Terahertz spectroscopy of plasma waves in high electron mobility transistors

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We report on systematic measurements of resonant plasma waves oscillations in several gate-length InGaAs high electron mobility transistors (HEMTs) and compare them with numerical results from a specially developed model. A great concern of experiments has been to ensure that HEMTs were not subject to any spurious electronic oscillation that may interfere with the desired plasma-wave spectroscopy excited via a terahertz optical beating. The influence of geometrical HEMTs parameters as well as biasing conditions is then explored extensively owing to many different devices. Plasma resonances up to the terahertz are observed. A numerical approach, based on hydrodynamic equations coupled to a pseudo-two-dimensional Poisson solver, has been developed and is shown to render accurately from experiments. Using a combination of experimental results and numerical simulations all at once, a comprehensive spectroscopy of plasma waves in HEMTs is provided with a deep insight into the physical processes that are involved. © 2009 American Institute of Physics. [DOI: 10.1063/1.3159032]

I. INTRODUCTION

In the early 1970s emerges the idea that plasma wave oscillations may exist in field effect transistors (FETs).1 The sequel appeared about 20 years later with the demonstration by Dyakonov and Shur2,3 that these oscillations can be controlled in frequency by varying the applied gate voltage and that with modern short gate-length devices they may fall in the terahertz range. At that point a growing interest was raised in the scientific community in order to exploit these oscillations for applications, either for emission or detection, mostly because of the lack of cheap electronic sources and detectors operating at room temperature. Terahertz detection was experimentally demonstrated only recently using high electron mobility transistors (HEMTs) at cryogenic temperature4,5 and then it was also achieved at room temperature.6,7 At the same time, plasma wave detection was also obtained in double quantum well FETs8,9 and multichannel structures aimed at controlling oblique modes10,11. Aside from direct terahertz illumination, an alternative approach involving the direct carrier excitation in the channel by means of an optical beam can activate plasma waves in transistorlike structures. In practice, two-laser beatings at the prescribed terahertz frequency impinge on the transistor channel material. Photoelectrons are thus generated in the two-dimensional electron gas (2DEG) of the channel and the resulting electron concentration is modulated by the terahertz component of the optical excitation. If resonant with the plasma wave in the 2DEG, an additional dc drain voltage is measured because of system nonlinearities. Up to now, such experiments have been realized only using InGaAs channel HEMTs. Depending on the substrate material, GaAs or InP, the InGaAs HEMT channel bandgap thus allows for indirect or direct carrier photoexcitation, respectively. An indirect excitation involves a multiphoton absorption process and it was demonstrated first in Refs. 12 and 13. More recently, InGaAs on InP HEMTs were considered, thereby allowing for a direct carrier density modulation in the channel that is much more efficient in plasma wave activation.14,15 As compared to direct terahertz detection, this kind of experiments allowed an exact spectroscopic analysis of the 2DEG undergoing plasma wave oscillations. The main reason is that with the optical excitation the modulation level in the channel is independent of the beating frequency, whereas for direct terahertz detection the 2DEG excitation level depends on the gate capture efficiency that is strongly frequency dependent. Although the optical excitation of plasma waves in 2DEG of HEMTs has shown its efficiency and greatest advantages for spectroscopic applications, unsolved questions still exist on both the experimental and the theoretical sides that this paper is intended to answer.

It is well-known that HEMTs are transistors characterized by a high gain up to very high frequencies. The common source mount required to fulfill plasma-wave oscillation prerequisites2 may thus induce an unstable behavior at giga-terahertz frequencies as it is well known in the microwave quadrupole theory.16 Among possible severe outcomes, the HEMT destruction may occur, or, even more critical, the self-oscillation regime may suddenly change the stationary regime of the HEMT that the plasma wave detection scheme can misinterpret. Aiming at investigating in depth the influence of geometrical parameters and HEMT biasing conditions on the occurrence of the plasma-wave oscillation and on its frequency, we had to define the experimental setup so as to prevent from such spurious oscillations. This has been a great concern of the experimental work described in the

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present article and has highly improved the results as compared to our previous experiments. Systematic experimental studies were then possible, providing a deeper insight of the physical processes involved in the plasma wave oscillation modes, even with HEMTs biased close to or within the saturation regime.

