REGULAR ARTICLE

Optimizing Terahertz Signal Detection in High Electron Mobility Transistors: Insights from Plasma Resonance Studies

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This analytical modeling study delves into the resonance behavior of plasma waves within the channel of High Electron Mobility Transistors (HEMTs) when subjected to Terahertz (THz) excitation. The core objective is to systematically examine the influence of various HEMT parameters on the dynamics of plasma resonance and the detection of THz signals. A noteworthy finding emerges: the most effective detection of THz signals materializes when both the gate and drain terminals simultaneously receive the THz excitation. Moreover, the modulation of biasing conditions, specifically represented by polarization voltages, exerts a substantial influence on plasma resonance frequencies, offering a promising avenue for tailoring HEMT responses. Further exploration reveals the substantial impact of access region characteristics, including length and doping concentration, on the excitation of 3D plasma waves within the HEMT, with the drain access region demonstrating particular significance. Additionally, we delve into the ramifications of gate geometry, encompassing width and channel-to-gate distance, revealing their capacity to significantly alter 2D plasma resonance frequencies. In extreme cases, the HEMT exhibits behavior akin to a simplified diode configuration, resulting in the absence of 2D plasma resonance. In summation, this research unfolds essential insights for the design and optimization of HEMT-based devices tailored to specific THz frequency applications. It underscores the pivotal roles of biasing conditions, access region properties, and gate geometries in shaping HEMT performance and THz signal detection.

Keywords: Terahertz signal, High electron mobility transistor, Submillimetre waves detection, Semiconductor devices modelling, Plasma waves, Field effect transistor.

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1. INTRODUCTION

The rapid advancement of electronic technology has ushered in an era of unprecedented connectivity, computational power, and information processing. Within this technological tapestry, High Electron Mobility Transistor (HEMT) devices emerge as quintessential components, exemplifying the confluence of cutting-edge semiconductor physics and innovative electronic design. HEMTs, classified as field-effect transistors (FETs), are not merely emblematic of modern semiconductor achievements; they stand as testament to the intricate interplay between theory and practice, where scientific inquiry and engineering acumen converge to create transformative devices [1, 2].

The scope of HEMT applications is extensive, encompassing domains such as high-frequency wireless communication systems, ultra-fast digital logic circuits, sensitive low-noise amplifiers, and precise radar and sensing technologies [3]. The HEMT's exceptional electron mobility, low noise figures, and formidable high-frequency capabilities have rendered it a linchpin in the arsenal of engineers and scientists working on the cutting edge of electronics[4].

However, the true marvel of HEMT technology transcends its conventional utility and extends to the realm of fundamental physics. It is here that we encounter the enigmatic phenomenon of plasma waves (collective oscillations of free electrons) within the confines of HEMT transistor channels [5, 6]. These plasma waves, resonating in the terahertz frequency range, introduce a layer of complexity and intrigue, beckoning researchers to embark on a journey of exploration and understanding [7].

The genesis of this academic endeavor can be traced back to the seminal work of Dyakonov and Shur, who, in the past, postulated the possibility of harnessing plasma waves as a means to detect and generate terahertz (THz) signals at ambient temperatures [8, 9]. Their theoretical predictions laid the foundation for a new frontier in semiconductor physics and technology, a frontier where plasma waves would dance to the tune of applied electric fields, promising an array of applications in THz communication, sensing, and imaging [10, 11].

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The past year marked a pivotal moment in this trajectory when experimental evidence of THz signal emission, arising from the oscillation of plasma waves in HEMT transistors at low temperatures, was reported [12, 13]. This milestone validated the theoretical constructs and kindled the pursuit of exploiting HEMTs as nonlinear elements for the detection and manipulation of incident THz signals at room temperature – an achievement with profound implications for the realization of compact and efficient THz devices [14].

This academic journey aims to traverse the intricate landscape of HEMT plasma waves, delving into the mechanisms governing their resonance, the myriad factors influencing their behavior, and the transformative potential they hold within the purview of THz technology.

Our pursuit extends beyond the confines of theoretical discourse; it involves the practicality of applying THz electric fields to gate and drain terminals, employing hydrodynamic simulations and the pseudo-2D Poisson equation to model THz signal detection, and systematically probing the impact of voltage polarization, gate geometry, and access region parameters on plasma wave resonance phenomena within HEMT structures [15, 16].

