Received 28 July 2020; accepted 6 September 2020. Date of publication 10 September 2020; date of current version 1 October 2020.
The review of this article was arranged by Editor M. J. Kumar.

Digital Object Identifier 10.1109/JEDS.2020.3023081

Thermal Modeling of GaN HEMT Devices With Diamond Heat-Spreader

M. MAHROKH [1], HONGYU YU [1,2,3] (Senior Member, IEEE), AND YUEJIN GUO [1]

1 School of Microelectronics, Southern University of Science and Technology, Shenzhen 518055, China
2 GaN Device Engineering Technology Research Center of Guangdong, Shenzhen 518055, China
3 Key Laboratory of the Third Generation Semi-Conductor, Shenzhen 518055, China

CORRESPONDING AUTHORS: H. YU and Y. GUO (e-mail: yuhy@sustech.edu.cn; guoyj@sustech.edu.cn)

This work was supported in part by Guangdong Science and Technology Department under Grant 2019B010128001 and under Grant JYCY20170412153356899; in part by Engineering Research Center of Integrated Circuits for Next-Generation Communications, Ministry of Education, Shenzhen, under Grant 2019B010142001; and in part by Shenzhen Institute of Wide-bandgap Semiconductors under Grant JYCY20180305180619573.

ABSTRACT Harvesting the potential performance of GaN-based devices in terms of the areal power density and reliability, relies on the efficiency of their thermal management. Integration of extremely high thermal conductivity Single-crystalline CVD-diamond serves as an efficient solution to their strict thermal requirements. However, the major challenge lies in the Thermal Boundary Resistance (TBR) at the interface of GaN/Diamond or SiC/Diamond. Junction temperature of the device shows a sensitivity of 1.28°C for every unit of TBR for GaN-on-Diamond compared to 0.43°C for every 10 units of TBR for GaN/SiC-on-Diamond. Finite Volume Thermal Analysis has shown a limit of around 22 m^2K/GW beyond which the merit of proximity to the heat-source for GaN-on-Diamond can no more outperform GaN/SiC-on-Diamond. Besides, due to the temperature dependency of the thermal conductivity K, an increase in the temperature causes an increase in the thermal resistivity of the device which is more significant in high power operations. Simplified assumption of constant K overestimates the device performance by resulting in 17.4°C lower junction temperature for the areal power density of 10W/mm. Other part of the project regarding the in-house growth of CVD-diamond to be bonded to the GaN device has been simultaneously in progress.

INDEX TERMS Areal power density, junction temperature, single-crystalline CVD-diamond, thermal boundary resistance (TBR), thermal resistivity.

I. INTRODUCTION

As a result of the increasing trend in the demands of the market for 5G telecommunication industry, as well as the stringent requirements for high power high frequency operation of RF amplifiers for a range of applications such as military jammers, warfare, and radar, group III-V wide bandgap GaN-based semiconductors—highly merited by the outstanding properties of high mobility and high breakdown voltage of GaN, respectively in the order of 1.5×10^7cm/s and 3×10^6V/cm [1]—have emerged as the promising candidate to meet these demands. Using these inherent properties, authors have reported power densities as high as 8 W/mm 55% PAE @30 GHz [2], 10 W/mm 34% PAE @40 GHz [3], and 15 W/mm 55%PAE @2.4 GHz [4]. Considering the PAE values, though relatively good efficiency has been obtained, one can imply that a significant proportion of the power would be dissipated in the form of heat which would cause a rise in the junction temperature, limiting power performance and in turn degrading reliability of the device. Thus, a major challenge in achieving the potential performance of GaN-based devices lies in their thermal management and heat spreading. Assuming a typical GaN HEMT device, the hot spot which can extend from 0.5∼1μm [5], is generated right next to the drain side of the gate edge. Given the high power density that needs to be dissipated from this tiny hot spot, it would require a strict and effective thermal management which can spread the heat from the hot spot through the back-side layers of the device. One effective solution would be using a substrate with a high thermal conductivity. GaN devices are mainly fabricated on

three different substrates, SiC, Si, and Sapphire. Among them, SiC with the highest vertical thermal conductivity of 420 W/mK [6], enables GaN-on-SiC technology to achieve the highest RF areal power density [5]. However, with the increasing demand of the market for highly efficient high-power density RF power amplifiers, substrates with higher thermal conductivities come to play a role in miniaturization of GaN devices. CVD-diamond with extremely high thermal conductivity of 2000 W/mK, being about 5X higher than that of SiC, can be the best candidate to lay the groundwork for this purpose.