An accurate description of a HEMT biased in plasma-wave conditions and illuminated by an optical beating is needed. Following the seminal work of Dyakonov and Shur, analytical models have been proposed with additions accounting for the photogeneration or a weak direct dc drain current. However, the general framework of these models rests on the gradual channel approximation of the Poisson equation, a uniform carrier density, drift velocity, and electric field profiles along the channel. Even if good qualitative descriptions of the physical phenomena have been obtained, a quantitative comparison with experimental results needs more and has to be built. Following a previous work, an appropriate hydrodynamic (HD) model based on velocity and energy conservation equations have been extended to simulate numerically HEMTs undergoing simultaneously arbitrary biasing conditions and optical illumination by terahertz beating.

In this article, we propose systematic measurements of plasma wave excitation by an external terahertz optical beating in micrometer and nanometer gate-length HEMTs. A great concern during experiments was to prevent from any spurious electronic oscillation that may obliterate the occurrence of plasma-wave oscillations. This is described in Sec. II together with photodetection measurements on InGaAs HEMTs. The numerical model is described in Sec. III and the final choice of the most pertinent model is given in conjunction with an experimental study that evaluates the influence of the HEMT gate-length and of the length of the cap layers on plasma wave (see Sec. IV). The next two sections (Secs. V and VI) experimentally consider the influence of HEMT biasing conditions on plasma-wave oscillations frequencies and compare them with the results of the numerical model.

II. PHOTOEXCITATION EXPERIMENTS

Figure 1 presents the experimental setup. Four commercially available InGaAs distributed feedback cw-laser sources (with central wavelengths of emission of $\lambda_1 = 1532$ nm, $\lambda_2 = 1540$ nm, $\lambda_3 = 1542$ nm, and $\lambda_4 = 1546$ nm) are used two-by-two to produce a tunable optical beating from 20 GHz up to 1 THz. Details on laser power, wavelength tunability, and temperature control can be found in Ref. 15. The resulting optical beam is purely linearly polarized within the incident plane ($p$-polarization) and collimated. To control the optical beating frequency and to optimize the incident optical power, the beam is separated in two parts with crossed polarizations by a beam-splitter prism associated with a half-wave plate. A small part of the beam is monitored by an optical spectrum analyzer. The major part of the beam is mechanically chopped before focusing on the HEMT backside (InP substrate) by an objective lens. The spot size (radius of $\approx 5 \mu m$) is aligned on the sample by an infrared camera placed on the top of the prober table.

A prober is used to plot both static and dynamic characteristics of transistors. The bias is applied to contacts using high frequency (HF) probes connected to bias-tees. The overall microwave bandpass of this system cover the 50 MHz to 40 GHz frequency range. In the experiments, HEMTs are connected in common source configuration and behave like HF single-stage transistor amplifiers. The prescribed bias conditions required for plasma oscillations (i.e., $Z=0$ at the source and $Z=\infty$ at the drain) make the resulting amplifier potentially unstable in the microwave domain because the input and output HF loads are uncontrolled and probably not appropriate. We cured this problem simply by loading the HF outputs of the bias-tees by a 50 $\Omega$ impedance while keeping the dc output fed by voltage and current sources for the gate and the drain, respectively.

The photocconductivity response, due to the generation of carriers by the difference-frequency term of the optical beating, is obtained by monitoring the modulation of the dc drain-to-source potential via a lock-in amplifier. The given photoresponse represents the actual measured photovoltage because the amplification of the lock-in amplifier and the gain of the low-noise pre-amplifier placed before the lock-in detection system are subtracted from the original measured signal.

Experiments were performed on HEMTs from InP technology schematically shown in Fig. 2(a), with several gate-length values, $L_g=200, 400, 800$, and 1500 nm. Layers consist of an InP substrate, a 200 nm thick In$_{0.52}$Al$_{0.48}$As buffer, a 15 nm In$_{0.7}$Ga$_{0.3}$As channel, a 5 nm thick undoped In$_{0.32}$Al$_{0.48}$As spacer, a silicon planar $\delta$-doping layer of 6...
thickness of the barrier layer, a 10 nm thick InGaAs channel, a 10 nm silicon-doped InGaAs cap layer, and a contact. The HEMT channel between source and drain contacts comprises three contacted regions. One is the gate itself with a $L_g$ length, and two are covered by the cap layers with a $L_w$ length each. Finally two window regions of length $L_w$ each complete the source-drain length $L_{sd}$ [Fig. 2(a)] given by

$$L_{sd} = L_g + 2L_w + 2L_w.$$  
(1)

As $L_{sd}=2.6$ μm is fixed for our devices, a variation of the gate length implies a variation of the length of regions with cap layer.