We endeavor to unravel the complexities surrounding plasma wave resonances in HEMTs, shed light on their multifaceted interactions with geometrical, electrical, and material parameters, and contribute to the burgeoning field of THz technology [17], where the fusion of fundamental scientific inquiry and engineering innovation continues to redefine the boundaries of what is possible in the realm of electronics and beyond [18].

2. RESEARCH PROCEDURE

To comprehensively elucidate the plasmonic Terahertz (THz) detection phenomenon within the semiconductor channel of a High Electron Mobility Transistor (HEMT), a thorough investigation of the underlying transport phenomena within these devices was undertaken. The endeavor called for the development of an analytical model capable of characterizing crucial physical parameters [19], encompassing charge carrier density n, velocity v, energy ϵ, current density J, and electric field E.

In pursuit of this goal, we adopted a judicious approach known as the Hydrodynamic model. This model offers a balanced compromise between the drift-diffusion model, known for its simplifications, and the computationally intensive Monte Carlo method, which demands substantial computational resources [20, 21].

Within the Hydrodynamic model, equations governing the transport of these physical quantities in the x direction were meticulously formulated. The first equation encapsulates the conservation of matter, representing the charge carrier density n. The second equation characterizes velocity v, while the third equation is dedicated to the conservation of energy ϵ. Detailed formulations of these equations are documented in references [22, 23].

To determine the remaining primary physical quantities, such as current density J and electric field E, a coupling was established between the hydrodynamic equations and the pseudo-2D Poisson equation [24, 25]. This integrated approach bestowed upon us the capacity to comprehensively analyze and understand the intricate interplay between various parameters and phenomena within the HEMT device, thereby providing valuable insights into the plasmonic THz detection process.

The fundamental physical quantities, current density J, and electric field E, were founded through the coupling of the hydrodynamic equations with the pseudo-2D Poisson equation, as represented by Equation (1.2) [25]:

$$\varepsilon_c \frac{\partial^2 V(x,t)}{\partial x^2} + \varepsilon_s \frac{V_{GS} + \Delta V_G + V(x,t)}{d\delta} = e(n - N_D) \qquad (1.2)$$

Where ε_c and ε_s denote the permittivities of the channel and insulator, respectively. The parameters d and δ signify the gate-channel distance and channel thickness, respectively, while e represents the electronic charge and N_D stands for the effective donor density in the channel. The term V_{GS} corresponds to the gate potential.

The THz signal excitation and capture by the gate antenna is described by Equation (2.2):

$$\Delta V_G = \delta V_G \cos(2\pi f t) \qquad (2.2)$$

Here, f denotes the frequency of the incoming THz signal, and δV_G represents its amplitude. The spatial-temporal potential in the channel of the HEMT is denoted as $V(x,t)$. Two boundary conditions for the Poisson equation are detailed in Equations (3.2) and (4.2):

$$V(0,t) = 0 \qquad (3.2)$$

$$V(L,t) = V_{DS} + \Delta V_{DS} \qquad (4.2)$$

The term in Equation (2.2) represents the THz signal excitation captured by the drain antenna of the HEMT, where f represents the frequency of the incoming signal, and δV_{DS} signifies its amplitude.

In Fig. 2, two small resonance peaks are evident at f_1 = 4.6 THz and f_2 = 7.6 THz in the spectrum response of the current. These peaks can be compared to those calculated using the theoretical expression of the Dyak-Shur model, as expressed in Equation (5.2):

$$f_{2D} = n \frac{1}{4L_g} \sqrt{\frac{eV_{GS}}{m}} \qquad (5.2)$$

Here, n = 1, 2, 3…, and it's noteworthy that the first two peaks correspond to the frequency of the 2D plasma resonance in the channel. Additionally, the peak with a higher value corresponds to the frequency of the 3D plasma resonance, as per Equation (6.2):

