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THz plasma wave instability in field effect transistor with electron diffusion current density

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Abstract

The plasma wave instability in rectangle field effect transistors (FETs) is studied with electron diffusion current density by quantum hydrodynamic model in this paper. General dispersion relation including effects of electrical thermal motion, external friction associated with electron scattering effect, electron exchange-correlation contributions and quantum effects were obtained for rectangle FETs. The electron diffusion current density term is considered for further analysis in this paper. It is found that the quantum effects, the electron diffusion current density and electrical thermal motion enhance the radiation power and frequencies. But the electron exchange-correlation effects and the electron scattering effects reduce the radiation power and frequencies. Results showed that a transistor has advantages for the realization of practical terahertz sources.

Keywords: the dispersion relation, THz plasma waves, instability, the radiation power, radiation frequency

(Some figures may appear in colour only in the online journal)

1. Introduction

The current-carrying state in an asymmetric field effect transistor (FET) can generate unstable plasma waves in the channel [1]. This instability phenomenon provides the reflected waves from the channel boundaries, which can lead to plasma wave amplification and excitation. Furthermore, the plasma wave is similar to 'shallow water' waves in a ballistic FET. It is indicated that the instability with zero ac voltage at the source and zero ac current at the drain can occurs when the asymmetric boundary conditions are satisfied [2, 3]. Most of the previous work demonstrated the THz plasma wave instability in short-channel FET is essential to the realization of practical non-resonant detectors [4–6], resonant detectors [7], and the terahertz emitters [8] in the terahertz domain [4]. This instability phenomenon is also studied by method of hydrodynamic simulation, Monte Carlo simulations [9–13], full-wave hydrodynamic simulations [14], and so on.

Presently, the nano-electronic devices were used in apparatus by advanced integrated technology, the quantum effect cannot be neglected. The quantum effect plays a vital role in a short-channel FET, and enhances the classical value of the short-pulse CL law [15], radiation power and frequency [16]. Previous works in quantum effect (QE) have taken into account, they have shown that the quantum effects increase the wave velocity [17]. The quantum dot in the channel of the FET has been subsequently studied [18, 19]. Electron scattering effects generate a strongly uneven distribution of potential in the device channel and affect the motion of carries, which reduce the plasma instability [20–22]. Some results of the theoretical analysis and computational simulation performed to investigate the plasma instabilities under the influence of carrier scatting in a ballistic FETs [20]. In addition, the electron exchange-correlation and electrical thermal motion have dramatic effects on the plasma waves instability in a nanometer FET [16]. And a study shows that the change of temperature of the charged plasma particles can change the instability increment, the dissipative instability and the resonant frequency [23]. On the other hand, the exchange-correlation would lead to an increase the plasma instability in a quantum semiconductor [24].