Figure 2(b) displays a scheme of the energy band diagram of the HEMT structure of the region under the gate, from the gate contact to the buffer layer, indicating for each layer the energy band gap ($E_g$). The photon energy of our 1.55 μm lasers ($E_{ph}=0.82$ eV) is smaller than the band gap of all layers except that of the channel layer ($E_g=0.6$ eV) where the absorption occurs. Photoelectrons are injected inside the channel where they modulate the density of 2D electrons with a beating frequency from 20 GHz up to 1 THz.

Figure 3 displays the transfer (a) and output (b) characteristics of a 200 nm gate-length HEMT at room temperature. The drain-to-source voltage $V_d$ was set at 100 mV and a threshold voltage $V_{th}=-220$ mV is extracted from the transfer characteristics [Fig. 3(a)]. The dc drain current (solid line) under the dark condition shows a normal gate bias dependence with saturation at around 0.9 mA. The current under illumination of the 1.55 μm laser irradiation (dashed line) with maximum power (=8 mW) exhibits a similar behavior. Output characteristics [Fig. 3(b)] are obtained by varying the applied gate voltage $V_g$ from 0 down to −300 mV with −50 mV steps under dark conditions (solid lines) and photocurrent (dashed lines). These results are in agreement with previously reported photovoltaic effects in HEMTs.21

Here we want to point out that in full analogy with the numerical model presented in Sec. III, the drain-current is applied by an external drain-voltage via a large resistance connected in series with the HEMT source-drain channel. So, in order to compare experiments and modeling, all the experimental results of plasma waves spectroscopy are given for different values of the drain voltage; the corresponding applied current is given in parenthesis.

Figure 4 displays the measured photoreponse versus optical beating frequency for three gate-length transistors [(a)
ing points. From previous findings, three biasing points.

and its value depends on the gate-length transistors at fixed swing voltage

plasma wave peaks, a large and broadband frequency photo-
are clearly observed. For each curves, superimposed to the
mental and higher odd modes of plasma waves oscillations

\[ f_0 = \sqrt{(eV_0/m^*)/4L_g} \]

are approximatively 140, 540, and 1000 GHz. We remark that by reducing the gate (while the total length \( L_{gd} \) is kept constant), a strong disagreement between experimental and analytical results is observed. An important influence of the regions surrounding the gate is suggested. As a matter of fact, in a real transistor, it is important to investigate the effects of the cap layers on the plasma waves. In our devices, as described in Fig. 2, the channel region under the gate cannot be considered as separated from the other parts of the transistor. Moreover the photoexcitation is applied to the whole device and not only to the gated region of the channel. The importance of the cap layer regions was theoretically predicted in Ref. 17, where it has been shown that increasing the length of these regions dramatically decreases the resonant frequencies. According to Ref. 17, the 2D electron gases in the sections of the channel strictly under the cap layers and under the gate exhibit similar collective dynamic behaviors. In other words, due to their high conductivity, the cap layers can be considered as additional gates biased by the drain or the source voltages. However, these assumptions have to be verified by our numerical simulations together with the comparison with experimental results.

III. NUMERICAL MODEL

The experiments have been performed on complex devices (with both gated and ungated regions) so that the different physical quantities are clearly not uniform along the structure. In particular, high electric field regions appear at the different junctions and especially at the drain extremity of the gate where a spatial overshoot of the drift velocity can be expected due to the high mobility of InGaAs. For this sake, to describe phenomena originated by free-carrier photoexcitation in the channel, we shall use here the model of self-consistent charge transport in HEMTs channels proposed and developed in Refs. 15 and 20, which accounts for these inhomogeneities in a natural way.

The model omits a photoexcited hole contribution into the space charge and current along the channel by supposing that the holes just after photoexcitation are practically immediately removed from the channel to gate. As a result, the charge conservation law takes into account the electron contribution only, given as

\[ \frac{\partial n}{\partial t} + \frac{\partial (nv)}{\partial x} = G(t) \]  

where \( x \) is the transport direction (along the channel), \( n \) and \( v \) are the electron concentration and velocity in the channel, respectively, and \( G(t) \) is the electron photoexcitation generation term.