$$f_{3D} = \frac{e}{2\pi} \sqrt{\frac{n}{m\varepsilon_c}} \qquad (6.2)$$

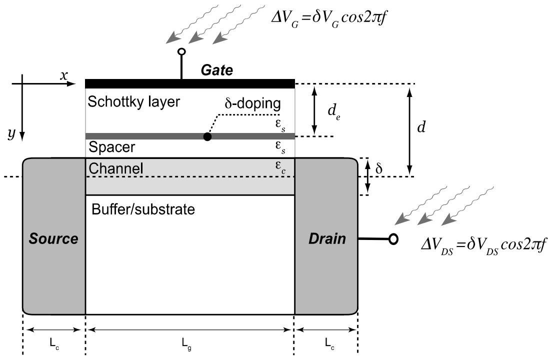

Fig. 1 – Schematic representation of a HEMT

The schematic representation of the simulated HEMT transistor is presented in Fig. 1, illustrating the constituent layers and components within the device structure. Where, from the top to bottom: the gate, the Schottky layer (of width d_e and dielectric coefficient ε_s), the δ-doping plan, the spacer (of dielectric coefficient ε_s), the channel (of width δ and dielectric coefficient ε_c) and the substrate. d is the distance between the gate and the center of the channel (gate-to-channel distance), The width of the transistor is $W = 2L_c + L_g$.

3. RESULTS AND DISCUSSION

In this section, we delve into the outcomes of our investigation, employing the Hydrodynamic model coupled with the pseudo-2D Poisson equation on a High Electron Mobility Transistor (HEMT) device. The HEMT used for our analysis comprises an $In_{0.53}Ga_{0.47}$ As semiconductor channel with specific geometrical parameters: a gate width L_g of 100 nm, a thickness δ of 10 nm, an effective donor density in the channel N_D of 1×10^{18} cm^{-3}, a channel gate distance d of 22 nm, an access region width L_c of 50 nm, and an access region electron concentration N^+ of 5×10^{18} cm^{-3}. The Schottky layer thickness d_e is 12 nm, and its dielectric constant ε_s is 11.8 ε_0, where ε_0 represents the vacuum permittivity. The HEMT is optimally polarized with $V_{GS} = -1$ mV and $V_{DS} = 40$ mV. The THz signal is modeled with δV_G =1 mV and $\delta V_{DS} = 1$ mV.

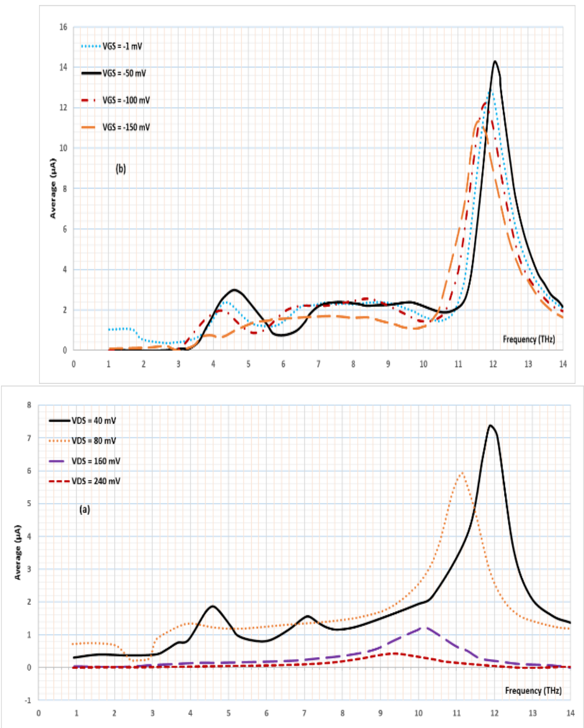

Fig. 2 – Drain current response as functions of the radiation frequency for different gate voltage, (a) excitation applied on the drain, (b) excitation applied on the gate

Our focus centers on studying the average current response at the drain of the HEMT, which represents the conversion of the THz signal into current. In previous work, we demonstrated that THz signals applied to both the gate and the drain antennas excite plasma waves in the HEMT channel. Additionally, we found that the best detection occurs when the drain and gate excitations are nearly in opposite phase. The presented results offer valuable insights into the behavior of plasma waves in High Electron Mobility Transistors (HEMTs) and their response to various parameters.

