



**HAL**  
open science

## **Thermal characterization of MBE-grown GaN/AlGa<sub>N</sub>/Ga<sub>N</sub> device on single crystalline diamond**

J. Kuzmik, S. Bychikhin, D. Pogany, E. Pichonat, O. Lancry, Christophe Gaquière,  
G. Tsiakatouras, G. Deligeorgis, A. Georgakilas

### ► **To cite this version:**

J. Kuzmik, S. Bychikhin, D. Pogany, E. Pichonat, O. Lancry, et al.. Thermal characterization of MBE-grown GaN/AlGa<sub>N</sub>/Ga<sub>N</sub> device on single crystalline diamond. *Journal of Applied Physics*, 2011, 109 (8), pp.086106. <10.1063/1.3581032>. <hal-00591315>

**HAL Id: hal-00591315**

**<https://hal.science/hal-00591315v1>**

Submitted on 25 May 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

# Thermal characterization of MBE-grown GaN/AlGaIn/GaN device on single crystalline diamond

Cite as: J. Appl. Phys. **109**, 086106 (2011); <https://doi.org/10.1063/1.3581032>

Submitted: 02 December 2010 • Accepted: 07 March 2011 • Published Online: 27 April 2011

J. Kuzmik, S. Bychikhin, D. Pogany, et al.



View Online



Export Citation

## ARTICLES YOU MAY BE INTERESTED IN

[Reducing GaN-on-diamond interfacial thermal resistance for high power transistor applications](#)

Applied Physics Letters **106**, 111906 (2015); <https://doi.org/10.1063/1.4913430>

[Low thermal resistance GaN-on-diamond transistors characterized by three-dimensional Raman thermography mapping](#)

Applied Physics Letters **104**, 083513 (2014); <https://doi.org/10.1063/1.4865583>

[Phonon conduction in GaN-diamond composite substrates](#)

Journal of Applied Physics **121**, 055105 (2017); <https://doi.org/10.1063/1.4975468>

Lock-in Amplifiers  
up to 600 MHz



Zurich  
Instruments



## Thermal characterization of MBE-grown GaN/AlGaIn/GaN device on single crystalline diamond

J. Kuzmik,<sup>1,a)</sup> S. Bychikhin,<sup>2</sup> D. Pogany,<sup>2</sup> E. Pichonat,<sup>3</sup> O. Lancry,<sup>3</sup> C. Gaquière,<sup>4</sup> G. Tsiakatouras,<sup>5</sup> G. Deligeorgis,<sup>5</sup> and A. Georgakilas<sup>5</sup>

<sup>1</sup>*Institute for Solid State Electronics Vienna University of Technology, Floragasse 7, A-1040 Vienna, Austria, and Institute of Electrical Engineering Slovak Academy of Sciences, Dubravská cesta 9, 841 04 Bratislava, Slovakia*

<sup>2</sup>*Institute for Solid State Electronics Vienna University of Technology, Floragasse 7, A-1040 Vienna, Austria*

<sup>3</sup>*LASIR-UMR 8516, Université des Sciences et Technologies de Lille, 59655 Villeneuve d'Ascq Cedex, France*

<sup>4</sup>*IEMN, Université des Sciences et Technologies de Lille, 59655 Villeneuve d'Ascq Cedex, France*

<sup>5</sup>*University of Crete, P.O. Box 2208, 71003 Heraklion-Crete, Greece and IESL-FORTH, P.O. Box 1527, 71110 Heraklion-Crete, Greece*

(Received 2 December 2010; accepted 7 March 2011; published online 27 April 2011)