![Graph](https://via.placeholder.com/150)

FIG. 4. Measured photoresponse vs the optical beating frequency for three gate-length transistors at fixed swing voltage \( V_0 = 170 \) mV and three biasing points. From (a) to (c): \( L_g = 1500 \) nm: \( V_g = 330 \) mV (\( I_g = 150 \) \( \mu \)A); \( L_g = 400 \) nm: \( V_g = 550 \) mV(\( I_g = 1.3 \) mA); \( L_g = 200 \) nm: \( V_g = 310 \) mV (\( I_g = 865 \) \( \mu \)A). Error bars are experimental data joined by eye guidelines.
The self-consistent electric potential \( V(x) \) along the channel is determined in the framework of the one-dimensional (1D) approximation for the 2D Poisson equation as \(^{20,22}\)

\[
\varepsilon_c \frac{\partial^2 V}{\partial x^2} + \varepsilon_s \frac{V_s - V(x)}{d'(x) \delta} = e[n(x) - N'_D(x)],
\]

which takes into account the gate influence [second term in left hand side of Eq. (3)] on the potential distribution. Here, \( e \) is the elementary charge (positive definite), \( V_s \) is the gate potential, \( d'(x) \) is the local gate-to-channel distance, \( \delta \) is the channel width, \( \varepsilon_c \) and \( \varepsilon_s \) are the dielectric constants in the channel and the gate-to-channel spacer, respectively, and \( N'_D(x) \) is the effective channel donors density. Let us stress that, on one hand, due to the spatial dependence of \( d'(x) \) and \( N'_D(x) \), the Poisson equation given by Eq. (3) allows us to describe all reasonable situations such as gated, ungated, \( T \)-gated channel regions, as well as a difference in effective donor concentration in different regions. On the other hand, even if Eq. (3) includes itself a description of the gate action on a potential distribution along the channel \( V(x) \) (thus, implying a 2D geometry for the structure), this equation remains a 1D second-order equation with respect to \( V(x) \). This means that boundary conditions at the source and drain terminals of the channel can be formulated by using merely local values of the potential (or longitudinal electric field) at the left and right boundaries of the channel, like \( V_s \) and \( V_p \), respectively. However, such a simple representation of terminals cannot describe correctly the real HEMT source/drain contacts. As follows from Fig. 2(a) the contacts cannot be considered as pointlike ones but as continuous planar layers that include the metal, cap-layer, and cap-to-channel spacer at least.

Such an interpretation of source/drain terminals can be realized in the framework of Eq. (3) by expanding the channel into the source/drain cap-layer regions and supposing that the magnitude of the gate potential \( V_g \) in Eq. (3) depends on \( x \). In our case, spatial regions of the expanded gate with different values of the potential are separated by ungated regions with \( d'(x) \to \infty \).

To close the system of electrodynamic Eqs. (2) and (3) it is necessary to formulate an additional equation that describes an average drift velocity component along the HEMT channel. Here we shall take advantage of the HD approach, which allows us to describe the spatiotemporal evolution of the longitudinal electron velocity \( v(x, t) \). By neglecting hot-carrier effects, it writes

\[
\frac{\partial v}{\partial t} = -v \frac{\partial v}{\partial x} + \frac{e}{m^*} \frac{\partial V}{\partial x} - \frac{\partial^2}{\partial x^2} \ln n - vv.
\]

Here, the channel kinetic parameters, namely, the effective mass is \( m^* = 0.04m_0 \), calculated by a Monte Carlo simulation of electron transport in bulk \( \text{In}_{0.116}\text{Ga}_{0.884}\text{As} \) at room temperature, the velocity relaxation rate is \( \tau_v = 10^{12} \text{ s}^{-1} \) and the variance of velocity fluctuations is \( \delta v^2 = 4 \times 10^{11} \text{ m}^2 \text{ s}^{-2} \), both estimated in Ref. 15 from the experimental value of the quality factor of plasma resonance peaks.

The optical generation term in Eq. (2) is taken in the form

\[
G(t) = G_0[1 + \cos(2\pi ft)],
\]

with \( f \) being the beating frequency and \( G_0 = 3 \times 10^{27} \text{ cm}^3 \text{ s}^{-1} \) obtained by estimating the power and the diameter of the focused spot of the IR-lasers.