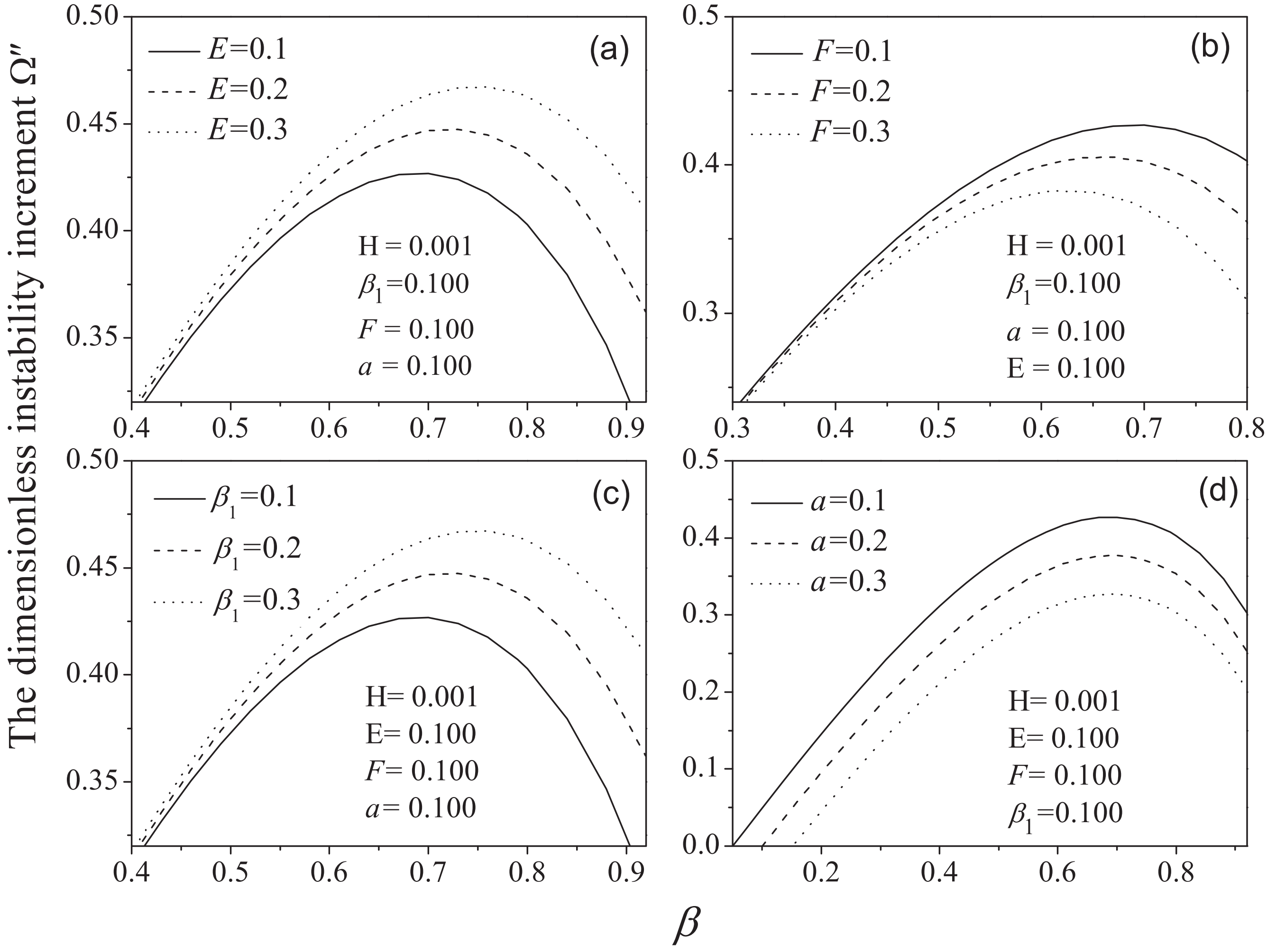

Figure 1. The instability increment Ω'' with β for different E, F, β_1, a.

The purpose of this paper is to have a more detailed elaboration of the radiation power and the radiation frequencies. In the applied electric field, the diffusion and drift motion of carries proceed simultaneously in EFT with different carries concentration, but the effect of electron diffusion current density have not been taken in previous works. Thus, the influences of the quantum effects, the external friction of electronic scattering with phonons and impurities, the electron exchange-correlation effect, the electron diffusion current density, and the electrical thermal motion on the current instability in the FET with asymmetrical boundary conditions are analyzed theoretically and numerically by quantum hydrodynamic model (QHM). Section 2 illustrates the theoretical model, section 3 accounts for the dispersion relation, section 4 shows the numerical results and analysis, while the conclusions are given in section 5.

2. Theoretical model

We assume that the carrier can propagate between source and drain contacts along the conductive channel in the transistor, while carrier flow is inexistent in transverse direction of channel. In the one-dimensional model, let us describe the carrier transport using the Euler equation and the continuity equation (hydrodynamic equations):

$$\frac{\partial n}{\partial t} + \frac{\partial n\boldsymbol{v}}{\partial x} = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \frac{\partial}{\partial x}\left[\frac{\boldsymbol{v}^2}{2} + \frac{e}{m}\Psi\right] = -e\delta D\frac{\partial n}{\partial x} - \boldsymbol{v}\delta + \frac{\hbar^2}{2m^2}\frac{\partial}{\partial x}\left(\frac{1}{\sqrt{n}}\frac{\partial^2\sqrt{n}}{\partial x^2}\right) - \frac{1}{m}\frac{\partial V_{\mathrm{xc}}}{\partial x} - \frac{1}{mn}\frac{\partial P}{\partial x}, \tag{2}$$

where n is the electron concentration, e is the electron charge, $\boldsymbol{v}$ is the electron velocity, δ is the electron velocity relaxation rate, m is the electron mass. Based on the concentration difference, the impurity particles diffused depends on its own thermal motion in space and clearance of crystals, which must be accompanied with the movement of quality and result in homogeneous particle concentration. Therefore, $e\delta D\frac{\partial n}{\partial x}$ presents the electron diffusion current density, D is the longitudinal diffusion coefficient, it describes the difficulty of the carrier movement in concentration gradient presence, given by the Einstein relation $D = k_{\mathrm{B}}T_{\mathrm{e}}\mu/e$. μ and e are the electron mobility and electron charge. The mobility and the

