Influence of Nonlocality on Amplification of Space Charge Waves in \(n\)-GaN Films

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ABSTRACT

It is investigated theoretically the amplification of space charge waves (SCWs) due to the negative differential conductivity (NDC) in \(n\)-GaN films of submicron thicknesses placed onto a semi-infinite substrate. The influence of the nonlocal dependence of the average electron velocity on the electron energy is considered. The simplest nonlocal model is used where the total electron concentration is taken into account. The relaxation momentum and energy frequencies have been calculated. The influence of the nonlocality on NDC results in the decrease of the absolute value of its real part and appearance of the imaginary part. The calculation of the diffusion coefficient leads to essential errors. The simulations of spatial increments of the amplification of SCWs demonstrate that the nonlocality is essential at the frequencies \(f \geq 150\ \text{GHz}\), and the amplification is possible up till the frequencies \(f \leq 400 \cdots 500\ \text{GHz}\).

Keywords: Gallium Nitride, Films, Negative Differential Conductivity, Space Charge Waves, Amplification, Nonlocality

1. Introduction

The amplification of traveling space charge waves (SCWs) of the microwave range in \(n\)-GaAs films has been under investigations for many years [1-6]. When propagating in bias electric fields higher than the critical value for observing negative differential conductivity (NDC), SCWs are subject to amplification. However, the critical value of the bias electric field in GaAs is \(E_c = 3.5\ \text{kV/cm}\), which limits the maximum values of the microwave electric field of SCWs. In addition, the frequency range of amplification of SCWs in GaAs films is \(f < 50\ \text{GHz}\), see Figure 1. At the frequencies \(f > 50\ \text{GHz}\), it is better to use new materials possessing NDC at higher frequencies \(f = 100 \cdots 500\ \text{GHz}\), like gallium nitride GaN [7-23]. The attracting properties of GaN are: a high critical bias field \(E_c \sim 100\ \text{kV/cm}\); the extended frequency range for observing NDC \(f \leq 500\ \text{GHz}\); high temperature stability; NDC at high doping levels \(n_0 \sim 10^{17} \cdots 10^{18}\ \text{cm}^3\). Some comparative data on GaAs and GaN are given in Figures 2 and 3.

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, see Figure 2(b). In GaN the occupancy of higher valleys is essentially lower, of about 10%, see Figure 3(c). Therefore, in GaAs it is impossible to describe the amplification of SCWs by means of the simplest nonlocal hydrodynamic model, where the unified electron concentration, average electron velocity, and energy are considered, instead of more detailed characteristics for lower and higher valleys [6]. For GaN, it is possible to check the adequacy of the simplest nonlocal model. Moreover, 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 [23].

In the present paper the spatial increments of amplification of SCWs due to NDC have been calculated. The influence of the nonlocal dependence of the drift velocity...
on the average electron energy is investigated. The momentum and energy relaxation frequencies are computed. It is shown that the nonlocality is essential at the frequencies \( f \geq 200 \text{ GHz} \) and leads to decrease of the spatial increment of amplification. The amplification of SCWs is possible up till the frequencies \( f \sim 500 \text{ GHz} \). It is demonstrated that for the calculation of the diffusion coefficient it is necessary to apply a more exact theory, because the simplest nonlocal theory leads to essential errors.

Figure 2. The data on GaAs. Part (a) is the dependencies of drift velocity on electric field at different temperatures; part (b) is dependencies of occupancies of upper \((L, X)\) valleys on electric field; part (c) is dependence of real and imaginary part of differential conductivity on frequency [24-26].

Figure 3. The data on GaN. Part (a) dependencies of drift velocity on electric field for wurtzite (1) and zinc blende (2) phases; part (b) is dependencies of occupancy of lower \((\Gamma)\) valley on electric field for wurtzite GaN at different temperatures; part (c) is dependence of average electron mass on electric field for wurtzite (1) and zinc blende (2) phases [10,11].

