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AlGaN/GaN high electron mobility transistors as a voltage-tunable room temperature terahertz sources

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We report on room temperature terahertz generation by a submicron size AlGaN/GaN-based high electron mobility transistors. The emission peak is found to be tunable by the gate voltage between 0.75 and 2.1 THz. Radiation frequencies correspond to the lowest fundamental plasma mode in the gated region of the transistor channel. Emission appears at a certain drain bias in a thresholdlike manner. Observed emission is interpreted as a result of Dyakonov–Shur plasma wave instability in the gated two-dimensional electron gas. © *2010 American Institute of Physics*. [doi:10.1063/1.3291101]

I. INTRODUCTION

Field effect transistors (FETs) are of considerable interest as compact solid state sources of terahertz radiation. This is because, for submicron gate lengths, the plasma frequencies are in the terahertz range and are expected to be tunable by the gate voltage. The radiation in terahertz and subterahertz ranges from transistors has been observed at room as well as at low temperatures.[1–9] However, very few authors report tunable emission of the terahertz radiation.[1] In the latter work, the emission was interpreted as due to plasma waves generated thermally by heating the electron gas by an external electric field.

Another mechanism for tunable terahertz emission in a FET was proposed by Dyakonov and Shur.[10,11] They have shown that the electron flow in the channel should be unstable because of plasma wave amplification due to reflection from the device boundaries. For nanometer transistors, the fundamental frequency is in the terahertz range and can be tuned by the gate bias. Recently, the theory of Dyakonov and Shur[10,11] has been extended to the two-dimensional case.[12] It was found that the dominant instability modes correspond to waves propagating in the direction perpendicular to the current and localized near the boundaries. This new type of instability should result in plasma turbulence with a broad frequency spectrum.

The first experiments on terahertz emission from nanometer FETs have been interpreted assuming that the emission was caused by the Dyakonov–Shur instability.[3] Indeed, the radiation frequencies corresponded to the lowest fundamental plasma mode in the gated region of the device and the emission appeared at a certain drain bias in a thresholdlike manner. However, the tunability of radiation by the gate bias could not be studied because the gate has been short circuited with the source to provide boundary conditions required by the theory.

Later, unsuccessful attempts were made to observe the dependence of the emission frequency on the gate bias both at 4 and 2 K, and at room temperature.[4,5] These studies have been carried out using FETs similar to those used in Ref. 3 (InGaAs/AlInAs HEMTs and AlGaN/GaN HEMTs). Boundary conditions close to the ideal ones were approached by driving the transistor into the saturation. As in previous experiments, emission appeared in a threshold manner, however, no frequency tunability by the gate bias was observed.

Nevertheless, the tuning of the detection frequency by the gate voltage has been observed when the same transistors have been studied as terahertz photodetectors.[13] The results could be successfully interpreted as excitation of plasma waves in the gated two-dimensional electron gas (2DEG) in accordance to predictions of the Dyakonov–Shur theory.[10] Thus the tunability of plasma wave resonance frequency in FETs has been demonstrated in detection experiments. However, up to now nobody has succeeded to observe it for terahertz emission. It is possible that tunable emission was obscured by hot plasmon or edge plasma wave instabilities both having wide spectrum.

In this work, we present experimental results on the terahertz emission from AlGaN/GaN-based high electron mobility transistors at room temperature, which clearly show the tunability emission frequency by the gate voltage.

II. SAMPLE DESCRIPTION

The samples are based on AlGaN/GaN heterostructures grown by metal-organic chemical-vapor deposition method.

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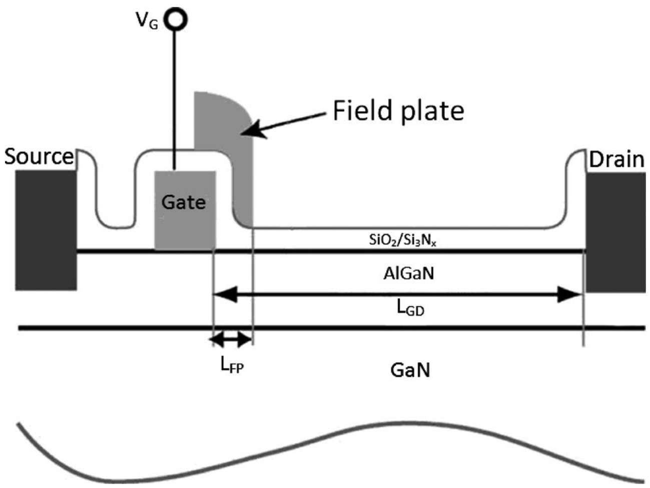

FIG. 1. Schematics of sample 2 with gate covered by a field plate.

