2010 7th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE 2010)
Tuxtla Gutiérrez, Chiapas, México. September 8-10, 2010.

# Amplification of Space Charge Waves in n-InP Films

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*Abstract* – **The non-linear interaction of space charge waves including the amplification in microwave and millimeter wave range in *n*-InP films, possessing the negative differential conductance phenomenon,** is **investigated theoretically. Both the amplified signal and the generation of harmonics of the input signal are demonstrated, which are due to non-linear effect of the negative differential resistance. It is possible to observe an amplification of the space charge waves in *n*-InP films of submicron thicknesses at essentially higher frequencies $f < 70$ GHz, when compared with *n*-GaAs films $f < 44$ GHz. The increment observed in the gain is due to the larger dynamic range in *n*-InP than in *n*-GaAs films.**

*Keywords* — **n-InP film, negative differential conductivity, and space charge waves.**

## I. INTRODUCTION

The millimeter and sub-millimeter microwave ranges are very important for applications in communications, radar, meteorology 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 non-linear wave interaction in active media. For example, the space charge waves in thin semiconductor films, possessing negative differential conductivity (InP, GaAs, GaN at 300K and strained Si/SiGe heterostructures at 77K), 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.

Space charge waves have been researched since a long time ago, which can be traced back to the 1950s [1]. The early experimental work on the amplification of space charge waves with a perturbation field started in the 1970s [2] and continues today [3, 4]. The first monolithic device using space charge waves was a two-port amplifier developed in the beginning of 1970s in the United States. This device contained an *n*-GaAs film on a 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, see Fig. 1. Obviously, the output signal is maximal when all the waves reach the output electrodes with the same phase [5].

Devices based on space charge waves use an attractive property of GaAs and InP. An electric field in excess of 15 kV/cm applied to an *n*-InP sample causes the differential electron mobility to become negative. To analyze wave phenomena in thin films of two-valley semiconductors [6], a set of equations to describe the charge transport is commonly used. In this theory, with small initial perturbations, continuity, momentum and energy equations, and Poisson's equation are solved. The solutions show that the modulations of electron density travel along the beam in the form of waves called space charge waves. The scope of space charge waves' applications is very large, because it can be useful to implement monolithic phase shifters, delay lines, and analog circuits for microwave signals.

The study of 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 the potential it represents in terms of amplification of micro- and millimeter-waves. However, in order to understand the behavior of non-stationary effects, a special attention must be paid to the transverse inhomogeneity, carrier-density fluctuations in the plane of the film, because it may affect, in a negative way, the non-linear wave interaction. Thus, a creation of effective algorithms and computer programs for simulations of non-linear interaction of space charge waves in semiconductor films, where the effects of non-locality and transverse inhomogeneity should be taken into account, becomes of high importance.

## II. THE EQUATIONS FOR SPACE CHARGE WAVES

Consider n-InP film placed onto substrate without an acoustic contact. It is assumed that the electron gas is localized in the center of film. The thickness of the n-InP 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 Z-axis, exciting and receiving antennas are parallel to Y-axis. 2D model of electron gas in the *n*-InP film is used. Thus, 2D electron concentration is presented only in the plane $x = 0$. The space charge waves possessing phase velocity equal to drift velocity of the electrons $v_0=v(E_0)$, $E_0=U_0/L_z$, are considered, where $U_0$ is bias voltage, $L_z$ is the length of the film.

IEEE Catalog Number: CFP10827-ART
ISBN: 978-1-4244-7314-4

Generally, a non-local dependence of drift velocity $v_d$ of electrons on the electric field takes place.

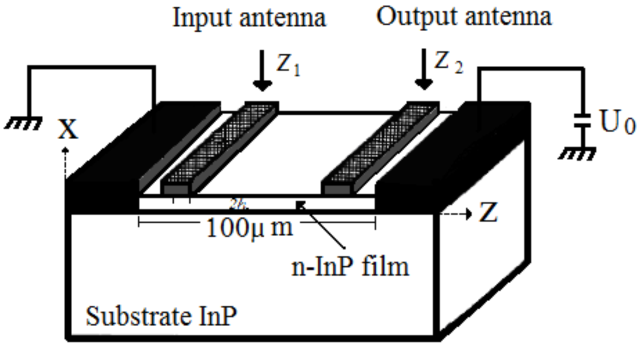


Figure 1. The structure of the *n*-InP traveling-wave amplifier fabricated with an epitaxial layer.