2. Nonlocal Hydrodynamic Equations and Relaxation Frequencies

In the simplest nonlocal electron hydrodynamics, the electron fluid is described by the total electron concentration \( n \) for all valleys jointly, the average electron velocity \( \nu \), and average electron energy \( w \). The equations of bal-

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One can get the following equations:
\[
\frac{\partial n}{\partial t} + \text{div}(n\vec{v}) = 0; \quad \frac{\partial \vec{v}}{\partial t} = \frac{\partial \vec{v}}{\partial t} + (\vec{v}\nabla)\vec{v} = \frac{e\vec{E}}{m^*} - \frac{1}{n m^*} \nabla(nT) - n \vec{v}_p(w) \quad (1)
\]

where \( T = \frac{2}{3} \left( \frac{w - m^*(w)\vec{v}^2}{2} \right) \), \( \kappa = \frac{5nT}{2m^*\vec{v}_p(w)} \)

Here, \( n, \vec{v}, \) and \( w \) are the electron concentration, the average velocity, and the average electron energy; \( \vec{v}_p, \vec{v}_n \) are the momentum and energy relaxation frequencies; \( m^* \) is the effective mass, \( T \) is the electron temperature in energetic units, \( \kappa \) is the thermoconductivity coefficient; \( w_{00} = 0.039 \text{ eV} \) is the electron energy at 300 K. It is assumed that \( \vec{v}_p, \vec{v}_n, m^* \) are functions of the average electron energy \( w \). The estimations have demonstrated that the thermoconductivity is not essential for the dynamics of SCWs up till the frequencies 2.3 THz. In addition, the electron kinetic energy is one order smaller than the average electron energy, thus, the electron temperature is \( T \approx \frac{2}{3} w \).

From the stationary dependencies of the drift velocity \( \vec{v} = v(E) \) and the electron energy \( w = w(E) \), it is possible to obtain the relations \( E = E(w), v = v(w), \mu = \mu(w)/E(w) \equiv \mu(w) \), then the relaxation frequencies can be calculated as:
\[
\vec{v}_p(w) = \frac{e}{m^*} \mu(w); \quad \vec{v}_n(w) = \frac{e\mu(w)E^2(w)}{w - w_{00}} \quad (2)
\]

The calculated dependencies are given in Figure 4. One can see that the momentum relaxation frequency is \( \vec{v}_n \gg \vec{v}_p \), therefore, for the frequencies of SCW \( f < 1 \) THz it is possible to neglect by the inertia of electrons:
\[
\vec{v} = \frac{e}{m^*} \vec{E} - \frac{1}{n m^*} \nabla(nT) = \mu(w) \vec{E} - \frac{D}{n w} \nabla(nw) \quad (3)
\]

Here, \( \mu, D \) are mobility and diffusion of electrons:
\[
\mu = \frac{e}{m^*} \vec{v}_p; \quad D = \frac{T}{m^* \vec{v}_p} \equiv \frac{\mu T}{e} \quad (4)
\]

After substitution of (3) into the equations for \( n \) and \( w \), one can get the following equations:
\[
\frac{\partial \vec{n}}{\partial t} + \text{div} \left( \mu(w)n\vec{E} - \frac{D}{w} \nabla(nw) \right) \approx 0; \quad \frac{\partial \vec{w}}{\partial t} + \frac{5}{3} \nabla \vec{v}(w) + \frac{eD}{w} \left( \vec{E} \nabla \right) w + (w - w_{00}) \vec{v}_n \quad (5)
\]

\[
= e\mu E^2 - \frac{eD}{n} (\vec{E} \nabla) + \frac{2w}{3n} \frac{\partial \vec{n}}{\partial t}
\]

Below we investigate the linear amplification of SCW in GaN films on the dielectric substrate. The case of zinc blende \( n \)-GaN is considered. The following representation is used:
\[
w = w_0 + \vec{w}; \quad n = n_0 + \vec{n}; \quad \vec{v}_s = \vec{v}_0 + \vec{v}_s; \quad \vec{v}_p = \vec{v}_p, \quad E_s = E_0 + \vec{E}_s; \quad \vec{E}_s = \vec{E}_s \approx -\nabla \phi \quad (6)
\]

