Correlation-based study of FEA and IR thermography to reveal the 2DEG temperature of a multi-fingered high-power GaN HEMT

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ABSTRACT

High electron mobility transistors (HEMTs) based on gallium nitride (GaN) with a wide range of application potentials need to be rigorously examined for reliability to take advantage of their intrinsically extraordinary properties. The most vital parameter of the reliability, the hotspot, or $T_{\text{max}}$, resides in the two-dimensional electron gas (2DEG) temperature profile inside the device where optical access is often restricted. The device surface temperature can be measured by widespread IR thermography with the limitation of diffraction-based IR transmission losses. However, $T_{\text{max}}$ on the sub-surface cannot be reached thermographically. Although finite element analysis (FEA)-based thermal simulations can easily reveal the 2DEG temperature profile, accuracy is tightly dependent on the realistic modeling of material/structure parameters. Because these parameters are rather sensitive to fabrication and processing, it is quite difficult to specify them accurately. To overcome these drawbacks, a method integrating both IR thermography and FEA thermal analysis is demonstrated on a fabricated high-power 40 $\times$ 360 $\mu$m packaged GaN HEMT as a proof-of-concept. Utilizing the simulation and measurement temperature profiles, a correlation algorithm is developed so that accuracy of the FEA thermal simulation is improved by calibrating the parameters specific to fabrication/processing conditions by thermographic measurement. Then, it is quantitatively shown that the proposed method is able to find the 2DEG temperature profile and $T_{\text{max}}$ with an accuracy that best suits the intrinsic and extrinsic characteristics of the device under test. The method sheds light on GaN reliability engineering by providing a feasible and reliable alternative to realistically reveal hotspot information for device lifetime assessments.

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I. INTRODUCTION

High-electron mobility transistors (HEMTs) based on gallium nitride (GaN) are attracting the attention of researchers day by day with the extensive advantages that they offer in a broad range of applications, such as high-power amplifiers, monolithic microwave integrated circuits (MMICs), high-performance radars, advanced satellite and space systems, emerging 5G and 6G communication, and digital and quantum computing electronics.1–5 The main features that make GaN HEMTs so advantageous are: (i) high current capacity resulting from the higher electron mobility and the saturation velocity due to the two-dimensional electron gas (2DEG) confinement at the heterostructure, (ii) resistance to the high...
voltages owing to the wide bandgap of the semiconductor material, (iii) operation at high frequencies in the GHz and THz ranges, and (iv) processing high powers thanks to the high current and the high voltage characteristics. GaN HEMT devices mostly operate at high power densities.

Self-heating occurs in the device due to Joule heating, which is more dominant at high powers. If this excess heat is not removed by suitable thermal and heat transfer methods, it will cause unwanted hotspot areas with a temperature higher than 300 °C in the device. Basic transport parameters, such as electron mobility and saturation velocity, which directly affect the device performance, are adversely influenced by the excessive temperature increases, especially in the channel region.

In addition, the mean-time-to-failure (MTF), which is an important numerical indicator of the device reliability, is exponentially dependent on the maximum temperature in the channel or 2DEG region of the device according to the Arrhenius equation as $MTF \propto \exp \left( \frac{E_a}{k_B T_{\text{max}}} \right)$. Here, $E_a$ is the activation energy, $k_B$ is the Boltzmann constant, and $T_{\text{max}}$ is the highest temperature value or hotspot mostly occurred along the 2DEG channel. In other words, $T_{\text{max}}$ is the maximum value of the 2DEG temperature profile ($T_{\text{2DEG}}$). The correct determination of the MTF, which is frequently used by the device reliability engineers, depends on the determination of the $T_{\text{max}}$ with the smallest possible error. As $T_{\text{max}}$ is located in $T_{\text{2DEG}}$ below the device surface, it is not easy to reach the 2DEG level optically.

