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To cite this article: A El Moutaouakil et al 2009 J. Phys.: Conf. Ser. 193 012068

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Spectral Narrowing of Terahertz Emission from Super-grating Dual-Gate Plasmon-Resonant High-Electron Mobility Transistors

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Abstract. Coherent terahertz emission from an original InGaP/InGaAs/GaAs plasmon-resonant high-electron-mobility transistor, having a super-grating dual-gate structure, is investigated. We report total emission from multi-mode of plasmons: thermally excited incoherent modes and instability-driven coherent modes, using the Fourier Transform Infrared (FTIR) spectroscopic measurement. We discriminate the coherent emission of ultrafast instability-driven plasmon self-oscillation from incoherent hot plasmons using the Electro-Optic Sampling (EOS) method. The resultant emission shows a clear optimal plasmon-resonant mode with sharp peak at 3.2 THz for an optimal bias condition of $V_d = 2V$. It indicates the spectral narrowing effect on the super-grating-gate structure.

1. Introduction
The Terahertz (THz) technology has attracted increasingly interest in nowadays industrial applications. The oscillation of the density of electrons in a two dimensional system can become unstable against the generation of electromagnetic radiation at specific bias conditions, which can be used for tunable detection/generation, and photomixing functions in the terahertz domain [1–6].

Recently, Otsuji et al. have proposed an original HEMT (High Electron Mobility Transistor) based on InGaP/InGaAs/GaAs with doubly interdigitated grating gates, succeeding in broadband generation
of terahertz radiations at room temperature due to incoherent/coherent excitation of the multimode plasmons [5-7]. The drain bias causes dispersion on the sheet electron density along the channel, resulting in spectral broadening [5]. The super-grating gate structure, in which the dispersion of the carrier density is compensated for the grating-finger size (cavity size), can unify the emission frequency under an optimal bias condition [8]. In the present paper, we report on experimental verification of the effect of the super-grating-gate structure and demonstrate the coherent terahertz emission from our original device.

2. Device structures and operation principle

2.1. Device structure

The device [7] was fabricated with InGaP/InGaAs/GaAs material systems as shown in Figure 1. The 2D plasmon layer is formed within a quantum well in the InGaAs channel layer. The metallic grating gate was formed with 65-nm thick Ti/Au/Ti by a standard lift-off process. The double interdigitated grating geometry was designed with gate 1 (G1): L_{G1} = 70 nm, and gate 2: L_{G2} = 1850 nm with 100 nm in space (See figure 1).

![Device Cross-section](image1.png)

**Fig.1:** Left: device cross-section for typical GaAs-based heterostructure material systems, right: SEM image of the new grating gate device, 15 fingers for G1 and 16 fingers for G2.

2.2. Operation principle

Suppose that the plasmons cavities under G1 are highly charged (10^{12} \text{ cm}^{-2}) while the regions under G2 are lightly charged (\leq 10^{11} \text{ cm}^{-2}). If a specific drain-to-source bias is applied to promote a uniform channel current, each cavity boundary may excite the plasmons, promoting current-driven instability of THz self oscillations. The hot electrons also may thermally excite the plasmons. Such coherent (former) and incoherent (latter) plasmons can be transformed to radiative THz electromagnetic radiation via broadband antenna functions of the grating gate structure. The drain bias causes the distribution of sheet carrier density along the channel, causing dispersion of plasma resonant frequencies. This spectral broadening effect can be compensated by introducing a super-grating gate structure; the grating finger size is varied along with the channel so as to unify the plasmon resonant frequencies over all the plasmon cavities under the grating fingers (see Figure 2.) [8].
3. Experimental results and discussion

First, the measurements using the Fourier-transformed far-infrared spectroscopic (FTIR) system were carried out. The experimental procedure is fully detailed in literature [7]. The FTIR measured spectra for the InGaP/InGaAs/GaAs HEMT is showing relatively broad emission spectra ranging from 1 to 6.5 THz (Figure 3) independently of the drain bias $V_{ds}$. Previous discussion concluded that the emission includes coherent and incoherent plasmon modes as mentioned in 2 [7]. The latter may conceal the narrowing effect. In order to discriminate the coherent mode of self oscillation from the incoherent mode, we introduced the time-resolved measurement: Electro-Optic Sampling (EOS) [7-9].

At zero bias (Figure 4(a)), a coherent photoconductive emission line around 2 THz is observed (width around 1 THz). For 2-V bias (Figure 4(b)), the resonant frequency increases up to 3.2 THz, and the line narrowing down to 0.4 THz is observed. This result shows that for the actual dimensions of our double grating structure, 2-V bias condition gives the optimal situation to compensate for the dispersion of plasmon resonant frequency.

When $V_{ds}$ increases up to 4-V (Figure 4(c)), out of the detuning range, we drive the device to much more deeper slope range of the sheet carrier density distributions along with the channel axis. Since the plasma frequency is in proportion to the square root of the sheet carrier density while be in inverse proportion to the cavity size (grating finger size), when the drain bias is detuned to disperse the sheet
carrier density from an optimal distribution, the super-grating structure cannot compensate the distribution anymore [9]. This may cause the spectral broadening. Besides, when the drain bias increases more, the carrier density in the channel, in particular near the drain side, will decrease, which may decrease the plasmon resonant frequencies. As a consequence, it is qualitatively interpreted in the result, shown in Figure 2(c), that the excess drain bias may cause the emission spectral broadening to the lower frequency region than the original spectral peak frequency position. There exists a detuning range around $V_{ds} = 2.0 \, \text{V}$ to preserve the spectral narrowing effect in a specific bandwidth.

4. Conclusion
Coherent terahertz emission from an original InGaP/InGaAs/GaAs plasmon-resonant high-electron-mobility transistor, having a super-grating dual-gate structure, was investigated. The spectral narrowing effect on the super-grating-gate structure has been successfully demonstrated using both FTIR and EOS measurement systems.

Acknowledgements
This work is financially supported in part by the Grant-in-Aid for Basic Research (S), JSPS, Japan. The device process for this work was carried out in part at the Laboratory for Nanoelectronics and Spintronics, RIEC at Tohoku University.

References