Tunable room temperature Terahertz sources based on two dimensional plasma instability in GaN HEMTs

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Abstract. In this work, we report on room temperature terahertz radiation from sub-micron size GaN/AlGaN based high electron mobility transistors (HEMTs). They could successfully replace the standard Fourier Transform spectrometer source and were investigated with a standard Si-bolometer as a detector. The relatively broad (~1THz) emission line was observed. The maxima were found to be tunable by the gate voltage between 0.75 and 2.1 THz. The observed emission was interpreted as due to the current driven plasma waves instability in the two-dimensional electron gas. The emitted power from a single device reached 150 nW, showing possible application of these transistors as compact sources for terahertz spectroscopy and imaging.

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1. Introduction

The channel of a High Electron Mobility Transistor (HEMT) can act as a resonator for the plasma waves propagating in 2D electron gas. The plasma frequency increases with decreasing the channel length and can reach the terahertz (THz) range for nanometer size transistors. As it was predicted by Dyakonov and Shur (DS theory) [1,2], when a current flows through a HEMT, the steady state can become unstable against generation of plasma waves leading to the emission of an electromagnetic radiation at THz frequencies. Three features that are intrinsic for this type of THz emission: threshold-like appearance, appropriate (THz) frequency range and tunability by the gate voltage.

Results of several experiments [3-7] have been tentatively interpreted in terms of DS theory [1]. Although the emission obtained from the nanotransistors really has been in the predicted frequency range and has appeared in the threshold manner, the tunability by the gate voltage has never been observed. In this work, we present the room temperature emission of terahertz radiations from GaN/AlGaN based nanometric high electron mobility transistors. We show that in our structures the emission frequency can be tuned by the gate voltage in agreement with theoretically dependence.

2. Experimental setup and results

The measurements were carried out at room temperature. The emission signal was excited by square source-drain voltage pulses with amplitude $V_{ds}$, pulse frequency 30 Hz and duty cycle 0.5. The registration of the emission was performed by Si bolometer whose frequency range of 0.2–4.5 THz was determined by incorporated filters. The total integrated radiation intensity has been measured by placing the samples directly in front of the bolometer. The spectral analysis of the device radiation was performed using vacuum Fourier Transform spectrometer (FTIR). The standard spectrometer source was replaced by our GaN/AlGaN THz source. THz emission was studied for the gate voltage range (-4Volt to 0Volt). Details about of GaN/AlGaN samples can be found in Ref. [8].

![Fig.1: Output characteristics and the emission intensity for Sample 1 (150nm) at gate biases $V_{gs}$=−3V and for Sample 2 (250nm) at $V_{gs}$=−1V.](image)

The signal in the fig.1 is shown for two values of the gate voltage. The emission spectrum shows a 2
threshold–like behaviour. The THz emission intensity increases drastically. At the same time a
drop of the drain current is observed. With a more negative gate bias, the total drain current drops
and the corresponding onset of the emission are shifted towards lower values of $V_{ds}$. This result has
been already observed and related to the plasma-wave instability at room temperature for transistors
based on different materials [7]. Using the calibration data of the bolometer we roughly estimated the
emission power, which was typically around 150nW. The strongest emission was observed for the
sample 2 (250 nm gate length). Our result shows a possible application of the GaNAlGaN transistors
as compact sources for terahertz spectroscopy and imaging [9].

Both $V_{gs}$ and $V_{ds}$ biases were fixed (within the range of the emission) and the THz radiation
spectra was taken using FFT spectrometer. In Fig. 2-a, we show typical emission spectra. A maximum
of the signal is changing from 0.75 THz to 2.2 THz for $V_{gs}=-3.5$ V to $V_{gs}= 0$ V. It can be clearly seen
that the signal is tuned by the gate bias. The figure 2-b shows the dependence of the resonant
frequency as a function of the gate bias for 150-nm and 250-nm gate length GaN/AlGaN HEMT’s.
The dotted points are extracted from the experiments and the line is simulation result. One can see that
the position of the maximum changes from 2.2 THz at $V_{gs}= 0$ V to 0.75 THz at $V_{gs}=-3.5$ V.

![Figure 2](image-url)

**Fig.2:** (a): The Emission spectrum for 150nm GaN and 250nm GaN at $V_{ds}= 4$ V. To highlight the tuning of the
spectrum by the gate bias, the arrows show the maxima of spectrum. For clarity, curves are vertically shifted;
(b): Maxima of resonant gate voltages corresponding to different frequencies of the radiation source for 150 and
250nm gate length.

### 3. Discussion

The results demonstrate THz emission that appears when the drain current exceeds a certain threshold
value. At the same time a drop of the current is observed. This may suggests that the generation of
THz radiation is related to negative differential resistance mechanism (NDR). In fact a strong heating
of electrons may lead to a real space transfer and/or to population of higher valleys. This could result in a negative differential resistance, which could in principle persist up to THz frequencies. Some possible mechanisms were recently discussed, Mateos et al [10].

The solid line on Fig.2-b shows the results of calculations according to simple equations of Ref. [1] with the effective gate length taken as geometrical one plus two spacer thickness [11]. One can see that the simple model gives a good quantitative description of experimental data. This result supports the plasma wave instability (rather than NDR) origin of the THz emission.

In conclusion: Efficient (150nW) room temperature THz emission from GaN/AlGaN HEMt was reported. Observed emission was frequency-tunable by the gate voltage and changed also with gate length – in agreement with theoretical predictions. These observations strongly support the interpretation of the observed emission as due to plasma wave instability and resonant Plasmon excitation.

Acknowledgement
This work was financially supported in part by the SCOPE Program from the MIC, Japan, and by the Grant in Aid for Basic Scientific Research (S) from the JSPS, Japan. The authors acknowledge also French-Japanese research program “Sakura.”. Y.M.M. acknowledges the support from RamonY Cajal program in Spain and Spanish MICINN through grant Number/Reference TEC2008-02281. The authors from Montpellier University acknowledge the CNRS guided GDR/GDR-E projects “Semiconductor sources and detectors of THz frequencies” and the support from Region Languedoc-Roussillon through the “Terahertz Platform” project.

References
[1] M. Dyakonov and M. Shur, Phys. Rev. Lett. 71, 2465 (1993)
[2] M. Dyakonov and M. Shur, IEEE 43, 380(1996)
[3] N. Dyakonova, F. Teppe et al, J. Appl. Phys., V 97, N 11, p.4313 ,(2005)
[4] J. Lusakowski, W. Knap et al. J. Appl. Phys., V 97, N 6, p.64307,( 2005)
[5] W. Knap, J. Lusakowski et al Appl.Phys. Lett., V. 84, N 13, pp.2331-2333,( 2004)
[6] A.El Fatimy, W. Knap et al, phys. stat. sol. (c), Vol 5, 244– 248 (2008)
[7] N. Dyakonova, A. El Fatimy et al, Appl. Phys. Lett. 88, 141906 (2006)
[8] A. El Fatimy, Thesis, Hall, 00182726, (2007)
[9] A. El Fatimy et al, Optics Communications, Volume 282, Issue 15, Pages 3055-3058 1 August (2009)
[10] J.Mateos, S. Pérez, et al, AIP Conf. Proc. 800, 423 (2005)
[11] W. Knap, Y. Deng, et al, Appl.Phys. Lett, V. 81, N 24, pp.4637-4638,(2002)