The most common methods of optically remote temperature measurement are IR thermography and micro-Raman imaging. Since the 2DEG level is masked by the metallic patterns on the device surface, access to the 2DEG level is optically restricted in both methods. A secondary limitation is that the spatial resolution of these measurements deteriorates at sub-micrometer dimensions due to the diffraction. Therefore, the measurements of these methods often underestimate the $T_{\text{max}}$ or 2DEG temperature profile. Compared to the Raman imaging, the IR thermographic approach is popularly preferred in many GaN R&D and production facilities because of the advantages of IR imaging systems such as being cheaper, easier to operate, and collecting data from spacious locations of the sample.

On the other hand, using 2D/3D finite element analysis (FEA) thermal simulations, the $T_{\text{max}}$ value can also be calculated with a certain accuracy. The correctness of these simulations is strongly linked to the true modeling of the material parameters, electrical/thermal boundary conditions, thermal boundary resistance (TBR), and the geometry of the device under test (DUT). As these parameters of the DUT vary from production to production and from process to process, it is not straightforward to determine them realistically.

In order to improve the aforementioned shortcomings, the IR method can be utilized to confirm the accuracy of the parameters. In this study, we correlate the surface temperature data obtained by the IR thermography with the 3D FEA thermal simulation for a multi-finger high-power packaged GaN HEMT device. In this way, the mentioned parameters specific to the device and fabrication/process conditions are calibrated by the thermographic measurement, enhancing the reliability of the FEA. We show that the proposed method is able to find the 2DEG temperature profile with an accuracy that best suits the intrinsic and extrinsic characteristics of the DUT.

In the article, Sec. II presents the correlation method between 3D FEA thermal simulation and IR thermographic measurement for the 40 × 360 μm packaged GaN HEMT. Section III describes the geometric/ material parameters and electrical/thermal boundary conditions for 3D FEA modeling and IR thermographic measurements. Obtained results from the FEA and thermography are given in Sec. IV. Moreover, the application of the suggested method as a proof-of-concept is demonstrated and discussed in this section. Finally, Sec. V highlights the conclusions of the study.

II. CORRELATION METHOD BETWEEN FEA AND IR THERMOGRAPHY

The schematic representation of the suggested method is illustrated in Fig. 1. As seen here, the method comprises two different groups exploring the surface temperature profile of the DUT. The first group on the left is the steady-state thermal analysis process with the 3D FEA, which takes the base temperature ($T_{\text{base}}$), device geometry, material parameters, thermal boundary resistance (TBR), and dissipated power ($P_{\text{diss}}$) as the input parameters. As a result of the FEA simulation made within the framework of these input parameters, the surface temperature profile is obtained as $T_{\text{sim}}(x)$.

In the second group on the right, the surface temperature profile of the DUT is measured by the IR thermography with a thermal microscope (QFI InfraScope TM-HST). The QFI thermal microscope is in a lab environment that is not exposed to extreme cold or heat. It operates in the mid-wavelength infrared (MWIR) spectrum with a liquid nitrogen cooled 512 × 512 InSb focal plane array (FPA) detector. A 4× magnification lens is selected for the IR thermographic measurements. During the thermographic measurement, the DUT (40 × 360 μm packaged GaN HEMT) is placed on an adapter and stage through which the electrical signals ($I_d$, $V_d$) and the base temperature of the DUT are controlled. Before the DUT is electrically activated, the emissivity calibration is performed on the surface of the DUT.

When the desired electrical and thermal conditions of the device reach the steady-state, the surface temperature profile $[T_{\text{mst}}(x)]$ is measured with the QFI thermal microscope. The actual surface temperature data of the DUT are subjected to various distortions and dispersions, starting from the DUT surface and transmitted by the IR radiation until it is detected thermographically in the InSb FPA. The main sources of these distortions are most likely the diffraction effect on the DUT surface and the distortions in IR transmission media (thermal microscope optics, atmosphere, etc.). Therefore, the amplitude and signal shape of the surface temperature profile obtained by IR measurement may differ from the actual temperature profile.

