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Rogue wave recurrence inHEMT

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Abstract

The GaN semiconductor bulk plasma is examined through developing a quantum hydrodynamicmodel and taking into account the electrons/holes degenerate pressure, Bohm potential, and theexchange/correlation effect. The basic set of quantum fluid equations is reduced to the nonlinearSchrödinger equation (NLSE). Numerical analysis of the latter predicts the rough (in) stabilitydomains, which allow for the rogue waves to occur. Our results are employed to explore the GaNhigh electron mobility transistors (HEMTs) and their intrinsic problems in high frequency/powerapplications. A physical solution is suggested rather than engineering due to the GaN HEMTsdrawbacks.

Keywords: Rogue waves, HEMT, the nonlinear Schrödinger equation,

1. Introduction

GaN physical characteristics have made it the ideal nominee for high power, high temperature,and high frequency electronics applications [1]. GaN High Electron Mobility Transistors(HEMTs) are increasingly in demand in wireless communications (mobile phones, satellitecommunications, TV broadcasting, broadband wireless internet connection, transmitterbase station amplifiers), military applications (radars, missile seekers), voltage converters,microwave radio frequency power amplifiers, high-voltage switching, microwave sources, andradio astronomy [2, 3]. However, great concerns about the reliability of GaN HEMTs-basedpower electronic devices have been raised due to self-heating which severely degrades theirperformance and lifetime [4]. The transient drain current collapse and gate-lag are two moreruinous accompanying mechanisms that are theorized to have occured because of trapping[5, 6]. Although, many researchers overwhelmingly combine on the location of the GaNHEMT traps, but the strange thing is that, they always give fuzzy reasons basically dependon random localization distribution of the causes like impurities, lattaice defect, anddislocations. Besides, they often give an inaccurate depiction of the quantum tunnelingeffect.

Recent research shed the light on many anomalous phenomena that have been observedin a variety of systems, ranging from discrete lattices [7, 8], fluids [9, 10], plasmas [11],ultracold quantum gases [12, 13], optics [14-17], lasers [18-20], optical fibers [21-23]. Theirsimilar characteristics that are governed by the nonlinear Schrödinger equation (NLSE) solutions could be considered as the clue to understand their nature. Rogue waves are oneof the most distinguished embodiments of extreme events in nonlinear dynamics, which areattributed to the modulation instability (MI). The MI or sideband instability is one of the most pervasive types of instabilities in nature [24], it originates as an interaction betweenstrong carrier harmonic waves and small sidebands. In this aspect, the MI plays a greatrole as an"intrinsic noise" in triggering a self-organization mechanism [25]. Instabilities andspontaneous pattern formation in numerous natural and artificial systems caused by roguewaves can have catastrophic consequences, but the situation could be better if we know theirmultiple scale hierarchies.

Quantum effects are expected to play an important role in GaN HEMT under the conditionsof extreme events. This situation becomes clear when the energy density of theplasma oscillations is equal or comparable to the Fermi electron thermal energy density. Even though the electron density is almost low in some applications for considering the typical quantum mechanical effects, such as tunneling, the situation in other applications maybe supposed to be of quantum nature. Our proposed collective interactions in these denseplasmas of electrons and holes will be studied by using the Schrödinger-Poisson model. Dueto the polar, piezo-electric polarization nature of the GaN crystal structure, inaddition to a large band-gap, it is anticipated that the plasma quasi-neutralityis achieved between electrons and holes [26-28]. It would be interesting to introducedifferent quantum effects, to examine the MI and to test the reaction of the quantum effectson the rogue wave profile. For this purpose, we focus our attention on the specific scenario ofbalancing between the group dispersion and the nonlinear effects caused by pressure force,Bohm and exchange-correlation potentials. It would be motivating to assess in more detailthe spectra of an unstable mode zone, and it would be promising to benchmark our resultswith an experimental observation. Accordingly, the goal of our investigation is twofold: (i)to demonstrate the existence region of the acoustic rogue waves (ARWs) and (ii) examinehow the ARWs are influenced by different quantum effects.

