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Propagation and collision of soliton rings in quantum semiconductor plasmas

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The intrinsic localization of electrostatic wave energies in quantum semiconductor plasmas can be described by solitary pulses. The collision properties of these pulses are investigated. In the present study, the fundamental model includes the quantum term, degenerate pressure of the plasma species, and the electron/hole exchange–correlation effects. In cylindrical geometry, using the extended Poincaré–Lighthill–Kuo (PLK) method, the Korteweg–de Vries (KdV) equations and the analytical phase shifts after the collision of two soliton rings are derived. Typical values for GaSb and GaN semiconductors are used to estimate the basic features of soliton rings. It is found that the pulses of GaSb semiconductor carry more energies than the pulses of GaN semiconductor. In addition, the degenerate pressure terms of electrons and holes have strong impact on the phase shift. The present theory may be useful to analyze the collision of localized coherent electrostatic waves in quantum semiconductor plasmas.

Actually, the primary motivation for rapid growth in the study of quantum plasma physics is in its potential applications in different scientific areas such as quantum computers, semiconductor devices, quantum wells, carbon nanotubes, quantum diodes, ultra-cold plasmas, and intense laser-solid density plasma experiments [1–4]. Quantum plasma physics has a very high particle number density and a low particle temperature in comparison with classical plasmas where the plasma particle number density is relatively low, and the plasma temperature is rather high. Furthermore, the rapid development of laser technology has provided excellent opportunities to construct table-top laser sources of femtosecond pulses and powerful laser pulses [5,6]. Such high power laser pulses will open a new window for carrying out research dealing with nonlinear interactions between intense laser beams and plasmas in quantum regimes [7,8]. In accordance with this, interactions of intense lasers with quantum plasmas have been an important topic of modern plasma researches. For example, the intense laser pulse interacting with matter can create electron–hole plasmas at high densities (i.e., quantum plasmas) [9], where electrons absorb the photon energy by single-photon or multi-photon absorption and transit from the valence to the conduction band with holes created in the valence band. Accordingly, the quantum mechanical effects ought to be considered, since the de Broglie thermal wave length of the charge carriers could be comparable to characteristic spatial scales of the system in modern miniature semiconductor electronic devices. Therefore, it is important to understand and investigate the quantum mechanical effects on the dynamics of the charged carriers (i.e., electrons and holes) in semiconductor quantum devices which work in nanoscale sizes, such as quantum wells and quantum dots. On the other hand, the quantum mechanical effects (e.g., tunneling of degenerate plasma species through the Bohm potential barrier, exchange interactions and correlations, pressures of degenerate particles, etc.) are expected to play a very important role in the collective behavior of the charged carriers at quantum scales in semiconductor electronic devices. It is well known that, strong nonlinear interactions of the electrons and holes in bounded quantum devices can be separated into a Hartree term due to the electrostatic potential of the total electron/hole density and an electron/hole exchange–correlation term. When the electron/hole density is sufficiently high, and the electron/hole temperature is low, especially, in bounded quantum devices, the electron/hole exchange–correlation effects should be important [10–13].

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Nonlinear solitary waves occur in various physical contexts [14]. In general; solitary waves are formed in plasmas due to a balance between nonlinear steepening and dispersion, and even maintained their shape after mutual interactions (collisions) [15], earning them later the name of "solitons" [16], to emphasize their particle-like character. Indeed, the unique effect due to the collision between solitary waves is their phase shift and the trajectories. Experimentally, the soliton have been carried out for a number of materials and semiconductors such as: Al_2O_3 [17–20], Si [17,21], sapphire [22], MgO [17,23], SiO_2 [17], and GaAs [24]. Theoretically, the features of solitary waves in different semiconductors are investigated [25–28]. For instance, it is found that the degenerate pressure term plays an important role in shrinking the pulse height and width more than the other quantum effects [26]. Recently, the modulational instability of quantum electrostatic acoustic waves in electron–hole quantum semiconductor plasmas is investigated using the quantum hydrodynamic model [27]. They illuminated that the damping rate is dependent on the quantum effects, the electron–phonon (hole–phonon) collision frequency, and the ratio of the electron effective mass to hole effective mass.