Possessing this outstanding property along with the huge progress in the growth of both poly-crystalline and single crystalline diamond thin films using chemical vapor deposition (CVD) method which in turn has led to their commercial availability at reasonable prices, CVD-diamond has attracted the attention of many researchers—striving to reach the potential performance of GaN-based devices—resulting in the introduction of methods of integration of CVD-diamond into these devices, direct growth and bonding. Unlike the direct growth method—either GaN-on-Diamond or Diamond-on-GaN—which needs to be done at extremely high temperatures, resulting in the challenges due to the inherent highly mismatched CTE and crystal structure of GaN and CVD-diamond, the second method, i.e., integration by bonding which is based on and inspired by the commonly available wafer bonding methods in the packaging industry, Thermo-Compression Bonding (TCB) and Surface Activated Bonding (SAB), has the capability of being done at temperatures as low as $< 150°C$ [5]. For this method, there have been proposed two ways in the literature—direct bonding to the host substrate and bonding to the GaN layer.

In the bonding process of CVD-diamond into the GaN layer, the host substrate of the device as well as all the transition and nucleation layers are etched away; typically a thick layer of AlN as the nucleation layer between the substrate and GaN, which is a major source of TBR. This etching process which is actually intended to improve the heat spreading efficiency of the device by moving the high conductivity diamond to the proximity of the hotspot, would also remove the major source of TBR typically existing between GaN and SiC. Bringing about the expectations of lower overall thermal resistance and higher efficacy of the thermal performance compared to the direct bonding of diamond to the host substrate, in this article we will investigate the sensitivity of the junction temperature of a typical GaN-on-SiC device integrated to a single-crystalline CVD-diamond heat spreader, to the TBR between SiC/diamond and GaN/diamond, for the two cases of GaN-on-Diamond and GaN/SiC-on-Diamond respectively.

This work has been done as part of the ongoing project regarding building a high power GaN PA with CVD-diamond heat-spreader. The CVD-diamond is grown in-house and to be integrated to the GaN PA by the aforementioned bonding methods for an efficient thermal solution of these devices.

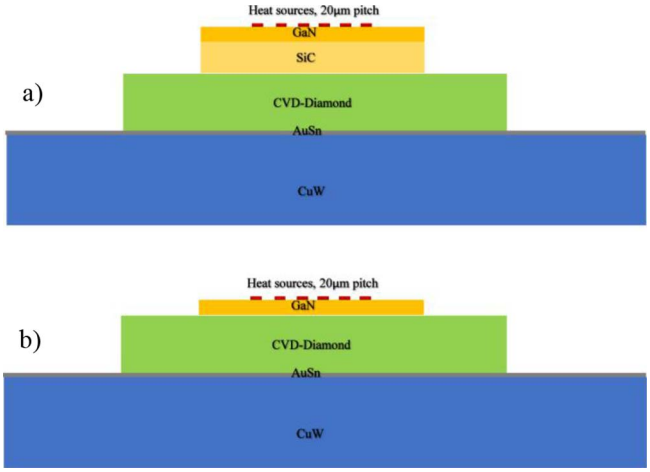

FIGURE 1. **The two methods of integration of CVD-diamond into GaN devices. a) GaN/SiC-on-Diamond, b) GaN/Diamond.**