2. Theory

We consider the propagation of nonlinear electrostatic acoustic waves in a two-componentcollisionless plasma composed of electrons and holes. The nonlinear dynamics of such disturbancesis governed by the normalized fluid equations for electrons

$$\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial x}(n_e u_e) = 0, \tag{1}$$

$$\left(\frac{\partial}{\partial t} + u_e \frac{\partial}{\partial x}\right) u_e - \frac{\partial \varphi}{\partial x} + a_1 \frac{\partial V_{xce}}{\partial x} + \beta_1 n_e^{-1/3} \frac{\partial n_e}{\partial x} - H_e^2 \frac{\partial}{\partial x}\left(\frac{\frac{\partial^2}{\partial x^2}\sqrt{n_e}}{\sqrt{n_e}}\right) = 0, \tag{2}$$

$$\frac{\partial n_h}{\partial t} + \frac{\partial}{\partial x}(n_h u_h) = 0, \tag{3}$$

$$\left(\frac{\partial}{\partial t} + u_h \frac{\partial}{\partial x}\right) u_h + M \frac{\partial \varphi}{\partial x} + b_1 \frac{\partial V_{xch}}{\partial x} + \beta_2 n_h^{-1/3} \frac{\partial n_h}{\partial x} - H_h^2 \frac{\partial}{\partial x}\left(\frac{\frac{\partial^2}{\partial x^2}\sqrt{n_h}}{\sqrt{n_h}}\right) = \tag{4}$$

The system is closed by the Poisson equation

$$\frac{\partial^2 \varphi}{\partial x^2} = n_e - n_h. \tag{5}$$

Here, n_e (u_e) and n_h (u_h) stand for the density (velocity) of the electrons and holes, respectively, $V_{xce,h}$ are the electrons and holes exchange-correlation potentials, and φ is theelectrostatic potential.

The variables appearing in Eqs. (1)-(5) have been appropriately normalized. Thus, n_e and n_h are normalized by the unperturbed electron (hole) numberdensity $n_{e0}(n_{h0})$, u_e, u_h are normalized by the Fermi electron speed $V_{Fe} = (k_B T_{Fe}/m_e^*)^{1/2}$ in terms of Fermitemperature T_{Fe} and φ is normalized by $k_B T_{Fe}/e$. The space and time variables are in unitsof the Fermi electron Debye radius $\lambda_{DFe} = (k_B T_{Fe} \varepsilon_0 / e^2 n_{e0})^{1/2}$ and the inverse of the plasmafrequency $\omega_{pe}^{-1} = (\varepsilon_0 m_e^* / e^2 n_{e0})^{1/2}$, respectively, $M = m_e^*/m_h^*$ is the electron-to-hole effectivemass ratio, ε_0 is the permitivity, e is the magnitude of the electron charge, and K_B is theBoltzmann constant. Furthermore, $a_1 = (K_B T_{Fe})^{-1}, b_1 = M(K_B T_{Fh})^{-1}, \beta_1 = n_0^{-1/3} C_1, C_1$ $2n_{e0}^{1/3}/3$, $\beta_2 = n_0^{-1/3} C_2, C_2 = 2n_{h0}^{1/3}/(3M)$, $H_e = (\hbar\omega_{pe}/2K_B T_{Fe})$, $H_h = (\hbar\omega_{pe}/2K_B T_{Fe})M$

The non-relativistic pressure law [32] of the degenerate electrons/holes is used in Eqs. (2)and (4), where $P_{e,h} = K_{e,h} n_{e,h}^{5/3}$, $K_{e,h} = \frac{3}{5}(\pi/3)^{1/3} \pi \hbar^2 / m_{e,h}^*$, $\hbar$ is the Planck constant dividedby 2π The exchange-correlation potentials for the electrons and holes are given by $V_{xce,h} = 0.985(e^2/\epsilon)(n_{e,h}^{1/3} + 0.034/a_{Be,h}^* \ln[1 + 18.37 a_{Be,h}^* n_{e,h}^{1/3}])$, where $a_{Be,h}^* = \epsilon\hbar^2/m_{e,h}^* e^2$ and ϵ is thedielectric constant of the material.

To examine the dynamics of the one-dimensional ARWs propagating in anelectron-hole plasma, we analyze the outgoing solutions of Eqs. (1)—(5), we obtain a system ofequations where the compatibility condition yields the NLSE

$$i\frac{\partial \varphi}{\partial \tau} + P\frac{\partial^2 \varphi}{\partial \xi^2} + Q\ |\varphi|^2 \varphi = 0, \tag{6}$$

where *P* and *Q* are given in Ref. [33]. A detailed description of the mathematicalmethod to obtain the NLSE can be found in Refs. [33, 34].