In simulations, an approximation of two-dimensional electron gas is used. The set of balance equations for concentration, drift velocity, and the averaged energy to describe the dynamics of space charge waves within the *n*-InP film takes a form, like in GaAs film [7]:

$$\frac{d(m(w)\vec{v}_d)}{dt} = -q(\vec{E} - \frac{\vec{v}_d E_s}{v_s}); \quad \frac{dw}{dt} = -q(\vec{E}\vec{v}_d - E_s v_s);$$

$$\frac{\partial n}{\partial t} + div(n\vec{v}_d - D\nabla n) = 0; \quad D(w) = \frac{2}{3}\frac{\tau_p(w)}{m(w)}\left(w - \frac{1}{2}mv^2\right);$$

$$\vec{E} = \vec{e}_z E_0 - \nabla\varphi + \vec{e}_z \widetilde{E}_{ext}; \quad \Delta\varphi = \frac{q}{\varepsilon_0\varepsilon}(n - n_0)\delta(x); \tag{1}$$

$$\widetilde{E}_{ext} = E_o \sin(\omega t)\exp\left(-\left(\frac{z - z_1}{z_0}\right)^2 - \left(\frac{y - y_1}{y_0}\right)^2\right)$$

where $v_d$ is drift velocity, $\varphi$ is the of potential, $n = n_0 + \tilde{n}$ where $n_0$ is constant electron concentration, $\tilde{n}$ is the varying part, $w$ is the electron energy, D is the diffusion coefficient, and $\varepsilon_0$ is the lattice dielectric permittivity of *n*-InP, $m(w)$ is averaged effective mass, $q$ is the electron charge, $\tau_{p,w}(w)$ are relaxation times, and $E_0$ is the 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 a sake of simplicity, instead of relaxation times, the parameter $E_s$ is introduced [7]:

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

In such a representation, the mean energy and effective mass of electron are denoted by $w$ and $m(w)$, the equilibrium value of $w$ is $w_0$; 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 $E_s$. The dependence of electron drift velocity on electric field in InP films is taken from our Monte Carlo simulation results, which are in good agreement with measured data (Fig. 2). Note that a local dependence between the drift velocity and the electric filed 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*-InP film.

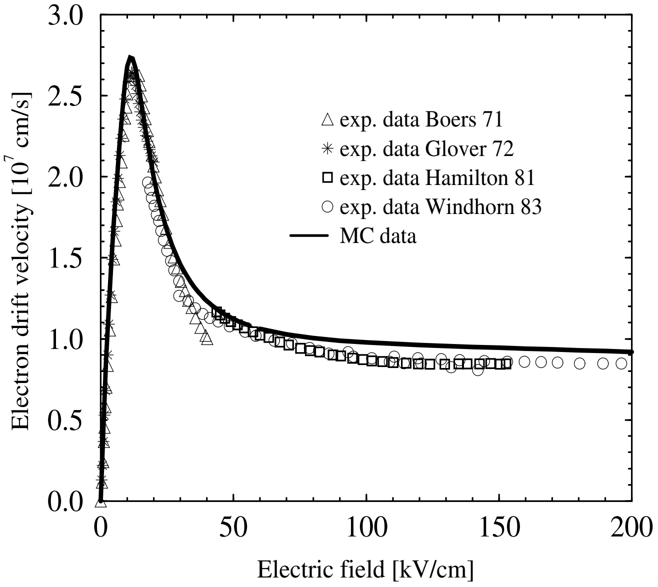


Figure 2. Electron drift velocity versus electric field; (-) MC data and experimental data: (Δ) Boers [8], (*) Glover [9], (□) Hamilton [10], and (○) Windhorn [11].

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 signal is applied, the excitation of space charge waves in 2D electron gas takes place. These waves are subject to amplification, due to negative differential conductivity.

The set of equations (1) form a set of non-linear coupled time dependent partial differential equations. These differential equations are discretized, using a finite-difference scheme and is solved numerically. 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 $n_0 = 5\text{x}10^{14}$ cm$^{-2}$, the initial uniform drift velocity of electrons is $v_0 = 2\text{x}10^7$ cm/s, the length of the film is $L_z = 0.1$ mm, the thickness of the film is $2h = 0.1$ - 1 μm.