Lately, the properties of linear and nonlinear quantum electrostatic acoustic waves in an electron–hole semiconductor quantum plasma taking into account the combined effects of the quantum recoil, the degenerate pressure effects, and the exchange–correlation potential due to spin are studied [28]. They demonstrated that the numerical simulations of the rarefactive solitons are stable and can withstand perturbations and turbulence for a considerable time. However, the reality which cannot be ignored is that the propagation of solitary waves may not be only a realistic situation in bounded quantum devices but also the collision of solitary waves with each other may be more realistic situation. Successfully, the extended Poincaré–Lighthill–Kuo (PLK) method is used in many branches of physics to investigate the interaction between solitons [29–34]. Anyway, the characteristics of the quantum plasma with electron exchange–correlation effects in bounded cylindrical domain have not been understood very well. To the best of our knowledge, this is the first study on propagation and collision of soliton rings (pulses) in quantum semiconductor plasmas. Therefore, the motive of this article is to present a theoretical model for investigating the geometry effect, degenerate pressure of plasma species effects, and the electron/hole exchange–correlation effects on the propagation and collision of soliton rings in an electron–hole semiconductor plasma.

Let us consider the propagation of nonlinear soliton rings in a cylindrical semiconductor plasma consisting of electrons and holes. The dynamics of nonlinear soliton rings can be described by the normalized quantum hydrodynamics equations [26,27,35,36].

$$\frac{\partial n_s}{\partial t}+\frac{\partial(n_s u_s)}{\partial r}+\frac{(n_s u_s)}{r}=0, \tag{1}$$

$$\frac{\partial u_s}{\partial t}+u_s\frac{\partial u_s}{\partial r}+\mu_s\frac{\partial\phi}{\partial r}-\gamma_s\frac{\partial V_{xcs}}{\partial r}+\sigma_s n_s^{-1/3}\frac{\partial n_s}{\partial r}$$
$$-2H_s^2\frac{\partial}{\partial r}\left(\frac{\frac{1}{r}\frac{\partial}{\partial r}\sqrt{n_s}+\frac{\partial^2}{\partial r^2}\sqrt{n_s}}{\sqrt{n_s}}\right)=0, \tag{2}$$

$$\frac{1}{r}\frac{\partial\phi}{\partial r}+\frac{\partial^2\phi}{\partial r^2}=n_e-n_h, \tag{3}$$

where subscript s is e for electrons and h for holes. Here, the variables n_s and u_s are the densities and the velocities of two fluids. ϕ is electrostatic potential. In Eq. (2), it should mentioned here that the fourth term is the exchange–correlation forces, where the exchange–correlation potentials two fluids

$$V_{xcs}=-0.985(e^2/\epsilon)n_0^{1/3}n_s^{1/3}$$
$$\times\left[1+\left(0.034/a_{Bs}^*n_0^{1/3}n_s^{1/3}\right)\ln\left(1+18.376a_{Bs}^*n_0^{1/3}n_s^{1/3}\right)\right],$$

the fifth term represents the degenerate pressure that is derived from $P_s=K_s n_s^{5/3}$, where $K_s=(5/3)(\pi/3)^{1/3}(\pi\hbar^2/m_s^*)$, and sixth term is the quantum recoil force associated with the Bohm potential due to the electrons/holes tunneling through a potential barrier. The charge neutrality at equilibrium requires, $n_{e0}=n_{h0}=n_0$. Here, for electrons, $\mu_e=-1$, $\gamma_e=1/k_B T_{Fe}$, $\sigma_e=(\pi/3)^{1/3}(\pi\hbar^2/m_e^*)(n_{e0}^{2/3}/k_B T_{Fe})$, $a_{Be}^*=(\epsilon\hbar^2/m_e^*e^2)$ and $H_e=(\hbar\omega_{pe}/2k_B T_{Fe})$, and for holes, $\mu_h=\mu=m_e^*/m_h^*$, $\gamma_h=\mu/k_B T_{Fh}$, $\sigma_h=(\pi/3)^{1/3}(\pi\hbar^2/m_h^*)(n_{h0}^{2/3}/k_B T_{Fh})$, $a_{Bh}^*=(\epsilon\hbar^2/m_h^*e^2)$ and $H_h=(\hbar\omega_{pe}/2k_B T_{Fh})\mu$. The following normalizations are used $n_s\to n_s/n_{s0}$, $u_s\to u_s/V_{Fe}$, $\phi\to e\phi/k_B T_{Fe}$, $t\to t\omega_{pe}$, and $r\to r\lambda_{DFe}$, where V_{Fe} $(=\sqrt{k_B T_{Fe}/m_e^*})$ is the Fermi electron speed, ω_{pe} $(=\sqrt{4\pi e^2 n_{e0}/m_e^*})$ is the electron plasma frequency, and λ_{DFe} $(=\sqrt{k_B T_{Fe}/4\pi e^2 n_{e0}})$ is the Fermi electron Debye radius. n_{e0} (n_{h0}) is the unperturbed electron (hole) density, m_e^* (m_h^*) is the electron (hole) effective mass, T_{Fe} (T_{Fh}) is the Fermi temperature of the electron (hole), $\hbar$ is Planck constant divided by 2π, ϵ is the dielectric constant of the material, e is the magnitude of the electron charge, k_B is Boltzmann constant.

