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Self-Heating Effects in GaN/AlGaN Heterostructure Field-Effect Transistors and Device Structure Optimization

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ABSTRACT

Gallium nitride and related compounds have established themselves as extremely important for next generation of high-power density devices for microwave communications and radar applications. GaN/AlGaN heterostructure field-effect transistors (HFET) demonstrated high frequency and low-noise operation. At the same time, performance of these devices has been limited by self-heating and other problems associated with the large defect densities. In this paper we present results of our simulation of temperature rise in GaN/AlGaN HFETs characterized by different geometry, layered structure, doping density and substrate type. In these simulations, we use the materials specific model for GaN thermal conductivity recently developed in our group.

I. INTRODUCTION

The gallium nitride materials system has established itself as extremely important for next generation of high-power density devices for microwave communications and radar applications. GaN/AlGaN heterostructure field-effect transistors (HFET) demonstrated high frequency and low-noise operation [1-3]. At the same time, performance of these devices has been limited by self-heating and other problems associated with the large defect densities [4-5]. Thus, accurate modeling of self-heating effects in GaN/AlGaN HFETs and device structure optimization for better thermal management becomes important for further development of nitride technology.

In this paper, we present results of our simulation of temperature rise in GaN/AlGaN HFETs characterized by different geometry, layered structure, doping density and substrate type. We do note make simplifying assumptions of the uniform thermal conductivity of the layered structure. Instead, the proposed self-heating simulation uses first-principle model for the GaN thermal conductivity developed in our group [6-7]. It allowed us to include the effects of thermal conductivity anisotropy due to crystalline structure, dislocation network orientation, Al content in the barrier and the presence of unevenly distributed dopants and defects. The results for temperature rise and mobility degradation were obtained on the basis of solution of the heat flow equation for 2D and 3D cases.

II. THEORETICAL MODEL

To obtain the temperature rise in the device structure, we solve the nonlinear heat flow equation given as

$$c \cdot \rho \cdot \left(\frac{\partial u}{\partial t} \right) = div(k \cdot grad(u)) + f, \qquad (1)$$

$$u\Big|_{left+right+back+front+bottom} = 0,$$

$$\frac{\partial u}{\partial z}\Big|_{top} = 0,$$

$$u\Big|_{t \le 0} = 0.$$

Here $u = T - T_a$ is the temperature rise above ambient temperature $T_a = 300K$, k is thermal conductivity taken as in Refs. [6-7], c is specific heat, ρ is mass density, $f = \frac{P}{W \cdot L \cdot a}$ is the heat-source term defined for the fixed generated power *P* and thin region of the following dimensions: a = 0.01 μm L =1 μm (L =0.25 μm), and W = 200 μm. It is assumed that $f = 0$ everywhere else, and that left, right, back, and front boundaries are far enough from the heat-generating region. The bottom of the substrate is maintained at the ambient temperature

$T_a = 300K$ via its good thermal contact (see Fig.1). The heat-generating region is positioned next to the gate contact, on the drain side, at the depth of $0.023\,\mu$m below the device top surface. The depth of $0.023\,\mu$m corresponds to the total thickness of the AlGaN cap layer shown in Fig.1. Our assumptions on heat source dimensions and depth are in line with the experimental data of temperature distribution for similar devices [8]. Since Joule heating is the dominant heating effect for a given device, one can write

$$f = \vec{j} \cdot \vec{E}\,. \tag{2}$$

This indicates that the strong heating occurs in a region with high electric field, and that our choice of the region geometry and position is rather realistic.

To gain an insight into the self-heating effects we perform non-isothermal simulations for a number of different heat-sources written as in Eq. (1). The results of simulations give temperature distribution in GaN/AlGaN HFET as a function of dissipated power. Finally we compare the self-heating in doped and undoped channel GaN/AlGaN HFETs. Earlier these devices have been compared in terms of their noise levels [3]. The higher *Al* content in the barrier layer of the undoped channel transistor approximately compensates for the absence of the channel doping and makes comparative study meaningful. The layered structure for the devices of both types is shown schematically in Fig. 1.