3.1. Influence of Polarization Voltages

Fig. 2, illustrates the average current response as a function of radiation frequency for two scenarios: (a) excitation applied to the drain $\delta V_G = 0$ mV, $\delta V_{DS} = 1$ mV, $V_{GS} = -1$ mV, for different drain voltages, and (b) excitation applied to the gate of the HEMT $\delta V_G = 1$ mV, $\delta V_{DS} = 0$ mV, $\delta V_{DS} = 40$ mV, for different gate-source voltages. Two small resonance peaks at $f_1 = 4.6$ THz and $f_2 = 7.6$ THz are evident.

In Fig. 2a, where excitation is applied to the drain, an increase in drain voltage results in a decrease in the 2D resonance peaks. This effect is attributed to the increase in electron velocity in the channel, making electron transport less ballistic. For $V_{DS} = 240$ mV, there is no plasma resonance in the channel due to the exceptionally high electron velocity, rendering the movement ballistic.

In Fig. 2b, with excitation applied to the gate, an increase in gate voltage enhances detection. The frequency and amplitude of the plasma resonance peaks are directly proportional to the gate voltage, following the Dyak-Shur model (Equation 2.5). However, for $V_{GS} > 50$ mV, the carrier concentration in the channel decreases, leading to a decrease in the plasma frequency. Where, the Fig. 2a the excitation applied on the drain ($\delta V_G = 0$ mV, $\delta V_{DS} = 1$ mV) for different drain voltage and $V_{GS} = -1$ mV. The Fig. 2b excitation applied on the gate ($\delta V_G = 1$ mV, $\delta V_{DS} = 0$ mV) for different gate voltage and $\delta V_{DS} = 40$ mV. The Access region width $L_c = 50$ nm, access region concentration $N^+ = 5 \times 10^{18}$ cm^{-3}, gate width $L_g = 100$ nm and channel-to-gate distance $d = 22$ nm.

The detection of THz signals at the gate of the HEMT excites plasma waves in the channel more effectively than detection at the drain.

The results indicate that the choice of polarization voltages, specifically the drain and gate biases, has a significant impact on the HEMT's response to Terahertz (THz) signals.

1. **Excitation Location:** When the THz signal is applied to the drain, the increase in drain voltage leads to a decrease in the 2D plasma resonance peaks. This is due to the increased electron velocity in the channel, making electron transport less ballistic. However, at very high drain voltages, there is no plasma resonance, as the electron movement becomes entirely ballistic.
2. **Gate Excitation:** When the THz signal is applied to the gate, higher gate voltages enhance THz detection. The frequency and amplitude of the plasma resonance peaks are directly proportional to the gate voltage, as predicted by the Dyak-Shur model. However, beyond a certain gate voltage threshold, the carrier concentration in the channel decreases, resulting in a decrease in plasma frequency.
3. **Best Detection:** The results suggest that the most effective THz signal detection occurs when the gate and drain excitations are nearly in opposite phases.

3.2. Influence of Access Regions

In this subsection, Fig. 3 presents the average response of drain current as a function of radiation frequency when a THz signal is received simultaneously by both the drain and gate of the HEMT $\delta V_G = 1$ mV, $\delta V_{GS} = 1$ mV.

The length of the access drain region affects the frequency of the 3D plasma resonance; longer access regions result in lower inductance and higher admittance. In contrast, the length of the access source region has a minimal influence on the frequency of the plasma in the HEMT channel, whether it is 2D or 3D.

Comparing the current response for THz signals detected separately by the gate and drain (Fig. 2) with signals detected by both (Figure 3), it is evident that the best detection occurs when THz excitation is received simultaneously by the gate and drain antennas of the HEMT.

