Suppression of the self-heating effect in GaN HEMT by few-layer graphene heat spreading elements

V S Volcheck and V R Stempitsky

Department of Micro- and Nanoelectronics, Belarusian State University of Informatics and Radioelectronics, 6 Brovki, Minsk 220013, Belarus

Abstract. Self-heating has an adverse effect on characteristics of gallium nitride (GaN) high electron mobility transistors (HEMTs). Various solutions to the problem have been proposed, however, a temperature rise due to dissipated electrical power still hinders the production of high power and high speed GaN devices. In this paper, thermal management of GaN HEMT via few-layer graphene (FLG) heat spreading elements is investigated. It is shown that integration of the FLG elements on top of the device structure considerably reduces the maximum temperature and improves the DC and small signal AC performance.

1. Introduction

Gallium nitride (GaN) high electron mobility transistors (HEMTs) have been contemplated to be very promising devices for applications in power electronics, microwave systems, and sensing technologies. High electron saturation velocity and breakdown voltage of GaN allow HEMTs to sustain large current densities, leading to extensive and non-uniformly distributed Joule heating, resulting in deterioration of the drain current, radio frequency gain and output power, as well as an increase in the gate leakage current. Numerous approaches to decrease the device temperature have been attempted, including atomic bonding or direct growing of the transistor structure on a diamond substrate, a conventional flip-chip technique to attach a heat sink, integration of heat spreading elements formed out of materials with high thermal conductivity, such as diamond and graphene/graphite combination. Nevertheless, in spite of these efforts, the self-heating effect still persists.

In this communication, we demonstrate that local thermal management of GaN HEMT can be significantly improved by means of additional top-surface heat spreading elements composed of few-layer graphene (FLG). The thermal conductivity of suspended exfoliated FLG is estimated in the range of 13 to 28 W/(cm-K) [1] and order-of-magnitude higher than that of GaN. Heat conduction of FLG is dominated by phonons and its quantitative properties are preserved even if layers of graphene stacked up have a total thickness of only several nanometers. Contrary to FLG, heat conduction in metallic films is limited by electrons and falls sharply with the decreasing film thickness. Advance in single- and few-layer graphene synthesis and patterning on arbitrary surfaces suggests that the proposed heat spreading elements can become technologically and economically expedient in the near future.

In comparison with single-layer graphene, the thermal conductivity of FLG is less prone to degradation caused by extrinsic effects, such as defects and disorder at the junctions. In addition, heat conduction of FLG is characterized by strong anisotropy and, as a result, the FLG elements take the heat away rather than dissipate it at the interface. FLG can also sustain large heat flow through its cross-section while retaining its mechanical flexibility.
2. Simulation details
To estimate the attainable improvement in thermal management of GaN HEMT, we performed a numerical simulation in Wachutka’s thermodynamically rigorous model of lattice heating [2] with the use of Silvaco software.

2.1. Structure
A two-dimensional representation of the initial (without any heat spreading elements) GaN HEMT structure is schematically illustrated in figure 1.

![GaN HEMT Structure Diagram]

**Figure 1.** Initial GaN HEMT structure.

The device structure consists of a 1 μm thick GaN buffer layer, a 20 nm thick aluminum gallium nitride (Al$_{0.2}$Ga$_{0.8}$N) barrier layer, and a 6 nm thick lanthanum oxide (La$_2$O$_3$) as the gate dielectric. The thickness of the sapphire substrate simulation domain is 18 μm. The source-to-gate and gate-to-drain distances equal 1 and 4 μm, respectively, and the gate length is 1 μm.

The spontaneous and piezoelectric components of polarization in Al$_{0.2}$Ga$_{0.8}$N are taken into account. The relatively thick GaN layer is assumed to be unstrained, and so polarization in it has only the spontaneous component. The two-dimensional electron gas density is adjusted to $6.4 \times 10^{12}$ cm$^{-2}$.

A La$_2$O$_3$/AlGaN interface is reported to accumulate a negative fixed charge, with its quantity depending heavily on annealing parameters [3]. To imitate this effect, a negative fixed charge with a density of $3 \times 10^{12}$ cm$^{-2}$ is placed on the gate dielectric/barrier layer interface. Since the position of the negative fixed charge is 20 nm away from the two-dimensional electron gas, the contribution of remote Coulomb scattering is neglected.

2.2. Wachutka’s model of lattice heating
Simulation of the self-heating effect in Wachutka’s model implies addition of a lattice heat flow equation to the set of basic semiconductor device equations, namely Poisson’s equation, the continuity and transport equations. The lattice heat flow equation has a form

$$C \frac{CT}{\partial t} = \nabla (\kappa \nabla T) + H, \quad (1)$$

where $C$ is the volumetric heat capacity (J/(cm$^3$·K)), $T$ is the temperature (K), $\kappa$ is the thermal conductivity (W/(cm·K)), and $H$ is the heat generation (W/cm$^3$).