II. THERMAL MODELING OF GAN-ON-DIAMOND DEVICES

Finite Volume Method has been performed using ANSYS Icepak to compare the thermal performance of the two methods of integration of CVD-diamond into GaN HEMT devices, i.e., direct transfer of the device with the host substrate to the high conductivity CVD-diamond, and transferring the device with the host substrate and all nucleation layers etched away. The thermal model for the first method includes a 10-finger GaN HEMT on SiC substrate, bonded to a single-crystalline CVD-diamond which is AuSn solder-attached to a CuW carrier. As shown in Fig. 1 a) the GaN-on-SiC has a 10×125 μm geometry as the hotspot, with a gate pitch of 20 μm—being one third of that of GaN-on-SiC devices—as the characteristic gate pitch for GaN-on-Diamond devices [5] with 1μm thick GaN and 100 μm thick SiC. A 7×7 mm^2 CVD-diamond with a thickness of 100 μm has been used as the heat-spreader. A thermal boundary condition of 25 °C has been set at the bottom side of CuW carrier. TBR between GaN and SiC is set to 4.4 m^{2}K/GW [7]. A summary of the details of this model are provided in Table 2.

As for the second method of the integration of CVD-diamond into GaN devices, we have used the same above-mentioned structure with the exclusion of SiC and the nucleation layers between GaN and SiC, which have been modeled with a TBR as previously mentioned in the first method.

Table 1 shows the material properties we have used in our thermal analysis in ANSYS Icepak. For the thermal conductivity of the materials, we have analyzed two models, constant-K—which actually uses the room-temperature value of K—and temperature-dependent-K model. Comparing the junction temperature results for both models and for the two methods, we will illustrate how the constant-K model can actually overestimate the thermal performance of the device and yield an overall lower thermal resistance. The

TABLE 1. Summery of parameters used in ANSYS Icepak thermal analysis.

Material	GaN-on-Diamond	GaN/SiC-on-Diamond
Device Geometry	10×125 μm	10×125 μm
GaN Thickness	1 μm	1 μm
SiC Thickness	--	100 μm, 50 μm
CVD-diamond	100 μm	100 μm
GaN/SiC Interface	--	TBR 4.4 m^2K/GW
SiC/Diamond Interface	--	TBR 0-75 m^2K/GW
GaN/Diamond Interface	TBR 0-75 m^2K/GW	--
Die-Attach	25 μm AuSn	25 μm AuSn
Base Plate/ Carrier	1.4 mm CuW	1.4 mm CuW
Base Temperature	25°C	25°C
SiC Thickness	--	100 μm, 50 μm
CVD-diamond	100 μm	100 μm
GaN/SiC Interface	--	TBR 4.4 m^2K/GW
SiC/Diamond Interface	--	TBR 0-75 m^2K/GW
GaN/Diamond Interface	TBR 0-75 m^2K/GW	--

TABLE 2. Material properties used for thermal analysis in ANSYS Icepak.

Material	Density (gm/cm^3)	Specific Heat (cal/g.K)	Thermal Conductivity (W/m.K)
GaN	6.1	0.117	125@300°K 100@400°K
SiC	3.2	0.1648	420@300°K 100@600°K
CVD-diamond	3.515	1.478	2000@300°K 1122@600°K
AuSn	14.7	0.0358	57
CuW	15.5	0.0453	220

data is taken from [6], [8], and [9] for GaN, SiC, and CVD-diamond respectively.

III. RESULTS

In this section we will provide simulation results of the thermal analysis using ANSYS Icepak for the two aforementioned methods of bonding of CVD-diamond to GaN devices—bonding to the host substrate and bonding to the GaN layer—using both constant-K and temperature-dependent K model. Moreover, we will provide the limits of TBR beyond which the merit of proximity to the heat-source for GaN-on-Diamond can no more outperform GaN/SiC-on-Diamond. Thus, there will be no need to bother the more intricate and challenging process of either bonding of CVD-diamond directly to the GaN layer, or direct growth of GaN on CVD-diamond.

A. SENSITIVITY OF THE JUNCTION TEMPERATURE TO THE TBR AT THE INTERFACE BETWEEN SIC AND CVD-DIAMOND

Fig. 2 provides simulation results for the direct bonding of CVD-diamond to the host substrate of the GaN-on-SiC device for a range of TBR values between 0 m^2K/GW, i.e., the ideal case, and 75 m^2K/GW, and for the areal power density of 10W/mm. Both constant-K and temperature-dependent K models have been applied to the same structure with two different thicknesses of the SiC substrate layer, 100 μm and 50 μm, corresponding to the intact, and back-side thinned version of the device respectively.