On the other hand, it would not be wrong to accept the surface temperature profile found with 3D FEA as the actual surface temperature profile of the DUT, depending on the correct modeling of the relevant input parameters. Therefore, there is a need to harmonize the discrepancy between the surface temperature from the FEA simulation and the thermographic measurement.
with a correlation-based matching. For this purpose, the correlation process, whose mathematical flow is shown in the middle of Fig. 1, is performed. A Gaussian spatial filter function \[ \text{Filter}(x) \] is chosen to represent the disturbances from the device surface to the InSb sensor output as

\[
\text{Filter}(x) = f_0 + \frac{A}{\pi^2} \exp\left\{-\frac{2\pi^2}{\sigma^2} (x-x_c)^2\right\}.
\]

Here, \( f_0 \), \( A \), \( x_c \), and \( w \) are the offset, area, center, and width of the Gaussian function, respectively. In our study, we fix \( A = 0.1 \) and set \( f_0 \) and \( x_c \) to zero. \( w = 2\times\sigma = \frac{\text{FWHM}}{\sqrt{2\times\pi}} \) where \( \sigma \) and FWHM are the standard deviation and the full width at half maximum of the Gaussian function. Then, the 3D FEA simulation temperature profile from the DUT surface is spatially convolved with this Gaussian function as \( T_{\text{conv}}(x) = \text{Filter}(x) \ast T_{\text{sim}}(x) \). We tune the FWHM of the Gaussian function so that the convolved and measured temperature profiles converge. The FWHM is physically related to the aforementioned distortions in the thermographic measurement caused by the diffraction and the IR transmission.

When we find the FWHM that satisfies the matching condition \( T_{\text{conv}}(x) \approx T_{\text{msmt}}(x) \), we achieve our goal of correlating the thermographic measurement and the 3D FEA for the DUT. Now, we can undoubtedly claim that the 2DEG temperature profile or \( T_{\text{max}} \) value that we reveal with 3D FEA is the most realistic for the specifications and the conditions of the DUT.

III. 3D FEA MODELING AND IR THERMOGRAPHIC MEASUREMENTS

A. 3D FEA modeling approach

The geometric properties and the FEA simulation conditions of the \( 40 \times 360 \mu m \) packed GaN HEMT that we fabricated as the DUT are depicted in Fig. 2. The 3D quarter-symmetric architecture of the DUT that we will use in Comsol FEA thermal simulations is given in Fig. 2(a). The die with a surface area of \( 0.82 \times 2.996 \text{ mm}^2 \) is adhered to the CMC (Copper Moly Copper) package (thickness = 1.4 mm, area = \( 2.8 \times 7.2 \text{ mm}^2 \)) via a 30 \( \mu m \) thick die-attached material (DAM, area = \( 0.90 \times 3.056 \text{ mm}^2 \)). In addition, 30 \( \mu m \) thick thermal paste is glued to the interface between the bottom of the CMC and the temperature stage at \( T_{\text{base}} = 50 \text{ C} \).

In the 3D FEA thermal simulations, the symmetric boundary conditions on the marked side surfaces, isothermal on the bottom surface \( (T_{\text{base}} = 50 \text{ C}) \), and the adiabatic boundary conditions on all other surfaces are employed. Radiative and convective heat transfer mechanisms are not used as their effects are negligible compared to the conductive heat transfer.

The close-up view of the die is illustrated in Fig. 2(b). In the multi-fingered top metallic (Au) pattern, there is a double gate spacing as Pitch 1 = 39.75 \( \mu m \) and Pitch 2 = 98.25 \( \mu m \). The length from the source to drain is 4 \( \mu m \). The thicknesses of GaN,
SiC, and sub-Au are 2, 98, and 5 μm, respectively. The thermal conductivity of the materials utilized in the FEA is presented in Table I. All metallizations in the DUT shown in yellow in Fig. 2 are taken as Au in the FEA.