Since thermal conductivity is generally temperature dependent, it is calculated in accordance with a model

$$\kappa = \kappa_{300} \left( \frac{T}{300} \right)^\eta, \quad (2)$$

where $\kappa_{300}$ is the thermal conductivity at 300 K and $\eta$ is the temperature index.
where $\kappa_{300}$ is the thermal conductivity at the temperature of 300 K and $\alpha$ is the temperature dependence coefficient.

The $\kappa_{300}$ and $\alpha$ parameters for the materials used in the simulation are given in table 1.

| Parameter | Material | La$_2$O$_3$ | Sapphire | GaN | AlN | FLG |
|-----------|----------|------------|----------|-----|-----|-----|
| $\kappa$ (W/(cm·K)) |          | 0.058      | 0.446    | 1.3 | 2.85 | 20  |
| $\alpha$ |          | -0.892     | -1.092   | -0.28 | -1.64 | 0 |

The values for La$_2$O$_3$ are derived from non-linear (power) regression equations obtained on a basis of experimental data given in [4]. The thermal conductivity of Al$_{0.2}$Ga$_{0.8}$N is interpolated as a linear function of composition fraction.

The thermal boundary condition is specified at the bottom surface of the substrate as a perfect heat sink to the temperature of 300 K. The adiabatic boundary conditions are set up at the top surface and the sidewalls of the structure.

2.3. Mobility models

The drift-diffusion transport model is used in the calculations with the Albrecht low field and the Farahmand high field mobility models for electrons in the device channel.

The Albrecht model [5], which treats the mobility in a low field as a function of doping and temperature, is described for GaN as follows:

$$\frac{1}{\mu_A} = \frac{2.61 \times 10^{-4} N}{10^{17}} \left( \frac{T}{300} \right)^{3/2} \ln \left[ 1 + 3 \left( \frac{T}{300} \right)^{2/3} \left( \frac{N}{10^{17}} \right)^{1/3} \right] + 2.9 \times 10^{-4} \left( \frac{T}{300} \right)^{3/2} \exp \left( \frac{1065}{T} \right) - 1,$$

where $\mu_A$ is the electron low field mobility (cm$^2$/V·s) and $N$ is the doping concentration (cm$^{-3}$).

The Farahmand high field mobility model [6] is based on a fit to Monte Carlo data and described for GaN as follows:

$$\mu_F = \mu_A \left( 1 + 6.2 \left( \frac{E}{220.9} \right)^{0.8} \right) + \left( \frac{E}{220.9} \right)^{7.2},$$

where $\mu_F$ is the electron high field mobility and $E$ is the electric field intensity (V/cm).

3. Results

When biased at high drain voltages, GaN HEMT is remarkable to have a hot spot formed at the drain-side gate edge. This region of the structure reveals decreased electron mobility, thus degrading device characteristics.

For the purpose of suppression of the self-heating effect, two FLG heat spreading elements are integrated on top of the initial GaN HEMT structure on both sides of the gate to specifically target the hot spot. An accurate placement of FLG in predetermined locations can be realized, for example, by a polymethyl methacrylate-assisted method. The thickness of the heat spreaders is chosen to be 4 nm, corresponding roughly to four-layer graphene. Since the heat spreading elements are supposed to connect directly with heat sinks outside of the device, two additional thermal boundary conditions are specified at their extreme sides.

A two-dimensional representation of the modified (with the FLG heat spreading elements) GaN HEMT structure is schematically illustrated in figure 2.
Figure 2. Modified GaN HEMT structure.

In figure 3, the temperature distribution profiles along the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ interface of the HEMT without and with the heat spreaders at different gate voltages $V_g$ are shown. $L$ is the distance from the source contact. As follows from figure 3, the peak temperature of the basic device structure rises from 439 K to 517 K when the gate voltage is raised from 0 V to 2 V at the drain voltage $V_d$ of 20 V. The FLG heat spreaders allow to reduce the peak temperature to 372 K and 402 K at $V_g = 0$ V and 2 V, respectively.

In figure 4, the corresponding mobility distribution profiles are shown. It is clear that the higher the temperature a point of the structure has, the lower the mobility of the respective electrons. At the hot spot, the mobility drops to a value as low as 21 cm$^2$/($\text{V} \cdot \text{s}$) at $V_g = 0$ V and 40 cm$^2$/($\text{V} \cdot \text{s}$) at $V_g = 2$ V. When the FLG heat spreaders are integrated, the hot spot electron mobility equals 24 cm$^2$/($\text{V} \cdot \text{s}$) (an increase of 14.29 %) at $V_g = 0$ V and 55 cm$^2$/($\text{V} \cdot \text{s}$) at $V_g = 2$ V (an increase of 37.5 %).

Figure 3. Temperature distribution profiles along the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ interface without (solid lines) and with (dashed lines) the FLG heat spreaders at $V_g = 0$ V (lines 1 and 3) and 2 V (lines 2 and 4), $V_d = 20$ V.