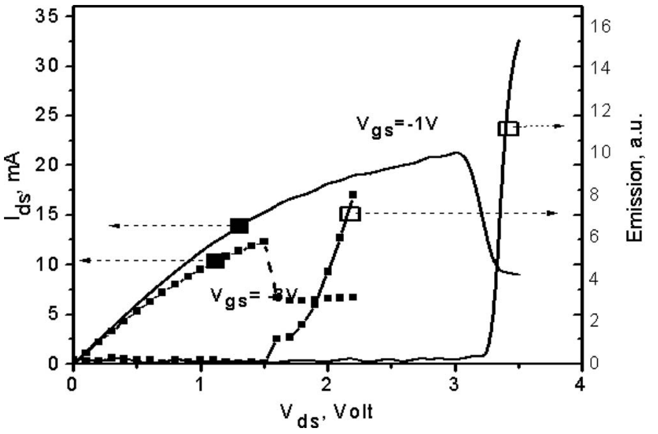

FIG. 2. Output characteristics and the emission intensity for sample 1 at gate biases $V_{gs}=-3$ V (squares) and for sample 2 at $V_{gs}=-1$ V (solid line).

The heterostructure used for fabrication samples 1 and 2 had differed by the Al content in the AlGaN layer and the thickness of the AlGaN barrier. First, a nucleation layer has been grown on the 4H-SiC substrate, followed by a 1 μm GaN buffer layer. Then an AlGaN layer has been deposited (29% content of Al for sample 1 and with 30% of Al content for sample 2). The thickness of the next not intentionally doped AlGaN barrier was 25 nm for sample 1 and 30 nm for sample 2. The electron density was around 1.1×10^{13} cm^{-2} (sample 1) and 1.3×10^{13} cm^{-2} (sample 2). The mobility of electrons in the 2DEG is estimated as $\approx$1500 cm^2/V s. More details about samples can be found in Ref. 5.

The gate layout of HEMTs had a T-shape with a gate width of 2×50 and 2×100 μm for samples 1 and 2, respectively. The gate length (L_g) was 150 nm for sample 1 and 250 nm for sample 2. The distance between the source and gate (L_{sg}) was 0.5 μm, the gate-drain spacing (L_{gd}) was 3.15 μm. The threshold voltage extracted at low drain bias was $V_{th}=-5.1$ V and -4.8 V for samples 1 and 2, respectively. The sample 1 was the standard HEMT, the gate of sample 2 was covered by the field plate (see Fig. 1). The field plate has been deposited between gate and drain terminals. It was connected to the gate at the gate pad (not shown). The length of the field plate was 0.6 μm.

Transistor structures were fabricated with a Ti/Al/Ni/Au (100/500/400/1000 Å) layers for ohmic drain and source contacts. The ohmic contacts were formed by annealing at 900 °C for 30 s using rapid thermal annealing in nitrogen ambient. Reactive ion implantation was employed to insulate the devices. A double resist layer technique is used to obtain a T-shaped gate structure. The Ni/Au (100/4000 Å) gate metal stack was deposited. Then, the whole wafer was covered by a 250 nm (SiO_2/Si_3N_x) dielectric layer deposited by plasma-enhanced chemical-vapor deposition at 340 °C as passivation layer. Finally, the field plate over the gate was deposited by using mark alignment. All metal layers were deposited by e-beam evaporation. All lithography steps were done by electron beam lithography to pattern resist.

III. EXPERIMENT

The measurements were carried out at room temperature. The emission signal was excited by square source-drain voltage pulses with pulse frequency 30 Hz and duty cycle 0.5, the source-gate voltage being constant.

The registration of the emission was performed by high sensitive 4 K Silicon bolometer whose frequency range of 0.2–4.5 THz was determined by incorporated filters. The integrated radiation has been measured by placing the sample directly in front of the bolometer.

For the spectral analysis of the radiation a Fourier transform spectrometer under vacuum has been used. The experimental procedure was as follows: first, the reference spectrum (the spectrum of the transistor without applied voltage inside the source vacuum chamber of the spectrometer) was measured. It contained information about the 300 K-blackbody emission modified by spectral function of all spectral elements (beam splitter, filters, etc.). The detection was performed by the bolometer coupled to spectrometer. The spectra of the sample at source-drain voltages were measured. The final results were obtained by normalizing the spectra of radiation from the biased transistor by the reference spectrum. Thus the normalized spectra reflect the relative increase in the emission due to the radiation from the AlGaN/GaN transistor.