The zoom from the source to the drain zone is seen in Fig. 2(c). The purple regions correspond to the Si$_3$N$_4$ passivation layers. (d) Close-up view of the gate region.

**TABLE I.** Thermal conductivities utilized in the FEA simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (K)</th>
<th>Thermal conductivity (W/m K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN$^{27,28}$</td>
<td>$T$</td>
<td>$150 \times \left(\frac{T}{300}\right)^{1.4}$</td>
</tr>
<tr>
<td>SiC$^{27,28}$</td>
<td>$T$</td>
<td>$387 \times \left(\frac{T}{293}\right)^{1.49}$</td>
</tr>
<tr>
<td>Air$^{29}$</td>
<td>$T$</td>
<td>$25 \times 10^{-3}$</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>$T$</td>
<td>290</td>
</tr>
<tr>
<td>CMC$^{31}$</td>
<td>$T$</td>
<td>200</td>
</tr>
<tr>
<td>DAM$^{32}$</td>
<td>$T$</td>
<td>5</td>
</tr>
<tr>
<td>Thermal paste$^{33}$</td>
<td>$T$</td>
<td>5</td>
</tr>
<tr>
<td>Au$^{29}$</td>
<td>100</td>
<td>327</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>323</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>284</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>270</td>
</tr>
</tbody>
</table>

The zoom from the source to the drain zone is seen in Fig. 2(c). The purple regions correspond to the Si$_3$N$_4$ passivation coated on the lateral and vertical surfaces with a thickness of 200 nm. The gray regions are still air. In the simulation, the

**TABLE II.** Source and drain dimensions.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Name</th>
<th>Value (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{s, ohmic}$</td>
<td>Length of ohmic layer in source</td>
<td>96</td>
</tr>
<tr>
<td>$L_{s, met1}$</td>
<td>Length of metal 1 layer in source</td>
<td>92</td>
</tr>
<tr>
<td>$L_{s, met2}$</td>
<td>Length of metal 2 layer in source</td>
<td>88</td>
</tr>
<tr>
<td>$L_{d, ohmic}$</td>
<td>Length of ohmic layer in drain</td>
<td>34</td>
</tr>
<tr>
<td>$L_{d, met1}$</td>
<td>Length of metal 1 layer in drain</td>
<td>30</td>
</tr>
<tr>
<td>$L_{d, met2}$</td>
<td>Length of metal 2 layer in drain</td>
<td>26</td>
</tr>
<tr>
<td>$W_{s, ohmic}$</td>
<td>Width of ohmic layer in source and drain</td>
<td>360</td>
</tr>
<tr>
<td>$W_{s, met1}$</td>
<td>Width of metal 1 layer in source and drain</td>
<td>356</td>
</tr>
<tr>
<td>$W_{s, met2}$</td>
<td>Width of metal 2 layer in source and drain</td>
<td>354</td>
</tr>
<tr>
<td>$t_{s, ohmic}$</td>
<td>Thickness of ohmic layer in source and drain</td>
<td>0.12</td>
</tr>
<tr>
<td>$t_{s, met1}$</td>
<td>Thickness of metal 1 in source and drain</td>
<td>1</td>
</tr>
<tr>
<td>$t_{s, met2}$</td>
<td>Thickness of metal 2 in source and drain</td>
<td>4</td>
</tr>
</tbody>
</table>
surface and the 2DEG temperature profiles are obtained along the black and red dotted lines running through the center of the die, respectively. Accordingly, the $T_{\text{surface}}$ line is at the height where the Si$_3$N$_4$ passivation on the gate ends, while the $T_{\text{2DEG}}$ line is at the upper interface of the GaN. The TBR is defined at the interface between the GaN and SiC substrate, the value of which will be changed later $^{34-36}$. The dimensions of the metallization in the source and drain, which are called 

![FIG. 3](image-url)

**FIG. 3.** (a) Adapter and stage where the electrical input-output signals and base temperature of the DUT can be controlled and monitored during the IR thermographic measurements. (b) Photograph of the fabricated $40 \times 360 \mu$m packaged GaN HEMT as DUT. (c) Close-up photograph of the die adhered to the CMC by means of the DAM.