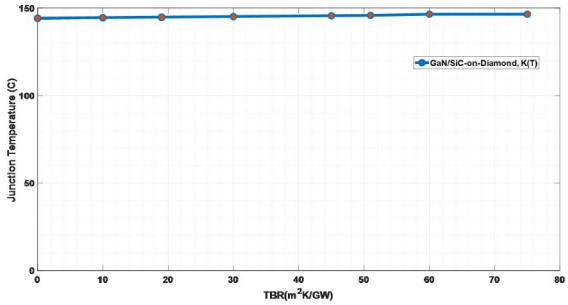

FIGURE 2. Junction temperature of GaN/SiC-on-Diamond as a function of the SiC/Diamond interface TBR using temperature-dependent K model.

Starting with the case of 100 μm thickness, as expected, for both constant-K and temperature-dependent K models, the junction temperature a positive slope toward the higher values of TBR. Additionally, this positive slope shows a higher sensitivity for higher power dissipation in our further analyses.

As for the positive slope toward the higher values of TBR, considering a range of TBR values between 30 m^2K/GW and 60 m^2K/GW for the case of 100 μm thickness of SiC, the junction temperature increases from a value of 145.1°C to 146.4°C, indicating a sensitivity of 0.43°C for every 10 units of TBR for the areal power density of 10W/mm respectively. This sensitivity is doubled for the thinned SiC with a thickness of 50 μm implying the fact that the reduced thermal resistance of the thinned SiC layer would be more comparable to the TBR.

Further analysis of the junction temperature for the two thermal models, constant-K and temperature-dependent-K, indicates 15.16°C lower temperature for the case of constant-K model with the areal power densities of 10W/mm; a clear overestimation of the device performance which is even more significant with an increase in the areal power density.

To verify the validity of the results, we have provided a plot of the mesh convergence of the FVM model used in our simulations for velocity, continuity, and energy equations, demonstrated in Fig. 3.

B. SENSITIVITY OF THE JUNCTION TEMPERATURE TO THE TBR AT THE INTERFACE BETWEEN GAN AND CVD-DIAMOND

Fig. 4 provides simulation results for the bonding of CVD-diamond to the *GaN layer* of the GaN-on-SiC *with the host substrate being etched away,* for a range *of* TBR values between 0 m^2K/GW, i.e., the ideal case, and 75 m^2K/GW, and for the areal power density of 10W/mm. Both constant-K and temperature-dependent K models have been applied to the same structure.

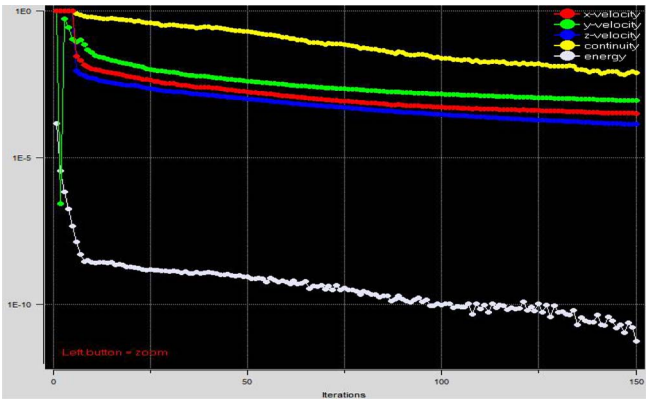

FIGURE 3. Mesh convergence of the FVM model for velocity, continuity, and energy equations.