To simulate the constant current operation, an additional equation accounting for a large resistance \( R \) connected in series with the HEMT source-drain channel has been used,

\[
V_d(t) = V_T - J_d(t)R,
\]

where \( V_T \) is the constant voltage applied to the whole source-drain-\( R \) circuit, \( J_d(t) \) and \( V_d(t) \) are the instantaneous total current and potential at the drain terminal calculated by the numerical procedure, and the source potential \( V_s = 0 \).

The simulation allows us to calculate the instantaneous drain voltage \( V_d(t) \) in response to a beating photoexcitation. By taking into account the main physically plausible contributions, we shall represent the total \( V_d(t) \) response as a sum of

\[
V_d(t) = V_{d,\text{dark}} + \Delta V_{d,\text{opt}} + \Delta V(f) + \Delta V(f)\cos[2\pi ft + \phi(f)].
\]

Here, \( V_{d,\text{dark}} \) is the drain voltage without photoexcitation, \( \Delta V_{d,\text{opt}} \) is the drain voltage component due to the constant part of the photoexcitation, \( \Delta V(f) \) is the dc additional voltage resulting from the system nonlinearity, and the last term presents the harmonic response to the optical beating \( \Delta V(f) \) supposing that all the higher-order harmonics responses are omitted. The three dc terms are obtained experimentally. Our experimental figures represented the dc photoresponse \( \Delta V_{d,\text{opt}} + \Delta V(f) \). The calculated term \( \Delta V(f) \), which represents the oscillation of the drain voltage induced by the beating photoexcitation, gives us some extra information on the plasma mechanism and can be useful to characterize a possible emission of terahertz radiation by the transistor.

**IV. CAP-LAYER EFFECT**

We simulate pseudo-2D structures similar to the HEMTs used in the experiments and schematized in Fig. 5. We use \( \delta = 15 \text{ nm} \) and we assume that \( d' \) and \( N'_D \) are constant along each region of the device. The modeled transistors are \( L_{\text{sd}} = 2.6 \text{ \mu m} \) long and are constituted by:

- A centered gated region whose length \( L_g \) is taken equal to 200, 400, 800, or 1500 nm. In this region, \( d'(x) = d = 23.5 \text{ nm} \), where \( d \) is the gate-to-channel distance. The effective donors density is calculated from the threshold voltage value \( V_{\text{th}} \) by applying the Poisson Eq. (3) to the static case \( V_s = V_{\text{th}} \) and \( V(x) = 0 \). \( N'_D(x) = N_D = -e_s V_{\text{th}} / (ed\delta) = 4.3 \times 10^{17} \text{ cm}^{-3} \) for \( V_{\text{th}} = -220 \text{ mV} \).
- Two \( L_u = 200 \text{ nm} \) long ungated regions surrounding this gate; \( d'(x) \to \infty \). The effective donors density can be deduced from \( N'_D \) by assuming that the only considered charge in a HEMT section is localized in the channel and in the doping plan. In this case, we found
pseudo-2D modeling of these two parts must be employed. To be taken into account. Therefore an appropriate these last two regions, the planar geometry of the device has as additional gated regions where $N_{D_2}$=12 nm is the thickness of the Schottky layer. The length (which is estimated between 100 and 200 nm) and the electron concentration in these recess regions are not well known. However, they are sufficiently short compared to the rest of the total device and with a high carrier concentration to have a negligible effect on the results.

- The two remaining regions, the “source cap region” and the “drain cap region,” between the Ohmic contacts and the gated channel whose lengths are equal to $L_c=(L_{sd}-L_g-2L_w)/2$.

As discussed in the previous section and in Ref. 17, in these last two regions, the planar geometry of the device has to be taken into account. Therefore an appropriate pseudo-2D modeling of these two parts must be employed.

For this purpose, the three geometries, represented on Fig. 5, are considered: (a) the two cap regions are considered as additional gated regions where $d'(x)=d$ and $N_{D_2}(x)=N_{D_1}$; (b) Only the source cap region is considered gated and the drain cap region is treated as an ungated doped region where $d'(x)\to \infty$ and $N_{D_2}(x)=N_{D_0}=10^{18}$ cm$^{-3}$. (c) The two cap regions are considered ungated. In addition, the source and drain metal contacts are modeled by two short 50 nm long doped 3D access regions. Figure 6 represents the calculated continuous photoresponse of the transistors for these different modeling of the cap regions. Clearly a good agreement with the experiments is obtained only with the model (b). This asymmetric scheme is able to reproduce the experimental results of Fig. 4(b) as concerning the number and the position of the peaks. This means that only the source cap layer must be considered as a second gate and, as a consequence, the HEMT will be treated in the following as a four-electrodes structure (i.e., source, source cap-layer, gate, and drain).