![FIG. 4](image-url)

**FIG. 4.** (a) FEA simulation (according to varying TBR) and thermographically measured ($T_{\text{QFI}}$) surface temperature profiles of the $40 \times 360 \mu$m packaged GaN HEMT at $T_{\text{base}} = 50^\circ\text{C}$ and $P_{\text{diss}} = 5.8 \text{ W/mm}$. (b) Zooming in the temperature profiles of (a) at $x = 0-160 \mu$m. The inset presents the zoom of the leftmost finger for better view of TBR effect.
ohmic, metal 1, and metal 2 from bottom to top, are presented in Table II.

The close-up view of the T-gate region is given in Fig. 2(d).

Here, \( L_{gs} = \) 1 \( \mu \)m, \( L_{gd} = 2.75 \mu \)m, \( L_{GateFoot} \) (i.e., gate length or \( L_g \)) = 0.25 \( \mu \)m, \( L_{GateHead} = 750 \) nm, \( W_G = 360 \mu \)m (for gate foot and head), \( t_{GateFoot} = 75 \) nm, and \( t_{GateHead} = 425 \) nm. ≈ 20 nm thick Al\(_{x}\)Ga\(_{1-x}\)N (\( x = 0.283 \)) layer in the fabricated DUT is omitted in the FEA for the sake of computational efficiency as it is thermally insignificant.\(^{27,37}\) The 2DEG channel properties of the fabricated DUT are obtained by conventional Hall measurement and photoluminescence techniques at room temperature. These are low field mobility of 1935 cm\(^2\)/(V s), sheet carrier density of 1.19 \times 10^{13} \) cm\(^{-2}\), and sheet resistance of 270 \( \Omega \)sq. The uniform heat source is preferred in the FEA because of its simplicity. Therefore, the constant dissipated power (\( P_{diss} \)) obtained at the measurement Q-point is applied just under the gate foot electrodes as a fixed heat generation flux with a length of \( L_g \).

**B. IR thermography**

We perform the IR thermographic measurements with the QFI thermal microscope by placing the DUT in the measurement setup in Fig. 3. The manufactured DUT (40 \times 360 \( \mu \)m packaged GaN HEMT) is placed on the adapter and stage in Fig. 3(a), allowing easy control and monitoring of the electrical input–output signals and base temperature. The close-up views of the DUT and die–DAM–CMC are presented in Figs. 3(b) and 3(c), respectively. First, in this setup, the \( T_{base} \) is set to 70 \( ^\circ \)C and \( P_{diss} = 5.8 \) W/mm.

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**FIG. 5.** (a) FEA surface temperature at \( TBR = 30 \) m\(^2\) K GW\(^{-1}\) and convolution results with Gaussian filter at FWHM of 3, 4, and 5 \( \mu \)m. \( T@QFI \) is the thermographically measured surface temperature profile. (b) Zooming in on the leftmost two fingers in (a). (c) FEA temperature profile at 2DEG level (\( T@2DEG \)) when \( TBR = 30 \) m\(^2\) K GW\(^{-1}\). (d) Zooming in on the leftmost two fingers in (c). In all the panels, DUT is 40 \times 360 \( \mu \)m packaged GaN HEMT at \( T_{base} = 50 \) \( ^\circ \)C and \( P_{diss} = 5.8 \) W/mm.
DC continuous wave high power mode at the drain bias signals of $V_D = 28$ VDC and $I_D = 3$ A. Therefore, with the base temperature of the DUT stabilized at $T_{base} = 50^\circ$C and the power consumption stabilized at $P_{bias} = 5.80$ W/mm, the surface temperature is measured with the QFI thermal microscope.

