# Electric field driven plasmon dispersion in AlGaN/GaN high electron mobility transistors*

Tan Ren-Bing(谭仁兵)[a)b)c)], Qin Hua(秦 华)[a)†], Zhang Xiao-Yu(张晓渝)[a)], and Xu Wen(徐 文)[d)]

[a)] *Key Laboratory of Nanodevices and Applications, Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou* 215123, *China*

[b)] *Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*

[c)] *University of Chinese Academy of Sciences, Beijing* 100049, *China*

[d)] *Institute of Solid State Physics, Chinese Academy of Sciences, Hefei* 230031, *China*

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We present a theoretical study on the electric field driven plasmon dispersion of the two-dimensional electron gas (2DEG) in AlGaN/GaN high electron mobility transistors (HEMTs). By introducing a drifted Fermi–Dirac distribution, we calculate the transport properties of the 2DEG in the AlGaN/GaN interface by employing the balance-equation approach based on the Boltzmann equation. Then, the nonequilibrium Fermi–Dirac function is obtained by applying the calculated electron drift velocity and electron temperature. Under random phase approximation (RPA), the electric field driven plasmon dispersion is investigated. The calculated results indicate that the plasmon frequency is dominated by both the electric field $\boldsymbol{E}$ and the angle between wavevector $\boldsymbol{q}$ and electric field $\boldsymbol{E}$. Importantly, the plasmon frequency could be tuned by the applied source–drain bias voltage besides the gate voltage (change of the electron density).

**Keywords:** two-dimensional electron gas, plasmon, AlGaN/GaN, high electron mobility transistor

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## 1. Introduction

Since the 1990s, there has been much effort to develop various solid state semiconductor devices aiming to generate and detect terahertz (THz) electromagnetic waves. The plasmon based THz source and detector constructed from high electron mobility transistors (HEMTs) have attracted much attention[1–17] because they can be easily controlled by external fields, such as electric fields, magnetic fields, or electromagnetic fields. Originating from the intrinsical strong spontaneous and piezoelectric polarization, there exists a high density two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures, which can reach up to $10^{13}$ cm$^{-2}$ even when the AlGaN barrier layer is not intentionally doped,[18] this high density of 2DEG leads to its plasmon oscillation frequency falling in the THz ($10^{12}$ Hz) range.[13] Thus, the AlGaN/GaN HEMTs have become a promising candidate for THz plasmonic devices.[7,9–12]

Generally, a THz emitter based on the HEMT always needs a source–drain bias voltage to convert the plasmon excitation energy to effective THz radiation.[4–7] When the bias voltage is applied, the produced electric field will accelerate and heat the 2DEG in the HEMT. Thus the momentum distribution of the 2DEG obeys a nonequilibrium Fermi–Dirac distribution instead of the equilibrium state distribution. As a result, the plasmon dispersion of the 2DEG is quite different from that in the equilibrium state. In this paper, we present a detailed investigation on the electric field driven plasmon of the 2DEG in AlGaN/GaN HEMTs by taking into account the interactions between phonons and electrons.

## 2. Theoretical approach

We consider a 2DEG sheet in an AlGaN/GaN HEMT whose growth direction is along the $z$ axis with a confining potential $U(z)$, and the electron transport occurs in the $xy$ plane. Due to $U(z)$, the 2DEG in the potential well will form subbands. For simplicity, we assume that the lowest subband is occupied by electrons and the confinement profile can be accurately described by the Fang–Howard variational wavefunction[19]

$$\psi(z) = \left(\frac{1}{2}b^3z^2\right)^{1/2}\exp\left(-\frac{1}{2}bz\right), \tag{1}$$

where $b$ is a variational parameter given by $b = (12m^*e^2N/\kappa\hbar^2)^{1/3}$, $\hbar$ is the reduced Planck constant, $N = (N_{\rm dep} + 11/32n_{\rm s})$ with $n_{\rm s}$ being the density of the 2DEG in the AlGaN/GaN interface, $\kappa$ and $N_{\rm dep}$ are the static dielectric constant of GaN and the depleted electron concentration in the barrier region, respectively.