The fact that the drain cap region is not involved in the plasma mechanism can be explained by two main reasons. (i) When a high drain voltage is applied, a strong electric field appears between the cap layers and the channel; both the conduction electrons drifting from the region under the gate and the photogenerated electrons are quickly removed from the channel as shown in Monte Carlo simulations.25 (ii) For high drain voltages, a depletion of the extremity of the gated channel close to the drain occurs; the resulting high resistivity of this region prevents the plasma waves to leak in the gate-to-drain part of the channel.17

Using the model of Fig. 5(b), we calculated the average photoresponses for the same transistors and swing voltages of Fig. 4 and the results are presented on Fig. 7. A good agreement is found between numerical and experimental results as concerning the frequency of the plasma peaks as well as the amplitude of the photoresponse. This confirms the fundamental role played by the cap layers in determining the dynamics of plasma waves in HEMT-like structures.

We remind that the discrepancy in the values of the peaks in Fig. 4 and 7 is in part attributed to the fact that the experimental curves correspond to the terms $\Delta V_{opt}^{fd}+\Delta V(\tilde{f})$ in Eq. (7) while the theoretical curve corresponds to the term $\Delta V(\tilde{f})$ only. Moreover, the simulation has been performed for lower values of $V_d$ than in experiments to take into account the presence of additional voltage drops associated with access regions of the HEMT, which have not been included in the simulation.

In order to compare the experimental results with different theoretical models, we reported in Fig. 8 the plasma waves frequency peak versus an effective gate length $L_g+L_d$. The numerical method here presented is able to reproduce the measured frequencies (fundamental and third harmonic) in the whole domain of lengths. In addition, we reported on Fig. 8, the analytical model of Ref. 17, which considers that in the saturation regime the resonant cavity is composed of both channel regions under the gate and under the source cap layer. In this framework, provided that the

![Fig. 5. Schematic of the three simulated pseudo-2D structures.](image)

![Fig. 6. Calculated average photoresponses as functions of the beating frequency at $V_g=170$ mV, $V_d=250$ mV, and $L_g=400$ nm for different modelings of the cap layers. (a) The two cap layers are considered as two $L_c=1 \mu m$ long additional gates (the two $L_c$-long access regions are simulated as the gated central region). (b) Only the source cap layer is considered as an additional gate (the access region next to the drain is simulated as a doped ungated region). (c) The two access regions are considered ungated.](image)
plasma velocity in the two above regions are similar and that the source window region is sufficiently short compared to the total length, the resonance frequency can be simply expressed with $s = 8.6 \times 10^5 \text{ m s}^{-1}$ (i.e., $V_0 \approx 170 \text{ mV}$).

$$f_0 \approx \frac{s}{4(L_c + L_g)}. \quad (8)$$

We remark that Eq. (8) describes appropriately the dependence of $f_0$ versus the effective gate length, thus confirming that the source cap region must be treated on the same basis as the gate region.

It should be emphasized that the physical effect, which could produce an additional lowering of the resonance frequency, is associated with the extension of the electric field at the boundaries of the gate as recently proposed in Ref. 24.

FIG. 7. Calculated average photoresponses as functions of the beating frequency at $V_0 = 170 \text{ mV}$ and $V_d = 350 \text{ mV}$ for different gate lengths: (a) $L_g = 1500 \text{ nm}$, (b) $L_g = 400 \text{ nm}$, and (c) $L_g = 200 \text{ nm}$. 

V. DRAIN VOLTAGE EFFECT

Figures 9 and 10 display the measured photoresponses versus the optical beating frequency for two gate-length transistors $L_g = 200 \text{ nm}$ and $L_g = 400 \text{ nm}$, respectively, for a fixed value of the swing voltage $V_0 = 170 \text{ mV}$ and for several values of the applied $V_d$. It is remarkable that in the short gate transistor a photoresponse peak up to a frequency of about 1 THz is detected by our experimental setup.

