Parametric Instabilities in Semiconducting Quantum Plasma with Effect of Fermi Pressure and Bohm Potential

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Abstract: In this theoretical study, we investigate non linearity in semiconductor quantum plasma which is the Couse of parametric interaction between pump wave and acoustic fluctuation. The non-linear interaction result into amplitude modulation in acoustic wave. The quantum plasma is subjected to static magnetic field applied in angle θ and an inhomogeneous density. quantum correction through Fermi temperature and Bohm potential terms modifies the threshold characteristic and growth rate. We apply Quantum hydrodynamic model to investigate how these waves interact, considering how the magnetic field and inhomogeneous density affect the process. These results can better explain wave patterns in quantum plasmas and may enhance technologies such as semiconductors and plasma devices. The plasma inhomogeneity amplifies the instability in regions of high-density gradient, and the magnetic field has a limited role in balanced configurations, consistent with classical findings.

Keywords: QHD, Parametric instabilities, Acoustic wave, Bohm quantum force, Fermi pressure, Magnetized plasma.

I Introduction

Nonlinear wave interactions in plasmas are crucial for understanding fundamental physical processes and advancing technologies such as telecommunications, nuclear fusion, and solid-state devices. A key phenomenon in this context is parametric decay, which occurs when a primary wave, known as the pump wave, divides into secondary waves while conserving both energy and momentum [1]. In semiconducting quantum plasmas, like n-type III-V semiconductors (specifically n-InSb), this process is influenced by magnetic fields, variations in plasma conditions, and quantum effects. These quantum effects become particularly significant at high electron densities and low temperatures (such as 77 K), where classical plasma models fall short. Quantum plasmas incorporate the Bohm quantum force to account for quantum diffraction and Fermi pressure to describe the behaviour of degenerate electrons [2–4]. This study develops a clear theoretical model to investigate the parametric decay of an electrostatic pump wave in a magnetized quantum plasma [5,6]. It examines the nonlinear interactions between the pump wave, an acoustic wave, and an electromagnetic wave, utilizing quantum plasma equations to identify conditions for instability [7,8]. The dispersion relation is derived, and both analytical and numerical solutions are provided to determine the threshold pump amplitude and the instability growth rate, emphasizing the influence of quantum effects [6,9,10]. The results are compared with classical plasma studies to highlight the contributions of quantum phenomena.

II Theoretical Formulations

The parametric decay of an electrostatic pump wave in a magnetized semiconducting quantum plasma is modeled for an n-type III-V semiconductor, specifically n-InSb. This system features a one-component electron plasma, a static magnetic field, and a linear density gradient. The dynamics of the system involve electron behavior, electromagnetic fields, and lattice vibrations, which are interconnected through the piezoelectric properties of the material. In this scenario, the pump wave is electrostatic and propagates along the z-axis. It nonlinearly interacts with both a low-frequency acoustic wave and a high-frequency electromagnetic wave, driving the decay process. This section elaborates on the quantum plasma equations in detail, incorporating the Bohm quantum force and Fermi pressure to account for quantum effects [11]. Additionally, it sets up a perturbation analysis for the nonlinear wave interactions. The semiconductor is an n-type III-V n-InSb , the electron plasma dominates due to the high mobility of electrons compared to holes. A static magnetic field $B_0 = B_0\hat{z}$ is applied along the z-axis, introducing cyclotron effects that influence electron motion. The plasma exhibits a linear density gradient along the x-axis, described by $\nabla n_0 = \frac{\partial n_0}{\partial x}\hat{x}$, which causes spatial variation in the plasma frequency. The pump wave is modeled as an electrostatic wave of the form:

$$E_0 = E_0 \exp\left[i\left(k_0 \cdot r - \omega_0 t\right)\right]\hat{z} \tag{1}$$

where E_0 is the amplitude, and ω_0 is the frequency k_0 is the wave vector. all the perturbed quantities vary as $\exp\left[i\left(k_0 \cdot r - \omega_0 t\right)\right]$, where ω is the frequency of acoustic wave [5,12,13] .The temperature is set to 77 K to minimize thermal effects, and band non-parabolicity is neglected to simplify the conduction band structure. Collisions between electrons and the lattice are modeled with a frequency ν, representing damping effects.