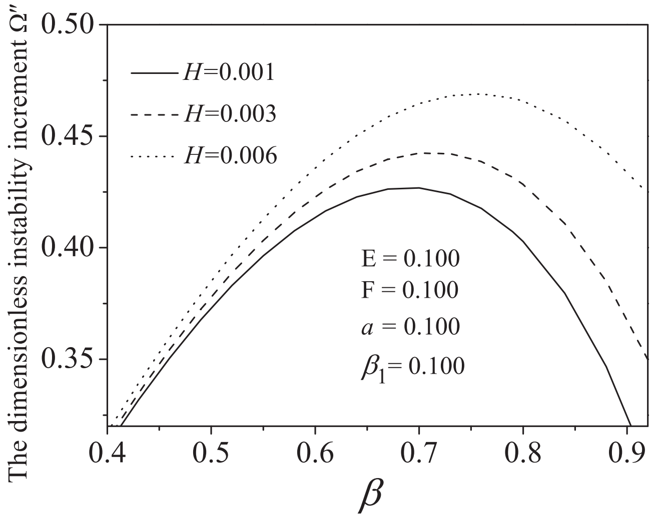

Figure 2. The instability increment Ω'' with β for H.

electron temperature become constants when the electrons are in equilibrium with the medium in low electric fields [25]. And Ψ is the potential, $E = \partial\Psi/\partial x$ is the electric field, $\frac{\hbar^2}{2m^2}\frac{\partial}{\partial x}\left(\frac{1}{\sqrt{n}}\frac{\partial^2\sqrt{n}}{\partial x^2}\right)$ is the quantum effects called Bohm potential in the model. $\boldsymbol{v}\delta$ accounts for external friction of electronic collisions with phonons and impurities. V_{xc} is the exchange-correlation potential which is given by $V_{\mathrm{xc}} = -0.985\frac{e^2}{\varepsilon}n^{\frac{1}{3}}\left[1 + \frac{0.034}{a_{\mathrm{B}}^{*}n^{1/3}}\,\mathrm{Ln}[1 + 18.376a_{\mathrm{B}}^{*}n^{1/3}]\right]$, where $a_{\mathrm{B}}^{*} = \varepsilon\hbar^2/me^2$, ε is the static dielectric constant of the main semiconductor. The pressure term P can make electron fluid system close on condition that P connect to electron related density n by the state equation. As a rule, we can use a polytropic relation $P = \bar{n}k_{\mathrm{B}}T_{\mathrm{e}}(n/\bar{n})^{\gamma}$, where $\bar{n}$ is a mean electron density, T_{e} is the electron temperature, $\gamma = 3$. Electron concentration n in the FET channel is relate to the potential Ψ, $\Psi = \Psi_{\mathrm{gc}}(x) - \Psi_{\mathrm{T}}$, as

$$n = \frac{C\Psi}{e}, \tag{3}$$

where Ψ_{T} is the threshold voltage, $\Psi_{\mathrm{gc}}(x)$ is the local gate-to-channel voltage, C is the gate capacitance per unit area. Equation (3) is gradual-channel equation, it is valid if the potential variation greater than the gate-to channel distance.

The asymmetric boundary conditions, zero ac potential at the source and zero ac conduction current at the drain, were studied by Dyakonov and Shur in their pioneering work [2], which has been considered essential for the instability to occur. The small electron flow in steady state is unstable against small perturbations, Ψ and V is shown to a constant Ψ_0 and V_0 respectively. The asymmetric boundary conditions has the form

$$n_1(x = 0) = 0,\ n(L, t)\boldsymbol{v}(L, t) = n_0 v_0, \tag{4}$$

where L is the distance from the source to drain contacts. Both the source connected to the ground directly or through a very large capacitance and the drain connected to the power source though an inductance can realize the boundary conditions. These two ways present a short circuit and open circuit at plasma wave frequencies, respectively.