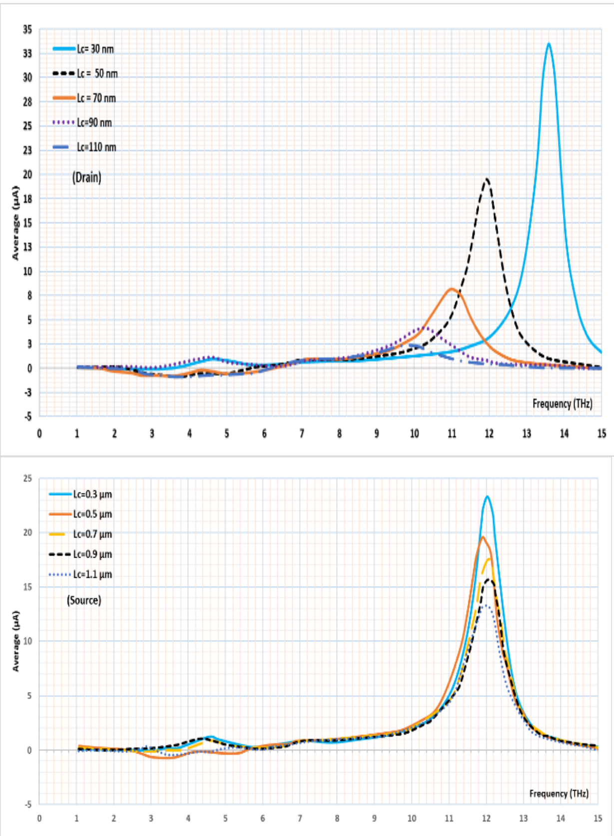

Fig. 3 – Drain current response as functions of the radiation frequency. Where, the THz excitation applied on the drain and the gate simultaneously ($\delta V_G = 1$ mV, $\delta V_{DS} = 1$ mV), the polarizations condition are $V_{DS} = 40$ mV and $V_{GS} = -1$ mV, the HEMT geometrics condition are access region concentration $N^+ = 5{\times}10^{18}$ cm^{-3}, gate width $L_g = 100$ nm and channel-to-gate distance $d = 22$ nm. For: (drain) different access drain region width, (source) different access source region width

Fig. 3, explores the influence of the concentration of the access region N^+ on the average response of the drain current for $V_{DS} = 40$ mV and $V_{GS} = -1$ mV. The results show that the concentration difference between the gate and access region significantly influences the frequency and quality factor of the 3D plasma wave resonance. The maximum frequency corresponds to $N^+ = 5 \times 10^{18}$ cm^{-3}, indicating a long-range Coulomb interaction between electrons in different carrier concentration regions. The variation of the resonance frequency of the 3D plasma wave with respect to the concentration of carriers in the N^+ access. The length of the access regions (source and drain) in the HEMT device was found to influence the THz detection process:

1. **Access Drain Region:** Longer access drain regions led to lower inductance and higher admittance, affecting the frequency of the 3D plasma resonance. This is important for tuning the HEMT's response to specific THz frequencies.
2. **Access Source Region:** In contrast, the length of the access source region had minimal influence on the plasma frequency in the HEMT channel.
3. **Simultaneous Detection:** The study demonstrated that the most effective detection of THz signals occurs when both the gate and drain antennas simultaneously receive the THz excitation.

Fig. 4, explores the influence of the concentration of the access region N^+ on the average response of the drain current for $V_{DS} = 40$ mV and $V_{GS} = -1$ mV. The results show that the concentration difference between the gate and access region significantly influences the frequency and quality factor of the 3D plasma wave resonance. The maximum frequency corresponds to $N^+ = 5 \times 10^{18}$ cm^{-3}, indicating a long-range Coulomb interaction between electrons in different carrier concentration regions.

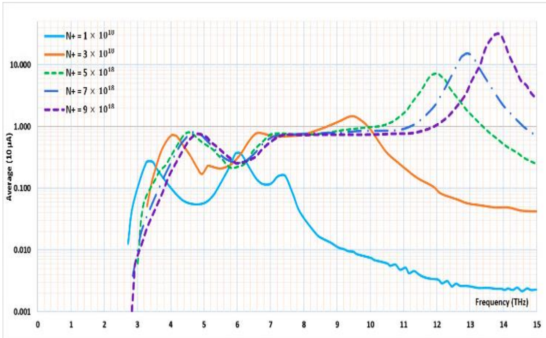

Fig. 4 – Average response of the drain current as functions of the radiation frequency for different access region concentration N^+. where the THz excitation applied on the drain and the gate simultaneously ($\delta V_G = 1$ mV, $\delta V_{DS} = 1$ mV), the polarizations condition are $V_{DS} = 40$ mV and $V_{GS} = -1$ mV, the HEMT geometrics condition are: gate width $L_g = 100$ nm, channel-to-gate distance $d = 22$ nm and access region length $L_c = 50$ nm.