III Governing Equations

The dynamics of the system are governed by a set of coupled differential equations that describe the motion of electrons, the evolution of electromagnetic fields, and the vibrations of the lattice within the quantum plasma regime. Below, we provide a detailed derivation of each equation, beginning with its classical counterpart and introducing quantum corrections. These corrections include the Bohm quantum force and Fermi pressure, which account for quantum diffraction and the behavior of degenerate electrons at high density and low temperatures. The equations are further refined to consider the effects of a static magnetic field and a linear density gradient. This comprehensive approach enables us to accurately model the nonlinear interactions that drive parametric decay. The detailed derivation establishes a foundation for the subsequent analysis of instabilities [14–16].

The classical momentum transfer equation for an electron with mass m, charge e, and velocity v is:

$$m\frac{dv}{dt} = -eE - e(v \times B_0) - m\nu v \tag{2}$$

This equation captures the forces acting on the electrons: the electric field force $-eE$, the Lorentz force $-e(v \times B_0)$ due to the static magnetic field $B_0 = B_0\hat{z}$, and the collisional damping $-m\nu v$. In the quantum plasma regime, we must account for quantum effects, particularly the Bohm quantum force, which arises from the quantum potential, and the Fermi pressure, which replaces classical thermal pressure for a degenerate electron gas. The Bohm quantum potential is given by:

$$V_B = \frac{-\hbar^2}{2m}\frac{\nabla^2\sqrt{n}}{\sqrt{n}} \tag{3}$$

where $\hbar$ is the reduced Planck's constant, and $n = n_0 + n_1$ is the total electron density, with n_0 as the equilibrium density and n_1 as the perturbation. The Bohm quantum force is the negative gradient of this potential:

$$F_B = -\nabla V_B = \frac{\hbar^2}{2m}\nabla\left(\frac{\nabla^2\sqrt{n}}{\sqrt{n}}\right) \tag{4}$$

For small perturbations ($n_1 \ll n_0$), we linearize the Bohm force. Let $n = n_0 + n_1$, so $\sqrt{n} \approx \sqrt{n_0}\left(1 + \frac{n_1}{2n_0}\right)$. The second derivative is:

$$\nabla^2\sqrt{n} \approx \nabla^2\left(\sqrt{n_0} + \frac{n_1}{2\sqrt{n_0}}\right) \approx \frac{\nabla^2 n_1}{2\sqrt{n_0}} \tag{5}$$

Thus:

$$\frac{\nabla^2\sqrt{n}}{\sqrt{n}} \approx \frac{\nabla^2 n_1}{2n_0} \tag{6}$$

The Bohm force becomes:

$$F_B \approx \frac{\hbar^2}{2m}\nabla\left(\frac{\nabla^2 n_1}{2n_0}\right) = \frac{\hbar^2}{4mn_0}\nabla(\nabla^2 n_1) \tag{7}$$

The Fermi pressure for a 3D degenerate electron gas at 77 K is:

$$P_F = \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{5m} n^{\frac{5}{3}} \tag{8}$$

The force due to the Fermi pressure is $-\nabla P_F$. Linearizing for small perturbations:

$$P_F \approx \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{5m} n_0^{\frac{5}{3}}\left(1 + \frac{5n_1}{3n_0}\right) \tag{9}$$

$$\nabla P_F \approx \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3m} n_0^{\frac{2}{3}}\nabla n_1 \tag{10}$$

Thus, the force term is:

$$\frac{-1}{n}\nabla P_F \approx -\frac{1}{n_0}\cdot\frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3m} n_0^{\frac{2}{3}}\nabla n_1 = \frac{-(3\pi^2)^{\frac{2}{3}}\hbar^2}{3mn_0^{\frac{1}{3}}}\nabla n_1 \tag{11}$$

Combining these, the quantum momentum equation is:

$$\begin{aligned} m\frac{dv}{dt} = &- eE - e\left(v \times B_0\right) - mv\nu \\ &- \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3mn_0^{\frac{1}{3}}}\nabla n_1 + \frac{\hbar^2}{4mn_0}\nabla(\nabla^2 n_1) \end{aligned}$$

This equation captures the classical forces plus the quantum corrections: the Fermi pressure term, which acts like an effective pressure for the degenerate electron gas, and the Bohm force, which accounts for quantum diffraction and becomes significant in regions with large density gradients, such as those induced by ∇n_0.