We observed that, in general, the frequency of the plasma modes decreases with increasing $V_d$. For instance, this effect is particularly evident in Fig. 9, where $f_0$ varies from 250 to 190 GHz when $V_d$ varies from 190 to 500 mV.

In order to compare the results of Fig. 10 with our numerical model, we reported in Fig. 11 the calculated average photoresponses for the same swing voltage $V_0 = 170 \text{ mV}$ ($L_g = 400 \text{ nm}$). Again we remark the good agreement between theory and experiments as concerning the frequency of the plasma peaks. This agreement is also found for the other values of $L_g$ (not reported here). Figure 12 summarizes the position of the plasma peaks as function of $V_d$ extracted from the numerical simulation, where the experimental behavior is well reproduced.

This result clarifies the effect of an applied drain voltage on the frequency in InGaAs HEMTs. This frequency redshift results from the increase in the electron drift velocity of the plasma wave as discussed in detail in Ref. 25. This effect predominates over the decrease in the effective gate length when the transistor is driven far into saturation regime which is expected to provide an opposite variation in the frequency.$^{17}$

We recall that additional physical information can be extracted from the harmonic photoresponse $[\delta V(f)$ in Eq. (7)] calculated by the numerical simulation because this quantity is useful to characterize a possible emission of terahertz radiation. Figure 13 reports these photoresponses for the same device and biasing conditions of Fig. 11. We observe on the calculated spectra, resonance peaks at the same frequency and the same redshift observed in the case of the average photoresponse.$^{15,20}$
Figures 14 and 15(a) present the measured and the calculated values of the average photoresponses at the fundamental frequency as functions of $V_d$ for several $L_g$, respectively. In both cases and for all gate length HEMTs, the same behavior is observed. It is clearly seen that the amplitude of the peaks practically increases exponentially with $V_d$. Such a behavior can be due to (i) the increase in the amplitude of the plasma oscillations by approaching the instability conditions because of the increase in the drift velocity $v$ and/or (ii) the enhancement of these oscillations rectification processes due to an increase in the devices nonlinearities.

The analysis of the harmonic photoresponse helps the clarification of this point. In Fig. 15(b), which presents the amplitude of the harmonic photoresponse at the fundamental plasma frequency, one can see that the increase in this quantity is quite smooth compared to the growth of the average response. This reveals the predominant influence of the enhancement of the nonlinearities involved in the appearance of $\Delta V_d$. Indeed, when the transistor is driven far-from-equilibrium and especially in saturation regime, important and highly nonuniform drift velocities are achieved. The nonlinear convective term $v \partial v / \partial x$ [in Eq. (4)], neglected in the analytical calculation of the average response of optically or electronically excited plasma waves, becomes very important and dominates the rectification process. This explains why the dc response is exalted while no significant effect on the harmonic oscillations is noticed when the transistor is driven in its saturation regime.

Moreover, for $V_d > 350$ mV the calculated amplitude of
the average photoresponse peak decreases at increasing $V_d$. Above this value of $V_d$, the HD calculations show that there appears a region of the transistor channel where the drift velocity is greater than the plasma velocity, which leads to the damping of the oscillations. Therefore the increase in the harmonic photoresponse at high $V_d$ cannot be attributed to a stronger excitation of the plasma waves. Rather it is associated with the nonresonant behavior shown in Fig. 13 in the case $V_d=410$ mV. Indeed, by making $V_d$ larger, the same optical photoexcitation produces oscillations of bigger amplitude in voltage because of the appearance of a region of high impedance near the drain contact, which contributes to the increase in the nonresonant background.

Concerning the width of the resonances, one can remark that sharper peaks are obtained in experiments with respect to results of numerical simulations. However, an exact determination of the quality factor is rather difficult due to the uncertainty in the background level. In our case the discrepancy between experimental and numerical result is estimated to be within a factor of 2. This can be attributed to the simplified transistor model here employed, which neglects 2D character of transport, especially in the drain region mainly responsible for the amplification and rectification phenomena.

Finally, one can notice that the smaller $L_g$, the larger
average and harmonic responses are obtained. Indeed, when the effective length \( L_g + L_c \) decreases, the transport in the resonant cavity becomes nearer to ballistic conditions, i.e., plasma waves are less damped, which leads to a more efficient sustainment of the oscillations.