The variation of the resonance frequency of the 3D plasma wave with respect to the concentration of carriers in the N^+ access region is notably larger compared to the variation of the 2D plasma frequency.

3.3. Influence of Geometries

In Fig. 5a, the average current response is plotted as a function of THz signal frequency for different gate widths. Wider gates lead to the removal of the 2D plasma resonance peaks toward lower frequencies, indicating less ballistic electron transport. When the gate width surpasses $L_g = 200$ µm, the 2D plasma waves become entirely extinct. This behavior aligns with Dyak-Shur's model (Equation 2.5), which predicts the influence of gate width on the plasma 2D frequency.

Fig. 5b demonstrates the drain current response as a function of THz signal frequency for different values of the channel-to-gate distance *d*. Higher quality factors and frequencies of the 3D plasma resonance are observed when the channel-to-gate distance is wider. This phenomenon is attributed to the reduced influence of the gate when the distance is wider. The optimal value for maximal 2D plasma resonance peaks is observed at d = 22 nm. Beyond this value, the gate effect becomes negligible, and the HEMT effectively functions as a simple N^+-N-N^+ diode. These observations reveal that wider gate widths and longer channel-to-gate distances influence the behavior of plasma waves in the HEMT channel, influencing both 2D and 3D plasma resonances.

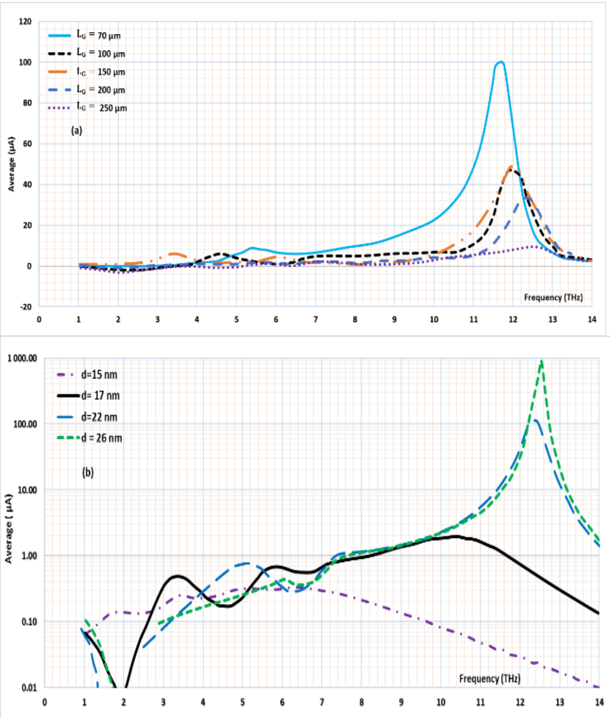

Fig. 5 – Drain current response as functions of the radiation frequency, (a) different gate length and channel-to-gate distance d = 22 nm and (b) different channel to gate distance and L_g = 100 nm. Where, the THz excitation applied on the drain and the gate simultaneously (δV_G = 1 mV, δV_{DS} = 1 mV), the polarizations condition are V_{DS} = 40 mV and V_{GS} = – 1 mV, the HEMT geometrics condition are: access region concentration N^+ = 5 × 10^{18} cm^{-3}, access region length L_c = 50 nm

The geometrical parameters of the HEMT, including gate width and channel-to-gate distance, were explored for their impact on plasma wave behavior.

1. **Gate Width:** Wider gates led to the removal of 2D plasma resonance peaks toward lower frequencies. This indicates that wider gates result in less ballistic electron transport.
2. **Channel-to-Gate Distance:** Greater channel-to-gate distances were associated with higher quality factors and frequencies of the 3D plasma resonance. This suggests that when the channel-to-gate distance is wider, the gate's influence diminishes.

