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GENERATION OF THz RADIATION DUE TO 2D-PLASMA OSCILLATIONS IN INTERDIGITATED GaN QUANTUM WELL STRUCTURES AT ROOM TEMPERATURE

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We report on room temperature electrically-induced terahertz emission from interdigitated GaN quantum well structures. The emission spectrum has been analysed in a Michelson interferometer using a 4K-Si bolometer as a terahertz detector. A resonant peak at the frequency of around 3 THz was observed in emission spectra. A threshold behaviour of the resonance with respect to applied voltage takes place. By using the proposed analytical model the measured/observed experimentally resonant behaviour of emission spectra is interpreted as a result of ungated stream-plasma instability in the channel.

Keywords: plasma waves, terahertz radiation emission

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1. Introduction

In the last years, there has been a growing interest in using terahertz (THz) radiations as a powerful tool to investigate materials, structures, and devices in physics and materials science, chemistry, biology, medicine, etc. [1–4]. To develop future electro-optic systems according to the THz roadmap [5, 6], it becomes mandatory to have efficient emitters and detectors, along with solid-state devices able to control and modify THz beam parameters such as intensity, polarization, phase, etc.

Rapid advances in group III nitrides provide materials with a great potential for high-power and high-frequency applications [7]. These materials present such a small electron relaxation time that electron response is expected up to the THz frequency range. Such a bandwidth was theoretically estimated [8] and observed in GaN [9, 10]. Nowadays, GaN quantum well heterostructures can be grown with excellent transport properties and sufficiently high electron concentration to ensure strong interaction with electromagnetic radiation in the THz range. As transport properties of two-dimensional electron gas in GaN quantum wells can be modified by an applied voltage, a frequency tunable THz emission at room temperature is expected using two-dimensional gated plasma waves [11] in field effect transistors (FETs) or high electron mobility transistors (HEMTs) and has been discussed in the literature [12]. However, plasma instability could also occur in ungated components [13]. Even if plasma wave mechanisms in FETs/HEMTs has been widely discussed in the literature, studies on ungated devices are limited to simulations [14, 15] and no experimental demonstration has, to our knowledge, yet been performed.

In this paper, we present experimental results on THz emission by ungated plasma waves in a GaN quantum well heterostructure under dc voltage driving operation and its theoretical explanation using a specifically developed model.

2. Studied structure

Studied devices are ungated GaN HEMT-like structures and their layers have been grown by molecular beam epitaxy and processed as described in [16]. As

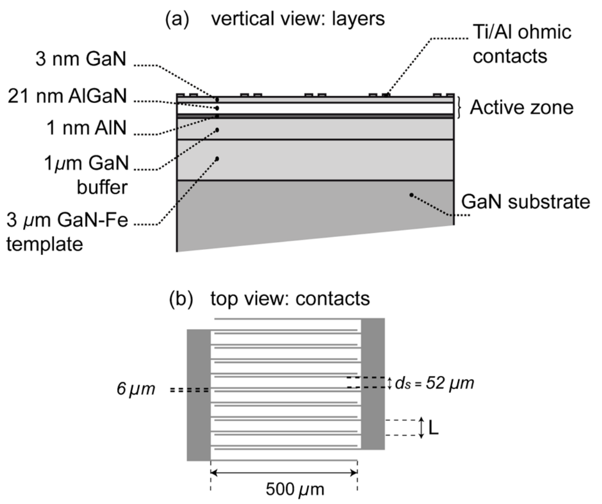

Fig. 1. (a) Studied device structure. (b) Contact pattern.

presented in Fig. 1(a), the structure consists of a GaN buffer, an iron-doped GaN on the GaN substrate, a GaN 1 μm thick buffer, a 1 nm-AlN/21 nm-$Al_{0.29}Ga_{0.71}N$, and a 3 nm-GaN active layer. This heterostructure is covered by interdigitated Ti/Al ohmic contacts with a distance between contacts of 6 to 52 μm (Fig. 1(b)). The total area of the device is roughly a square area of 500×500 μm^2.