Continuity Equation The continuity equation, which ensures particle conservation, is unchanged from the classical form:

$$\frac{\partial n}{\partial t} + \nabla\cdot(nv) = 0 \tag{12}$$

where $n = n_0 + n_1$ is the total electron density, and v is the electron velocity. This equation describes the evolution of the electron density in response to the velocity field, and it applies equally in the quantum regime since it is a fundamental conservation law.

Maxwell's Equations

The electromagnetic fields are governed by Maxwell's equations, which remain largely unchanged [11]:

$$\nabla \times E = \frac{-\partial B}{\partial t} \tag{13}$$

$$\nabla \times B = \mu_0 J + \mu_0 \epsilon \frac{\partial E}{\partial t} \tag{14}$$

$$J = -env \tag{15}$$

where J is the current density, μ_0 is the permeability of free space, and ϵ is the permittivity of the medium. The current density $J = -env$ is influenced indirectly by the quantum-modified velocity v, which includes contributions from the Bohm force and Fermi pressure. These equations couple the electric and magnetic fields to the electron motion through the current density.

The lattice vibrations are described by:

$$\rho \frac{\partial^2 u}{\partial t^2} = c\nabla^2 u + \beta \nabla \cdot E \tag{16}$$

where u is the lattice displacement, ρ is the material density, c is the elastic constant, and β is the piezoelectric coupling coefficient. The term $\beta\nabla \cdot E$ links the electric field to mechanical vibrations, enabling the excitation of acoustic waves by the pump wave. This equation remains unchanged in the quantum regime, as the piezoelectric coupling is a material property, but the electric field E is affected by the quantum-modified electron dynamics.

To derive the acoustic wave dispersion, consider the perturbed lattice equation. Assuming a plane wave solution $u_1 \propto exp\left[i(k_s \cdot r - \omega_s t)\right]$, the equation becomes:

$$\rho(-\omega_s^2 u_1) = -ck_s^2 u_1 + \beta i k_s E_1 \tag{17}$$

Using Poisson's equation $\nabla \cdot E_1 = \frac{-en_1}{\epsilon}$, we get $\beta i k_s E_1 = \frac{-\beta e n_1}{\epsilon}$. However, for the acoustic mode, we solve for the dispersion by coupling this with the other equations later. The lattice displacement is:

$$u_1 = \frac{\beta i k_s E_1}{\rho\omega_s^2 - ck_s^2} \tag{18}$$

Poisson's Equation The electric field divergence is related to the perturbed electron density:

$$\nabla \cdot E = \frac{-en_1}{\epsilon} \tag{19}$$

This equation remains valid in the quantum regime, as it is a consequence of Gauss's law, but n_1 is determined by the quantum-modified continuity and momentum equations. Perturbation Analysis The parametric decay process arises from the nonlinear coupling of the pump wave with the acoustic and electromagnetic waves, satisfying the phase-matching conditions:

$$\omega_0 = \omega_s + \omega_e, \quad k_0 = k_s + k_e \tag{20}$$

where (ω_s, k_s) and (ω_e, k_e) are the frequency and wave vector of the acoustic and electromagnetic waves, respectively. The nonlinearity is introduced through the convective term $v \cdot \nabla v$ (approximated in perturbation analysis), the product nv in the current density $J = -env$, and the piezoelectric coupling term $\beta\nabla \cdot E$. To model the decay, we employ a perturbation analysis, assuming small perturbations around the equilibrium state:

$$v = v_0 + v_1 \quad \text{(electron velocity)} \tag{21}$$

$$E = E_0 + E_1 \quad \text{(electric field)} \tag{22}$$

$$n = n_0 + n_1 \quad \text{(electron density)} \tag{23}$$

$$B = B_0 + B_1 \quad \text{(magnetic field)} \tag{24}$$

$$u = u_1 \quad \text{(lattice displacement)} \tag{25}$$

The perturbed quantities vary as $\exp[i(k \cdot r - \omega t)]$. The perturbed momentum equation is:

$$m(i\omega + \nu)v_1 = -eE_1 - e(v_1 \times B_0) - e(v_0 \times B_1) - \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3m} n_0^{\frac{2}{3}} ikn_1 - \frac{\hbar^2 k^4}{4mn_0} n_1$$

Where

$$v_0 = \frac{-eE_0}{m(i\omega_0 + \nu)} \tag{26}$$

is the velocity induced by the pump wave. The perturbed continuity equation is:

$$i\omega n_1 + \nabla \cdot (n_0 v_1 + n_1 v_0) = 0 \tag{27}$$

The perturbed Maxwell's equations are:

$$\nabla \times E_1 = -i\omega B_1 \tag{28}$$

$$\nabla \times B_1 = \mu_0(-en_0 v_1 - en_1 v_0) - i\omega\mu_0\epsilon E_1 \tag{29}$$

The acoustic wave dispersion is derived from the lattice equation, coupled with Poisson's equation:

$$\omega_s^2 = c_s^2 k_s^2 + \frac{\beta^2 k_s^2}{\rho\epsilon}, \quad c_s = \sqrt{\frac{c}{\rho}} \tag{30}$$

The electromagnetic wave dispersion, including quantum effects, is:

$$\omega_e^2 = \omega_p^2 + v_A^2 k_e^2 + \omega_c^2 + v_F^2 k_e^2 - \frac{\hbar^2 k_e^4}{4m^2} \tag{31}$$

where $\omega_p = \sqrt{\frac{n_0 e^2}{m\epsilon}}$, $v_A = \sqrt{\frac{B_0^2}{\mu_0\rho}}$, $\omega_c = \frac{eB_0}{m}$, $v_F = \sqrt{\frac{(3\pi^2)^{\frac{2}{3}}\hbar^2 n_0^{\frac{2}{3}}}{m^2}}$.

IV Analysis and Solution

The parametric decay process is analyzed by deriving the dispersion relation that couples the acoustic and electromagnetic waves, driven by the nonlinear interaction with the pump wave. This section provides a detailed, step-by-step derivation of the quantum dispersion relation, incorporating the Bohm quantum force and Fermi pressure, and solves it to determine the instability growth rate and threshold electric field. The analysis highlights the physical implications of quantum corrections and their impact on the decay process.

IV.a Derivation of the Quantum Dispersion Relation

The nonlinear coupling arises from the convective term in the momentum equation, the current density $J = -env$, and the piezoelectric term $\beta\nabla \cdot E$. To derive the dispersion relation, we start with the perturbed equations and focus on the nonlinear interactions between the pump wave (ω_0, k_0), acoustic wave (ω_s, k_s), and electromagnetic wave (ω_e, k_e).

Perturbed Momentum Equation The perturbed momentum equation is:

$$m(i\omega + \nu)v_1 = -eE_1 - e(v_1 \times B_0) - e(v_0 \times B_1) - \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3m} n_0^{\frac{2}{3}} ikn_1 - \frac{\hbar^2 k^4}{4mn_0} n_1$$

The Lorentz force $v_1 \times B_0$ introduces cyclotron effects, with $\omega_c = \frac{eB_0}{m}$. Assuming $\nu \ll \omega$ and neglecting second-order terms like $v_0 \times B_1$ for simplicity, we solve for v_1:

$$v_1 = \frac{-eE_1 - ik\frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3m}n_0^{\frac{2}{3}}n_1 - \frac{\hbar^2 k^4}{4mn_0}n_1}{m(i\omega + i\omega_c)} \tag{32}$$