Self-heating effects in a molecular beam epitaxy-grown GaN/AlGaIn/GaN structure on a single crystalline diamond is investigated. A transient interferometric method, in combination with a three dimensional model, is used to describe a pulsed operation of a transistor-like heater, and a micro-Raman technique is used in a steady state. Good agreement is found between the techniques. The thermal conductivity of the diamond is found to be 2200 W/m K, and the thermal boundary resistance to the III-N epi-structure is  $< 1 \times 10^{-8} \text{ m}^2 \text{ K/W}$ . The excellent cooling efficiency of the diamond is manifested by the fast saturation of the temperature at 1  $\mu\text{s}$  and by a record low normalized thermal resistance of 3.5 K mm/W. © 2011 American Institute of Physics. [doi:10.1063/1.3581032]

As the power density of state-of-the-art GaN-based amplifiers increases, device cooling and heat removal into a substrate becomes crucial. The material parameters of the substrate, such as thermal conductivity,  $k$ , and the thermal boundary resistance (TBR) at the substrate/III-N junction determine the level of the device self-heating.<sup>1</sup> TBR may arise due to an acoustic mismatch at the junction<sup>2</sup> and reported TBR values for SiC and Si substrates range from  $1 \times 10^{-8}$  to  $1 \times 10^{-7} \text{ m}^2 \text{ K/W}$  (see Refs. 1, 3 and 4). With respect to  $k$ , diamond offers the highest value of up to 2200 W/m K [see Ref. 5] from all the known substrate alternatives. Consequently, using diamond may be the best choice to limit device self-heating. AlGaIn/GaN HEMTs fabricated on the GaN buffer which was atomically attached to the diamond substrate was initially reported.<sup>6</sup> The first direct growth and electrical performance of AlGaIn/GaN HEMTs on the single crystalline diamond has only recently been reported.<sup>7</sup> However, neither report analyzes the thermal performance of the devices. In the present study we investigate the thermal aspects of the GaN-based structures grown on the diamond.

A GaN/AlGaIn/GaN heterostructure with a total thickness of 1.4  $\mu\text{m}$  was grown on the single crystalline diamond supplied by Element Six Ltd. using a N-plasma MBE. A consecutively processed device is represented by a 50  $\mu\text{m}$  wide heater which is composed of two ohmic contacts separated by a 3  $\mu\text{m}$  channel (“ungated” transistor). We used an optical transient interferometric mapping technique (TIM) in combination with a three-dimensional thermal model<sup>1,8</sup> to investigate the transistor-like self-heating effects in the time

domain. The optical signal of the TIM method is represented by the phase shift,  $\Delta\phi$ , of a laser probing beam ( $\lambda = 1.3 \mu\text{m}$ ), and  $\Delta\phi$  is proportional to the product of the dissipated heat and the material refractive index change with temperature  $dn/dT$ .<sup>1,8</sup> The heater is stressed by an 80 V rectangular pulse for 15  $\mu\text{s}$ , giving us the dissipating power density,  $P \sim 12.5 \text{ W/mm}$ . To extract the heater temperature increase,  $\Delta T$ , in the channel and the thermal parameters of the diamond/GaN system ( $k_{\text{diamond}}$  and TBR), the model is fitted to the TIM optical signal. Next, the micro-Raman technique is used to measure  $T$  in the steady state as a function of  $P$ . We used a Labram system equipped with a 514 nm argon-ion laser and  $T$  is obtained from a calibrated GaN phonon frequency. The device thermal resistance,  $R_{\text{th}} = \Delta T/P$ , normalized to the channel width, is extracted from both of these experimental methods.

To make the thermal model feasible, it was first necessary to determine  $dn/dT$  of the diamond. This was done by fitting the model to the optical signal under the conditions when the signal originates mostly from the diamond, i.e., for sufficiently long (100  $\mu\text{s}$ ) electrical pulses applied on the heater. Results of the procedure (not shown) indicate  $(dn/dT)_{\text{diamond}} = 8 \times 10^{-6} \text{ K}^{-1}$  which is in good agreement with the data in the literature.<sup>9</sup> The relevant material parameters of GaN used in the model were:  $(dn/dT)_{\text{GaN}} = 4 \times 10^{-5} \text{ K}^{-1}$  and  $k_{\text{GaN}} = 130 \text{ W/m K}$  [Ref. 1].