In relatively high temperatures (typically higher than 77 K), the phonon–electron interactions are the main scatter-

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†Corresponding author. E-mail: hqin2007@sinano.ac.cn

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ing mechanism in the AlGaN/GaN HEMTs. The Hamiltonian describing the general electron–phonon interaction takes the form

$$H_{\rm ep} = \sum_{q_z} [V_{\boldsymbol{Q}} a_{\boldsymbol{Q}} \, {\rm e}^{\,{\rm i}(\boldsymbol{Q}\cdot\boldsymbol{R}+\omega_{\boldsymbol{Q}}t)} + V_{\boldsymbol{Q}}^{*} a_{\boldsymbol{Q}}^{\dagger} \, {\rm e}^{\,-{\rm i}(\boldsymbol{Q}\cdot\boldsymbol{R}+\omega_{\boldsymbol{Q}}t)}], \quad (2)$$

where $\boldsymbol{Q} = (\boldsymbol{q}, q_z) = (q_x, q_y, q_z)$ is the phonon wavevector, $V_{\boldsymbol{Q}}$ is the electron–phonon interaction coefficient, $\omega_Q$ is the phonon frequency, $a_{\boldsymbol{Q}}^{\dagger}$ and $a_{\boldsymbol{Q}}$ are the phonon creation and annihilation operators, respectively. In such a system, the rate of electronic transition induced by the electron–phonon interaction can be obtained from Fermi's golden rule. The probability for scattering an electron from initial state $|\boldsymbol{k}\rangle$ to final state $|\boldsymbol{k}'\rangle$ can be expressed as

$$W(\boldsymbol{k},\boldsymbol{k}') = \frac{2\pi}{\hbar} \sum_{\boldsymbol{q}_z} \begin{bmatrix} N_Q \\ N_Q + 1 \end{bmatrix} |V_{\boldsymbol{Q}}|^2 G(q_z) \times \delta_{\boldsymbol{k}',\boldsymbol{k}+\boldsymbol{q}} \delta[E(\boldsymbol{k}) - E(\boldsymbol{k}') \pm \hbar\omega_Q], \quad (3)$$

where $\boldsymbol{q} = (q_x, q_y)$ is the change of the electron wavevector during an electron scattering event, and the upper (lower) case refers to the absorption (emission) of a phonon, $N_Q = ({\rm e}^{\hbar\omega_Q/k_{\rm B}T} - 1)^{-1}$ is the phonon occupation number, $k_{\rm B}$ is the Boltzmann constant, $T$ is the lattice temperature, and $G(q_z) = |\int {\rm d}z \; \psi^*(z)\psi(z)\,{\rm e}^{\,{\rm i}q_z z}|^2$ is the form factor for the electron–phonon interaction in a 2DEG system.

In this work, we take into account longitude polar optical (LO) phonons, deformation potential phonons, and piezoelectric phonons as the main scattering mechanisms. For the electron–LO-phonon interaction described by the Fröhlich Hamiltonian, we have[20]

$$|V_{\rm LO}(\boldsymbol{Q})|^2 = 4\pi\alpha L_0 (\hbar\omega_{\rm LO})^2 / Q^2, \quad (4)$$

where $\alpha = 0.458$ is the electron–LO-phonon coupling constant, $\hbar\omega_{\rm LO} = 90.5$ meV is the LO-phonon energy, $L_0 = (\hbar/2m^*\omega_{\rm LO})^{1/2}$ is the polaron radius with the effective electron mass $m^* = 0.21 m_{\rm e}$ in GaN. The squares of the interaction coefficient $|V_{\boldsymbol{Q}}|^2$ for the deformation potential, longitudinal piezoelectric and transverse piezoelectric scatterings are given by[20]

$$|V_{\rm DP}(\boldsymbol{Q})|^2 = \frac{{E_{\rm D}}^2 \hbar Q}{2\rho v_{\rm l}}, \quad (5)$$

$$|V_{\rm LP}(\boldsymbol{Q})|^2 = \frac{32\pi^2\hbar^2 (eh_{14})^2}{\kappa^2 \rho v_{\rm l}} \frac{(3q_x q_y q_z)^2}{Q^7}, \quad (6)$$

