Modern Electronic Materials (2016) 2, 1–6

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Modern Electronic Materials

Nitride HEMTs vs arsenides: The ultimate battle?☆, ☆☆

Yuri V. Fedorov*, **Sergey V. Mikhaylovich**

Institute of Ultra-High Frequency Semiconductor Electronics, Russian Academy of Sciences, 7/5 Nagornyi Proezd, Moscow 117105, Russia

KEYWORDS
Arsenide and nitride heterostructures;
Breakdown voltage

Abstract
In this paper, we have studied the limit capabilities of nitride and arsenide HEMTs and shown that the frequency limit of these devices has already been reached. The nature of these frequency constraints arises from device design rather than from semiconductor properties. In particular we have established that the product $t_B C_{dg}$ is the critical parameter which could not be minimized any further technologically. In summary it could be stated that nowadays InP pHEMTs offer the highest frequencies and GaN HEMTs on SiC substrate are the most powerful devices. In addition we have shown that the breakdown voltages and power density of nitride HEMTs at a given operating frequency are controlled by heterostructure barrier layer thickness, increasing with a decrease of the latter. Therefore it is necessary to develop high efficiency nitride nanoheterostructures with t_B less than 10 nm. In this respect the AlN/GaN heterostructures are beyond comparison due to the good performance of 2D gas and relative simplicity of growth process.

Introduction

The exploration of the THz range in the recent decade has been one of the most important development trends for RF semiconductor devices. The frequency parameters of high electron mobility transistors (HEMT) based on arsenide heterostructures (In, Ga, Al, P)As on InP substrates [1-3] and nitride heterostructures (In, Ga, Al)N on Al_2O_3, SiC and Si substrates (hereinafter arsenide and nitride HEMT, respectively) in this period have grown at highest rates (Figure 1) [4]. This has become possible due to the development of transistor technologies:

☆The article was written based on an interdisciplinary scientific and practical seminar “Mathematical Modeling in Materials electronic nanostructures”, held in the Institution of Russian Academy of Sciences Dorodnicyn Computing Centre of RAS.

☆☆This study was supported by the Ministry of Education and Science of the Russian Federation, (Grant № 14.604.21.0136, unique project identifier RFMEFI60414X0136).

Peer review under responsibility of the National University of Science and Technology MISiS.

*Corresponding author.
E-mail address: yuraf2002@mail.ru (Y.V. Fedorov).

http://dx.doi.org/10.1016/j.moem.2016.08.006

Peer review under responsibility of the National University of Science and Technology MISiS.

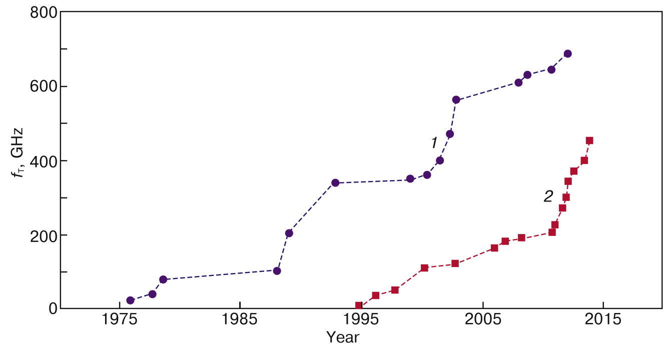

Figure 1 Dynamics of the limit frequency of arsenide and nitride HEMT [4]: (*1*) $In_xGa_{1-x}As$ and (*2*) GaN.

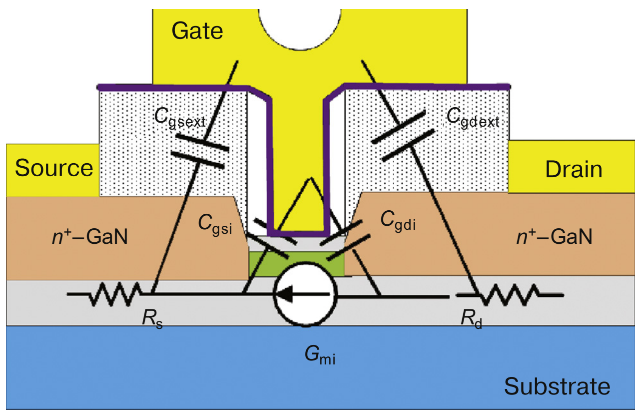

Figure 2 Equivalent electrical diagram of HEMT with parasitic elements [5].