The experiment configuration was improved compared to our previous work.[5] Additional adjustments allowed increasing the radiation power received by the entrance mirror of the spectrometer. As a consequence, the spectral resolution was improved (from 15 to 1 cm^{-1}) and the dynamic range of the measurable signal was increased.

IV. RESULTS

Figure 2 shows both the integrated emission and the output characteristics measured simultaneously as function of the drain-source bias. One can see that the emission appears in a thresholdlike manner and is accompanied by a drop of the drain current. It should be noted that the emission exists in a limited range of V_{gs} values, which depends on the drain

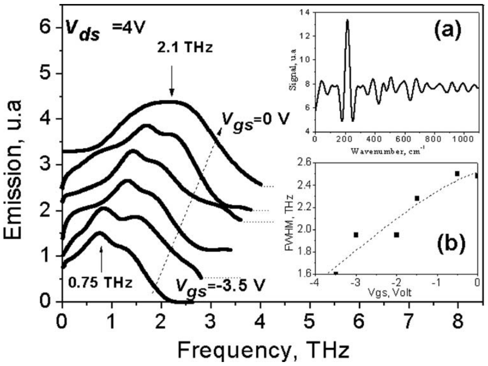

FIG. 3. The Emission spectra for GaN/AlGaN transistor ($L_g=250$ nm) at $V_{ds}=4$ V. Inset (a): the emission interferogram at $V_{ds}=4$ V and $V_{gs}=-3$ V. Inset (b): full width at half maximum of the spectra as a function of V_{gs} (dotted line is a guide to the eye).

to source bias. On increasing the negative gate bias, the current drops and the corresponding onset of emission are shifted toward lower values of V_{ds}.

This result has been already observed at room temperature for transistors based on other materials including GaN.[5] The phenomenon has been related to plasma wave instability although the tunability of the emission frequency by the gate bias has not been observed. It should be noted that in Ref. 5, the spectral analysis of the emission could only be done in a range of gate bias which was too small to see a distinct shift in the spectrum. In this work the optimization of the set up optical configuration permitted to extend the useful gate voltage rang, and this has given the possibility to reveal the shift of the emission spectrum.

Emission spectra for one of the samples are shown in Fig. 3. While fixing the drain bias at $V_{ds}=4$ V, the gate bias was changed from -3.5 to 0 V. One can see that the emission maxima are considerably shifted (from 0.75 to 2.1 THz). To assure that the signal to background ratio was high enough, we show one of the emission interferograms (temporal profile) in the inset (a) of Fig. 3.

Inset (b) in Fig. 3 shows the evolution of the full width at half maximum with the gate voltage. The width of the spectra increases when the carrier density increases.

The position of the maxima of emission spectra as a function of the gate voltage is presented in Fig. 4. One can see that the gate bias dependence of the maxima position is observed for both transistors although it is more pronounced for the sample with the field plate.

V. DISCUSSION

The plasma wave instability in a gated two-dimensional gas has been predicted by Dyakonov and Shur.[10,11] It has been shown that plasma waves can be excited if the drain current exceeds a certain threshold value. The instability develops because of successive reflections of plasma waves from source and drain sides of the channel. The required boundary conditions, ideally, correspond to a zero gate-source impedance and infinite gate-drain impedance. As it has been calculated in Ref. 3 such conditions can be approached near saturation.

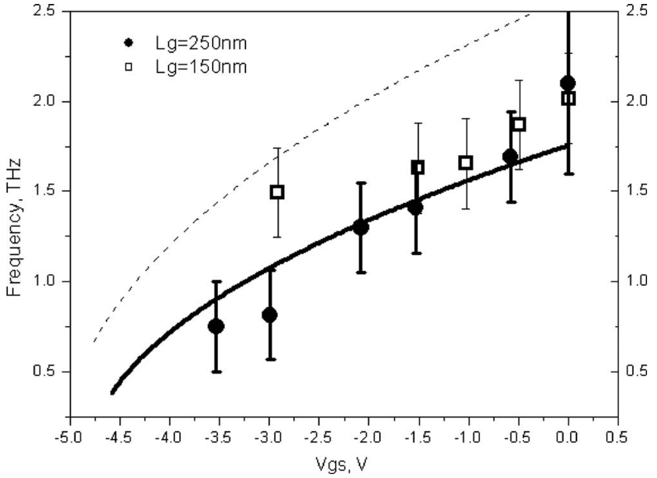

FIG. 4. Position of emission spectrum as a function of gate bias for AlGaN/GaN transistors with gate length 150 and 250 nm at drain to source voltage $V_{ds}=4$ V. Solid lines are calculations using Eqs. (1) and (2).

