

Hyperspectral Thermoreflectance Imaging for AlGa_N/Ga_N Power HEMTs

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Abstract—This paper presents early results of a new high spatial resolution thermal characterization technique using a thermoreflectance imaging system on a commercial sample. This technique, hyperspectral thermoreflectance imaging, enables us to obtain a clean thermal image in CW mode with 45 nm spatial resolution. We propose to show the imaging results for a AlGa_N/Ga_N HEMT on a SiC substrate. Although the zone of interest has narrow geometry and some grainy surfaces, the results show a very good linearity of reflection response with changing temperature with a significantly smaller error.

Keywords—Thermoreflectance; hyperspectral imaging; thermal characterization; optical method; AlGa_N/Ga_N HEMT.

I. INTRODUCTION

There have been significant advances in AlGa_N/Ga_N heterostructure based technologies in the last decades, with AlGa_N/Ga_N high electron mobility transistors (HEMTs) showing high power performance at Gigahertz frequencies for communication, space, radar and defense industries [1]. The conjunction of the remarkable properties of the AlGa_N/Ga_N heterojunction and the high thermal conductivity of the silicon carbide substrate enables Ga_N on SiC-based high electron-mobility transistors (HEMTs) to be very efficient for RF applications. However, this very high power density leads to self-heating under operating conditions and has important consequences for both performances and reliability [2]. Since these devices are going to be increasingly smaller and powerful with time, a method of measuring the self-heating is a great concern for thermal management, temperature control, and optimizing simulation software [3].

Several papers reviewed the most reliable techniques for characterizing micro and nanoscale semiconductors in general [4] and Ga_N based devices more specifically [5]. In this way thermoreflectance (TR) thermography achieves submicron spatial resolution, 50 mK temperature and 50 ns time resolution

[6, 7]. The TR technique is based on the optical reflection of illumination ratio ($\Delta R/R$) which changes linearly with changing surface temperature (ΔT) as described in Eq (1) [8].

$$\frac{\Delta R(\lambda)}{R(\lambda)} = C_{th}(\lambda) \cdot \Delta T \quad (1)$$

The thermoreflectance coefficient (C_{th}) is a function of illumination wavelength λ since the refractive index R changes with wavelength and is considered to maintain a fixed value for a calibrated temperature range and it is time independent. This C_{th} value also depends on the material, the material surface characteristics, the passivation layer, etc [8]. Thus it is necessary to determine it experimentally for each studied sample. One of the challenges of TR measurement is the signal to noise ratio due to the small value of C_{th} , ranging in magnitude of $10^{-5} \sim 10^{-6}$. Hence a time averaging technique is typically used for steady state thermal measurement [9].

In the conventional method the first step is to realize a scan wavelength on the sample. That is a measurement of $\Delta R/R$ for each wavelength in a given range, in order to see which wavelength will give a sufficiently high $\Delta R/R$ and C_{th} to observe a good signal to noise ratio during the testing of the device. This method enables a measurement of only a single material of the sample since the optimum illumination wavelength will not necessarily be the same on another surface material.

Hence the present study is not limited to a particular material but a generic method for steady-state measurement. This method has already been investigated with a simple structured sample [10] and we show here the results with a most difficult commercial sample and the way to observe the coherence of the measurements.

II. EXPERIMENTAL METHOD

A. Device and equipment

The sample is an AlGaIn/GaN HEMT on a SiC substrate with a gate width about 280 μm and the visible channel width approximately 1 μm . The thermoreflectance imaging was performed with the commercially available Microsanj imaging system with a 1624 x 1236 CCD camera, enabling a spatial resolution of 45 nm per pixel. The bias conditions of the device under test (DUT) were $V_{\text{DS}} = 30 \text{ V}$, $V_{\text{GS}} = -1.19 \text{ V}$, $I_{\text{D}} = 500 \text{ mA}$ so $P_{\text{D}} = 15 \text{ W}$. During the measurement the temperature of the chuck is controlled at 27 $^{\circ}\text{C}$.

B. Hyperspectral Thermoreflectance Imaging

The reflection intensity of light is a property of the material and is dependent on the material's surface condition as a function of illumination wavelength [11]. Conventional thermoreflectance methods have typically used a single wavelength for illumination. The approach presented here illuminates the wavelength dependency hyperspectrally, namely hyperspectral thermoreflectance imaging (HTI)¹. This means a full band of wavelength over a specific range of wavelength, ($\lambda_1 - \lambda_2$). In our approach, all reflective intensity changes ($\Delta R/R$) for the full spectrum of wavelength is collected and from this data pixel-by-pixel calibration for C_{th} as a function of wavelength can be obtained.

