

The Effect of the Thermal Boundary Resistance on Self-Heating of AlGaIn/GaN HFETs

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We have calculated the thermal boundary resistance at the GaN/SiC, GaN/sapphire and GaN/AlN interfaces in the diffuse mismatch approximation. The obtained values were then used to examine the effect of the thermal boundary resistance on heat diffusion in AlGaIn/GaN heterostructure field-effect transistors. The results show that the thermal boundary resistance at the device layer interfaces can strongly influence the temperature rise in the device channel.

1 Introduction

The GaN materials system has established itself as being very important for the next generation of high-power density devices for optical, microwave, and radar applications [1] [2] [3] [4] [5]. At the same time, performance of these devices has been limited by self-heating [1] [6]. Thus, accurate modeling of heat diffusion and self-heating effects in AlGaIn/GaN heterostructures and device optimization based on such modeling become crucial for further development of nitride technology. Simulation of heat diffusion in GaN and related materials is complicated by large discrepancy in the reported experimental thermal conductivity data and its dependence on defects and dislocations [7] [8] [9]. We have previously shown that the temperature rise in AlGaIn/GaN heterostructure field-effect transistors (HFETs) is different for doped and undoped channel devices [10].

Recently, there have been experimental indications that the overall thermal resistance of AlGaIn/GaN device structures is larger than the simple model estimates from the acoustic mismatch theory (AMT) [11]. One of the possible explanations of this fact can be a relatively large thermal boundary resistance (TBR) at the interface between GaN layer and the substrate. It has been experimentally determined in Ref. [11] that the TBR of the GaN/sapphire interface at 4.2K is about *three orders of magnitude* higher than AMT predictions. A strong effect of TBR on heat diffusion in device structures has been observed for other materials systems [12] [13] [14].

In this paper, we calculate TBR for GaN/SiC, GaN/sapphire and GaN/AlN interfaces using the diffuse mis-

match model (DMM). The obtained values are then used to simulate heat diffusion and temperature rise in GaN/AlGaIn HFETs with characteristic biasing parameters.

2 Thermal Boundary Resistance

TBR is used to describe thermal transport across an interface and is defined as the inverse of thermal boundary conductivity

$$R_{Bd} = \left[\frac{\dot{Q}}{A \cdot \Delta T} \right]^{-1} \quad (1)$$

Here \dot{Q} is a heat flow across an interface, A is an area and ΔT is the temperature difference between the two sides of the interface. In order to calculate TBR at the interfaces between different layers in a HFET structure we use the DMM approach, which assumes that the phonons incident on the interface will all undergo diffuse scattering [15]. In the framework of this model, TBR can be written as

$$R_{Bd} = \left[\frac{1}{2} \cdot \sum_j v_{1,j} \cdot \Gamma_{1,j} \cdot \int_0^{\omega_{Debye}} \hbar \omega \frac{dN_{1,j}(\omega, T)}{dT} d\omega \right]^{-1} \quad (2)$$

where

$$N_{1,j}(\omega, T) = \frac{\omega^2}{2\pi^2 v_{1,j}^3 \left[\exp\left(\frac{\hbar \omega}{k_B T}\right) - 1 \right]}. \quad (3)$$

Here k_B is Boltzmann's constant, \hbar is Planck's constant, and the averaged transmission coefficients are given by

$$\Gamma_{1,j} = \frac{1}{2} \frac{\sum_j v_{2,j}^{-2}}{\sum_{i,j} v_{i,j}^{-2}}, \quad (4)$$

where $v_{i,j}$ are phonon velocities, index $i = 1$ stands for GaN and $i = 2$ for SiC, sapphire or AlN. Another index $j = 1, 2, 3$ indicates longitudinal (LA) and two transverse (TA) sound velocities, respectively. The limit of integration is the Debye frequency

$$\omega_1^{Debye} = v_s \cdot k_d, \quad (5)$$

where $v_s = \left[\frac{1}{3} \sum_j v_{1,j}^{-3} \right]^{-\frac{1}{3}}$ is the average sound velocity in GaN. The cut off wave vector is given by

$$k_d = \left(6\pi^2 N_A \frac{\rho}{M} \right)^{\frac{1}{3}}, \quad (6)$$

where N_A is the Avogadro number, ρ is the mass density, M is the atomic weight.