The NLSE (9) has a rational solution that is located in a nonzero background and localizedboth in the ζ and τ directions [34, 35] as

$$\varphi(\tau, \xi) = \sqrt{P/Q}\left[\frac{4(1 + 2iP\tau)}{1 + 4P^2\tau^2 + 4\xi^2} - 1\right]\exp(iP\tau). \tag{7}$$

Solution (7) prognosticates the concentration of the ARWs energy into a small regionthat is caused by the nonlinear behavior of the plasma medium. Indeed, rogue waves areusually an envelope of a carrier wave with a wavelength smaller than the central region ofthe envelope. Rogue waves are able to focus (self-trapping) significant amounts of waveenergy into a relatively small area, which may provide the basis for the illustration of theARWs in semiconductor plasma.

The analyses of the NLSE (6) disclose the existence of either unstable or stable pulses.The appropriate tool to examine the region of (in)stabitliy of the envelope pulse amplitudefor external perturbations is the sign of the ratio *P/Q*. For a negative *P/Q*, the modulatedenvelope is stable, while for a positive *P/Q* the modulated envelope will be unstable againstexternal perturbations. In the latter case, the carrier wave is modulationally unstable; soit may either "collapse", due to (possibly random) external perturbations, or lead to theformation of "bright" envelope modulated wavepackets, i.e. localized envelope "pulses"confining the carrier wave. The instability is usually saturated by the formation of a trainof envelope pulses, the so-called bright solitons. These bright solitons can be stationary intime, but the system can also oscillate periodically back and forth between the soliton stateand an almost homogeneous state, usually referred to as the Fermi-Pasta-Ulam oscillation[32]. For a negative *P/Q*, the carrier wave is modulationally "stable", and dark solitonsexist. Our aim is to study the case of an unstable solution for *P/Q*>0, which is a typicalsituation for ARWs formations [38].

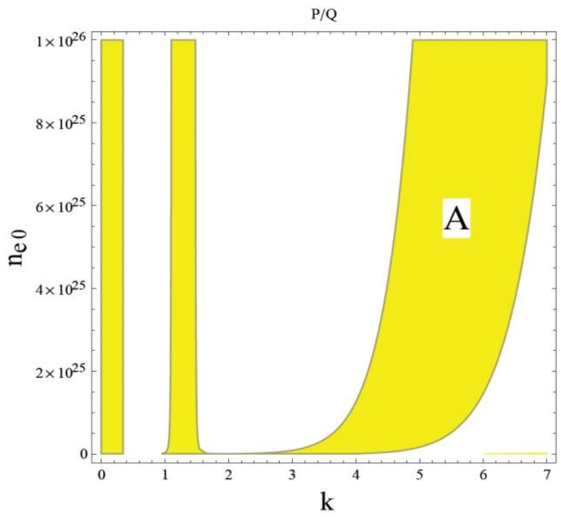

Figure 1 a

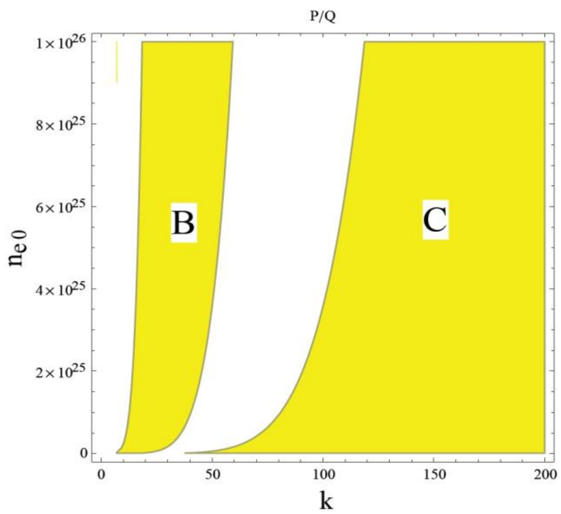

Figure 1 b

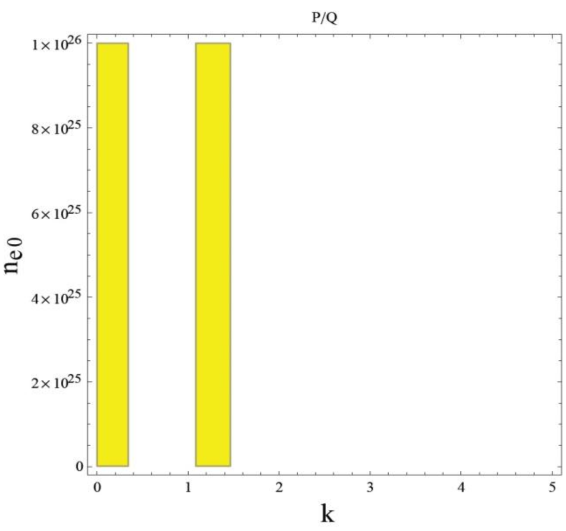

Figure 1 c

Figure 1:(Color online) The ratio *P/Q* contour is depicted against the wave number k and electron number density n_{e0}; the yellow (white) color represents the region where the unstable (stable) waves set in. (a) and (b) with all quantum effects and (c) without Bohm potential effect.

