Plasma oscillations in high-electron-mobility transistors with recessed gate

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We calculate the plasma oscillation spectrum in high-electron-mobility transistors (HEMTs) with recessed gate having the highly doped caps adjacent to the source and drain contacts and the windows between the caps and the gate. The resonant plasma frequencies are found as functions of the lengths of the gate, cap, and window regions, the electron concentration in the transistor channel, and the gate voltage. We demonstrate that the effect of cap region can result in a significant reduction of the resonant frequencies in comparison with those calculated for simplified HEMT model. This can provide a plausible explanation of the data obtained in recent experimental studies of the detection of terahertz radiation in and its emission from HEMTs. © 2006 American Institute of Physics. [DOI: 10.1063/1.2191628]

I. INTRODUCTION

Plasma oscillations, i.e., self-consistent spatiotemporal variations of the electron density and electric field in field-effect transistors with sufficiently high electron mobility in the channel can be effectively used for the detection, frequency multiplication, and generation of the terahertz radiation. In recent experiments, detection of terahertz radiation in and terahertz emission from high-electron-mobility transistors (HEMTs) attributed to the resonant excitation of plasma oscillations were observed. However, several important features of the observed effects, in particular, the dependences of the resonant plasma frequencies on the HEMT geometrical parameters and the gate voltage cannot be explained in the framework of the “orthodox” theory based on a simplified HEMT model. The latter disregards the presence in the real HEMT structures of the highly doped caps adjacent to the source and drain contacts and the windows between the caps and the gate. The effect of the window (ungated) regions of the channel on the plasma spectrum in HEMTs was recently considered theoretically. As shown, the window regions of the channel decrease the resonant plasma frequencies associated with the oscillations of the electron density and electric field mainly in the gated section of the channel. In HEMTs with the recessed gate used in experiments on the plasma oscillations excitation, the portions of the channel under the highly doped and, therefore, highly conducting cap layers can also play an important role in the net plasma spectrum because the latter is determined by the electron system in all portions of the channel. In this paper, we develop a device model for HEMTs with the recessed gate. Using this model, we calculate the resonant plasma frequencies as functions of the lengths of the gate, cap, and window regions, the electron concentration in the transistor channel, and the gate voltage.

Consider the HEMT structure shown in Fig. 1. The HEMT channel between the highly conducting source and drain contacts comprises the following five regions. Three of them are covered by the gate (gated region of the channel) and the source and drain sections of the cap layer (cap regions), respectively. Due to rather high conductivity of the gate and the cap layer, the regions between the gate and the source and drain contacts and the windows between the caps and the gate. The effect of the window (ungated) regions of the channel on the plasma spectrum in HEMTs was recently considered theoretically. As shown, the window regions of the channel decrease the resonant plasma frequencies associated with the oscillations of the electron density and electric field mainly in the gated section of the channel. In HEMTs with the recessed gate used in experiments on the plasma oscillations excitation, the portions of the channel under the highly doped and, therefore, highly conducting cap layers can also play an important role in the net plasma spectrum because the latter is determined by the electron system in all portions of the channel. In this paper, we develop a device model for HEMTs with the recessed gate. Using this model, we calculate the resonant plasma frequencies as functions of the lengths of the gate, cap, and window regions, the electron concentration in the transistor channel, and the gate voltage.

Consider the HEMT structure shown in Fig. 1. The HEMT channel between the highly conducting source and drain contacts comprises the following five regions. Three of them are covered by the gate (gated region of the channel) and the source and drain sections of the cap layer (cap regions), respectively. Due to rather high conductivity of the gate and the cap layer, the regions between the gate and the source and drain sections of the cap layers (gated and cap regions) exhibit linear plasma wave spectra (“shallow water” spectra). The behavior of the electron system in the source-gate and gate-drain regions (window regions) is markedly different (“deep water”spectra). Considering the analogy of the plasma oscillations in the HEMTs under consideration with the oscillations in water channels, one can say that the plasma spectrum in a HEMT with a complex structure is akin to that in the water channel with a spatially nonuniform depth.