VI. GATE VOLTAGE EFFECT

To complete our investigation of the HEMT plasma waves, we reported in Fig. 16 the measured photoresponses for different swing voltages. The results of the numerical simulations for different swing voltages but a constant \( V_d = 250 \) mV are presented in Fig. 17 and, similarly to the cases studied in the previous sections, they are in good agreement with the experiments. Indeed, the HD model is able to reproduce correctly the influence of \( V_0 \) on the measured spectra. We remark that by changing the gate voltage from 70 to 220 mV, it is possible to tune the frequency of the fundamental mode of about 40–50 GHz.

As expected from Ref. 2 an increase in the carrier concentration in the channel due to the applied gate voltage produces an increase in the frequency of the plasma modes. Our results confirm this expectation for the fundamental plasma mode even if a small discrepancy between theory and experiments is observed for the third harmonic plasma mode.
We want to stress that one should be careful in interpreting the frequency shift observed in Figs. 16 and 17 as the effect of change in carrier concentration only and, as a consequence, in plasma velocity. As a matter of fact, by increasing \( V_g \) and for the same \( V_{ds} \), the transistor operation point moves toward the linear regime of the \( IV \) characteristic [see Fig. 3(b)]. This implies a decrease in the average drift velocity whose effect adds to the previous one to produce the observed increase in the frequency of the plasma peaks.

To conclude, we notice that in this kind of technology, characterized by cap layers with length greater than that of the gate, the applied gate voltage is able to control the carrier concentration only in a small part of the channel. Therefore, the gate voltage cannot tune efficiently the resonance frequency.

VII. CONCLUSIONS

We presented a systematic experimental and theoretical investigation of plasma waves excited by an external terahertz optical beating in InGaAs HEMTs with different gate lengths and bias conditions.

Experiments have been performed using commercially available InGaAs DFB lasers to produce an optical beating from 20 GHz to 1 THz, which is then used to excite plasma waves in the HEMTs channels. Using a specific experimental setup, particular attention has been paid to avoid HF electrical oscillations in the transistors because, by frequency multiplication, these oscillations may result in resonances in the terahertz domain which could be erroneously interpreted as the effect of plasma waves. To enhance the photoresponse, given by the modulation of the dc drain-to-source potential, experiments have been performed under the common source configuration by biasing the HEMTs with a constant gate voltage and a constant drain current. As a result, in all cases, superimposed to a large broadband photoresponse, clear and reproducible peaks are evidenced.

Due to the complex topology of the studied devices, which were often biased in the saturation regime, an original theoretical model has been developed based on a self-consistent numerical solution of a system of equations constituted by the charge conservation equation, a quasi-2D approximation of the Poisson equation and closed by a HD equation describing the average drift-velocity component along the HEMT channel. By adding a generation term describing the optical beating to the first equation, it is possible to calculate directly the instantaneous drain voltage, which not only includes an average term directly comparable to experiments but also a harmonic term useful to complement the physical interpretation.

A comparative analysis of experimental and numerical results enabled us to demonstrate that HEMT contacts cannot be interpreted as pointlike and their planar geometry must be taken into account. Accordingly, a simple model to describe the real source-drain HEMT planar contacts is proposed. The response spectrum of plasma waves at the beating frequency is thus determined by a resonant cavity, which includes the contribution of the cap layers.

We also observed that the frequency of the plasma modes systematically decreases with increasing drain voltage (current). The theoretical model clarifies that the dominant effect on this frequency shift when our devices are biased deeply into saturation regime is associated with the increase in the drift velocity in the channel.

The analysis of the peaks amplitudes show that, while those associated with the average photoresponse increase almost exponentially with the applied drain voltage (current), those associated with the harmonic photoresponse exhibit a much smoother behavior. This suggests that the dominant role on the enhancement of the photoresponse is played by the device intrinsic nonlinearities. Moreover, in short channel transistors, plasma waves are less damped, thus leading to stronger photoresponses.

The study is completed by the analysis of the gate voltage effect. Even if our results in this case confirm previous
experimental and analytical findings, it must be noticed that the important role played by the cap layers in HEMTs reduces significantly the possibility to tune the resonance frequency by changing the gate voltage.

In conclusion, using a combination of experiments and numerical simulations, we achieved a comprehensive spectroscopy of plasma waves in HEMTs at terahertz frequencies by changing the gate voltage.

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