3. Dispersion relation

As is usually done for the analysis of instability of steady state, we put $n = n_1 + n_0$, $\boldsymbol{v} = \boldsymbol{v}_1 + v_0$, $n_1, \boldsymbol{v}_1 \sim \exp(-\mathrm{i}\omega t + \mathrm{i}kx)$ and linearize equations, and can infer from equation (3) that the equation (6) is obtained by using equations (1) and (2). The equations become

$$(\omega - kv_0)n_1 = kn_0\boldsymbol{v}_1, \tag{5}$$

$$(\omega - kv_0 + \mathrm{i}\delta)\boldsymbol{v}_1 = \left[\frac{e^2}{mC}k + e\delta\, Dk + \frac{\hbar^2}{4m^2 n_0}k^3 + \frac{3k_{\mathrm{B}}T_{\mathrm{e}}}{mn_0}k - \left(0.53\frac{e^2 n_0^{-\frac{2}{3}}}{m\varepsilon} - 3.77\frac{\hbar^2 n_0^{-\frac{1}{3}}}{m^2}\right)k\right]n_1. \tag{6}$$

To simplify the equations (5) and (6) by omitting small quantities, the dispersion relation for the plasma waves should be of the form

$$(\omega - kv_0)(\omega - kv_0 + \mathrm{i}\delta) = \frac{e^2 n_0}{mC}k^2 + e\delta\, Dn_0 k^2 + \frac{\hbar^2}{4m^2}k^4 + \frac{3k_{\mathrm{B}}T_{\mathrm{e}}}{m}k^2 - \left(0.53\frac{e^2 n_0^{\frac{1}{3}}}{m\varepsilon} - 3.77\frac{\hbar^2 n_0^{\frac{2}{3}}}{m^2}\right)k^2. \tag{7}$$

According to equation (7), the wave number k has four roots including two real roots in accord with waves traveling downstream and upstream in numerical results, consider setting them to k_1 and k_2, respectively. The n_1 and $\boldsymbol{v}_1$ via equation (6) were given by

$$n_1 = A\exp(\mathrm{i}k_1 x) + B\exp(\mathrm{i}k_2 x), \tag{8}$$

$$\boldsymbol{v}_1 = \frac{\left[\frac{e^2}{mC}k + e\delta\, Dk + \frac{\hbar^2}{4m^2 n_0}k^3 + \frac{3k_{\mathrm{B}}T_{\mathrm{e}}}{mn_0}k - \left(0.53\frac{e^2 n_0^{-\frac{2}{3}}}{m\varepsilon} - 3.77\frac{\hbar^2 n_0^{-\frac{1}{3}}}{m^2}\right)k\right]n_1}{\omega - kv_0 + \mathrm{i}\delta}. \tag{9}$$