## III. SPATIAL INCREMENT OF SPACE CHARGE WAVES

In The spatial increment of space charge waves is investigated by the dispersion equation, D($\omega$,$k$) = 0, the relation between angular frequency, $\omega = 2\pi f$, and wave vectors, consider these like complex, $k = k' + ik''$, where

$k' > 0$. The dispersion relation is obtained using balance equations model, set equations (1), with some transformation we can obtain Eq. 3,

$$\frac{\partial \tilde{n}}{\partial t} + n_0 \frac{\partial \tilde{v}}{\partial z} + v_0 \frac{\partial \tilde{n}}{\partial z} - D \frac{\partial^2 \tilde{n}}{\partial z^2} = 0 \qquad (3)$$

but if we assume that $\tilde{n}$ obeys the law ~ exp($i\omega t$-$ikz$), Eq. (3) gives the dispersion relation:

$$\left[i(\omega - kv_0) + Dk^2\right]\tilde{n} - ikn_0\tilde{v} = 0 \qquad (4)$$

In general, we consider the cases where $f$ is real and $k = k'+ik''$ has real and imaginary part. The case $k'' > 0$ corresponds to spatial increment (amplification), whereas the case $k''< 0$ corresponds to the decrement (damping). In Fig. 3, the spatial increment of space charge waves in an $n$-InP film is shown in the curve 1. Curve 2 and 3 are results for $n$-GaAs films using simple drift-diffusion model and balance equation model, respectively. It can be seen that an amplification of space charge waves in InP films occurs in a wide frequency range, and the maximal spatial increment is $k'' = 3\text{x}10^5$ m$^{-1}$ at the frequency $f$ = 35 GHz. When compared with a case of the GaAs film, it is possible to observe an amplification of space charge waves in InP films at essentially higher frequencies $f$ > 44 GHz. To obtain an amplification of 25 dB, it is necessary to use a distance between the input and output antennas of about 0.09 mm.

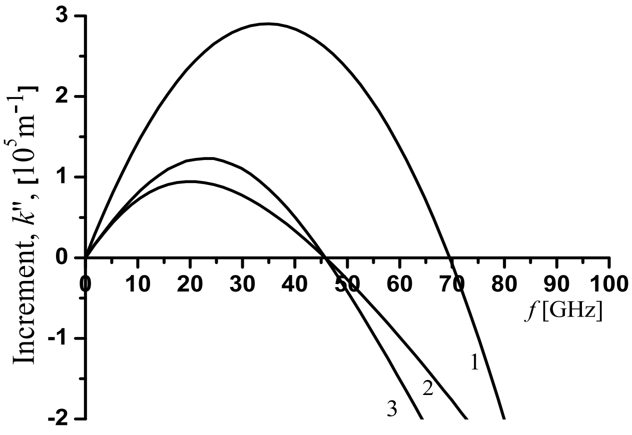


Figure 3. Spatial increments of instability $k''(f)$ of space charge waves. Curve 1 is for InP films with $E_0$ = 20 kV/cm, $n_0$ =5x$10^{14}$ cm$^{-3}$ and film thickness $2h$ = 0.05 μm. Curves 2 and 3 show results for an $n$-GaAs film using drift-diffusion and balance equation model, respectively [13]

## IV. RESULTS AND SIMULATION

The propagation and amplification of space charge waves in $n$-GaAs thin films with negative difference conductance have been studied in the last decade [12, 13], however $n$-InP films have not been addressed yet, and are subject of this work. We address the device presented in Fig. 1 by means of numerical simulations. An $n$-InP epitaxial film of thickness 0.1 - 1 μ$m$ is put on an InP semi-insulating substrate. The two-dimensional electron density in the film is chosen to be $n_0$ = 5x$10^{14}$ cm$^{-3}$. On the film surface are the cathode and anode ohmic contacts (OCs), together with the input and output coupling elements (CEs). Designed as a Schottky-barrier strip contacts, the CEs connect the sample structure to microwave sources. A dc bias voltage (above the Gunn threshold, 20 kV/cm) was applied between the cathode and anode OCs, causing negative differential conductivity in the film. The CEs perform the conversion between electromagnetic waves and space charge waves, where the excitation of space charge waves in the 2D electron gas takes place. In the simulations an approximation of two-dimensional electron gas is used.

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 $f$ is in the microwave range: $f$ = 1 GHz – 100 GHz. 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 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 have been chosen: 2D electron concentration in the film is $n_0 \approx 5\text{x}10^{14}$ cm$^{-3}$, the initial uniform drift velocity of electrons is $v_0 \approx 2\text{x}10^7$ cm/s ($E_0$ =15 – 20 kV/cm), 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 $f$ = 12 GHz. The amplitude of the input electric microwave signal is $E_m$ = 25V/cm. Although the growth rate decreases as the $rf$ frequency increases, for our case an amplification of 25 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. One can see both the amplified signal at the first harmonic of the input signal and the harmonic generations of the input signal, which is generated due to the non-linearity of space charge waves. The spatial distributions of the alternate component of the electric field $E_z$ and the alternative part of the electron drift velocity $v_z$ are shown in Fig. 5. One can see the maximum variations are in the output antenna. The length of the film is 0.1mm. The transverse width of the film along Y axis is 1mm. 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. Direct numerical simulations have confirmed pointed below results on linear increments of space charge waves amplification. Also a possibility of non-linear frequency doubling and mixing is demonstrated. To get the effective frequency doubling in the millimeter wave range, it is better to use the films with uniform doping.