Overall, the results highlight the intricate interplay between various parameters in HEMT devices and their influence on plasma wave behavior and THz signal detection. These findings have important implications for optimizing HEMT designs for specific THz frequency ranges and performance requirements in applications such as THz communication and sensing. Moreover, they underscore the importance of carefully selecting polarization voltages and geometrical parameters to achieve desired resonance frequencies and detection sensitivities in HEMT-based THz devices.

4. CONCLUSION

In this analytical modeling study, we have explored the resonance behavior of 2D and 3D plasma waves within the channel of a High Electron Mobility Transistor (HEMT). By employing this model, we calculated the average drain current response to Terahertz (THz) excitation detected by either the gate or the drain of the HEMT. Our investigation primarily aimed to evaluate the influence of various HEMT parameters on plasma resonance phenomena.

Our key findings and conclusions are as follows:

Optimal THz Signal Detection: We have demonstrated that the optimal detection of THz signals by the HEMT occurs when both the gate and the drain terminals of the device simultaneously receive the THz signal. This synchronized excitation results in enhanced THz signal detection.

Biasing Conditions: We found that varying the polarization voltages (V_DS and V_GS) can significantly affect the frequencies associated with plasma resonance waves within the HEMT channel. Higher biasing conditions can lead to lower resonance frequencies, which is an important consideration for tuning the HEMT's response to specific THz frequencies.

Influence of Access Regions: The length and doping concentration in the access regions were shown to exert a significant influence on plasma resonance phenomena. Specifically, these parameters impact the excitation of 3D plasma waves within the HEMT. Longer access regions can lead to lower inductance and higher admittance, affecting resonance frequencies.

Gate Geometry: The geometric characteristics of the gate were found to significantly impact 2D plasma resonance within the HEMT channel. Wider gates and greater channel-to-gate distances can lead to changes in resonance frequencies. In extreme cases, when gate geometric parameters reach high values, the HEMT behaves like a simplified N^+-N-N^+ diode configuration, resulting in the absence of 2D plasma resonance.

In summary, our study sheds light on the intricate interplay of various HEMT parameters and their influence on plasma resonance behavior. These findings have important implications for the design and optimization of HEMT-based devices for specific THz frequency ranges and applications. Understanding the impact of biasing conditions, access region properties, and gate geometries is crucial for tailoring HEMT devices to meet desired performance requirements in THz communication and sensing applications.

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Оптимізація виявлення терагерцового сигналу в транзисторах з високою рухливістю електронів: висновки з досліджень плазмового резонансу

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Проведено аналітичне моделювання досліджує резонансну поведінку плазмових хвиль у каналі транзисторів з високою рухливістю електронів (HEMT), коли вони піддаються терагерцовому (ТГц) збудженню. Основна мета полягає в систематичному дослідженні впливу різних параметрів HEMT на динаміку плазмового резонансу та виявлення ТГц сигналів. Найефективніше виявлення сигналів ТГц фіксується, коли і затвор, і термінали стоку одночасно отримують збудження ТГц. Крім того, модуляція умов зміщення, зокрема представлена поляризаційними напругами, суттєво впливає на частоти плазмового резонансу, пропонуючи багатообіцяючий шлях для адаптації відповідей HEMT. Подальше дослідження вказує на сильний вплив характеристик області доступу, включаючи довжину та концентрацію легування, на збудження тривимірних плазмових хвиль у HEMT, причому область доступу до стоку демонструє особливе значення. Крім того, детально вивчено розгалуження геометрії затвора, охоплюючи ширину та відстань від каналу до затвора, виявляючи їх здатність суттєво змінювати частоти 2D плазмового резонансу. У екстремальних випадках HEMT демонструє поведінку, подібну до спрощеної конфігурації діода, що призводить до відсутності 2D плазмового резонансу. Дане дослідження розкриває суттєві ідеї для проектування та оптимізації пристроїв на основі HEMT, адаптованих до конкретних додатків частоти ТГц. Це підкреслює ключову роль умов зміщення, властивостей області доступу та геометрії воріт у формуванні продуктивності HEMT і виявлення ТГц сигналу.

Ключові слова: Терагерцовий сигнал, Транзистор з високою рухливістю електронів, Детектування субміліметрових хвиль, Моделювання напівпровідникових приладів, Плазмові хвилі, Польовий транзистор.