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Room-temperature terahertz spectroscopy of optically excited plasma waves in HEMTs

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Abstract. We report on systematic measurements of resonant plasma waves oscillations in several gate-length InGaAs 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 such as gate-length or cap-layer length as well as biasing conditions is then explored extensively owing to many different devices. Plasma resonances up to the THz are observed.

1. Introduction
In a Field Effect Transistor (FET) channel of given gate-length \( L_g \), excitation of plasma waves [1] is of particular interest because of the feasibility to control their oscillation frequency by varying the applied gate-voltage. For the submicron gate lengths, it has been shown [2] that the nonlinear properties of such waves can be exploited for selective tuneable terahertz (THz) detection and bridge the lack of cheap electronic detectors operating at room temperature. The THz detection was experimentally demonstrated only recently using high electron mobility transistors (HEMTs) at cryogenic temperature [3] and then it was also achieved at room temperature [4, 5]. Besides the direct THz illumination, an alternative approach involving the direct carrier excitation in the channel by means of an optical beam can activate plasma waves in transistor-like structures [6]. 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 [7]. As compared to direct THz detection, this kind of experiments have allowed an exact spectroscopic analysis of the two-dimensional electron gas (2DEG) undergoing plasma wave oscillations. 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.

2. Photoexcitation experiments
The key point of the set-up is the use of a prober to plot both static and dynamic characteristics of transistors (details on experimental configuration can be found in ref. [8]). 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 - 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 [9]. 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 photocathode 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. 1, 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 15nm In$_{0.7}$Ga$_{0.3}$As channel, a 5nm-thick undoped In$_{0.52}$Al$_{0.48}$As spacer, a silicon planar $\delta$-doping layer of $6 \times 10^{12}$ $\text{cm}^{-2}$, a 12 nm-thick In$_{0.52}$Al$_{0.48}$As barrier layer, a 10nm-silicon-doped In$_{0.53}$Ga$_{0.47}$As 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 $L_c$ length each. Finally two window regions of length $L_w$ each complete the source-drain length $L_{sd}$ (Fig. 1) given by $L_{sd} = L_g + 2L_c + 2L_w$.

**Figure 1.** Scheme of the studied InGaAs HEMTs presenting the different layers lengths.

### 3. Cap-layers effect

Figure 2 displays the measured photoresponse versus optical beating frequency for three gate-length transistors ($L_g = 1500$ nm (a); $L_g = 400$ nm (b) and $L_g = 200$ nm (c)) at a fixed value of the swing voltage $V_0 = V_g - V_{th} \approx 170$ mV for three biasing points and at room temperature.

On each figure, several peaks are clearly observed. Similarly to previous findings [7], peaks corresponding to the fundamental and higher odd modes of plasma waves oscillations are clearly observed. The reason because only odd modes appear in the spectra come from the boundary condition (i.e. $Z = 0$ at the source and $Z = \infty$ at the drain), that form a $\lambda/4$ cavity for the plasma waves. For each curves, superimposed to the plasma wave peaks, a large and broadband frequency photoresponse appears. This continuous photoresponse comes from driving the transistors in their current saturation region and its value depends on the I-V characteristics of each transistor. Its value is around 1.4 mV for Fig. 2 (a), 19 mV for Fig. 2 (b) and 29 mV for Fig. 2 (c). The non-resonant detection, due to a mismatching between the plasma wave oscillation frequency in a cavity of given length and the optical beating frequency, is also included in the background continuum.

On one hand, the measured fundamental frequencies are 90 GHz for $L_g = 1500$ nm, 160 GHz for $L_g = 400$ nm and 200 GHz for $L_g = 200$ nm. On the other hand, the values predicted by the analytical formula [2] which only considers the gated channel, $f_0 = \sqrt{(eV_0/m^*)/4L_g}$ are approximatively 140 GHz, 540 GHz and 1000 GHz. We remark that by reducing the gate (while the total length $L_{sd}$ 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, the channel region under the gate cannot be considered as separated from the other parts of the transistor. The importance of the cap layer regions was theoretically predicted in [10] where it has been shown that increasing the length of these regions dramatically decreases the resonant frequencies. According to Ref. [10], the 2D electron gas in the sections of the channel strictly under the cap layers and under the gate exhibit similar collective dynamic behaviors.

Using the model detailed in [11], we have calculated, in Fig. 2 (bottom) the average photoresponses for the same transistors and swing voltages of Fig. 2 (top). 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.

**Figure 2.** Room temperature measured (top) and calculated (bottom) photoresponses versus the optical beating frequency for three gate-length transistors at fixed swing voltage $V_0 \approx 170$ mV and three biasing point. Experiments : from (a) to (c) : $L_g = 1500$ nm : $V_d = 330$ mV ($I_d = 150$ µA); $L_g = 400$ nm : $V_d = 550$ mV ($I_d = 1.3$ mA); $L_g = 200$ nm : $V_d = 310$ mV ($I_d = 865$ µA). Model : $V_d = 350$ mV for different gate lengths: (a) $L_g = 1500$ nm, (b) $L_g = 400$ nm, (c) $L_g = 200$ nm. Error-bars are experimental data joined by eye guidelines.

4. Drain voltage effect

Figure 3 displays the measured photoresponses versus the optical beating frequency for two gate-length transistors $L_g = 200$ nm and $L_g = 400$ nm respectively, for a fixed value of the swing voltage $V_0 = 170$ 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 set-up.

We have observed that, in general, the frequency of the plasma modes decreases with increasing $V_d$. For instance, this effect is particularly evident in Fig. 3, where $f_0$ varies from 250 to 190 GHz when $V_d$ varies from 190 to 500 mV. This frequency red-shift results from the increase of the electron drift velocity of the plasma wave as early discussed in ref. [11]. This effect predominates over the decrease of the effective gate length when the transistor is driven far into saturation regime which is expected to provide an opposite variation of the frequency [10]. Moreover the amplitude of the peaks practically increases exponentially with $V_d$. Such a behaviour can be due to: (i) the increase of the amplitude of the plasma oscillations by approaching the instability conditions because of the increase of the drift velocity, and/or (ii) the enhancement of these oscillations rectification process due to an increase of the devices non-linearities. Indeed, when the transistor is driven far-from-equilibrium and especially in saturation regime, important and highly non-uniform drift velocities are achieved. The non-linear convective term $v \partial e/\partial x$ [eq. (4) of ref. [8]], 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 (see ref. [8] for more details) when the transistor is driven in its saturation regime.

Figure 3. Photoresponses as functions of the optical beating frequency and versus the applied drain-source current for a 200 nm gate-length transistor with $V_d = 170$ mV. (a) $V_d = 500$ mV ($I_d = 970$ μA), (b) $V_d = 310$ mV ($I_d = 865$ μA) and (c) $V_d = 190$ mV ($I_d = 780$ μA). Error-bars are experimental data joined by eye guidelines.

5. Conclusions
We have presented room temperature systematic experimental and theoretical investigations of plasma waves excited by an external THz optical beating in InGaAs HEMTs with different gate lengths and bias conditions.

A comparative analysis of experimental and numerical results of a home-made pseudo-2D HD model enabled us to demonstrate that HEMT contacts cannot be interpreted as point-like, and their planar geometry must be taken into account. 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 have 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 of the drift velocity in the channel.