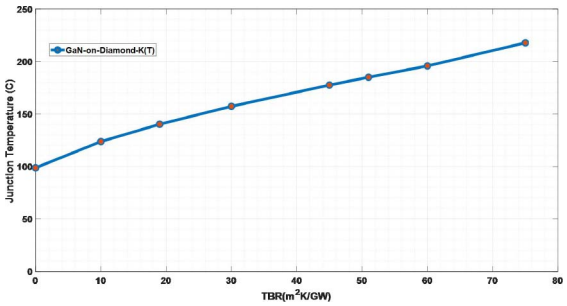

FIGURE 4. Junction temperature of GaN-on-Diamond as a function of the GaN/Diamond interface TBR using temperature-dependent K model.

As expected, for both constant-K and temperature-dependent K models, the junction temperature a positive slope toward the higher values of TBR. Additionally, this positive slope shows a higher sensitivity for higher power dissipation in our further analyses.

As for the positive slope toward the higher values of TBR, considering a range of TBR values between 30 m^2K/GW and 60 m^2K/GW for the case of temperature-dependent K model, the junction temperature increases from a value of 157.3°C to 195.8°C, indicating a sensitivity of 1.28°C for every unit of TBR for the areal power density of 10 W/mm. Authors reported a sensitivity of 0.8°C to 1.1°C for every unit of TBR for a power density of 8 W/mm [5].

Further analysis of the junction temperature for the two thermal models, constant-K and temperature-dependent-K, for a TBR value of 30 m^2K/GW, indicates 17.4°C lower temperature for the case of constant-K model with the areal power densities of 10W/mm; an obvious overestimation of the device performance which tends to be even more significant both with an increase in the areal power density and the value of TBR.

Fig. 5 provides a comparison of our simulated results of the junction temperature with the ones in previous work [10] as a function of TBR for a range of 0 to 75 m^2K/GW. Temperature-dependent K model has been used in the simulations. For a more consistent comparison, we

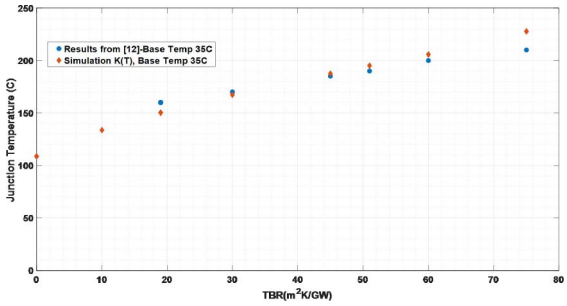

FIGURE 5. Comparison of the junction temperature as a function of the interface TBR for GaN-on-Diamond with previously reported results [10].

have used a 10-finger structure similar to that of [10], with the same base temperature of 35°C. However, different values of thermal conductivity are used in [10]. For example, the authors used a commercially available diamond substrate with thermal conductivity of 1200 W/m.K, while this value is 2000 in our simulations.

As can be seen in Fig. 5, the gap between the circles, and diamond symbols (representing the data in previous work [10], and obtained from simulations), tends to become larger with an increase in TBR. This is because a higher value of TBR implies a higher junction temperature, and thermal conductivity of the layers reduces with temperature which causes a further increase in the device junction temperature.

C. COMPARISON OF THE JUNCTION TEMPERATURE SENSITIVITY TO THE INTERFACE TBR FOR GAN-ON-DIAMOND AND GAN/SIC-ON-DIAMOND

In this section we will elaborate more on the thermal performance of GaN devices bonded to CVD-diamond and introduce the limits of TBR beyond which the merit of immediate proximity to the hotspot as a result of bonding of the CVD-diamond to the GaN layer, can no more outperform the case of the CVD-diamond being bonded directly to the host substrate. Fig. 6 provides a comparison of the junction temperature sensitivity to the interface TBR between GaN and CVD-diamond for the case of CVD-diamond bonded to the GaN layer—and to the interface TBR between SiC and CVD-diamond for the case of CVD-diamond directly bonded to the host substrate of GaN-on-SiC device.