The time evolution of the experimental  $\Delta\phi$  in the middle of the device channel, which is compared with the model with the best fitting, is shown in Fig. 1(a). Good agreement between the curves could be obtained for  $k_{\text{diamond}} = 2200 \text{ W/m K}$  without considering TBR. Inutility of the TBR indicates a low reflection of the heat at the III-N/diamond junction, despite the lattice-mismatch and inevitably low

<sup>a)</sup>Author to whom correspondence should be addressed. Electronic mail: jan.kuzmik@savba.sk.

crystalline quality at the III-N/diamond junction. To establish the upper range of the possible TBR we calculated  $\Delta\varphi$  for  $\text{TBR} = 1 \times 10^{-8} \text{ m}^2 \text{ K/W}$  as shown in Fig. 1(b). A clear difference between the model and the experiment for this value allows us to suggest that  $\text{TBR} < 1 \times 10^{-8} \text{ m}^2 \text{ K/W}$ .

The reason for an extremely low TBR is not known and may be unique to the diamond. Conversely, the heat reflection at the III-N/substrate junction is a complex effect depending upon various material parameters, as was recently pointed out.<sup>2</sup> As an example, for particular values of phonon group velocity and tangential correlation length and for a particular substrate choice, the transmission probability of the heat was shown to be alternatively insensitive, to decrease (at the GaN/SiC junction) or even increase (at the GaN/Si junction) with the roughness at the interface.<sup>2</sup>

In Fig. 2 we show the calculated time ( $t$ ) evolution of the temperature in the heater for the two cases already analyzed, i.e., for (a)  $k_{\text{diamond}} = 2200 \text{ W/m K}$  and  $\text{TBR} = 1 \times 10^{-8} \text{ m}^2 \text{ K/W}$ , (b)  $k_{\text{diamond}} = 2200 \text{ W/m K}$  and no TBR, and for (c)  $k_{\text{diamond}} = 600 \text{ W/m K}$  and no TBR. We tested  $k_{\text{diamond}} = 600 \text{ W/m K}$  which hypothetically corresponds to the poor quality diamond to see the impact of the substrate. Obviously, the lowest  $\Delta T \sim 44 \text{ K}$  is obtained for case (b) which corresponds to our experiment. However, the difference between the cases became obvious only after about  $t_1 = 100 \text{ ns}$  from the start of the pulse. Before that time instant,  $\Delta T$  seems to be insensitive to the substrate quality as the heat wave only gradually penetrates to the substrate. Alternatively, at about  $t_2 = 1 \mu\text{s}$  the cooling effect from the substrate starts to dominate and  $\Delta T$  saturates. While  $t_1$  is

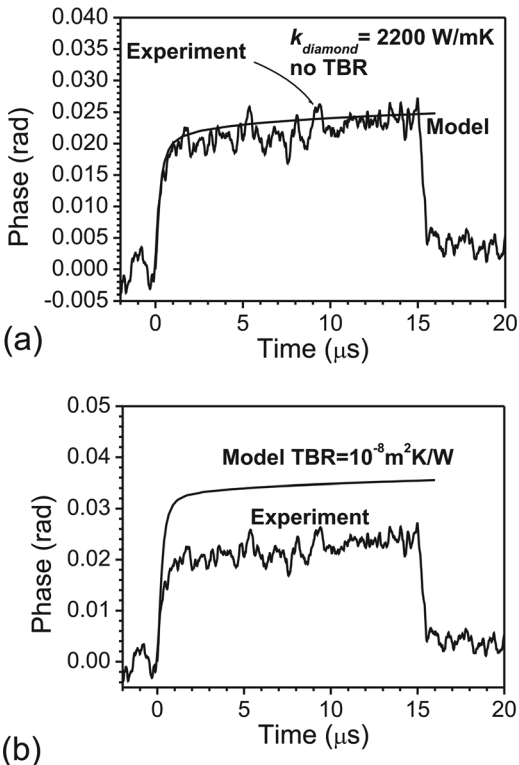


FIG. 1. Calculated and experimental TIM optical signal in the middle of the heater channel during a  $15 \mu\text{s}$  electrical pulse. (a) Model is calculated to get the best fit and (b) for  $k_{\text{diamond}} = 2200 \text{ W/mK}$  and  $\text{TBR} = 1 \times 10^{-8} \text{ m}^2 \text{ K/W}$ .