$$|V_{\rm TP}(\boldsymbol{Q})|^2 = \frac{32\pi^2\hbar^2 (eh_{14})^2}{\kappa^2 \rho v_{\rm t} Q^5} ({q_x}^2 {q_y}^2 + {q_y}^2 {q_z}^2 + {q_z}^2 {q_x}^2) - \frac{(3q_x q_y q_z)^2}{Q^2}, \quad (7)$$

where $E_{\rm D} = 8.5$ eV is the deformation potential constant, $\rho = 6.1$ g/cm$^3$ is the density of GaN, $\kappa = 9.5$ is the dielectric constant, $h_{14} = 4.28 \times 10^7$ V/cm is the piezoelectric constant, $v_{\rm l} = 6.6 \times 10^5$ cm/s and $v_{\rm t} = 2.7 \times 10^5$ cm/s are the longitudinal and transverse sound velocities in GaN, respectively.

In the present study, we use the semiclassic Boltzmann equation to study the transport properties of the 2DEG driven by electric field $E_x$ along the $x$ direction. In degenerate statistics, the steady-state Boltzmann equation can be written as[21]

$$-\frac{eE_x}{\hbar} \frac{\partial f(\boldsymbol{k})}{\partial k_x} = g_{\rm s} \sum_{i,\boldsymbol{k}'} [F(\boldsymbol{k}',\boldsymbol{k}) - F(\boldsymbol{k},\boldsymbol{k}')], \quad (8)$$

with $F(\boldsymbol{k},\boldsymbol{k}') = f(\boldsymbol{k})[1 - f(\boldsymbol{k}')]W_i(\boldsymbol{k},\boldsymbol{k}')$, $g_{\rm s} = 2$ accounts for the spin degeneracy, $f(\boldsymbol{k})$ is the momentum-distribution function for an electron at state $|\boldsymbol{k}\rangle$, and $i$ stands for different scattering mechanism.

It is well known that there is no simple and analytical solution to the Boltzmann equation with the electronic transition rate given by Eq. (3). Here, we employ the usual balance-equation approach to solve the problem.[22–24] The balance-equation approach based on the Boltzmann equation can be used to solve the linear and nonlinear transport problems for an electron gas system. The advantage is that one can avoid the difficulties of solving the Boltzmann equation directly and the physical properties can be calculated on the basis of the statistical momentum-distribution functions. Here we assume that the momentum-distribution function for a carrier can be described by a drifted energy-distribution function

$$f(\boldsymbol{k}) \simeq f(E(\boldsymbol{k}^*)), \quad (9)$$

where $E(\boldsymbol{k}) = \hbar^2 k^2 / 2m^*$ is the energy dispersion, $\boldsymbol{k}^* = \boldsymbol{k} - m^*\boldsymbol{v}/\hbar$ is the drifted momentum due to the presence of the driving field $E_x$, $\boldsymbol{v} = (v, 0, 0)$ is the average drift velocity of the electrons, $T_{\rm e}$ is the electron temperature, and $f(x, T_{\rm e}) = [{\rm e}^{(x-E_{\rm F})/k_{\rm B}T_{\rm e}} + 1]^{-1}$ with $E_{\rm F}$ being the Fermi energy of the 2DEG system, which is determined by the electron density $n_{\rm s} = g_{\rm s} \sum_{\boldsymbol{k}} f(\boldsymbol{k})$. For the first moment, the momentum-balance equation can be derived by multiplying $g_{\rm s} \sum_{\boldsymbol{k}} k_x$ to both sides of Eq. (8), which reads

$$eE_x n_{\rm s} = 4\hbar \sum_{i,\boldsymbol{k}',\boldsymbol{k}} (k_x' - k_x) F(\boldsymbol{k},\boldsymbol{k}'). \quad (10)$$

For the second moment, the energy-balance equation can be derived by multiplying $g_{\rm s} \sum_{\boldsymbol{k}} E(\boldsymbol{k})$ to both sides of Eq. (8), which reads

$$eE_x v n_{\rm s} = 4 \sum_{i,\boldsymbol{k}',\boldsymbol{k}} [E(\boldsymbol{k}') - E(\boldsymbol{k})] F(\boldsymbol{k},\boldsymbol{k}'). \quad (11)$$

The drift velocity $v$ and electron temperature $T_{\rm e}$ for a given electric field can be obtained by solving the momentum- and energy-balance equations self-consistently. Then the nonequilibrium electron distribution function under an electric field can be obtained by using Eq. (9).