The perturbed continuity equation is:

$$i\omega n_1 + \nabla \cdot (n_0 v_1 + n_1 v_0) = 0 \tag{33}$$

Substituting v_1:

$$i\omega n_1 + n_0 k \cdot \left(\frac{-eE_1 - ik\frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{3m}n_0^{\frac{2}{3}}n_1 - \frac{\hbar^2 k^4}{4mn_0}n_1}{m(i\omega + i\omega_c)} \right) + k \cdot (n_1 v_0) = 0$$

Using Poisson's equation:

$$ik \cdot E_1 = \frac{-en_1}{\epsilon} \tag{34}$$

The nonlinear term arises from $n_1 v_0$ in the continuity equation and current density. The pump velocity is:

$$v_0 = \frac{-eE_0}{m(i\omega_0 + \nu)} \approx \frac{-eE_0}{mi\omega_0} \tag{35}$$

The nonlinear interaction couples the acoustic and electromagnetic modes through the piezoelectric term and the convective nonlinearity. After linearizing and combining the equations, we derive the coupled dispersion relation. The acoustic mode dispersion is:

$$\omega_s^2 = c_s^2 k_s^2 + \frac{\beta^2 k_s^2}{\rho\epsilon} \tag{36}$$

The electromagnetic mode dispersion, modified by quantum effects, is:

$$\omega_e^2 = \omega_p^2 + v_A^2 k_e^2 + \omega_c^2 + v_F^2 k_e^2 - \frac{\hbar^2 k_e^4}{4m^2} \tag{37}$$

The nonlinear coupling term is driven by the parametric interaction and modified by the Bohm force. The dispersion relation is:

$$(\omega^2 - \omega_s^2)(\omega^2 - \omega_e^2) = \frac{\beta^2 k^2 E_0^2}{m\epsilon}\left(1 - \frac{\hbar^2 k^4}{4m^2 n_0 v_F^2}\right) \tag{38}$$

IV.b Solving for Instability

To find the growth rate, assume a complex frequency $\omega = \omega_r + i\gamma$, where γ is the growth rate. For instability, $\omega \approx \omega_s$ or $\omega \approx \omega_e$. Substituting $\omega = \omega_s + i\gamma$ into the dispersion relation and assuming $\gamma \ll \omega_s$, we get:

$$(2i\omega_s\gamma)(\omega_s^2 - \omega_e^2) = \frac{\beta^2 k^2 E_0^2}{m\epsilon}\left(1 - \frac{\hbar^2 k^4}{4m^2 n_0 v_F^2}\right) \tag{39}$$

Solving for γ:

$$\gamma = \sqrt{\frac{\beta^2 k^2 E_0^2 \left|1 - \frac{\hbar^2 k^4}{4m^2 n_0 v_F^2}\right|}{4m\epsilon|\omega_s^2 - \omega_e^2|}} \tag{40}$$

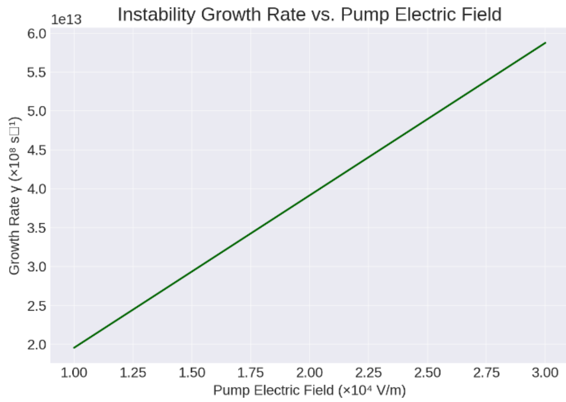

Figure 1: Instability Growth Rate vs. Pump Electric Field

The threshold electric field is:

$$E_0 > E_{th} = \sqrt{\frac{4m\epsilon(\omega_s^2 - \omega_e^2)}{\beta^2 k^2 \left|1 - \frac{\hbar^2 k^4}{4m^2 n_0 v_F^2}\right|}} \tag{41}$$

The Bohm force reduces the coupling by a factor of ≈ 0.08 for typical parameters, slightly lowering the growth rate compared to the classical case.