3. Experimental set-up

The device under test lays at the focal point of an experimental set-up composed of two parabolic mirrors, a Michelson interferometer and a liquid helium cooled Si bolometer. It is biased by a pulsed voltage from 0 to 25 V with a filling factor of 0.5 and a frequency of 123 Hz. A lock-in amplifier is synchronized with the excitation pulses to improve the signal to noise ratio. The beam splitter used in those experiments allows us to work on the frequency range extending from 0.6 up to 4.5 THz with a frequency resolution of 15 GHz. The experimental procedure was as follows: first, the reference background spectrum, e. g. the spectrum of the sample with no current flowing through the channel, was measured. This spectrum contains information about the 300 K blackbody emission modified by spectral functions of all spectral elements (beamsplitter, filters, ...) of the spectrometer. Then, the spectra of the sample for dc-bias voltages were measured. The final results were obtained by normalizing the spectra with applied voltage by the reference spectrum.

4. Experimental results

Figure 2 shows an example of measured smoothed Fourier transformed spectra for different bias-voltages from 2.5 up to 25 V. Lorentzian fits of the emission spectra were used to determine the peak positions. As a first result, for each value of the applied voltage, a peak corresponding to an emitted radiation to the surrounding space at around 3 THz clearly appears. This peak has an estimated quality factor $Q = f/\Delta f$ of around 5 for applied voltages between 12.5 and 17.5 V. This value strongly decreases while the applied voltage increases.

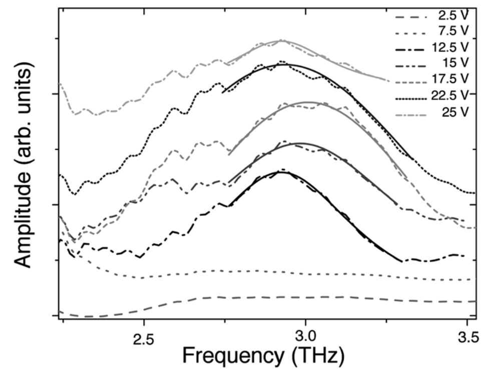

Fig. 2. Emission intensity spectrum. Each curve represents the emission of the same structure for different applied biases from 2.5 up to 25 V. Curves have been randomly translated vertically for clarity and Lorentzian fits of the emission spectra have been used to determine the peak positions.

As predicted in [11, 13], in the absence of an external applied voltage (e. g. electrical excitation), there is no measurable emission from the device related to the self-excitation of ungated plasma waves. As observed in Fig. 3(a), a sharp resonant growth of the peak amplitude was measured by Fourier transform spectroscopy at $T = 300$ K at values of the voltage drop between source-drain contacts higher than $U_{sd} \sim 10$ V. Once the threshold is overcome, the peak amplitude remains more or less constant. Figure 3(b) presents the variation of the central frequency of the emitted radiation while increasing the applied voltage over the threshold value. By increasing the applied dc bias up to 17.5 V the central frequency of the peak varies from 2.8 to 3 THz. Then, increasing even more the applied voltage, the peak is red shifted to lower frequencies down to 2.9 THz.

5. Theoretical model

In this Section, we will analyse in detail the experimentally measured THz emission with threshold-like behaviour and frequency tuning when the GaN-based quantum wells are biased by an external voltage. Here, we shall consider a simplified theoretical model which