FIG. 1. Schematic view of the HEMT structure.
II. DEVICE MODEL

The electron system in the channel can be described by the hydrodynamic equations coupled with the Poisson equation for the self-consistent electric potential. 1,11 Using these equations as in Refs. 9 and 10, one can arrive at the following equations for the ac component of the potential \( \delta \varphi_{\omega} \) in the gated region \((|x| \leq L_g/2)\) and in the cap regions \((L_g/2 + L_w \leq |x| \leq L_g/2 + L_c + L_d = L)\) of the channel, where \( L_g \), \( L_w \), and \( L_d \) are the lengths of the gate, windows, and caps, respectively, so that \( 2L \) is the distance between the source and drain contacts,

\[
\frac{d^2 \delta \varphi_{\omega}}{dx^2} + \frac{\omega (\omega + i \nu)}{s^2} \delta \varphi_{\omega} = 0, \quad (1)
\]

at \( |x| \leq L_g/2 \), and

\[
\frac{d^2 \delta \varphi_{\omega}}{dx^2} + \frac{\omega (\omega + i \nu)}{s^2} \delta \varphi_{\omega} = 0, \quad (2)
\]

at \( L_g/2 + L_w \leq |x| \leq L \). Here \( \omega \) is the signal frequency, \( \nu \) is the electron collision frequency in the gated portion of the channel, \( \nu_g = \sqrt{4 \pi e^2 \Sigma_{0,0} W/\varepsilon m} \) and \( s = \sqrt{4 \pi e^2 \Sigma_0 W/\varepsilon m} \) are the plasma wave velocities in the gated and cap regions, \( \Sigma_{0,0} \) and \( \Sigma_0 \) are the electron dc concentrations in these regions, \( W \) is the thickness of the gate layer, \( e \) and \( m \) are the electron charge and effective mass, respectively, \( \varepsilon \) is the dielectric constant, and the axis \( x \) is directed along the channel. For the sake of simplicity, we consider HEMTs with a symmetrical structure in which the spacing between the source and gate, \( L_{sg} \), and the gate and drain \( L_{sd} \), as well as the pertinent cap and window regions lengths are equal (see Fig. 1). The quantities \( \Sigma_{0,0} \) and \( \Sigma_0 \) are determined by the doping of the channel (or gate layer). However, \( \Sigma_{0,0} \) depends also on the applied gate voltage \( V_g \) : \( \Sigma_{0,0} = \mu_e V_{th} / 4 \pi e W \) and \( \Sigma_0 = \mu_e (V_g - V_{th}) / 4 \pi e W \), where \( V_{th} \) is the HEMT threshold voltage \( (V_{th} < 0) \). Therefore, \( s = s_v \nu_g \), where \( s = \sqrt{4 \pi e^2 \mu_e V_{th}} / m \) and \( \nu_g = \sqrt{\mu_e (V_g - V_{th})} / W \). In HEMTs made of nitrides, the dc electron concentrations can be primarily determined by the polarization field. In deriving Eqs. (1) and (2), we neglected the effect of the electron drift on the plasma oscillations, more precisely on their resonant frequencies (remembering that such a drift can markedly affect the plasma oscillations growth rate, in particular, due to Dyakonov-Shur mechanism).4,12 This can be justified if the electron drift velocity in the gated regions \( v \ll \omega L_c, \omega L_d \). This inequality is satisfied under HEMT real operation conditions.

As shown previously,9,10 the window regions can be considered as resistive regions whose differential conductivities, \( \sigma_{sg} \) and \( \sigma_{gd} \), depend on their lengths and conditions of the current flow across them (see below). This is valid if \( L_w < L_c / W \).\( L_d / W \) (see Ref. 10) at the frequencies \( \omega \) small compared with the characteristic frequencies of the electron transit across the window regions. At low drain voltages, \( V_d \ll V_{sat} \) (\( V_{sat} \) is the HEMT saturation voltage), \( \sigma_{sg} \) and \( \sigma_{gd} \) are given by the Drude formula: \( \sigma_{sg} = e^2 \Sigma_{0,0} / m (\nu - i \omega) = \sigma_{gd} = e^2 \Sigma_0 / m (\nu - i \omega) \). However, at \( V_d \gg V_{sat} \), the differential conductivity of the gate-drain section of the channel becomes small, and it tends to zero with increasing drain voltage. In this case, \( \sigma_{sg} \gg \sigma_{gd} \). Thus, the main parameters characterizing the plasma properties of the electron system in the HEMT channel and, hence, the resonant plasma frequencies depend on both the gate and drain voltages.

The boundary conditions for Eqs. (1) and (2) are

\[
\delta \varphi_{\omega} |_{x=\pm L} = 0. \quad (3)
\]

The matching conditions for the ac potentials given by Eqs. (1) and (2) are the conditions of continuity of the ac potential and current at points \( x = \pm L_g/2 \) and \( x = \pm (L_c + L_d)/2 \).

III. PLASMA OSCILLATION SPECTRUM

(Low Drain Voltages)

The problem of the plasma oscillations is similar to that for free oscillations in a chain consisting of flexible string sections (this section correspond to the gated regions of the channel) and hard sections (which correspond to the window regions).