The three solid lines with an obviously higher slope in Fig. 6, represent the junction temperature of the GaN-on-Diamond device for the areal power density of 10W/mm. Starting with the ideal case of 0 m^2K/GW, the GaN-on-Diamond device shows significantly lower junction temperatures than the GaN/SiC-on-Diamond device with a difference of 45.34°C. This value reduces to 20.7°C—and further to 4,4°C for 10 m^2K/GW and 19 m^2K/GW respectively; indicative of the fact that the merit of immediate proximity to the hotspot shrinks in value with an increase in TBR which clearly shows a much higher junction temperature for the case of GaN-on-Diamond than GaN/SiC-on-Diamond; a sensitivity of 1.28°C for every unit of TBR compared to 0.43°C

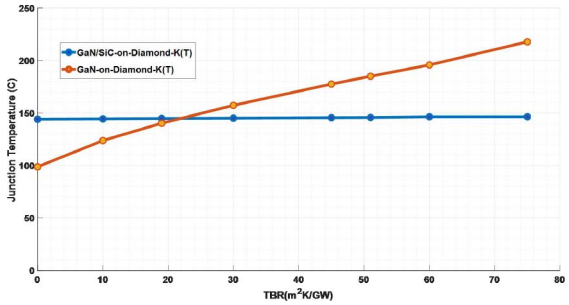

FIGURE 6. Comparison of the junction temperature as a function of the interface TBR for GaN-on-Diamond and GaN/SiC-on Diamond.

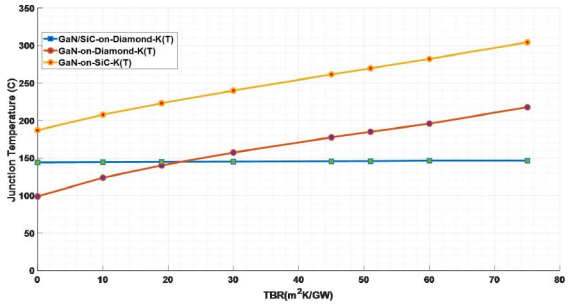

FIGURE 7. Comparison of the sensitivity of the junction temperature as a function of the interface TBR for GaN-on-SiC, GaN-on-Diamond, and GaN/SiC-on Diamond.

for every 10 units of TBR as mentioned in previous sections. Considering the intersection of the junction temperature of GaN-on-Diamond with that of GaN/SiC-on-Diamond, the critical TBR for the former is found to be around 22 m^2K/GW beyond which the concept of immediate proximity to the hotspot can no more outperform the later with SiC thickness of 50 μm. However, for low values of TBR corresponding to a high quality bonding, the effect would be undeniably consequential.

D. GAN-ON-SIC VS GAN/SIC-ON-DIAMOND AND GAN-ON-DIAMOND

To illuminate more on how CVD-Diamond effects the junction temperature of the device depending on the structure, we provide an additional comparison of three structures, GaN-on-SiC, GaN-on-Diamond and GaN/SiC-on-Diamond. As shown in Fig. 7, the first two structures show similar sensitivity to the increase in TBR that is 1.42°C and 1.28°C per unit of TBR respectively. This is due to the fact that for both structures, the TBR, is in immediate proximity of the heat sources, and the layer in between is GaN with a thermal conductivity of 125 at room temperature, which drops significantly with increase in temperature.

Thus, basically for high power densities, implying high operating temperatures, there is a layer with low thermal conductivity plus an additional TBR which directly hinders the heat spread even further from the heat sources. However, the factor that causes a tremendous drop in junction temperature for GaN-on-Diamond compared to GaN-on-SiC, is that the thermal conductivity of Diamond is about 5 times higher that SiC. This can cause about 86°C at a TBR of 4.4 m^2K/GW. Authors have reported a difference of about 80°C for a TBR of 19 m^2K/GW and power dissipation of 10W/mm [5].

However, for the GaN/SiC-on-Diamond structure, this TBR is far enough from the heat sources with an additional high thermal conductivity layer, SiC, in between which causes a some part of heat to be spread from the hot spot before reaching Diamond with a much higher thermal conductivity. Therefore, in this structure the maximum device temperature shows a much lower sensitivity of 0.43°C for every 10 units of TBR.

