Piezoelectric Semiconductor Plasma: Dynamics of Coupled Waves and Spiky Solitons

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The miniaturization of electronic components through the use of semiconductors relies on the precise adjustment of charge carriers' de Broglie wavelengths to match the spatial variations in doping profiles. Consequently, typical quantum mechanical effects are expected to wield a fundamental influence on the behavior of forthcoming electronic components. For modern physicists dealing with quantum structures such as quantum wells, quantum wires, and quantum dots, comprehending both the linear and nonlinear characteristics of waves and instabilities driven by carrier dynamics in semiconductors is imperative. Furthermore, the development of wireless electronic devices has raised significant concerns regarding wireless power sources. In this context, piezoelectric semiconductors emerge as natural candidates for the conversion of mechanical energy into electrical energy and vice versa. This conversion is facilitated by the coupling between lattice ion vibrations and electrokinetic modes through piezoelectricity [1,2], which has sparked substantial and sustained interest. Within semiconductor nanostructures, electron and holes are governed by Fermi-Dirac statistics rather than the classical Boltzmann distribution.

The quantum effects can be explored through quantum hydrodynamic (QHD) equations, with the Bohm potential encapsulating the quantum tunneling along with other quantum effects [3]. The quantum hydrodynamic model (QHD) for plasmas was initially formulated by Manfredi and Hass [4,5]. The QHD model has successfully derived the dielectric tensor and dispersion relations for both the longitudinal and transverse electromagnetic waves in semiconductor quantum plasmas [6]. Notably, quantum corrections have a significant impact on longitudinal waves, leading to rapid decay due to Landau damping [7]. Moreover, quantum surface modes can manifest at the interface between plasmas and vacuum in magnetized electron-hole semiconductor plasmas, as revealed by the QHD model [8]. This is particularly significant, as the quantum effects lower the threshold electric field for parametric amplification making it easier to achieve the necessary pump electric field, especially in unmagnetized piezoelectric semiconductors [9].

This study investigates the coupling of lattice ion vibrations with electron waves in piezoelectric semiconductor quantum plasmas, analyzing nonlinearities and spiky solitons. Utilizing a quantum hydrodynamic model incorporating Fermi pressure, the quantum Bohm potential, and exchange correlation potential, we establish dispersion relations and nonlinear evolution equations. Through two-time scale theory, we obtain soliton solutions using modified quantum Zakharov equations. Our findings reveal a gradual decline in transmission feasibility in quantum plasmas and an increase in electric field amplitude of cusp solitons due to quantum corrections, sensitive to particle density and coupling strength. These insights advance energy harvesting and conversion technologies, with implications for piezoelectronics by elucidating the coupling of lattice ion vibrations and electron waves.

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