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Tunable plasma wave resonant detection of optical beating in high electron mobility transistor

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We report on tunable terahertz resonant detection of two 1.55 μm cw-lasers beating by plasma waves in AlGaAs/InGaAs/InP high-electron-mobility transistor. We show that the fundamental plasma resonant frequency and its odd harmonics can be tuned with the applied gate-voltage in the range 75–490 GHz. The observed frequency dependence on gate-bias is found to be in good agreement with the theoretical plasma waves dispersion law.

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Operating optic-to-electronic data conversion at the terahertz (THz) frequency range is one of the most promising issue of optoelectronic devices. Recently, experimental studies on the plasma resonant detection in high electron mobility transistors (HEMTs) and in a single and a double quantum well field effect transistors (FETs) have been published [1–6]. For submicron gate-lengths, fundamental plasma frequencies reach the THz range [7]. THz detection by plasma waves is easily tunable by changing the gate-voltage. Spectral profiles of THz plasma waves resonances were first reported by T. Otsuji et al., the HEMT being excited by means of interband photoexcitation using the difference-frequency component of a photomixed laser beam [8]. With a similar experiment, we investigate in this letter the plasma waves resonances excited in the channel of HEMTs by the beating of two cw-lasers. We show that the plasma resonant frequencies follow the square-root dependence versus applied gate-voltage as initially predicted by Dyakonov-Shur theory [9].

Experiments were performed using an AlGaAs/InGaAs/InP HEMT with gate-length \( L_g = 800 \text{ nm} \) and a threshold voltage of \( V_{th} = -150 \text{ mV} \) extracted from the transfer characteristics (inset (a) of Fig. 1). The active layers consisted of a 200 nm In\(_{0.52}\)Al\(_{0.48}\)As buffer, a 15 nm In\(_{0.75}\)Ga\(_{0.25}\)As channel, a 5-nm-thick undoped In\(_{0.52}\)Al\(_{0.48}\)As spacer, a silicon planar doping layer of 6 \( \times 10^{12} \text{ cm}^{-2} \), a 12-nm-thick In\(_{0.52}\)Al\(_{0.48}\)As barrier layer and a 10-nm-silicon-doped In\(_{0.53}\)Al\(_{0.47}\)As cap layer (inset (b) of Fig. 1).

The whole HEMT structure is transparent to the incident radiation excepted the InGaAs-channel where the interband photoexcitation occurs. By using a tunable optical beating this photoexcitation is modulated over a large frequency range. Two commercially-available cw-lasers sources centered at \( \lambda_1 = 1543 \text{ nm} \) and \( \lambda_2 = 1545 \text{ nm} \) are used. Each powerful laser (\( \approx 20 \text{ mW} \)) can be tuned over a range of \( \pm 1 \text{ nm} \) by varying the temperature. Their mixing produces a tunable optical beating from 0 to 600 GHz. The collimated beams are mechanically chopped at 120 Hz and focused onto the

FIG. 1: Transfer characteristics of AlGaAs/InGaAs/InP HEMT. \( L_g = 800 \text{ nm} \) and \( V_{th} = -150 \text{ mV} \). Inset (a) : output characteristics at \( T = 300 \text{ K} \) for \( V_g = +0.1 \text{ V}, 0 \text{ V}, -0.1 \text{ V} \) and -0.2 V. Inset (b) : schematic of the InGaAs HEMT with the incoming photomixed laser beam by the rear facet.
HEMT backside using an objective lens (spot size diameter ≈ 5 μm). The photoconductivity response, due to the difference frequency generation, is obtained by monitoring the modulation of the dc drain-to-source potential.

Figure 2 shows the photoconductive response versus excitation frequency at room temperature. The photoresponse intensity normalized to unity is plotted versus the modulation of the dc drain-to-source potential. Arrows are for \( f_0 \), \( 3f_0 \) and \( 5f_0 \).

\[
R_\omega = \frac{e \eta_\omega}{\hbar \omega} \left( \frac{\tan(\beta_\omega L_q)}{\beta_\omega L_q} - 1 \right)
\]

where \( R_\omega \) is the responsivity of the HEMT under illumination is when \( \omega \eta_\omega \) becomes on the order of unity, the detection becomes resonant; \( \omega \) being the fundamental plasma pulsation. The quality factor experimentally obtained from the linewidth (full width at half maximum (FWHM)) of the resonance for \( V_0 = 65 \) mV is \( Q = \omega \tau_{\text{eff}} \approx 1.2 \). This value is in good agreement with the calculated values of \( \omega \tau_{\text{eff}} \approx 1 \) obtained taking into account the electron drift velocity \( v_0 \approx 8 \times 10^5 \text{ m/s} \) according to Monte Carlo simulation [4]. In order to determine the theoretical spectral response of plasma waves resonances, the experimental data are compared to the model developed by V. Ryzhii et al. [12] on the plasma mechanism of terahertz photomixing in HEMTs (solid lines in Fig. 2). The responsivity of the HEMT under illumination is

\[
\beta_\omega^2 = \frac{\omega(\omega + iv)}{s^2}
\]

\[
s = \sqrt{\frac{eV_0}{m^*}}
\]

where \( v_0 \) is the electron drift velocity, \( m^* \) is the electron effective mass, \( \mu = 13000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \). With increase of the drain-source voltage, the electron drift velocity increases leading to the increase of \( \tau_{\text{eff}} \). When \( \omega \tau_{\text{eff}} \) becomes on the order of unity, the detection becomes resonant; \( \omega \) being the fundamental plasma pulsation. The quality factor experimentally obtained from the linewidth (full width at half maximum (FWHM)) of the resonance for \( V_0 = 65 \text{ mV} \) is \( Q = \omega \tau_{\text{eff}} \approx 1.2 \). This value is in good agreement with the calculated values of \( \omega \tau_{\text{eff}} \approx 1 \) obtained taking into account the electron drift velocity \( v_0 \approx 8 \times 10^5 \text{ m/s} \) according to Monte Carlo simulation [4].

The frequency dependence of the plasma waves is plotted in Fig. 3 versus the swing-voltage. The experimental data for the fundamental frequency and its odd harmonics are obtained by picking-up the frequency position of.
FIG. 3: Frequency dependence of the maxima of the plasma resonant peak versus swing voltage. Experiments: $f_0$ (▲), $3f_0$ (■) and $5f_0$ (●). Lines are calculations using (4) with $L_g = 800$ nm. Solid line denotes for $f_0$, dashed line for $3f_0$ and dotted line for $5f_0$.

the plasma-wave resonance maxima in Fig. 2 for several values of $V_g$. Lines are calculations using (4)

$$f_n = \frac{2n + 1}{4L_g}$$

where $n = 0, 1, 2, \ldots$, and $L_g = 800$ nm. Theoretical calculations well support experimental data for fundamental plasma waves frequency and its odd harmonics.

In conclusion, the excitation of plasma waves in AlGaAs/InGaAs/InP HEMT channel was performed at room temperature by using a pair of commercially available cw-lasers delivering a THz optical beating. We show that the fundamental plasma resonant frequency and its odd harmonics can be tuned with the applied gate-voltage in the range 75–490 GHz and follow the predicted square-root behaviour. A good quantitative agreement between experiments and Dyakonov-Shur theory is obtained.

Future works will involve shorter gate-length devices to reach higher plasma frequencies thus allowing ultrahigh optoelectronic data conversion.

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