Using the definition $\theta^{Debye} = \frac{\hbar \omega^{Debye}}{k_B}$ we estimated Debye temperature for GaN to be $\theta^{Debye} \approx 614K$ if LA and TA sound velocities values are taken along [0 0 1] and $\theta^{Debye} \approx 716K$ if the sound velocities values are taken along [1 0 0]. The first value coincides with the one given in Ref. [16]. Taking numerically the integral in Equations (2) and (3) with the materials parameter values from Refs. [15] [16] [17] [18], we obtained TBR as a function of temperature. We have also evaluated TBR in the low temperature limit, where the integral of Equation (2) reduces to the Riemann Zeta function. The calculated TBR value for the GaN/sapphire interface at 4.2K is $0.31 \cdot 10^{-4} \text{ m}^2\text{K/W}$ which is closer to the experimentally determined value of $1.05 \cdot 10^{-4} \text{ m}^2\text{K/W}$ in Ref. [11] than the estimates from AMT. The room tempera-

ture TBR values for GaN interface with relevant materials are summarized in Table 1. The temperature dependence of the GaN/SiC TBR is shown in Figure 1.

One should note here that based on the data reported for other materials systems the TBR values calculated from Equations (2) and (3) correspond to the lower bound limit. The actual TBR can be up to an order of magnitude larger depending on the interface quality and roughness [14].

3 Heat Flow in AlGaIn/GaN HFET

Using TBR values obtained in the previous section, we simulated heat diffusion in AlGaIn/GaN HFET layered structure. To obtain the temperature rise in the device structure we numerically solve the nonlinear heat flow equation

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

$$u \Big|_{z_{\text{gate}}+v_{\text{gate}}+\text{back}+\text{front}+\text{bottom}} = 0, \frac{\partial u}{\partial z} \Big|_{z_{\text{top}}} = 0, u \Big|_{z=0} = 0. \quad (7)$$

Here $u = T - T_a$ is the temperature rise above ambient temperature $T_a = 300K$, k is thermal conductivity taken as in Refs. [8], 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: $a = 0.01 \mu\text{m}$ $L = 1 \mu\text{m}$ ($L = 0.25 \mu\text{m}$), and $W = 200 \mu\text{m}$. 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 Figure 2). The heat-generating region is positioned next to the gate contact, on the drain side, at the depth of $0.023 \mu\text{m}$ below the device top surface. The dimensions of the structures are chosen such as to allow comparison with experimental data in Ref. [19].

The boundary value problem set by Equation (7) has been solved numerically using the finite element method. The results of the simulation of temperature profiles for the GaN/AlGaIn HFET on SiC substrate with the two different TBR values, assigned to the boundary elements, are shown in Figure 3. Comparing temperature profiles in Figure 3, one can see that $1.2 \cdot 10^{-8} \text{ m}^2\text{K/W}$ value of the TBR leads to approximately 20% increase of the maximum temperature in the device channel. One can also note from the left panel in Figure 3 that even with the theoretically determined value of TBR the constant temperature curves undergo strong

discontinuity at the GaN/SiC interface. For higher values of TBR the GaN/SiC interface acts as thermal insulator that keeps the heat in the active channel and creates a hot spot. Higher temperature may lead to mobility degradation and negative differential resistance. We have obtained the dependence of the maximum temperature on TBR for different substrates and heat source lengths (see Figure 4). For example, for SiC substrate with the GaN/SiC TBR value of $4 \times 10^{-8} \text{ m}^2\text{K/W}$ the increase in the maximum temperature in the channel is up to 60%. As it can be seen from Figure 4, for the sapphire substrate, thermal boundary resistance is less significant than that for SiC substrate due to the relatively low value of thermal conductivity of sapphire.

The results of our heat flow calculations of the temperature rise for the AlGaIn/GaN HFETs are in good agreement with experimental data of Ref. [19].

4 Conclusions

We theoretically investigated the thermal boundary resistance and heat diffusion in AlGaIn/GaN heterostructure field-effect transistors on SiC substrate. From our calculations, based on the diffuse mismatch model, the room-temperature thermal boundary resistance at the interface between GaN and SiC is estimated to be $1.2 \cdot 10^{-9} \text{ m}^2\text{K/W}$. Solving the heat diffusion equation for a given device structure, we found that the GaN/SiC interface thermal boundary resistance can strongly influence the temperature rise in the AlGaIn/GaN device channel.