In the following experiments, the window of wavelength spectrum ranges from 410 nm to 530 nm with 10 nm step. This selection is based on the fact that an illumination with 480 nm works well on GaN, as well as 530 nm with the gold, as we can see in Figure 1. For the calibration, the C_{th} is calculated pixel-by-pixel from a derivative temperature with $\Delta T = 73 \text{ K}$ over ambient temperature.

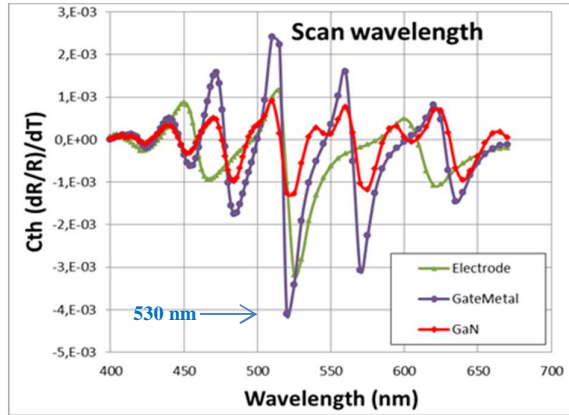


Figure 1: Scan wavelength of the sample in the range of wavelength 400 nm - 640 nm. The 530 nm is shown as one of the best choice to characterize gold.

C. Post processing step

After collecting the $\Delta R/R$ values with the DUT image and C_{th} values with the calibration image, both of these images are superimposed to get access to the temperature distribution pixel by pixel. Following the raw data it is necessary to realize a

spatial smoothing to improve the readability of the spatial distribution, removing the unwanted edge effects or the less accurate points.

III. RESULTS AND DISCUSSIONS

A. Preliminary studies

Figure 2 shows the accuracy of the thermoreflectance measurement and in the same time the limit to the conventional method.

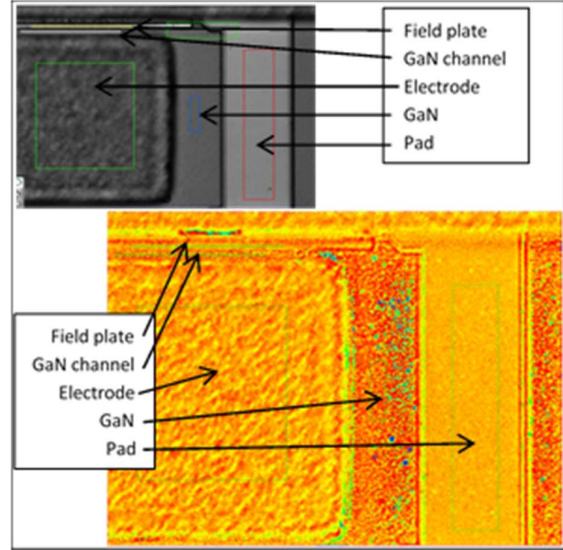


Figure 2: The chuck is heated and the thermocouple fixed on the sample is measured 57.9 $^{\circ}\text{C}$. The microscope view of the sample is shown on top left and below the temperature imaging. We see on the bottom left different areas with their error rate compared to the thermocouple measurement. View with a 100x lens and a 530 nm LED.

Table 1 shows the values of the measured temperatures.

Temperature measurement of heated sample (57.9 $^{\circ}\text{C}$)		
Area of measurement	Extracted temperature ($^{\circ}\text{C}$)	Percentage of error
Electrode	59.2	2%
Field Plate	58.4	0.09%
Pad	58.0	0.02%
GaN channel	61.5	6%
GaN bigger zone	64.6	12%

Table 1: Temperature measurement following the observed area and the percentage of error based on the thermocouple measured.

The chosen wavelength is 530 nm with a 100x lens; a calibration was realized from 27 $^{\circ}\text{C}$ to 80 $^{\circ}\text{C}$ and the C_{th} has been extracted point by point. The chuck is then heated and the thermocouple on the sample measured 57.9 $^{\circ}\text{C}$. The error ratio of each observed area was deducted from the thermocouple temperature. We can see that for the gold material the

¹ Patent pending

temperature extracted shows quite low inaccuracies; 2% error for the electrode, 0.09% for the Field Plate and 0.02% for the Pad. The lower temperature resolution for the electrode is due to the surface roughness compared to the pad and Field Plate (FP) that have cleaner surfaces. The little difference between the pad and the FP could be due to the fact that this last is a smaller observation area and the surface is not quite as clean as the pad. We can also observe that this wavelength permits us to obtain GaN information but with a much lower temperature resolution; 6% error for GaN channel and 12% for GaN larger area. This difference can be due to the passivation that produces optical artifacts at this wavelength.

So we can see that the measurements can have high temperature resolution by choosing the optimized LED wavelength, but we sacrifice other material. We will now present the results of the hyperspectral imaging that employs a range of wavelengths.