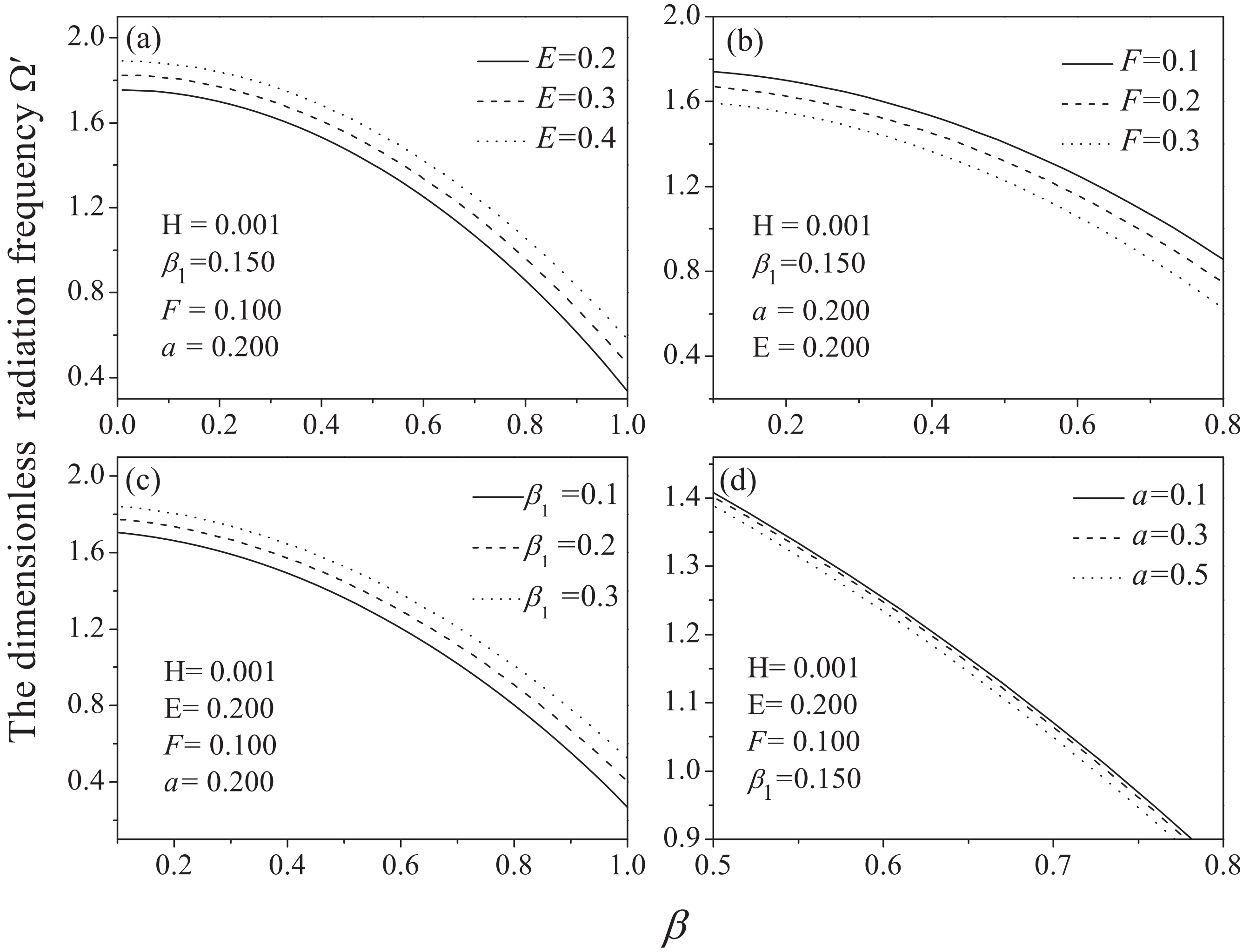

Figure 3. The radiation frequency Ω' with β for different E, F, β_1, a.

According to the boundary conditions, A and B are constants, then the solution of equations (4), (8) and (9) is given by

$$\exp[\mathrm{i}(k_1 - k_2)L] = \frac{k_1}{k_2}, \tag{10}$$

where $\omega = \omega' + \omega''$ is the complex frequency, ω' is the real part, ω'' is the imaginary part which determine the steady state current instability. As the $\omega'' > 0$, the plasma waves become unstable.

We normalize the dimensionless electron velocity $\boldsymbol{v}$ to the velocity $s = \sqrt{e^2 n_0/mC}$, the length to L, the thermal velocity of electron $v_e = \sqrt{3k_B T_e/m}$ to s and the frequency to s/L, the time to L/s. So there is the dimensionless dispersion relation

$$HK^4 + (1 + \beta_1 + E - F - \beta^2)K^2 + (2\Omega + \mathrm{i}a)\beta K - \Omega^2 - \mathrm{i}a\Omega = 0. \tag{11}$$

Introducing a dimensionless frequency Ω, a dimensionless wave number K, a dimensionless electron flux velocity $\beta = \boldsymbol{v}_0/s$, a dimensionless thermal velocity of electrons corresponding to the temperature $\beta_1 = \boldsymbol{v}_e/s$, a dimensionless external friction of electronic collisions with phonons and impurities $a = L\delta/s$, a dimensionless electron diffusion current density $E = \frac{e\delta D n_0}{s^2}$, $H = \hbar^2/4m^2 s^2 L^2$ is the quantum effects corresponding to the dimension of the device, $F = 0.53\frac{e^2}{s^2 m\varepsilon}n_0^{1/3} - 3.77\frac{\hbar^2}{s^2 m^2}n_0^{2/3}$ is depending on the electron exchange-correlation.