From the drifted Fermi–Dirac distribution function, we can study the electric field driven plasmon dispersion of the

2DEG system in the AlGaN/GaN HEMTs. In the random phase approximation (RPA),[25,26] the dielectric function of the 2DEG system is

$$\epsilon(q,\omega) = 1 - v(q)\Pi(q,\omega), \tag{12}$$

where $v(q) = 2\pi e^2/\kappa q$ is the 2D Coulomb interaction, and $\Pi(q,\omega)$ is the electron density–density correlation function, which can be expressed as

$$\Pi(q,\omega) = \sum_{\boldsymbol{k}} \frac{f(E(\boldsymbol{k}^*+\boldsymbol{q})) - f(E(\boldsymbol{k}^*))}{E(\boldsymbol{k}+\boldsymbol{q}) - E(\boldsymbol{k}) - \hbar\omega - \mathrm{i}\delta}. \tag{13}$$

The real and imaginary parts of the density–density correlation function can be written as

$$\Pi_1(q,\omega) = \sum_{\boldsymbol{k}} \frac{f(E(\boldsymbol{k}^*+\boldsymbol{q})) - f(E(\boldsymbol{k}^*))}{E(\boldsymbol{k}+\boldsymbol{q}) - E(\boldsymbol{k}) - \hbar\omega}, \tag{14}$$

$$\Pi_2(q,\omega) = -2\pi \sum_{\boldsymbol{k}} [f(E(\boldsymbol{k}^*+\boldsymbol{q})) - f(E(\boldsymbol{k}^*))] \times \delta(E(\boldsymbol{k}+\boldsymbol{q}) - E(\boldsymbol{k}) - \hbar\omega). \tag{15}$$

The plasmon dispersion is determined by

$$\epsilon(q,\omega) = 0. \tag{16}$$

In the long wavelength limit ($q \to 0$), the electric field driven plasmon dispersion has an analytic solution, which reads

$$\omega(q, E_x) = \omega_0 + \boldsymbol{q}\cdot\boldsymbol{v}, \tag{17}$$

where $\omega_0 = \sqrt{2\pi n_s e^2 q/m^*\kappa}$ is the classical plasmon frequency[25] when there is no source–drain bias voltage applied. As $v$ is electric field dependent, the plasmon frequency can be tuned by the driven electric field via changing the source–drain voltage.

## 3. Numerical results and discussion

In the numerical calculations, we set the two-dimensional electron density to be $n_s = 5\times10^{12}$ cm$^{-2}$. Since the optical phonon has a large energy, the hot-phonon effect can only be observed under a very intense driven electric field. Thus, the equilibrium phonon distribution is applied in the present work.

Figure 1 shows the drift velocity of the 2DEG with applied electric field $E_x$ in the AlGaN/GaN HEMT at different lattice temperatures $T$ based on Eqs. (10) and (11). It can be found that the drift velocity $v$ increases linearly with increasing electric field in the low field regime and the threshold $E_x$ increases with increasing lattice temperature. The drift velocity begins to increase smoothly when the threshold field reaches to 0.1 kV/cm, 1 kV/cm, and 5 kV/cm at the lattice temperatures of $T = 77$ K, 200 K, and 300 K, respectively. The inset of Fig. 1 gives the electron temperature as a function of $E_x$. We find that the electron temperature is very close to the lattice temperature in the linear regime. At the same time, the lower $E_x$, the less difference between the electron temperature and the lattice temperature. Finally, the electron temperatures at different temperatures reach the same value when $E_x$ is higher than 60 kV/cm. In the $E_x \to 0$ limit, the solution of the balance equations yields $T_e = T$. In this regime, the electric field mainly accelerates electrons and the electrons are not heated. In the nonlinear regime, the electron temperature becomes higher than the lattice temperature, and $T_e$ increases rapidly with increasing electric field. Therefore, it is observed that the higher the lattice temperature is, the wider the linear response regime is. The calculation indicates that electrons can more easily gain energy from the electric field at low lattice temperature than that at higher temperature.