- reduction of the resistivity of ohmic contacts by developing the technology of repeated growth of highly doped n^+-InGaAs or n^+-GaN contact layers;
- development of a self-aligned technology of gates and contacts minimizing transistor channel resistivity both for arsenide and for nitride HEMT;
- reduction of gate length to 20 nm [4,5].

However, as can be seen from Figure 1, the growth of the limit current frequency f_T for InP HEMT stopped at the f_T=668 GHz threshold back in 2011 [3], whereas nitride HEMT after reaching the f_T=454 GHz threshold in 2013 [4] also seem to have exhausted their further development capacity.

The aim of this work is to analyze the causes of the current situation and possibilities for further increasing the frequencies of arsenide and nitride HEMT as well as comparing their achievable parameters.

Limit RF parameters of high electron mobility transistors

Studying the limit RF parameters of HEMT is the most convenient using their equivalent circuits (Figure 2, [5]) showing the internal and external parasitic elements affecting their operation. It is commonly believed that the limit current frequency f_T of a field-effect transistor depends on the total recharging time τ_{tot} of its internal and external capacities, i.e. $f_T=1/2\pi\tau_{tot}$ where $\tau_{tot}=\tau_{int}+\tau_{ext}+\tau_{par}$ and can be expressed as follows [4]:

$$\tau_{tot} = \frac{C_{gsi}+C_{gdi}}{G_{mi}} + \frac{C_{gsext}+C_{gdext}}{G_{mi}} + (R_s+R_d)\left[C_{gd}+(C_{gs}+C_{gd})\frac{G_d}{G_{mi}}\right], \quad (1)$$

where G_{mi} is the internal transconductance, G_d is the output conductivity of the HEMT, $C_{gd}=C_{gdext}+C_{gdi}$ is the total gate-drain capacity, $C_{gs}=C_{gsext}+C_{gdi}$ is the total gate-source capacity, and R_s and R_d are the resistivities of the source and the drain, respectively.

Obviously, to increase the speed of HEMT one should reduce its parasitic capacities and increase the internal transconductance G_{mi} - and these are the goals of recent arsenide and nitride HEMT technology development.

Applying trivial transformation to Eq. (1) and taking into account the following well-known relationships

$$\frac{G_{mi}}{C_{gsi}} = \frac{V_{e\_dr}}{L_G};$$

$$C_{gsi} = \varepsilon_0\varepsilon_B W_G \frac{L_G}{t_B},$$

one can obtain the following expression describing the product $f_T L_G$ (the HEMT figure of merit) as a function of the $K_{asp}=L_G/t_g$ aspect ratio:

$$f_T L_G = \frac{V_{e\_dr}}{2\pi}\left\{1+(R_s+R_d)G_d + \frac{C_{gd}[1+(R_s+R_d)(G_{mi}+G_d)]+C_{gsext}(R_s+R_d)G_d}{\varepsilon_0\varepsilon_B W_G \frac{L_G}{t_B}}\right\}^{-1}. \quad (2)$$

Here V_{e_dr} is the effective drift speed of electrons under the transistor gate, t_g is the distance from the gate to the 2D electron gas which is approximately the thickness of the heterostructure barrier layer, ε_g is the dielectric permeability of the barrier, and W_G and L_G are the gate width and length, respectively.

Experimental $f_T L_G$ vs L_G/t_g functions are widely used for comparing the quality of transistors during technology development. However, this work seems to be the first time to present Eq. (2) in an explicit form. We will now consider its applicability for the analysis of real life devices on the basis of available literary data. We use earlier work [6] where analysis of massive experimental data for nitride