Figure 4. Mobility distribution profiles along the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ interface without (solid lines) and with (dashed lines) the FLG heat spreaders at $V_g = 0$ V (lines 1 and 3) and 2 V (lines 2 and 4), $V_d = 20$ V.

The transfer and transconductance characteristics of the simulated GaN HEMT without and with the FLG heat spreading elements are presented in figures 5 and 6, respectively. The initial transistor exhibits the maximum transconductance of 0.147 S/mm at $V_d = 5$ V, while the modified one has the maximum value of this parameter equal to 0.158 S/mm (an improvement of 7.48 %).
Figure 5. Transfer characteristics of the GaN HEMT without (line 1) and with (line 2) the FLG heat spreaders at $V_d = 5$ V. 

Figure 6. Transconductance characteristics of the GaN HEMT without (line 1) and with (line 2) the FLG heat spreaders at $V_d = 5$ V.

In figure 7, the output current-voltage characteristics for both variants of the GaN HEMT are shown.

Figure 7. The output characteristics of the GaN HEMT without (solid lines) and with (dashed lines) the FLG heat spreaders at $V_g = 0$ V (lines 1 and 3) and 2 V (lines 2 and 4).

As follows from figure 7, the self-heating effect brings about negative differential conductance through the decreased mobility. When the basic device is biased at $V_g = 0$ V and $V_d = 20$ V, the drain current equals 0.173 A/mm, a degradation of 39.08 % from its peak value of 0.284 A/mm. At $V_g = 2$ V and $V_d = 20$ V, the drain current is 0.213 A/mm, a decrease of 46.21 % from the maximum value of 0.396 mA/mm. The GaN HEMT with the FLG heat spreading elements demonstrates much improved output characteristics. When it is biased at $V_g = 0$ V and $V_d = 20$ V, the negative differential conductance is almost eliminated as the drain current reduction equals to only 3.40 %. At $V_g = 2$ V and $V_d = 20$ V, the drain current is 0.438 A/mm, a decrease of 10.61 % from its peak value of 0.49 A/mm.

After solving for the DC condition, a small signal sinusoidal AC analysis is performed. The GaN HEMT is biased at $V_g = 0$ V and $V_d = 20$ V. The AC performance is evaluated via the cut-off and
maximum oscillation frequencies. The frequency dependencies of the AC current gain ($h_{21}$) and unilateral power gain ($U$), derived from calculated S-parameters, are presented in figures 8 and 9. The cut-off frequency of the transistor equals 6.4 GHz and is increased by 51.56% to the level of 9.7 GHz in case of the presence of the FLG heat spreading elements. The maximum oscillation frequency equals 16.1 GHz and is increased by 56.52% to the value of 25.2 GHz.

![Figure 8](image1.png) ![Figure 9](image2.png)

**Figure 8.** Frequency dependence for the AC current gain of the GaN HEMT without (line 1) and with (line 2) the FLG heat spreaders.

**Figure 9.** Frequency dependence for the AC unilateral power gain of the GaN HEMT without (line 1) and with (line 2) the FLG heat spreaders.

4. Conclusions

FLG heat spreading elements allow to suppress the self-heating effect in GaN HEMT, thus improving device DC and small signal AC performance. Progress in single- and few-layer graphene synthesis and patterning on arbitrary surfaces suggests that the proposed in this paper heat spreaders can become technologically and economically expedient in the near future.

Acknowledgments

This work was supported by the grants 1.8.05 of Belarusian National Scientific Research Program “Informatics, Space, Safety” and 3.2.01 of Belarusian National Scientific Research Program “Photonics, Opto- and Microelectronics”.

References

[1] Balandin A A 2011 Thermal properties of graphene and nanostructured carbon materials Nat. Mater. 10 569–81
[2] Wachutka G K 1990 Rigorous thermodynamic treatment of heat generation in semiconductor device modeling IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst. 9 1141–9
[3] Chen J, Kawanago T, Wakabayashi H, Tsutsui K, Iwai H, Nohata D, Nohira H and Kakushima K 2016 La$_2$O$_3$ gate dielectrics for AlGaN/GaN HEMT Microelectronics Reliability 60 16–9
[4] Fornarini L, Conde J C, Alvani C, Olevano D and Chiussi S 2008 Experimental determination of La$_2$O$_3$ thermal conductivity and its application to the thermal analysis of a-Ge/La$_2$O$_3$/c-Si laser annealing Thin Solid Films 516 7400–5
[5] Albrecht J D, Wang R P, Ruden P P, Farahmand M and Brennan K F 1998 Electron transport characteristics of GaN for high temperature device modeling J. Appl. Phys. 83 4777–81
[6] Farahmand M, Garetto C, Bellotti E, Brennan K F, Goano M, Ghillino E, Ghione G, Albrecht J D, Ruden P P 2001 Monte Carlo simulation of electron transport in the III-nitride wurtzite phase materials system: binaries and ternaries IEEE Trans. Electron Dev. 48 535–42