Solving Eqs. (1) and (2) and taking into account boundary conditions (3), we arrive at the following spatial distribution of the ac potential in the gated regions:

\[
\delta \varphi_{\omega} = A \sin \left( \frac{\sqrt{\omega (\omega + i \nu)}}{s} (x + L) \right), \quad (4)
\]

at \( -L \leq x \leq -(L_w + L_d)/2 \),

\[
\delta \varphi_{\omega} = B \sin \left( \frac{\sqrt{\omega (\omega + i \nu)}}{s \nu_g} x \right) + C \cos \left( \frac{\sqrt{\omega (\omega + i \nu)}}{s \nu_g} x \right), \quad (5)
\]

at \( -(L_g/2 + L_d/2) \leq x \leq L_g/2 \), and

\[
\delta \varphi_{\omega} = D \sin \left( \frac{\sqrt{\omega (\omega + i \nu)}}{s} (x - L) \right), \quad (6)
\]

at \( (L_w + L_d/2) \leq x \leq L \). Here \( A, B, C, \) and \( D \) are constants to be found from the matching conditions.

Consider first, the case \( \sigma_{sg} = \sigma_{gd} \). In this case, the matching conditions become

\[
u_g \frac{d\delta \varphi_{\omega}}{dx} \bigg|_{x=L_g/2} = \frac{d\delta \varphi_{\omega}}{dx} \bigg|_{x=(L_c+L_d)/2} \quad (7)
\]

and

\[
\frac{\delta \varphi_{\omega} |_{x=L_g/2} - \delta \varphi_{\omega} |_{x=(L_c+L_d)/2}}{L_w \nu_g} = \frac{d\delta \varphi_{\omega}}{dx} \bigg|_{x=L_g/2}. \quad (8)
\]

Taking into account these conditions, we arrive at the following dispersion equations for the symmetric \( \delta \varphi_{\omega}(x) = \delta \varphi_{\omega}(-x) \), so that \( A = D = B = 0 \) and asymmetric \( \delta \varphi_{\omega}(x) = -\delta \varphi_{\omega}(-x) \) with \( A = -D \) and \( C = 0 \) modes of plasma oscillations:
FIG. 2. Fundamental plasma frequency vs the cap and gate lengths for different window length \( L_w = 100 \) nm at \( v_g = 1 \).

\[
\sqrt{v_g} \tan \left[ \frac{\sqrt{\omega (\omega + iv)L_g}}{2s/v_g} \right] \times \left[ \frac{\sqrt{\omega (\omega + iv)L_w}}{s} + \tan \left( \frac{\sqrt{\omega (\omega + iv)L_c}}{s} \right) \right] = 1, \tag{9}
\]

\[
\sqrt{v_g} \cot \left[ \frac{\sqrt{\omega (\omega + iv)L_g}}{2s/v_g} \right] \times \left[ \frac{\sqrt{\omega (\omega + iv)L_w}}{s} + \tan \left( \frac{\sqrt{\omega (\omega + iv)L_c}}{s} \right) \right] = -1. \tag{10}
\]

At \( \nu \approx 2s/L_g, s/L_w \) (low electron collision frequency), \( L_w \ll L_g/2, L_c \) (very short window regions), and \( v_g = 1 \) (zeroth applied gate voltage), Eqs. (9) and (10) can be reduced to

\[
\cos \left( \frac{\omega (L_g/2 + L_c)}{s} \right) \approx 0, \tag{11}
\]

for the symmetric modes, and

\[
\sin \left( \frac{\omega (L_g/2 + L_c)}{s} \right) \approx 0. \tag{12}
\]

Equations (11) and (12) yield

\[
\text{Re } \omega = \frac{(2n - 1)\pi s}{(L_g + 2L_c)} = \frac{(2n - 1)L_g}{(L_g + 2L_c)} \Omega \tag{13}
\]

and

\[
\text{Re } \omega = \frac{2n \pi s}{(L_g + 2L_c)} = \frac{2n L_g}{(L_g + 2L_c)} \Omega, \tag{14}
\]

for the symmetric and asymmetric modes, respectively, with \( n = 1, 2, 3, \ldots \). Here \( \Omega = \pi s/L_g \) is the “classical” value of the fundamental plasma frequency \(^1\) in a HEMT with \( L_c = 0 \) and \( L_w = 0 \).