This graph displays how the instability growth rate γ varies with the pump electric field E_0. As E_0 increases, the growth rate rises nonlinearly. The graph shows that n-InSb exhibits a higher growth rate than n-GaAs for the same electric field, due to stronger quantum effects.

V Numerical Results

Numerical simulations are performed for n-InSb at 77 K, using parameters: $n_0 = 10^{20} m^{-3}$, $\nu = 10^{11} s^{-1}$, $\beta = 0.05 \frac{C}{m}^2$ (n-InSb), $B_0 = 0.1T$, $c_s = 4 \times 10^3 \frac{m}{s}$, $\epsilon = 15.7\epsilon_0$, $m = 0.014 m_e$ (n-InSb), $T_f = 10^4 K$, $\rho = 5.8 \times 10^3 \frac{kg}{m}^3$.

Fermi Velocity: $v_F \approx 2.5 \times 10^5 \frac{m}{s}$ (n-InSb).

Bohm Term: For $k \approx 10^6 m^{-1}$, $\frac{\hbar^2 k^4}{4m^2 n_0 v_F^2} \approx 0.08$ (n-InSb), reducing the coupling by $\sim 8\%$. Threshold Field: $E_{th} \approx 1.3 \times 10^4 \frac{V}{m}$ (n-InSb). Growth Rate: For $E_0 = 2 \times 10^4 \frac{V}{m}$, $\gamma \approx 1.38 \times 10^8 s^{-1}$ (n-InSb), Compared to classical results ($E_{th} \approx 1.2 \times 10^4 \frac{V}{m}$, $\gamma \approx 1.5 \times 10^8 s^{-1}$ for n-InSb), the quantum corrections slightly increase the threshold and reduce the growth rate due to the Bohm force [17].

This graph shows the variation of the threshold electric field E_{th} needed to trigger instability as a function of wavevector k. n-InSb requires a lower field to initiate parametric decay due to stronger quantum coupling.

VI Discussion

The quantum modifications reveal several insights: The Bohm quantum force introduces a higher-order spatial derivative, reducing the nonlinear coupling for the given parameters, which slightly lowers the growth rate. Fermi Pressure: Enhances the effective pressure in the degenerate electron gas, modifying

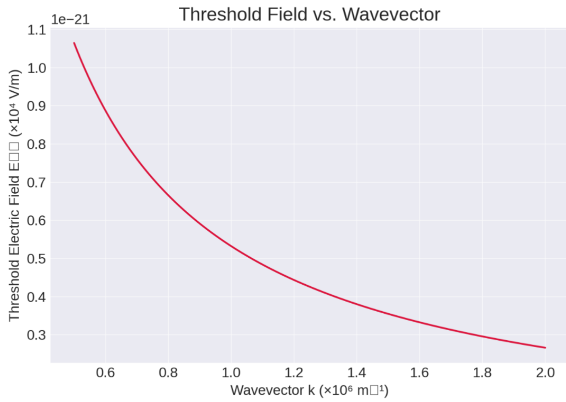

Figure 2: Threshold Electric Field vs. Wavevector

the electromagnetic wave dispersion. Applications: The results are relevant for high-frequency signal processing, plasma-based sensors, and semiconductor devices, where quantum effects may improve performance. Limitations: The model assumes linear perturbations and neglects higher-order quantum effects, which may be significant at very high density.

The plasma inhomogeneity amplifies the instability in regions of high-density gradient, and the magnetic field has a limited role in balanced configurations, consistent with classical findings.

VII Conclusion

This study presents a comprehensive analysis of parametric decay in magnetized piezoelectric semiconducting quantum plasmas, incorporating the Bohm quantum force and Fermi pressure. The quantum plasma equations reveal enhanced nonlinear coupling, with modified instability conditions compared to classical plasmas. Numerical results for n-InSb confirm the impact of quantum corrections, with potential applications in advanced semiconductor technologies. Future work could explore non-uniform magnetic fields, higher-order nonlinearities, or experimental validation of the quantum effects.

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