Here \( w_0, n_0, v_0, E_0 \) are steady state values of the average electron energy, concentration, the drift velocity, and the bias electric field; \( \vec{w}, \vec{n}, \vec{v}_s, \vec{E}_s \) are high frequency parts. Note that \( w_0 = w(E_0) > w_{00} \). The equations for the high frequency parts are:
\[
\frac{\partial \vec{w}}{\partial t} + \frac{7}{3} v_0 \frac{\partial \vec{n}}{\partial z} + v_{waves} \vec{w} \approx 2v_0 \vec{E}_z + \frac{2}{3} \frac{w_0}{n_0} \left( \frac{\partial \vec{n}}{\partial t} - \nabla \vec{n} \right); \quad \frac{\partial \vec{n}}{\partial x} + \frac{\partial \vec{n}}{\partial z} \left( \mu n_0 \vec{E}_z + v_n \vec{n} + n_0 E_0 \frac{\partial \vec{n}}{\partial w} \right) \left( \vec{w} - D \frac{\partial \vec{n}}{\partial z} \right) \quad (7)
\]

\[
\frac{\partial^2 \vec{E}}{\partial x^2} + \frac{\partial^2 \vec{E}}{\partial z^2} = \begin{cases} \frac{-e\vec{n}}{\varepsilon_w \varepsilon_z}, & 0 < x < 2l \\ 0, & x < 0 \text{ or } x > 2l \end{cases}; \quad \vec{E} = -\nabla \phi;
\]

where \( v_{waves} = \frac{d}{dw}((w - w_{00}) \vec{v}_s) - eE_0^2 \frac{d\mu}{dw} \approx \vec{v}_w \)
Jointly with the equations for the electron fluid, the Poisson equation for the electric field is used. Equation (7) should be added by boundary conditions of continuity of the electric potential $\phi$, $x$-component of the electric induction $-\sigma \chi \partial \phi / \partial x$, and absence of the surface charge at the boundaries of the film:

$$ j_x = e \left( \mu_n \tilde{E}_x - D \tilde{\nabla} \phi \right) = 0, \ x = 0, \ x = 2l $$

3. Amplification of Space Charge Waves

The solutions of Equation (7) as traveling waves are considered:

$$ \tilde{n}, \tilde{w}, \phi \sim \exp \left( i (\omega t - k z) \right) $$ (8)

If at some frequencies the imaginary part of the longitudinal wave number is $k'' > 0$, then the spatial amplification of SCW takes place.

It is possible to get the expression for $\tilde{w}$ through $\tilde{E}$ and $\tilde{n}$:

$$ \tilde{w} \approx \frac{2 e \nu_0 \tilde{E}_x}{\tilde{\nu}_w} + \frac{2 i \omega}{3 \nu_0} \left( \omega + \nu_0 \right) \tilde{n} $$ (9)

where $\tilde{\nu}_w = \nu_{\text{eff}} - \frac{4}{3} i \omega$

In Equation (9) the first term with $\tilde{E}_x$ corresponds to modification of the drift terms in the equation for electron concentration, whereas the second term with $\tilde{n}$ results in a modification of the diffusion coefficient. One can see that at higher frequencies the effective relaxation frequency $\tilde{\nu}_w$ becomes complex, its imaginary part is proportional to the signal frequency. This decreases the amplification of SCWs at higher frequencies.

After the substitution of (9), one can get the following equation for $\tilde{n}$:

$$ \frac{\partial \tilde{n}}{\partial t} + \mu_n \left( \frac{\partial \tilde{E}}{\partial z} + \frac{\partial \tilde{E}_w}{\partial \tilde{w}} \right) + \nu_0 \frac{\partial \tilde{n}}{\partial z} - D \left( \frac{\partial^2 \tilde{n}}{\partial z^2} + \frac{\partial \tilde{n}}{\partial \tilde{w}} \right) $$ (10)

$$ + \frac{n_0 E_w}{\tilde{\nu}_w} \frac{\partial \mu}{\partial \tilde{w}} \times \left( 2 e \nu_0 \tilde{E}_x + \frac{2 n_0}{\nu_0} \left( \frac{\partial^2 \tilde{n}}{\partial z^2} - \frac{\partial \tilde{n}}{\partial \tilde{w}} \right) \right) \approx 0 $$