In order to study the collision between soliton rings, let us assume two soliton rings S_1 and S_2 in electron–hole semiconductor quantum plasma, which are asymptotically, far apart in the initial state and travel toward each other. After some time they interact, collide, and then depart. In addition, we also consider soliton rings have small amplitudes $\sim\varepsilon$ (where ε is a smallness formal perturbation parameter characterizing the strength of nonlinearity) and the interactions between soliton rings are weak. Hence, we expect that the collision will be quasielastic, so it will cause only shifts of the postcollision trajectories (phase shift). Now, let us use the extended PLK method to derive two coupled Kortwege–de Vries (KdV) equations. According to this method, the dependent variables are expanded as $\Psi=\Psi^{(0)}+\sum_{n=1}^{\infty}\varepsilon^{(n+1)}\Psi^{(n)}$, where $\Psi=[n_e,n_h,u_e,u_h,\phi]$, and $\Psi^{(0)}=[1,1,0,0,0]$. Furthermore, the independent variables can be stretched as $\xi=\varepsilon(r-\lambda t-r_1)+\varepsilon^2 P^{(0)}(\eta,R)+\ldots$, $\eta=\varepsilon(r+\lambda t-r_2)+\varepsilon^2 Q^{(0)}(\xi,R)+\ldots$, and $R=\varepsilon^3 r$, where ξ and η denote the trajectories of two soliton rings traveling toward to each other. Here r_1 and r_2 are the initial positions of two soliton rings and $r_2>r_1>0$ for the cylindrical geometry. The functions of $P^{(0)}(\eta,R)$, $Q^{(0)}(\xi,R)$, and the wave velocity λ are to be determined later. Substituting the stretched variables ξ, η, and R, and dependent variables n_e, n_h, u_e, u_h and ϕ into Eqs. (1)–(3), one can obtain the lowest nonzero order in ε,

$$n_e^{(1)}(\xi,\eta,R)=\left(-1/\left(\lambda^2-\alpha_e-\beta_e-\sigma_e\right)\right)$$
$$\times\left(\phi_1^{(1)}(\xi,R)+\phi_2^{(1)}(\eta,R)\right),$$
$$n_h^{(1)}(\xi,\eta,R)=\left(\mu/\left(\lambda^2-\alpha_h-\beta_h-\sigma_h\right)\right)$$
$$\times\left(\phi_1^{(1)}(\xi,R)+\phi_2^{(1)}(\eta,R)\right),$$
$$u_e^{(1)}(\xi,\eta,R)=\left(-\lambda/\left(\lambda^2-\alpha_e-\beta_e-\sigma_e\right)\right)$$
$$\times\left(\phi_1^{(1)}(\xi,R)-\phi_2^{(1)}(\eta,R)\right),$$

and

$$u_h^{(1)}(\xi,\eta,R)=\left(\mu\lambda/\left(\lambda^2-\alpha_h-\beta_h-\sigma_h\right)\right)$$
$$\times\left(\phi_1^{(1)}(\xi,R)-\phi_2^{(1)}(\eta,R)\right).$$