IV. CONCLUSION

In this article, we have investigated the junction temperature sensitivity of a typical GaN-on-SiC device integrated to a single-crystalline CVD-diamond heat spreader, to the TBR at the interface of SiC/diamond and GaN/diamond, for the two cases of GaN-on-Diamond and GaN/SiC-on-Diamond respectively; FVM analysis in ANSYS Icepak has shown a much higher junction temperature sensitivity for the case of GaN-on-Diamond than for GaN/SiC-on-Diamond, i.e., a sensitivity of 1.28°C for every unit of TBR compared to 0.43°C for every 10 units of TBR respectively. Based on the same analysis we have shown the critical TBR for the former is found to be around 35 m^2K/GW beyond which the merit of immediate proximity to the hotspot can no more outperform the later with SiC thickness of 50 μm. However, for low values of TBR corresponding to a high quality of either bonding or direct growth of GaN-on-Diamond, the effect would be undeniably consequential.

We have also analyzed and compared the junction temperature of the GaN-on-SiC device integrated to a single-crystalline CVD-diamond heat spreader for the two cases of GaN-on-Diamond and GaN/SiC-on-Diamond using both constant-K and temperature-dependent K model. A quick comparison of the junction temperature of the two structures GaN/SiC-on-Diamond and GaN-on-Diamond for the two thermal models at a TBR of 30 m^2K/GW, indicates 15.16°C, and 17.4°C lower temperature results for the case of constant-K model with the areal power density of 10W/mm; a clear overestimation of the device performance which is even more significant with an increase in the areal power density.

ACKNOWLEDGMENT

The authors would like to thank Dr. Quan Chen for his helpful discussions. Marzieh Mahrokh also would like to thank her lab mates Wei-Chih Cheng, and Robert Sokolovskij for their generosity and true sense of cooperation.

REFERENCES

[1] B. Gelmont, K. Kim, and M. Shur, "Monte Carlo simulation of electron transport in gallium nitride," *J. Appl. Phys.*, vol. 74, pp. 1818–1821, Aug. 1993.

[2] J. S. Moon, D. Wong, and M. Hu, "55% PAE and high power Ka-band GaN HEMTs with linearized transconductance via n+ GaN source contact ledge," *IEEE Electron Devices Lett.*, vol. 29, no. 8, pp. 834–837, Aug. 2008.

[3] T. Palacios *et al.*, "High-power AlGaN/GaN HEMTs for Ka-band applications," *IEEE Electron Devices Lett.*, vol. 26, no. 11, pp. 781–783, Nov. 2005.

[4] H. Jia, Y. Luo, Q. Wu, and Y. Yang, "A novel GaN HEMT with double recessed barrier layer for high efficiency-energy applications," *Superlatties Microstruct.*, vol. 111, pp. 841–851, Nov. 2017.

[5] P.-C. Chao *et al.*, "Low-temperature bonded GaN-on-diamond HEMTs with 11 W/mm output power at 10 GHz," *IEEE Trans. Electron Devices*, vol. 62, no. 11, pp. 3659–3664, Nov. 2015.

[6] T. Kawamura, D. Hori, Y. Kangawa, K. Kakimoto, M. Yoshimura, and Y. Mori, "Thermal conductivity of SiC calculated by molecular dynamics," *Jpn. J. Appl. Phys.*, vol. 47, no. 12R, pp. 8898–8901, Apr. 2008.

[7] F. Mu *et al.*, "High thermal boundary conductance across bonded heterogeneous GaN-SiC interfaces," *ACS Appl. Mater. Interfaces*, vol. 11, no. 36, pp. 33428–33434, 2019.

[8] W. Liu and A. A. Balandin, "Thermal conduction in $Al_xGa_{1-x}N$ alloys and thin films," *J. Appl. Phys.*, vol. 97, no. 7, Mar. 2005, Art. no. 073710.

[9] L. Chen, S. Chen, and Y. Hou, "Understanding the thermal conductivity of diamond/copper composites by first-principles calculations," *Carbon*, vol. 148, pp. 249–257, Jul. 2019.

[10] T. Liu *et al.*, "3-inch GaN-on-diamond HEMTs with device-first transfer technology," *IEEE Electron Device Lett.*, vol. 38, no. 10, pp. 1417–1420, Oct. 2017.