ISBN: 978-1-4244-7314-4

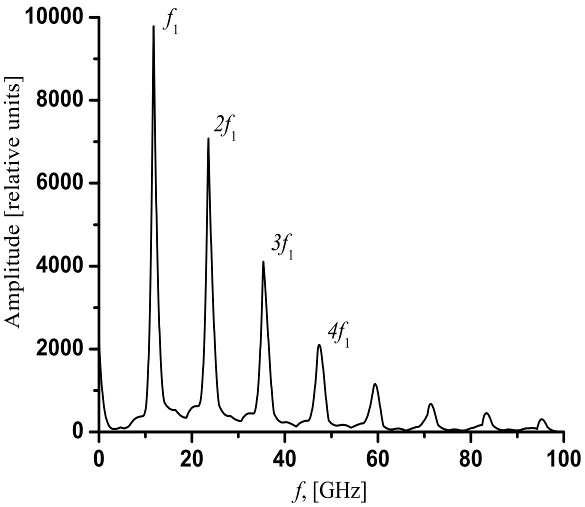
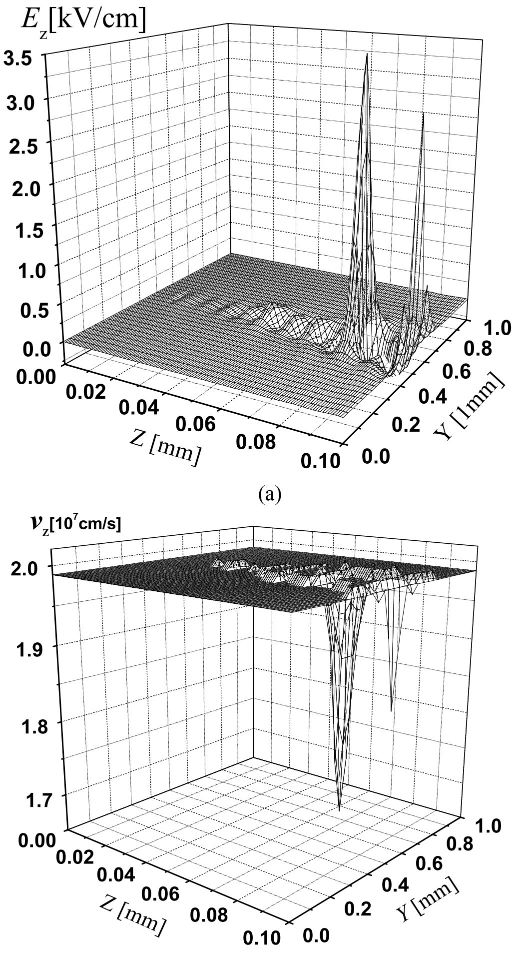


Figure 4. Spectral components of the electric field of space charge waves. The effective excitation of harmonics is presented. The input carrier frequency is $f = 12$ GHz



(a)

(b)

Figure 5. The spatial distributions of the alternative part of the electric field component $E_z$ of space charge wave (a) and the component of the electron drift velocity $v_z$ (b).

## V. CONCLUSIONS

A theoretical study of two-dimensional amplification and propagation of space charge waves in *n*-InP films is presented. A microwave frequency conversion using the negative differential conductivity phenomenon is carried out when the harmonics of the input signal are generated. A comparison of the calculated spatial increment of instability of space charge waves in *n*-GaAs and *n*-InP films is performed. An increment in the amplification is observed in InP films at essentially higher frequencies $f > 44$ GHz than in GaAs films, which is due to its larger dynamic range. The maximum amplification (gain of 25 dB) is obtained at $f = 35$ GHz, using a distance between the input and output antennas of about 0.09 mm.

## ACKNOWLEDGMENT

This work was supported by the Austrian Science Funds (FWF), START Project No. Y247-N13, and partially supported by the Austrian Agency for International Cooperation in Education & Research (OeAD), Ernst-Mach Scholarship, and PROMEP and CONACyT, Mexico.

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