of the space charge waves, can be seen in Fig.4.

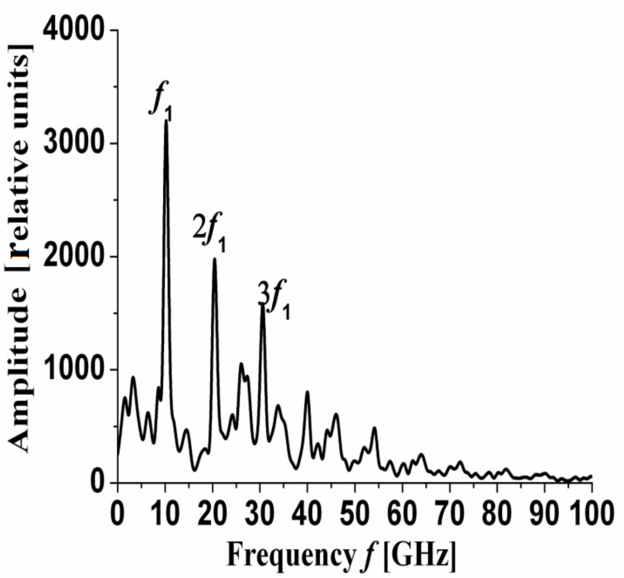
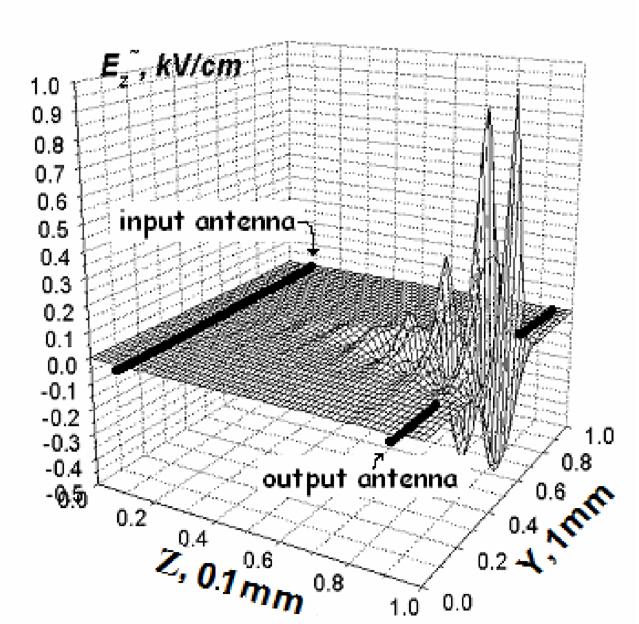
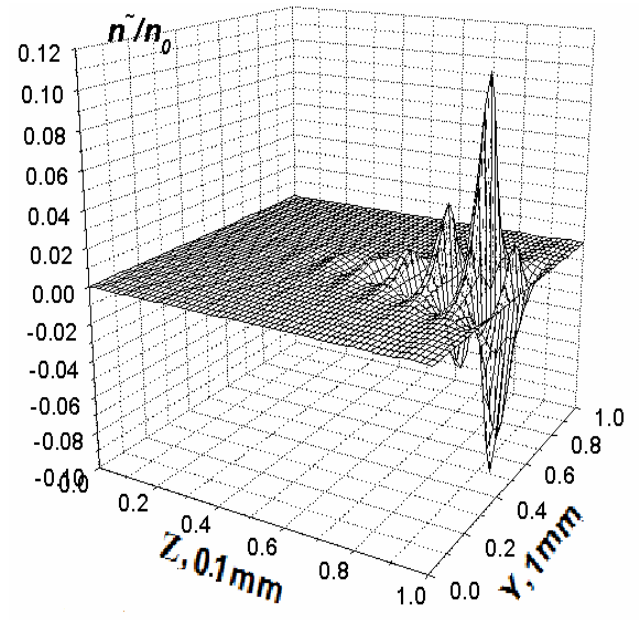


Fig. 4. Spectral components of the electric field of space charge waves. The effective excitation of the second and third harmonics is presented. The input carrier frequency is f = 10 GHz.

The spatial distributions of the alternate components of the electric field $E^{\sim}_z$ and of the electron concentration $n^{\sim}$ are shown in Fig. 5a and 5b, respectively. The length of the film is 0.1 mm. The transverse width of the film along Y-axis is 1 mm. The duration of the input electric pulse is 2.5 ns. The spatial distributions are presented for the time moment 1.5 ns after the maximal value of the input signal. The maximum variation occurs in the output antenna.



(a)



(b)

Fig. 5. Spatial distributions of the alternate components of the electric field $E_z^{\sim}$ of the space charge wave (a) and of the electron concentration $n^{\sim}$ (b).

IV. Conclusion

The amplification of space charge waves at very high electric fields in n-GaAs films is presented. In comparison with our previous results, carried out using the negative differential mobility at moderate electric fields (3 - 10 kV/cm), in this work, we explore this effect at very high electric fields (10 - 300 kV/cm) where the dynamic range is shorter, but however, the non-linear phenomenon is also present and the generation of harmonics is guaranteed.

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