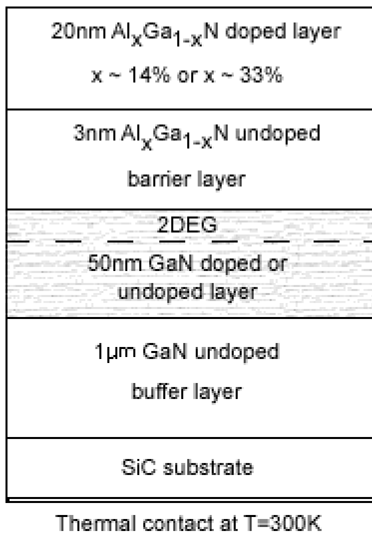

Figure 1. Layered structure of the doped / un-doped heterostructure field-effect transistor (HFET).

We numerically solve the boundary value problem set by Eq. (1) using the finite element method. The adaptive mesh is generated using the Delaunay triangulation algorithm (see Fig. 2).

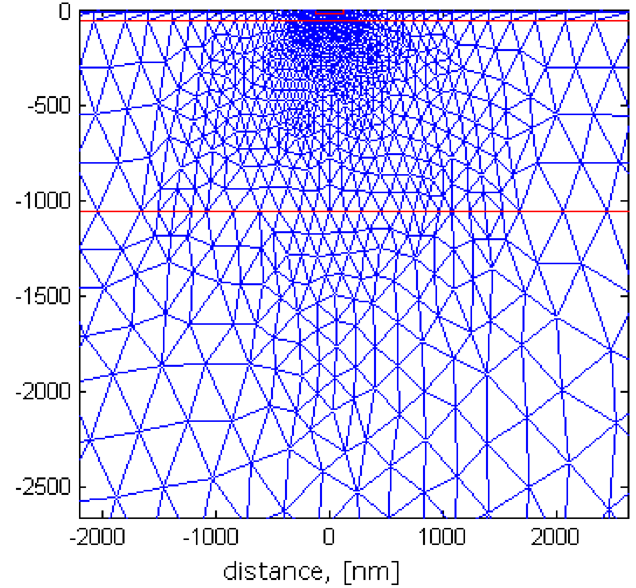

Figure 2. A triangular mesh used in simulations with the mesh size determined from the structure geometry and required accuracy.

III. RESULTS AND DISCUSSION

The results of the simulation of temperature-rise profiles for the undoped and doped channel GaN/AlGaN HFETs on SiC substrate are shown in Fig. 3 (a-b). The dissipated power is P = 10 *W/mm*. Comparing Figs. (a) and (b), one can see that at given power level the doping of the 50 *nm* active layer leads to an approximately 15% increase of temperature maximum for the $L = 1\,\mu m$ -long heat source. The increase is 43% for the heat source with $L = 0.25\,\mu m$. One can also notice from Fig. 3 that the doped GaN layer acts as a thermal insulator that keeps the heat in the active channel and creates a hot spot. Higher temperature leads to mobility degradation and, thus, to a negative dynamic resistance of the device. For the smaller device units (smaller gate length and drain to source separation), the negative effect of channel doping is even more pronounced. Some of the reported GaN/AlGaN devices had 100 *nm* - thick doped layer [9] of GaN which is two times thicker than we have considered here. For these devices the

temperature increase in the active channel is predicted to be even higher.