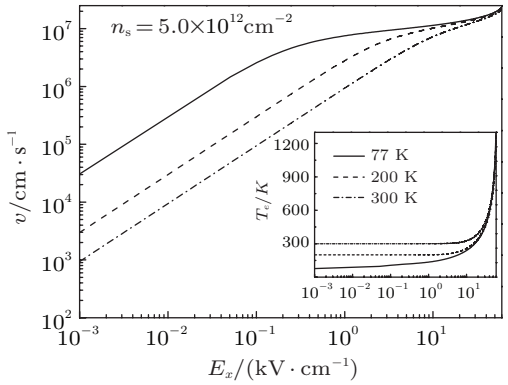



**Fig. 1.** (color online) Drift velocity $v$ and electron temperature $T_e$ (inset) as a function of the electric field $E_x$ at different lattice temperatures $T$.

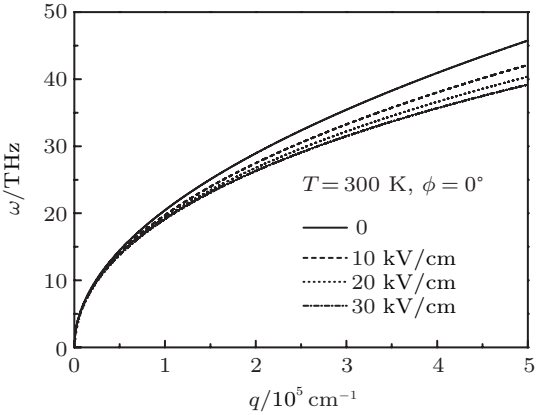



**Fig. 2.** (color online) Plasmon dispersions for different electric fields $E_x$ at room temperature, $\phi$ is the angle between $\boldsymbol{q}$ and $E_x$.

Figure 2 displays the plasmon dispersions for four different electric fields at room temperature. It can be seen that the frequency of the plasmon oscillation ($\omega/2\pi$) falls into the THz range in a wide range of wavevector $q$, which indicates that the AlGaN/GaN HEMT is suitable for THz plasmonic devices at room temperature. Furthermore, at a fixed wavevector parallel to the electric field, the plasmon frequency decreases with increasing electric field, as $v$ and $T_e$ increase with the increase

of $E_x$. Figure 3 shows the plasmon frequency as a function of the electric field at different lattice temperatures when the wavevector is a constant $q = 10^5$ cm$^{-1}$. A large discrepancy of plasmon frequency is observed at different lattice temperatures in the linear regime, and the discrepancy becomes smaller with $E_x$ increasing. This corresponds to that the drift velocity is getting close with $E_x$ increasing in the nonlinear regime for different lattice temperatures.

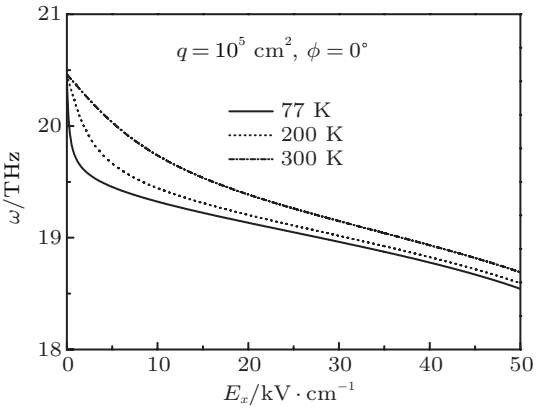



**Fig. 3.** (color online) The plasmon frequency as a function of the electric field at different lattice temperatures when $q = 10^5$ cm$^{-1}$, $\phi$ is the angle between $\boldsymbol{q}$ and $E_x$.