Equation (9) is written as

$$\exp[\mathrm{i}(K_1 - K_2)] = K_1/K_2. \tag{12}$$

4. Numerical results

It is known from equations (11) and (12) that the instability increment corresponding to the radiation power and frequencies depends on the electron exchange-correlation effect, the quantum effects, the electronic scattering effect with phonons and impurities, the electrical thermal motion, and the electron diffusion current density. We solve equations (11) and (12) by a numerous simulation program to explore the plasma wave instability. Figures 1 and 2 show the relationship between instability increment (Ω'') and electron flux velocity

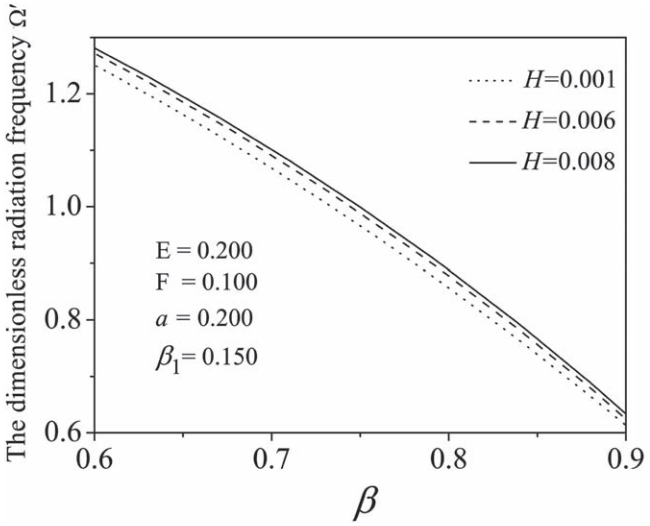

Figure 4. The radiation frequency Ω' with β for H.

(β) for different H, F, E, a, β_1. A positive imaginary part $\Omega'' > 0$, the steady current is unstable. Figures 1(a), (c) and 2 show that the electron diffusion current density E, the electrical thermal motion β_1 and the quantum effects H broad the instability range of the Mach number β and enhance the instability increment Ω''.

Figures 1(b) and (d) illustrates that the electron exchange-correlation contributions F and the external friction associated with electron scattering a shorten the instability range of the electron flux velocity β and reduce the instability increment.

The variation of instability increment with the electron flux velocity is nonlinear, that is, for lower electron flux velocity, the instability increment increases with the electron flux velocity, however, for higher electron flux velocity, the instability increment decreases with the electron flux velocity. It can be seen from figures 1(a)–(c) and 2 that the influence of physical quantities (H, β_1, E, F) on instability increment is significant at relatively high electron flux velocity, but that is insignificant at relatively low electron flux velocity. Figure 1(d) indicates that the external friction associated with electron scattering has a dramatically impact on instability increment for all electron flux velocity.

Figures 3 and 4 present that the radiation frequencies for variable electron flux velocity (β) are changed with different H, β_1, E, a, F. Figures 3(a) and (c) indicate that the radiation frequencies Ω' increase with quantum effects H, the electron diffusion current density E and the electrical thermal motion β_1 enhance the radiation frequencies Ω', while the electron exchange-correlation effects F and the electron scattering effect a reduce the radiation frequencies.

From the above figures, it can be concluded that the quantum hydrodynamic analytical model satisfies the numerical results well in general. The role of quantum effects is more attracting as electronic devices become smaller and smaller, so quantum effect is also changed by modulating the size of the device, and then by selecting the appropriate other parameters to increase the radiation frequency. As can be seen from figures 1–4, the value of electron flux velocity β is more suitable in the range of 0.6–0.8. The radiation ability and frequency are improved and enhanced by increasing the parameters H, β_1, E, and decreasing the parameters a, F at this time. Since non-uniform carrier concentration can cause carrier diffusion leading to self-built fields, the energy band is changed in presence of an electric field, which may lead to unstable current. The figure is just a few symbolic curves illustrating the influence of the parameters, therefore we can adjust the size of the parameters according to specific needs. The results of analysis and simulation in this article proved that terahertz wave radiation source can be obtained.

5. Conclusion

In summary, the electricity instability and the excitation of plasma waves in rectangle FET by QHM have been analyzed in this paper. Obtained results is that the radiation power and the radiation frequencies can enhance though increasing the quantum effects, the thermal motion of electrons, and the electron diffusion current density and. But the electron exchange-correlation contributions and the external friction associated with electron scattering can reduce the radiation power and frequencies. We can determine device parameters for experimentally observe the plasma wave instability. This property could be useful to design practical terahertz oscillations.

Acknowledgments

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