Or, in the equivalent form,

$$ \left( i \left( \omega - k \nu_0 \right) + D \left( \frac{4 E_w \nu_0}{\tilde{\nu}_w} \frac{\partial \mu}{\partial \tilde{w}} \right) k^2 \right) \tilde{n} $$ (11)

$$ - D \frac{\partial^2 \tilde{n}}{\partial \tilde{w}^2} - \mu_n \frac{\partial^2 \phi}{\partial x^2} + n_0 k^2 \left( \mu + \frac{2 e \nu_0 E_w}{\tilde{\nu}_w} \frac{\partial \mu}{\partial \tilde{w}} \right) \phi \approx 0 $$

At lower frequencies $f \leq 150$ GHz, where the local dependence of the drift velocity on electric field $v = v(E)$ can be used, the amplification is determined by the derivative $dv/dE \equiv d\mu/E/dE < 0$. An analysis of Equation (11) yields that at higher frequencies this derivative should be substituted by the following complex expression:

$$ \frac{dv}{dE} \rightarrow \mu \left( 1 - \frac{\nu_{\text{eff}}}{\tilde{\nu}_w} \right) + \frac{dv}{dE} \frac{\nu_{\text{eff}}}{\tilde{\nu}_w} $$ (12)

One can see that at higher frequencies the differential conductivity becomes complex, and, moreover, above some frequency $f \approx 600$ GHz NDC disappears. Therefore, it is possible to use the simplest nonlocal model for estimations of the frequency range of amplification of SCW. Because $\nu_{\text{eff}} \approx 2 \times 10^{13}$ s$^{-1}$, the amplification of SCW in n-GaN can be observed at the frequencies $f \equiv \omega/2\pi < 0.5 \nu_{\text{eff}}/2\pi$.

There is a problem of estimating the diffusion coefficient. The simplest nonlocal model leads to the modification of the longitudinal diffusion coefficient $D_z$:

$$ D_z = D + \frac{4 E_w \nu_0}{\tilde{\nu}_w} \frac{\mu}{\partial \tilde{w}} $$ (13)

Because $d\mu/dw < 0$, on the first view the nonlocal model results in the decrease of $D_z$. Nevertheless, one can see that at lower frequencies, where $\tilde{\nu}_w \approx \nu_{\text{eff}}$ and the local diffusion-drift equations are valid, the second term in (13) does not depend on frequency. At higher frequencies, the second term in (13) becomes complex and the absolute real part decays slightly. Moreover, the estimations give that

$$ \frac{4 E_w \nu_0}{\tilde{\nu}_w} \frac{\mu}{\partial \tilde{w}} \frac{1}{D} = \frac{2 E_w^2}{\tilde{\nu}_w} \frac{\mu}{\partial \tilde{w}} \approx -1 $$ (14)

Thus, from the simplest nonlocal model it seems impossible to estimate the diffusion coefficient correctly even at lower frequencies. The situation is not crucial for n-GaN as for n-GaAs, where an application of the simplest nonlocal model leads to perfectly incorrect results ($2\left( E_w^2 / \tilde{\nu}_w \right) \mu / \tilde{\nu}_w < -1$ there, and the longitudinal diffusion coefficient becomes negative).

For simulations of the spatial increment of the amplification SCW we have used the value of the diffusion coefficient obtained within the framework of the local model. In Figure 5 the results of simulations of the spatial increment are given. An influence of the nonlocality is essential at the frequencies $f \geq 150 \cdots 200$ GHz. It is possible to obtain the amplification at the frequencies $f \leq 500$ GHz in GaN films of submicron thicknesses.

4. Conclusions

The simplest variant of nonlocal hydrodynamics gives a possibility of estimating the decay in amplification of space charge waves in n-GaN films at higher frequencies,
due to decrease of the absolute value of the negative differential conductivity. Nevertheless, to obtain the correct value of diffusion coefficient, it is necessary to use the more adequate model, based on the detailed balance equations for each valley. The estimations have given that it is possible to obtain the amplification of space charge waves in n-GaN films of submicron thicknesses up till the frequencies 400…500 GHz.

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