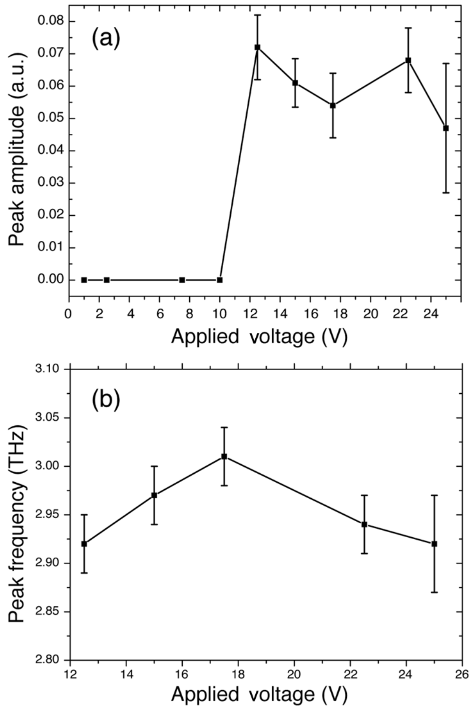

Fig. 3. Amplitude (a) and frequency (b) of the emitted radiation in function of the applied voltage.

describes frequency features of experimentally observed emission of the structure under investigation.

The investigated sample will be interpreted as a conducting δ-layer with 2D concentration of free carriers, σ^{2D} placed on one surface of the isolated substrate characterized by the width d and dielectric constant ϵ_s. At the surface of the conducting δ-layer, the ohmic contacts with the period L are periodically placed (see Fig. 1(b)). The periodic sequences consisting of N anode and cathode contacts are shifted one with respect to the other by the distance d_s.

Between the cathode and the anode contacts a certain potential difference U_0 is applied. It supports the current flow J in an external loading circuit for the considered structure. As this source produces the electromagnetic radiation emission into the space surrounding the considered structure (vacuum with $\epsilon_1 = 1$) we shall consider thermal/diffusion fluctuations of the current flowing along the conducting δ-layer.

Furthermore, we shall suppose that distributions of the potential, $U(x, y)$, of the carrier density, $\sigma^{2D}(x, y)$, and of currents in the conducting δ-layer, $j^{2D}(x, y)$, are independent of the coordinate y along the multi-finger contacts. In such a case, the spatial distribution of fluctuations appearing in the considered structure will depend merely on the coordinate x in the direction transverse to the sequence of the contacts. So it can be represented as

$$\delta A(x) = \sum_{0}^{\pm\infty} \delta A_n \exp[\mathrm{i}\frac{2\pi}{L} nx], \qquad (1)$$

where n is the number of spatial harmonics (modes) and δA stands for δU, δj^{2D}, $\delta\sigma^{2D}$.

5.1. *Selection rules for spatial modes*

The restrictions put by the geometry of the structure under investigation on the spatial distribution of the potential applied to the δ-layer and the currents which flow along it impose for spatial modes with index n to satisfy

$$\sin(\frac{2\pi}{L} d_s n) = 0. \qquad (2)$$

For the structure with $L = 58$ μm and $d_s = 52$ μm investigated in the present work, the selection rules for spatial harmonics given by Eq. (2) show that the contribution into emission can be given only by very high harmonics/modes. As a result we obtain $n = 29k$ with $k = 1, 2, \ldots$ which corresponds to the spatial period $\lambda = 2$ μm.

In the experiment, the resonance of the emission is observed at the frequency of about $f \sim 3$ THz. This corresponds to an electromagnetic wave with the length $\lambda \approx 100$ μm radiated by the structure under investigation into the surrounding space. Therefore, one can conclude that the structure under investigation cannot be considered directly as the antenna which emits radiation into the open space, since the spatial period of oscillations of the current δj^{2D} and the charge density $\delta\sigma^{2D}$ which can take place in the structure ($\lambda \approx 2$ μm) are considerably less than the detected radiation length.

In such conditions, the role of the source of the observed emission resonances can be played by the currents oscillations due the excitation of non-radiative plasma waves in the conducting δ-layer of the structure under investigation, while the role of the antenna which radiates into the open space is played by the external circuit which loads the structure under investigation.

Below we shall consider the frequency features of such plasma excitations in the δ-layer of the structure under investigation in the framework of the scalar (non-radiative) potential formalism.