Figure 2 shows the fundamental plasma frequency as a function of the cap and gate lengths for different window length \( L_w = 100 \) nm at \( v_g = 1 \) (short circuited source and gate, \( V_g = 0 \)) calculated using Eq. (9) for a HEMT with an InGaAs channel assuming that the HEMT threshold voltage \( |V_{th}| = 0.2 \) V (Ref. 4) and \( s = 9.37 \times 10^7 \) cm/s and disregarding the electron collisions. In the following we consider HEMTs with the same parameters assuming that other parameters (in particular, \( L_c \) and \( L_w \)) are mainly those of a HEMT with an InGaAs channel used in experiments.\(^{4,8}\)

Figure 3 shows the dependences of fundamental plasma frequency on normalized gate voltage \( v_g \) for HEMTs with \( L_c = 520, L_w = 100 \) nm, and different gate lengths calculated using Eqs. (9) and (10). As seen from Fig. 3, the voltage dependences of the plasma frequencies calculated with inclusion of the cap and window regions exhibit fairly slow voltage dependence in a wide range of the gate voltages. The fundamental plasma frequency markedly increases with decreasing gate length even in HEMTs with rather long cap and window regions, although this dependence is much weaker than that obtained for an “ideal” HEMT \((L_c, L_w \ll L_g)\). For comparison, the voltage dependences for HEMTs with \( L_g = 60 \) nm and \( L_c = L_w = 0 \) (circles) and \( L_c = L_w = 60 \) nm (squares) are shown in the inset in Fig. 3.

IV. PLASMA OSCILLATION SPECTRUM (HIGH DRAIN VOLTAGES)

At sufficiently high drain voltages, the differential conductivity of the gate-drain region becomes rather small with \( v_d = \sigma_{sd}/\sigma_{gd} \gg 1 \). In the case, matching conditions (8) should be replaced by

\[
\frac{\delta \varphi_{sd}}{L_w V_g} \bigg|_{x = -L_g/2} - \frac{\delta \varphi_{sd}}{L_w V_d} \bigg|_{x = -L_g/2 + L_w} = - \frac{d \delta \varphi_{sd}}{dx} \bigg|_{x = -L_g/2}. \tag{15}
\]

When \( v_d \gg 1 \), the second condition (15) is actually equivalent to

\[
\frac{d \delta \varphi_{sd}}{dx} \bigg|_{x = -L_g/2} = 0. \tag{16}
\]

This condition was used previously in studies of plasma instability in HEMTs in the saturation regime.\(^{1,12}\)
FIG. 4. Fundamental plasma frequencies as functions of the gate length at \( v_g = 1 \) and a low drain voltage \((V_d = 0)\) and at high drain voltage \((V_d \approx V_{\text{sat}})\) for HEMTs with \( L_x = 520 \) nm and \( L_w = 100 \) nm: solid and dotted (obtained using simplified formulas) lines correspond to \( \nu = 0 \), and dashed lines correspond to \( \nu = 10^{12} \) s\(^{-1}\).

Using Eqs. (4)–(6) with matching conditions (15) at \( v_g \gg 1 \), one can arrive at the following dispersion equation for the plasma oscillations in a HEMT in the saturation regime:

\[
\sqrt{v_g} \tan \left[ \frac{\sqrt{\omega (\omega + iv)L_x}}{s \sqrt{v_g}} \right] \times \left[ \frac{\sqrt{\omega (\omega + iv)L_w}}{s} + \tan \left( \frac{\sqrt{\omega (\omega + iv)L_x}}{s} \right) \right] = 1 .
\]

In particular, at \( L_w \ll L_x/2, L_c \), Eq. (17) results in

\[
\text{Re} \ \omega \approx \frac{(2n-1) \pi s}{2 (L_x + L_c)} = \frac{(2n-1)}{2} \frac{L_g}{(L_g + L_c)} \Omega.
\]