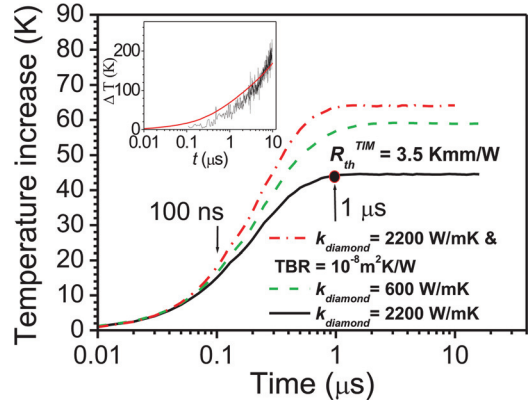


FIG. 2. (Color online) Calculated transient temperature increase in the middle of the heater channel for different diamond substrate parameters:  $k_{\text{diamond}} = 2200 \text{ W/mK}$  and  $\text{TBR} = 1 \times 10^{-8} \text{ m}^2 \text{ K/W}$  (upper curve),  $k_{\text{diamond}} = 600 \text{ W/mK}$  and no TBR (middle curve), and  $k_{\text{diamond}} = 2200 \text{ W/mK}$  and no TBR (curve on the bottom, corresponding to the parameters of the experiment). Arrows highlight  $100 \text{ ns}$  and  $1 \mu\text{s}$  where  $R_{\text{th}}^{\text{TIM}}$  is calculated for the experiment. Inset shows experimental and calculated  $\Delta T$  for a device grown on sapphire (see Ref. 10).

obviously given by the thickness and  $k$  of the III-N epi-structure, the fast  $\Delta T$  saturation at  $t_2$  is due to the diamond substrate. This is also illustrated in the inset of Fig. 2 where we show our previous results (both experimental and the model) on a device grown on sapphire and dissipating about the same power density ( $11.9 \text{ W/mm}$ ).<sup>10</sup> No  $\Delta T$  saturation can be observed for the sapphire substrate and  $\Delta T$  steadily increases well above  $200 \text{ K}$ .

Finally, in Fig. 3 we show steady-state  $\Delta T$  values obtained for the GaN/diamond heater using our micro-Raman experiment which indicates that  $R_{\text{th}}^{\text{Raman}} \sim 3.7 \text{ K mm/W}$ . The  $R_{\text{th}}^{\text{Raman}}$  value can be correlated with the results of the TIM-related thermal model at the time instant when  $\Delta T$  saturates. At  $t_2 = 1 \mu\text{s}$ , the TIM model (see Fig. 2) indicates  $R_{\text{th}}^{\text{TIM}} \sim 3.5 \text{ K mm/W}$ . Thus the TIM experiment is in good agreement with the micro-Raman experiment. Additionally, in Fig. 3 we also show the values for an AlGaIn/GaN/SiC HEMT reported by Simms *et al.*<sup>11</sup> Our values of  $R_{\text{th}}$  for the device grown on the diamond is less than half of what was obtained for the device grown on SiC.