5.2. *Influence of the isolated substrate on the spatial modes of the potential*

Here, we shall consider the influence of the isolated substrate – surrounded by two dielectric media of dielectric permittivity ϵ_1 – characterized by the dielectric permittivity ϵ_s and the width d on the distribution of potential fluctuations $\delta U(x, z)$ induced by free-carrier charge fluctuations $\delta\sigma^{2D}$ in the plane transverse to the conducting δ-layer.

By using the harmonic representation of the fluctuations of the potential and charge density (where $q=\frac{2\pi}{L}n$ is the wave vector of the nth mode of the plasma waves in the δ-layer) the Poisson equation, which describes the fluctuations of $\delta U(x, z)$, takes the form

$$-q^2\ \epsilon(z)\delta U_q(z)+\frac{\partial}{\partial z}\left[\ \epsilon(z)\frac{\partial}{\partial z}\delta U_q(z)\right] = -\frac{e}{\epsilon_0}\delta\sigma_q^{2\mathrm{D}}\delta(z)\,. \tag{3}$$

From the homogeneous solution of Eq. (3) (that is without the term in the r.h.s.) valid for all the values of z (except the boundaries of the dielectric substrate at $z = 0$ and $z = -d$) one can obtain the explicit expression of the amplitude of qth harmonic of the potential $\delta U_q(0) = A_1^+$ in the conducting δ-layer:

$$\delta U_q(0)=\frac{e}{2\ \epsilon_0\epsilon_{\mathrm{ef}}}\frac{1}{|q|}\sigma_q^{2\mathrm{D}}, \tag{4}$$

where

$$\epsilon_{\mathrm{ef}}=\frac{1}{2}\frac{(\epsilon_{\mathrm{s}}+\epsilon_1)^2\exp(2|q|\,d)-(\epsilon_{\mathrm{s}}-\epsilon_1)^2}{(\epsilon_{\mathrm{s}}+\epsilon_1)\exp(2|q|\,d)+(\epsilon_{\mathrm{s}}-\epsilon_1)} \tag{5}$$

is the effective dielectric permittivity of the medium surrounding the conducting δ-layer. At $d \to 0$ or $\epsilon_{\mathrm{s}} \to \epsilon_1$ the influence of the substrate which contains at its surface the conducting δ-layer becomes negligible since $\epsilon_{\mathrm{ef}} \to \epsilon_1$. In this limit one obtains the well-known expression for the amplitude of q-th harmonic of the potential δU_{q} in the δ-layer placed in the vacuum ($\epsilon_1 = 1$) [13].

5.3. Kinetics of free-carrier transport in the conducting δ-layer

By the help of the transport and fluctuation equations of free carriers in the conducting δ-layer in the framework of the kinetic approach based on the Boltzmann equation as developed in [17], one obtains the following system of interconnected material equations which relate amplitudes of fluctuations of spatial harmonics of the current and potential, $\delta j_q^{2\mathrm{D}}$ and δU_q with fluctuations of thermal source η_q:

$$\begin{gathered}\omega\delta\sigma_q^{2\mathrm{D}}=q\delta j_q^{2\mathrm{D}}\,,\\ \mathrm{i}\left[-\omega\delta j_q^{2\mathrm{D}}+q\frac{e}{m}\sigma_q^{2\mathrm{D}}\delta U_q\right]=\eta_q+\sum\nolimits_{q'}\left[\frac{e}{m}E_{q'}^{0}\,\delta\sigma_{q-q'}^{2\mathrm{D}}\right].\end{gathered} \tag{6}$$

Equation (6) jointly with (4) form the full set of equations which allows to determine the spectrum of current fluctuations $\delta j_q^{2\mathrm{D}}$ induced by the source of thermal fluctuations μ_q. In the general case the solution of those equations is sufficiently difficult due to mixing of spatial harmonics, i. e. due to the presence of the sum over q' in the r. h. s. of (6). Below we shall consider the simple case when the mixing effects of spatial harmonics are not essential and they can be neglected.