In what follows, we analyze the parametric dependence of the rogue wave profile onthe plasma density and wave number for GaN semiconductor bulk plasmas with typicalparameters [39-41]$n_o \sim 10^{22} - 10^{26} m^{-3}, m_e^* = 0.13\ m_e, m_h^* = 1.3 m_e, and\ \epsilon = 11.3.$

3. Results

First, the sign of the ratio *P/Q* is depicted in Fig. 1. The yellow region stands for *P/Q*>0and the white region stands for *P/Q*<0Figure 1a shows the positive regionof *P/Q*for small wave numbers band (i.e. $k = 0 - 7$), which shows that there are threeregions of instability. Increasing the wave number (k = 7 − 200) as depicted in Fig. 1b,it is obvious that if there is one cut-off region of instability (i.e. $k \sim 40 - 100$) then theinstability region continuously exists. Of course, the $(n_{oe} - k)$ plan is an important toolto precisely define the propagation region of the rogue waves.

Now, we know the expectedregion and parameters that may allow the existence of rogue waves in a GaN semiconductor.However, could the quantum effects such as Bohm potential or exchange-correlation termschange the $n_{oe} - k$plan. In an analogous manner, we neglect/cancel the Bohm potentialterm (i.e. by putting $H_e = H_h = 0$) and replot the $(n_{oe} - k)$graph as depicted in Fig. 1c. Itis clear that there are only two narrow regions of instability at a low wave number band (i.e.k = 1−2). Furthermore, neglecting the exchange-correlation terms has no significant affecton the $(n_{oe} - k)$ plan, so we did not include that figure here. Therefore, the presence of Bohmpotential is the main quantum factor for creating instability in the GaN semiconductor.

It would be intresting to notice that the rogue semiconductor waves can be generatedwithin the unstable zone that is represented by the yellowpart of the $(n_{oe} - k)$ plan. Creating arogue wave as a self-trapping effect is due to sucking the energy/carriers from the background(as it depletes the 2-dimension electron gas (2DEG)) into a small area, which produces highlylocalized self modulated pulses. The confinement of this energy/carriers cannot be producedwithout the tunneling effect of carriers (cf. Fig. 1c). The tunneling effect gives the electronsthe way to penetrate the rogue wave trapping center, which will be near to the more denseelectron streams. This mechanism degrades pinch-off characteristics and decreases the GaNtransconductance. These "bulk traps" in the GaN buffer region have been suggested to bethe reason for dispersion in a GaN HEMTs, current collapse, and gate-lag [43]. Therefore,the relaxation time in current lag effects in HEMTs is increased.