IV. RESULTS AND DISCUSSION

The thermographically measured surface temperature profile ($T@QFI$) and 3D FEA thermal simulation surface temperature profiles along the midline of the die under these electrical and thermal conditions are presented in Fig. 4. The FEA is performed under the simulation conditions detailed in Fig. 2. Since the TBR value at the GaN and SiC interface can generally vary according to the manufacturing, the surface temperature profiles are obtained by changing the TBR value between 5 and 60 K m²/GW in the FEA to observe its impact. Two points are explicitly discernible in Fig. 4(a). First, the peak and dip locations in measurements and simulations agree with each other throughout the die. Second, the amplitude in both the measurement and simulation temperature profiles rises as the center of the die ($x = 0$ μm) is approached. The zoomed part of the first two fingers closest to the die center is shown in Fig. 4(b). The inset here brings to light that there is a maximum change of approximately 20 °C in the simulated surface temperature profile relative to the increase in the TBR.

As a final step, we are ready to implement the previously detailed correlation method utilizing the temperature profiles of the thermographic measurement and the FEA thermal analysis for the DUT surface. To represent the simulated surface temperature profile of the DUT, we select the surface temperature profile at TBR = 30 K m²/GW, the middle value of the TBR scans in Fig. 4. Subsequently, we apply the correlation method suggested in Fig. 1 to this measurement and simulation pair. In other words, we apply spatial convolution with a Gaussian filter with variable FWHM and the surface temperature simulation profile at TBR = 30 K m²/GW. Since the QFI thermal microscope detects within the 3–5 μm MWIR band, we alter the FWHM associated with these values as shown in Figs. 5(a) and 5(b). The measurement profile ($T@QFI$) is also indicated in these figures. Therefore, it can be observed at which FWHM value the convolution result best matches the measurement. When we examine the convolution results in Fig. 5(a), especially in the non-peak regions where the spatial variation frequency is low, we see that the results of different FWHMs are the same. This is an expected result and it means that IR imaging is performed from the DUT surface outside the hot fingers where spatial fluctuations in the temperature profile are relatively small. That is, IR imaging losses are negligible at these optically large and diffraction-free locations. The fact that the simulation temperature profile remains the same during the convolution with the Gaussian filter for the aforementioned locations also confirms that the selected filter is working properly.

On the other hand, in the upper and near hot finger positions where the variation in the spatial temperature profile is quite high, the filter operates depending on the FWHM. As FWHM increases, that is, as the filter expands spatially, it becomes less sensitive to high-frequency spatial changes. As a result of the process with $FWHM = 5$ μm, it is seen that the measurement and convolution simulation results match each other well, especially in terms of amplitude. This situation can be better visualized in Fig. 5(b) where the leftmost two fingers are zoomed in on. Despite the amplitude matching, the inconsistency in the waveform is due to the fact that the QFI thermal microscope measurement is performed at 4× magnification. Therefore, the QFI measurement resolution is limited to 6 μm as this magnification is selected to be able to observe the temperature profile across the entire die. If the IR imaging is performed with a larger magnification, the resolution will increase and the shape mismatch will be minimized. After successfully completing the correlation method, we reveal the 2DEG temperature profile of the DUT with the FEA as shown in Figs. 5(c) and 5(d) that is the most suitable for the device conditions.

V. CONCLUSIONS

In conclusion, we have demonstrated a proof-of-concept on a fabricated high-power 40 × 360 μm packaged GaN HEMT that the 2DEG temperature profile and $T_{max}$ can be most realistically revealed based on device conditions by a correlation method using common IR thermography and 3D FEA thermal analysis. Thanks to this method, the accuracy of the FEA thermal simulation is improved by calibrating the parameters specific to the device under test and fabrication/process conditions by thermographic measurement. The proposed method provides GaN HEMT RF and reliability engineers a viable and reliable alternative to realistically unveil the hotspot location and value for MTF and lifetime calculations.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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