5.4. Approximation of independent spatial modes/harmonics

If in the r.h.s. of Eq. (6) only the term with $q' = 0$ remains under the sum sign, the system of interconnected equations given is splitted into the set of independent equations which describe the behaviour of current fluctuations of each spatial mode with the wavevector q. Such an approximation is physically valid under conditions close to thermal equilibrium for the distribution function $f(v, x)$ of free carriers in the δ-layer. This is satisfied when a strong electric field and hot carrier effects do not prevail. In this case Eq. (6) takes the form

$$\begin{gathered}\delta\sigma_q^{2\mathrm{D}}=\frac{q}{\omega}\delta j_q^{2\mathrm{D}}\\ (-\mathrm{i}\omega+\nu_0)\delta j_q^{2\mathrm{D}}=\mathrm{i}q\frac{e}{m}\sigma_0^{2\mathrm{D}}\delta U_q=\eta_q\,.\end{gathered} \tag{7}$$

By solving Eq. (7) jointly with Eq. (4) one obtains:

$$\delta j_q^{2\mathrm{D}}=\frac{-\mathrm{i}\omega\eta_q}{\omega^2+\mathrm{i}\omega\nu_0-\omega_q^2} \tag{8}$$

where

$$\omega_q=\sqrt{\frac{e^2\sigma_0^{2\mathrm{D}}}{2\ \epsilon_0\epsilon_{\mathrm{ef}}\ m}|q|} \tag{9}$$

is the frequency of plasma oscillations of free carriers in the δ-layer corresponding to excitation of the spatial harmonic with the wavevector q.

As follows from Eq. (8) the amplitude of currents $\delta j_q^{2\mathrm{D}}$ of the qth harmonic/mode of plasma oscillations in the δ-layer excited by thermal source η_q has the resonant growth at $\omega \to \omega_q$. Let us estimate the frequency of such resonanses for the case of the structure experimentally measured in this work. Accordingly with the selection rules considered above, only high-frequency modes with $n = 29k$ ($k = 1, 2, ...$) can be excited in the structure under investigation:

$$q=\frac{2\pi}{L}n=\frac{2\pi}{(L/29)}k, \tag{10}$$

where $L = 58\ \mu$m. Taking into account the structure parameters (the substrate thickness $d = 46\ \mu$m, $\epsilon_{\mathrm{s}} = 12$ (what corresponds to $\epsilon_{\mathrm{ef}} = 6.5$ in accordance with Eq. (5)), carrier concentration in δ-GaN-layer $\sigma_0^{2\mathrm{D}} = 1\cdot 10^{13}$ cm^{-2}, and corresponding effective mass $m = 0.2\ m_0$, one obtains:

$$f_{\mathrm{res}} = \frac{\omega_q}{2\pi} \approx 3.1\sqrt{k}\ (\mathrm{THz}). \tag{11}$$

Since the amplitude of the current $\delta j_{\mathrm{q}}^{\mathrm{2D}}$ is transferred into the external circuit which plays the role of antenna emitting radiation, the current resonances of the permitted harmonics correspond to the resonance emission. Comparing the presented in Eq. (11) estimations of permitted resonant frequencies with the experimental result (see Fig. 3) we have a good quantitative agreement for the first permitted harmonic with $k = 1$.

6. Conclusion

We have measured by THz-FTIR experiments the room-temperature THz emission from GaN quantum wells structures with a threshold-like behaviour in respect of the applied dc bias. The frequency tuning of the line between 2.9 up to 3.4 THz has also been demonstrated. We have also shown, in the framework of the independent modes approximation, that the above-proposed analytical model well describes the frequency of the emission resonance of the structure under investigation measured near $f \approx 3$ THz. In accordance with such a model, we determine that the resonance is caused by the thermal excitation of ungated 2D-plasma waves in the conducting δ-layer with the characteristic period of spatial oscillations of about 2 μm.