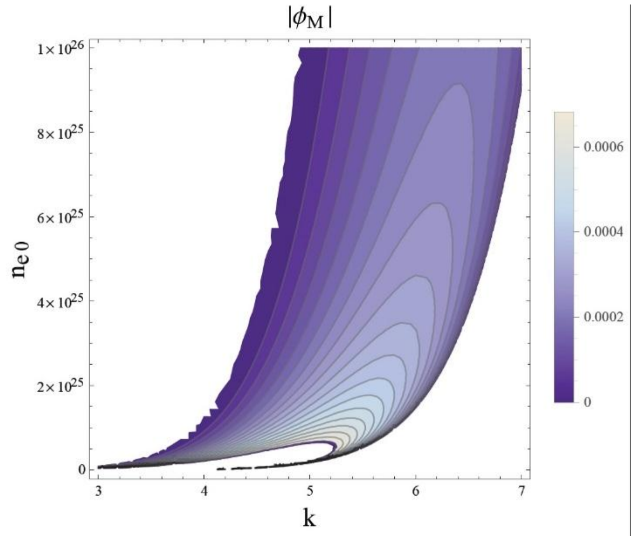

Figure 2 a

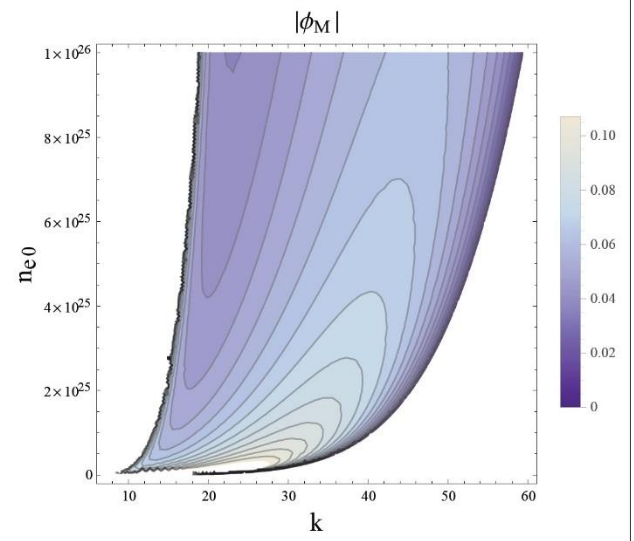

Figure 2 b

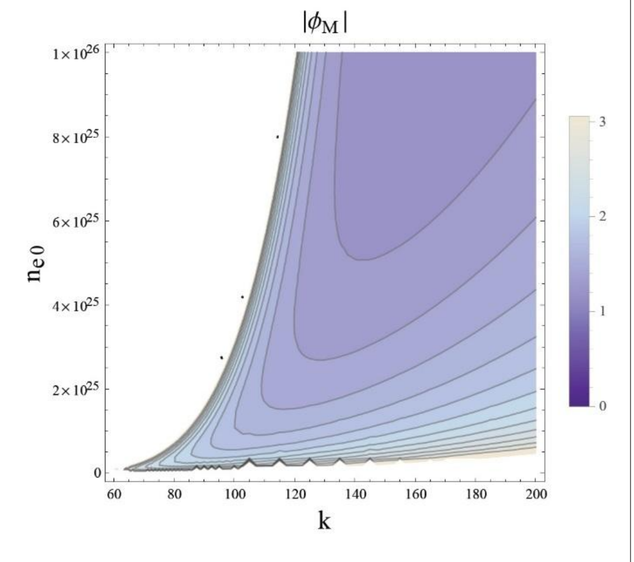

Figure 2 c

Figure 2: (Color online) Maximum rogue wave amplitude $|\varphi_M|$ contour is depicted against the wave number k and electron number density n_{oe} for different regions of $|\varphi_M|$.Light-colored regions correspond to high values of $|\varphi_M|$.

Now, our aim is to numerically analyze the maximum ARWs envelope amplitude $|\varphi_M|$for the GaN and investigate how the plasma number density n_{oe} and the wave number $k$alter its profile. In order to gain some insight, we have depicted the rogue wave profile aswell as the contour plot of $|\varphi_M|$ with n_{oe} and k as in Fig. 2. The rogue wave profile thatmay propagate for GaN plasma parameters within the yellow or unstable region is depictedin Fig. 2a. We have divided the instability regions into three parts A, B, and C (cf. Fig.1a and 1b). Figure 2a shows the region A, it is seen that an increase of the plasma numberdensity would lead to the reduction of the rogue wave amplitude. However, for $k \geq 5$ thewave amplitude has higher values than for $k < 5$ The same behavior is found in partBand isrepresented in Fig. 2b. The value of the maximum ARWs envelope amplitude $|\varphi_M|$is muchgreater than (even a hundred times) Fig. 2a. It means that for larger wave numbers therogue waves suck more energy, which causes high amplitude pulses. This analysis could giverise to the self-heating mechanism, where this localized envelope attracts and compressesmore charged carriers energies in a very small bulk size. Then, the higher the carrier density,the more the temperature increases. Figure 2c corresponds to part C, it is clear that fora high plasma number density n_{oe} the maximum envelope amplitude decreases, but for ahigher wave number the amplitude increases up to very high values.

Conclusions

In conclusion, we have shown that rogue waves can be exclusively responsible for theproduction and concentration of very high wave energy in the GaNsemiconductor and itsconsequences related to the operation of the HEMTs. Analysis of the NLSE provides uswith the existence regions for the rogue waves. The analysis is also able to qualitativelyexplain the transient collapse of the transconductance and the self-heating of the GaN.

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