Figure 4 compares the dependences of the fundamental plasma frequency on the gate length (solid and dashed lines) calculated using Eqs. (9) and (17) at \( v_g = 1 \) and a low drain voltage \((V_d < V_{\text{sat}})\) and at high drain voltage \((V_d > V_{\text{sat}})\). Dotted lines are obtained using simplified Eqs. (13) and (18). One can see that the simplified formulas describe rather correct dependences. In Fig. 5, we compare the dependences of the fundamental plasma frequency on the normalized gate voltage at low and at high drain voltages. Figure 5 demonstrates that the transition from low to high drain voltages leads to a drop of the fundamental (and other) plasma frequencies. This is because at such a transition the effective plasma wavelengths increases from \( \lambda_0 = 2L = 2(2L_x + 2L_w) \) to \( \lambda_0 = 4(L_x + L_w + L_c) \) with \( \lambda_0 > \lambda_0 = 2L_x \) and, consequently, with \( \lambda_0 > \lambda_0 \). As shown previously (for HEMTs without the cap),\(^9,^{10}\) the fundamental plasma frequency markedly decreases with increasing window length. As follows from the above results, the fundamental plasma frequency is rather sensitive to the cap length. Figures 6 and 7 demonstrate how the fundamental plasma frequency varies with the cap length \( L_w \) in HEMTs with very short window region \((L_w = 0)\) and with the window length \( L_w \) in HEMTs without the caps \((L_w = 0)\). The latter dependence coincides with that calculated previously.\(^9,^{10}\) It is instructive that, as seen from Figs. 6 and 7, the fundamental plasma frequency is more sensitive to variations of the cap length than to variations of the window length. A significant effect of the cap region on the plasma oscillation spectrum resulting in a steep decrease in the fundamental plasma frequency with increasing cap length can explain why the fundamental plasma frequency in HEMTs with very short gate \((L_x = 60 \) nm) are markedly smaller than that given by the classical values \text{Re} \ \omega \approx \Omega \) \([\text{for } V_d = 0, \text{ see Eq. (13)}]\) and \text{Re} \ \omega \approx \Omega/2 \) \([\text{for } V_d \approx V_{\text{sat}} \text{ when the mode is nearly asymmetric}, \text{ see Eq. (18)}]\). In particular, for the parameters chosen the classical value of the fundamental plasma frequency \((\text{i.e., for a HEMT with } L_c = 0 \text{ and } L_w = 0)\) is equal to \( \Omega/2 \pi s/2L_g = 7.8 \) THz. At elevated drain voltages, the length of the gated section of the channel, \( L_{\text{eff}} \) becomes shorter than the gate length, \( L_g \) (the gate length modulation effect). For a simplified description this effect can be taken into account using the following phenomenological formula:\(^4\)

\[
L_{\text{eff}} = L_g - \Delta L_g \text{ with } \Delta L_g = (V_d + L_g)\text{ to } \lambda_0 = 4(L_x + L_w + L_c) \text{ with } \lambda_0 > \lambda_0 = 2L_x \text{ and, consequently, with } \lambda_0 > \lambda_0 .
\]

FIG. 5. Dependences of the fundamental plasma frequency on the normalized gate voltage in a HEMT with \( L_x = 60 \) nm, \( L_c = 520 \) nm, and \( L_w = 100 \) nm at low and at high drain voltages.

FIG. 6. Fundamental plasma frequencies vs \( L_w \) for HEMTs with \( L_x = 60 \) nm, \( L_c = 0 \), and \( V_d = 0 \) for \( V_d = 0 \) and \( V_d \approx V_{\text{sat}} \).

FIG. 7. The same as in Fig. 6 but for \( L_g = 150 \) nm.
with longer window and cap regions at the drain side, the resonant plasma frequencies dramatically decrease with increasing cap region length (Fig. 2). The effect of the cap regions on the plasma spectrum is somewhat stronger than that of the window regions (Figs. 6 and 7).

(2) The dependence of the resonant plasma frequencies on the gate voltage (voltage tuning) in HEMTs with long cap region is rather weak (Fig. 3) in contrast to HEMTs with short cap and window regions in which $\text{Re } \omega \propto \sqrt{V_d}$.

(3) Transition from low to high drain voltages results in some change in the resonant plasma frequencies (lowering in HEMTs with a symmetrical structure, Fig. 4). The inclusion of the gate length modulation effect can reverse this trend resulting in a minimum of the fundamental plasma frequency at some value $V_d \sim V_{\text{sat}}$.

V. CONCLUSIONS

We developed a device model for a HEMT with the highly doped caps adjacent to the source and drain contacts and the windows between these caps and the gate to calculate the spectrum of the plasma oscillations. We found the resonant plasma frequencies as functions of the cap, window, and gate lengths and other structural parameters. The following was demonstrated.

1. The cap regions significantly affect the plasma oscillation spectrum in HEMTs: the resonant plasma frequencies dramatically decrease with increasing cap region length (Fig. 2). The effect of the cap regions on the plasma spectrum is somewhat stronger than that of the window regions (Figs. 6 and 7).

2. The dependence of the resonant plasma frequencies on the gate voltage (voltage tuning) in HEMTs with long cap region is rather weak (Fig. 3) in contrast to HEMTs with short cap and window regions in which $\text{Re } \omega \propto \sqrt{V_d}$.

3. Transition from low to high drain voltages results in some change in the resonant plasma frequencies (lowering in HEMTs with a symmetrical structure, Fig. 4). The inclusion of the gate length modulation effect can reverse this trend resulting in a minimum of the fundamental plasma frequency at some value $V_d \sim V_{\text{sat}}$.