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References

[1] A. Redo-Sanchez and X. Zhang, IEEE J. Select. Topics Quant. Electron. **14**, 260 (2008).
[2] J.A. Zeitler and L.F. Gladden, Eur. J. Pharm. Biopharm. **71**, 2 (2009).
[3] P.H. Siegel, IEEE Trans. MTT **52**, 2438 (2004).
[4] D. Dragoman and M. Dragoman, Progr. Quant. Electron. **28**, 1 (2004).
[5] M. Tonouchi, Nat. Photon. **1**, 97 (2007)
[6] J. Federici and L. Moeller, J. Appl. Phys. **107**, 111101 (2010).
[7] S. Pearton, F. Ren, A. Zhang, and K. Lee, Mater. Sci. Eng. R **30**, 55 (2000).
[8] V.N. Sokolov, K.W. Kim, A.A. Kochelap, and D.L. Woolard, Appl. Phys. Lett. **84**, 3630 (2004)).
[9] W. Zhang, A.K. Azad, and Grischkoowsky, Appl. Phys. Lett. **82**, 2841 (2003).
[10] T. Nagashima, K. Takata, S. Nashima, H. Harima, and M. Hangyo, Jpn. J. Appl. Phys. **44**, 926 (2005).
[11] M. Dyakonov and M. Shur, Phys. Rev. Lett. **71**, 2465 (1993).
[12] N. Dyakonova, A. El. Fatimy, J. Luzakowski, W. Knap, M. Dyakonov, M. Poisson, E. Morvan, S. Bollaert, Y. Roelens, C. Caraquiere, D. Theron, and A. Cappy, Appl. Phys. Lett. **88** (2006).
[13] M. Dyakonov and M.S. Shur, Appl. Phys. Lett. **87**, 111501 (2005).
[14] V.V. Popov, O.V. Polischuk, and M.S. Shur, J. Appl. Phys. *98*, 033510 (2005).
[15] A. Satou, V. Ryzhii, I. Khmyrova, M. Ryzhii, and M.S. Shur, J. Appl. Phys. **95**, 2084 (2004).
[16] Y. Cordier, M. Azize, N. Baron, S. Chenot, O. Tottereau, and J. Massies, J. Cryst. Growth **309**, 1 (2007).
[17] P. Shiktorov, E. Starikov, V. Gružinskis, T. Gonzales, J. Mateos, D. Pardo, L. Reggiani, L. Varani, and J.-C. Vaissiere, Riv. Nuovo Cimento **9**, 1 (2001).

2D PLAZMOS VIRPESIŲ SUKELTAS THZ SPINDULIUOTĖS GENERAVIMAS SUNERTŲ PIRŠTŲ PAVIDALO GaN DARINIUOSE SU KVANTINIAIS ŠULINIAIS KAMBARIO TEMPERATŪROJE

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Santrauka

Kambario temperatūroje tirta elektriškai indukuota terahercinė emisija iš sunertų pirštų pavidalo GaN darinių su kvantiniais šuliniais. Emisijos spektras buvo ištirtas Michelsono interferometru naudojant 4K-Si bolometrą. THz emisija iš GaN darinių su kvantiniais šuliniais turi slenkstinį pobūdį pridėtos nuostoviosios įtampos atžvilgiu. Pademonstruota emisijos dažnio derinimo galimybė nuo 2,9 iki 3,4 THz. Mūsų pasiūlytas analitinis modelis gerai aprašo tiriamo darinio emisijos rezonanso dažnį, išmatuotą $f \approx 3$ THz dažnio aplinkoje. Sutinkamai su šiuo modeliu nustatėme, kad rezonansas atsiranda dėl 2D plazminių bangų terminio sužadinimo δ sluoksnyje su erdvinių osciliacijų periodu apie 2 μm.