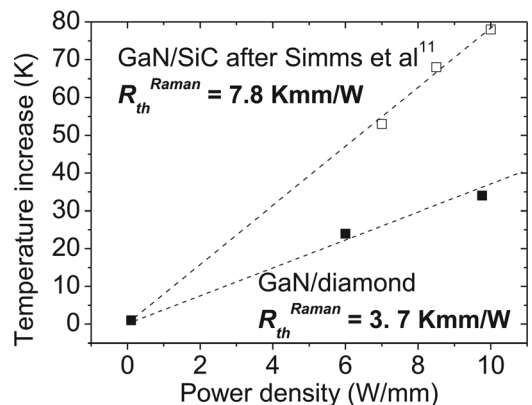


FIG. 3. Steady-state temperature increase obtained by the micro-Raman technique on the GaN/diamond transistor-like heater compared to the results on AlGaIn/GaN/SiC HEMT reported by Simms *et al.* (Ref. 11).

We note that the precision of  $R_{\text{th}}^{\text{TIM}}$  and TBR extraction is limited by the simplifications introduced into the model, such as by the assumption of the isotropic  $k$  values, and by the limitations of the TIM method. A more precise value of the TBR could be expected by using 3-D confocal micro-Raman thermography.<sup>4</sup> Nevertheless, the coincidence between our TIM and micro-Raman experiments confirms the excellent efficiency of the heat transfer from GaN to the diamond.

In conclusion, using TIM, the three-dimensional thermal model, and the micro-Raman technique we analyzed the thermal behavior of the GaN-based device grown on the single crystalline diamond. Extremely high thermal conductivity of the diamond has been observed which, together with the negligible thermal boundary resistance, secures the unique cooling capability of the diamond substrate. The temperature increase in the device is already saturated after 1  $\mu\text{s}$  from the start of the heat dissipation and we obtain the device normalized thermal resistance to be about 3.5 K mm/W. For GaN-based devices this is the lowest reported normalized thermal resistance ever.

This work was supported by the MORGAN European Project No. FP7 NMP IP 214610.

- <sup>1</sup>J. Kuzmik, S. Bychikhin, D. Pogany, G. Gaquière, E. Pichonat, and E. Morvan, *J. Appl. Phys.* **101**, 054508 (2007).
- <sup>2</sup>M. Kazan, *Appl. Phys. Lett.* **95**, 141904 (2009).
- <sup>3</sup>A. Manoi, J. Pomeroy, N. Killat, and M. Kuball, *IEEE Electron Dev. Lett.* **31**, 1395 (2010).
- <sup>4</sup>A. Sarua, H. Ji, K. P. Hilton, D. J. Wallis, M. J. Uren, T. Martin, and M. Kuball, *IEEE Trans. Electron Devices* **54**, 3152 (2007).
- <sup>5</sup>D. J. Twitchen, C.S.J. Pickles, S. E. Coe, R. S. Sussmann, and C. E. Hall, *Diamond Relat. Mater.* **10**, 731 (2001).
- <sup>6</sup>Q. Diduk, J. Felbinger, L. F. Eastman, D. Francis, J. Wasserbauer, F. Faili, D. I. Babiác, and E. Ejeckam, *Electron. Lett.* **45**, 758 (2009).
- <sup>7</sup>M. Alomari, A. Dussaigne, D. Martin, N. Grandjean, C. Gaquière, and E. Kohn, *Electron. Lett.* **46**, 299 (2010).
- <sup>8</sup>J. Kuzmik, S. Bychikhin, M. Neuburger, A. Dadgar, A. Krost, E. Kohn, and D. Pogany, *IEEE Trans. Electron. Devices* **52**, 1698 (2005).
- <sup>9</sup>T. Ruf, M. Cardona, C. S. J. Pickles, and R. Sussmann, *Phys. Rev. B* **62**, 16 578 (2000).
- <sup>10</sup>J. Kuzmik, S. Bychikhin, R. Lossy, H.-J. Würfl, M.-A. di Forte Poisson, J.-P. Teyssier, C. Gaquière, and D. Pogany, *Solid-State Electron.* **51**, 969 (2007).
- <sup>11</sup>R. J. T. Simms, J. W. Pomeroy, M. J. Uren, T. Martin, M. Kuball, *IEEE Trans. Electron. Devices* **55**, 478 (2008).