## 4. Summary

We have studied the electric field driven plasmon dispersion in AlGaN/GaN HEMTs based on the drifted Fermi–Dirac distribution and the balance equation approach. The calculated results indicate that the plasmon frequency in the AlGaN/GaN HEMT can also be tuned by the applied drain–source bias voltage besides the gate voltage. The theoretical approach provides an effective method for modeling THz plasmonic devices based on HEMTs.

## References


[1] Okisu N, Sambe Y and Kobayashi T 1986 *Appl. Phys. Lett.* **48** 776
[2] Dyakonov M and Shur M 1993 *Phys. Rev. Lett.* **71** 2465
[3] Dyakonov M and Shur M 1996 *IEEE Trans. Electron Devices* **43** 380
[4] Otsuji T, Meziani Y M, Hanabe M, Ishibashi T, Uno T and Sano E 2006 *Appl. Phys. Lett.* **89** 263502
[5] Meziani Y M, Handa H, Knap W, Otsuji T, Sano E, Popov V V, Tsymbalov G M, Coquillat D and Teppe F 2008 *Appl. Phys. Lett.* **92** 201108
[6] Saxena H, Peale R E and Buchwald W R 2009 *J. Appl. Phys.* **105** 113101
[7] Fatimy A E, Dyakonova N, Meziani Y, Otsuji T, Knap W, Vandenbrouk S, Madjour K, Théron D, Gaquiere C, Poisson M A, Delage S, Prystawko P and Skierbiszewski C 2010 *J. Appl. Phys.* **107** 024504
[8] Peralta X G, Allen S J, Wanke M C, Harff N E, Simmons J A, Lilly M P, Reno J L, Burke P J and Eisenstein J P 2002 *Appl. Phys. Lett.* **81** 1627
[9] Sun Y F, Sun J D, Zhou Y, Tan R B, Zeng C H, Xue W, Qin H, Zhang B S and Wu D M 2011 *Appl. Phys. Lett.* **98** 252103
[10] Sun Y F, Sun J D, Zhang X Y, Qin H, Zhang B S and Wu D M 2012 *Chin. Phys. B* **21** 108504
[11] Sun J D, Sun Y F, Wu D M, Cai Y, Qin H and Zhang B S 2012 *Appl. Phys. Lett.* **100** 013506
[12] Sun J D, Qin H, Lewis R A, Sun Y F, Zhang X Y, Cai Y, Wu D M and Zhang B S 2012 *Appl. Phys. Lett.* **100** 173513
[13] Rabbaa S and Stiens J 2011 *J. Phys. D: Appl. Phys.* **44** 325103
[14] Nakamura S, Mukai T and Senoh M 1994 *Appl. Phys. Lett.* **64** 1687
[15] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 *Jpn. J. Appl. Phys.* **35** L74
[16] Chow T P and Tyagi R 1994 *IEEE Trans. Electron Devices* **41** 1481
[17] Tilak V, Green B, Kaper V, Kim H, Prunty T, Smart J, Shealy J and Eastman L 2001 *IEEE Electron Device Lett.* **22** 504
[18] Ambacher O, Foutz B, Smart J, Shealy J R, Weimann N G, Chu K, Murphy M, Sierakowski A J, Schaff W J, Eastman L F, Dimitrov R, Mitchell A and Stutzmann M 2000 *J. Appl. Phys.* **87** 334
[19] Stern F and Howard W E 1967 *Phys. Rev.* **163** 816
[20] Lei X L, Birman J L and Ting C S 1985 *J. Appl. Phys.* **58** 2270
[21] Chattopadhyay D and Queisser H J 1981 *Rev. Mod. Phys.* **53** 745
[22] Xu W, Peeters F M and Devreese J T 1991 *Phys. Rev. B* **43** 14134
[23] Xu W and Zhang C 1997 *Phys. Rev. B* **55** 5259
[24] Tan R B, Xu W, Zhou Y, Zhang X Y and Qin H 2012 *Physica B* **407** 4277
[25] Stern F 1967 *Phys. Rev. Lett.* **18** 546
[26] Wang X F 2005 *Phys. Rev. B* **72** 085317