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FIGURES

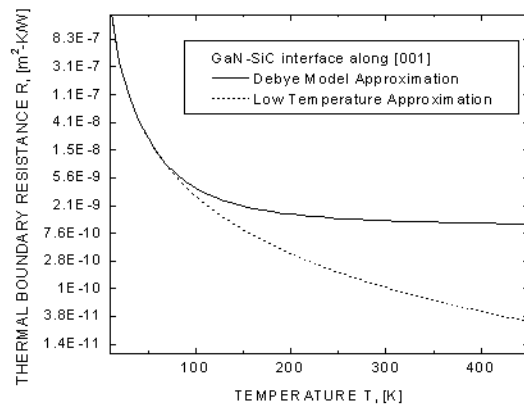


Figure 1. Thermal boundary resistance as a function temperature for GaN/SiC interface. Results are shown in semi-log scale. The dashed line corresponds to the low temperature approximation.

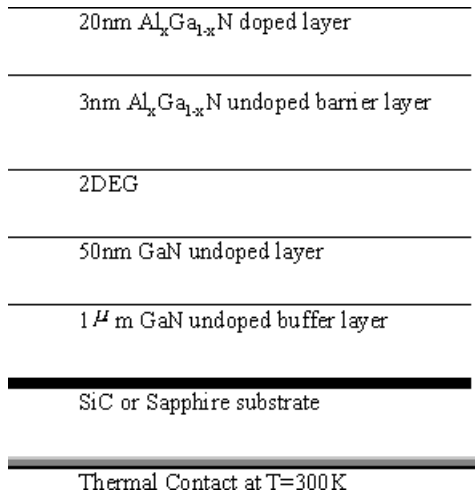


Figure 2. Layered structure of the AlGaIn/GaN heterostructure field-effect transistor.

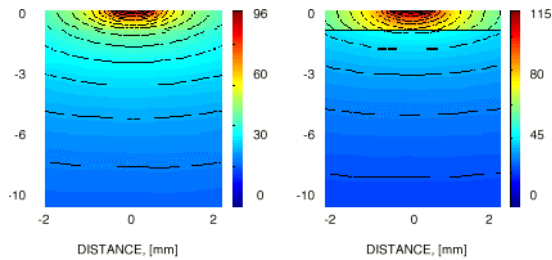


Figure 3. Temperature profiles in GaN/AlGaIn HFETs on SiC substrate for two different values of the thermal boundary resistance. Left panel shows the results for $R = 1.2 \cdot 10^{-9} \text{ m}^2\text{K/W}$, right panel shows the results for $R = 1.2 \cdot 10^{-8} \text{ m}^2\text{K/W}$. The dissipated power is $P = 12 \text{ W/mm}$ in both cases. Note the different temperature scale in two figures.

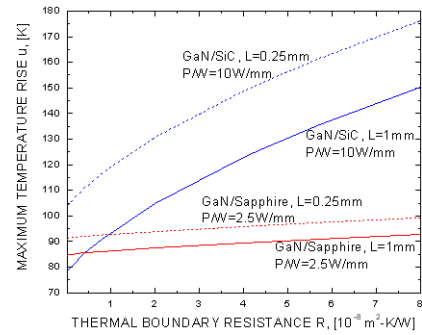


Figure 4. Temperature maximum in the drain-gate opening as a function of the thermal boundary resistance for the GaN/SiC interface (dissipated power is $P/W = 10\text{W/mm}$) and for GaN/Sapphire interface (dissipated power is $P/W = 2.5\text{W/mm}$). The results are shown for the two different HFETs with $L=250\text{nm}$ heat-source length (blue curves) and $L=1\text{mm}$ (black curves).

TABLES

Table 1. Thermal Boundary Resistance at 300K

| | SiC | Sapphire | AlN |
|--|------|----------|------|
| $R_{Bdt} [10^{-9} \text{ m}^2\text{K/W}]$, Wurtzite GaN along [0 0 1] | 1.2 | 1.0 | 0.98 |
| $R_{Bdt} [10^{-9} \text{ m}^2\text{K/W}]$, Wurtzite GaN along [1 0 0] | 0.91 | 0.76 | 0.74 |