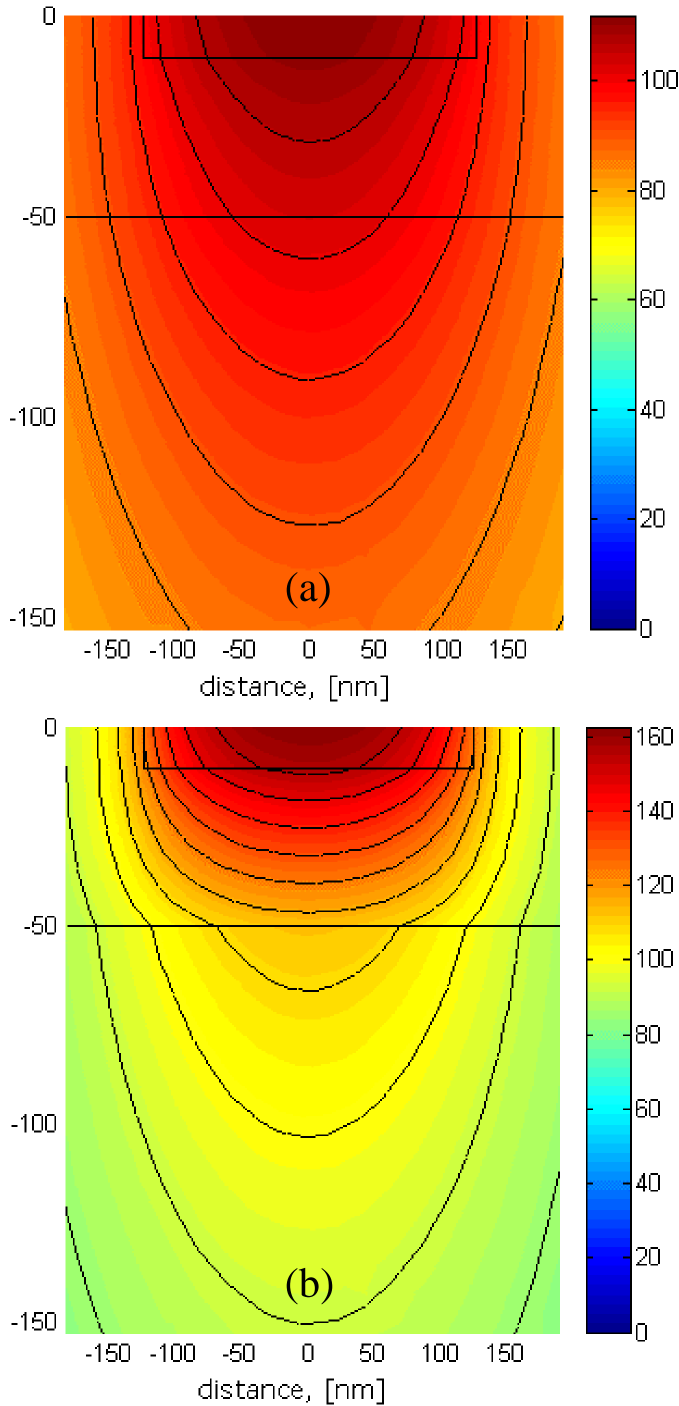

Figure 3. Temperature rise profiles in the undoped (a) and doped (b) channel GaN/AlGaN HFETs on SiC substrate. Note the different temperature scale in two figures.

In Fig. 4 we show the maximum temperature in the drain-gate opening of the HFETs as a function of dissipated power. All four considered cases are characterized by almost liner dependence. It is important to mention here that the results presented in Fig. 4 were obtained taking into account temperature dependence of the coefficient of thermal conductivity, which was extracted from the first-principle models of Refs.[6-7].

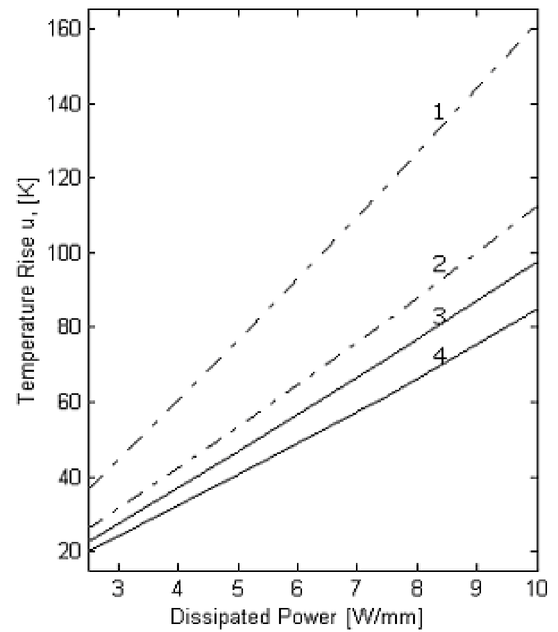

Figure 4. Temperature maximum in the drain-gate opening as function of the dissipated power per channel width *P/W* in AlGaN/GaN HFET. The results are shown for doped HFET with 0.25 μm heat-source length (curve 1); undoped HFET with 0.25 μm heat-source length (curve 2); doped HFET with 1 μm heat-source length (curve 3); and undoped HFET with 1 μm heat-source length (curve 4).

The developed simulation procedure that uses materials specific model for thermal conductivity can be used for the device structure optimization. The simulation of self-heating effects in various GaN/AlGaN layered structures on different substrates will help finding parameters of the device structure optimum for thermal management.

IV. CONCLUSIONS

We have presented the results of the heat flow simulation for GaN/AlGaN heterostructure field-effect transistors. Temperature rise profiles and dependence of the maximum temperature in the drain-gate opening on the dissipated power have been obtained for such devices. Using the developed simulation tools we compared different types of GaN/AlGaN HFETs, e.g. doped-channel vs. undoped-channel, with respect to their thermal management.

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