The fundamental frequency of plasma waves is given by

$$f=\frac{1}{4}\frac{s}{L_{\text{eff}}}\left(1-\frac{v^2}{s^2}\right), \tag{1}$$

where $s=(eU_0/m)^{1/2}$ is the plasma wave velocity, e is the electron charge, v is the electron drift velocity, m is the effective electron mass ($m=0.2\ m_0$, where m_0 is the free electron mass), and U_0 is the gate-to-channel voltage swing. In our gate bias range the ratio v^2/s^2 is small and can be neglected.

The effective gate length L_{eff} is the length of the channel controlled by the gate. It depends on the gate-to-channel separation d, and can be estimated as[3]

$$L_{\text{eff}}=L_g+2d, \tag{2}$$

where L_g is the geometric gate length and d is the thickness of the wide band barrier layer.

The dependence of the fundamental frequency on the gate bias given by Eq. (1) for both samples is presented by lines in Fig. 3. One can see that for sample 2, the theoretical curve fits perfectly well the experimental points. For sample 1, the accordance between experiment and the theory is not so striking, however the points follow the theory in a qualitative way: (a) measured radiation frequency is not far from the calculated one, (b) it is higher than for the sample 2 in accordance with the values of the gate length, and (c) the frequency decreases when the gate bias becomes more negative. Thus, the observed shift in the radiation frequency as a function of the gate bias strongly supports the interpretation of the observed emission as being caused by plasma waves excited in transistor channel.

The dependence of the emission line width on the gate bias gives an additional confirmation of this interpretation. Indeed, since the damping of plasma waves is determined the momentum relaxation time, it should depend on the mobility of the electrons in the transistor channel. It is known that the mobility in the transistor channel depends on the applied gate bias.[14,15] It was shown that that increasing of the carrier density under the gate can degrade the mobility through the enhancement of the interface-or barrier-related carrier scattering. Consequently, the emission spectrum should broaden with the increase in electron density. Indeed, we observe this in our experiments (see inset in Fig. 3). We estimate that the observed spectrum broadening corresponds to the mobility degradation from 1700 to 1100 $\text{cm}^2/\text{V s}$ which are quite reasonable values for our samples.[14,15]

Thus, the main features of the observed terahertz emission are: (i) it appears at a certain drain bias in a threshold-like manner, (ii) the radiation frequency corresponds to the lowest fundamental plasma mode in the gated region of the transistor, and (iii) the radiation frequency is tuned by the gate bias which modifies velocity s of plasma waves. These features are inherent attributes of Dyakonov–Shur plasma wave instability in the two-dimensional gated electron gas, and their presence provides a convincing argument that we observe this phenomenon.

In previous experiments,[5] the observed terahertz emission did not show tunability by the gate bias neither at room temperature nor at 4 K. Even though the position of the spectrum changed slightly with the gate voltage, the shift was not significant. We believe that there might be several reasons for that.

First, previously the gate bias range (about 2 V for AlGaN/GaN transistors) was not large enough to see a noticeable shift in the radiation maximum. As seen in Fig. 4, for sample 1 the shift is less pronounced, so that it could be missed in a narrower bias range. In this work, the optimization of the set-up at 300 K allowed to observe the emission in a wider gate bias range (~ 3.5 V) and to reveal the frequency tuning.

Second, it is possible that the plasma wave excitation is favored by the presence of the field plate covering the gate on the drain side. Indeed, for sample 2 with the field plate the tuning of the emission frequency is more pronounced and better fits the theory (see Fig. 4). Generally, the field plate is used to increase the breakdown voltage in high power FETs.[16,17] This effect is achieved through the expansion of the depletion region toward the drain contact and the weakening of the surface trap effects at the drain side.[18] The boundary conditions needed for the plasma wave excitation could also be affected. Since the experimental and the theoretical results are very similar for sample 2, we speculate that the presence of the field plate approaches the experimental situation to the theoretical model and favors the plasma wave excitation.

In summary, we present experimental results on the terahertz radiation from high electron mobility transistors at room temperature, which clearly show the tunability of the emission frequency by the gate voltage. The characteristic features of this emission are consistent with the Dyakonov–Shur theory of plasma wave instability in the two-dimensional gated electron gas.

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