B. Hyperspectral Thermal Imaging (HTI) results

Figure 3 shows the thermal image with HTI method and on inset the 20x microscope view with probed areas.

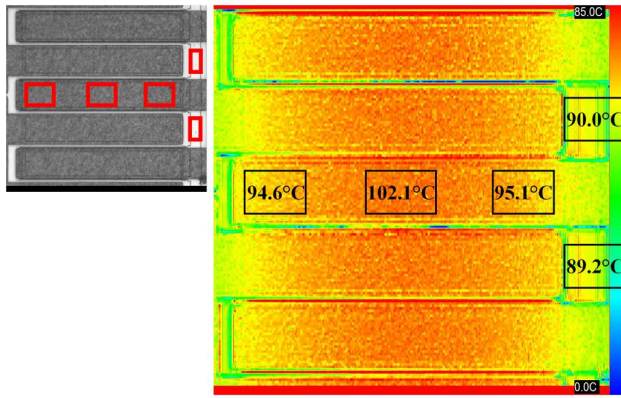


Figure 3: Thermal image of the DUT with the hyperspectral imaging method. We can see the microscope view on top left inset. 20X lens.

A spatial smoothing with 2x2 pixels has been realized to yield more intuitive temperature distribution because of the surface roughness. We can see the temperature distribution compared to the room temperature, so we have to add the 27°C chuck temperature. That means we have along the central source from left to right; 94.6°C, 102.1°C and 95.1°C and on the visible pads on the top one we have 90.0°C and on the bottom one, 89.2°C.

Temperature measurement of different areas in Figure 4 (100X)	
Area of measurement	Temperature (°C)
Top electrode (source)	94.9
Bottom electrode (drain)	96.2
Field plate	125.9
Pad	87.0
GaN channel	104.0

Table 2: Temperature measurement of zones shown in Figure 4.

Figure 4 shows the microscope view of a 100x lens and the thermal image of the DUT in the region of the top pad seen in Figure 3. This method and magnification give access to the temperature of different zones (see Figure 4.a); the field plate (in yellow), the GaN channel (red), the source (orange), the drain (blue) and the pad (in black). The temperatures of these areas are shown in Table 2.

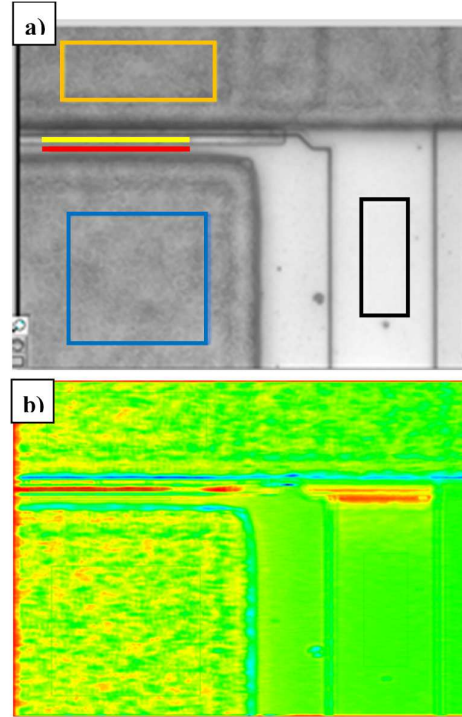


Figure 4: Thermal image of the zone of the top pad as seen in Figure 3: Thermal image of the DUT with the hyperspectral imaging method. We can see the microscope view on top left inset. 20X lens with the HIT method. 100X lens.

We can observe that the temperatures extracted for source and pad with 20x and 100x lens are very similar; 3.2% of difference for pad and 0.3% difference for source.

The following curves show the linearity of the thermorefectance coefficient (C_{th}) and the change in reflection ($\Delta R/R$). It helps to show the accuracy of the measurements, if the slope of C_{th} versus $\Delta R/R$ is linear is that each wavelength used calculated the same ΔT value. Figure 5 shows an example of linearity of C_{th} versus $\Delta R/R$ of the central area of the source and of the top pad; both of these zones are referred to Figure 3.

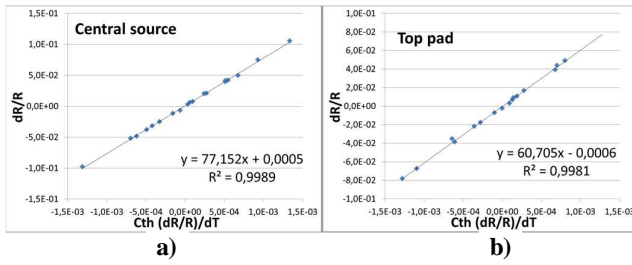


Figure 5: Linearity of C_{th} as function of temperature for Figure 3. (a) Gold of the central source and (b) gold of the top pad.

These correlation coefficients (r^2) and those of the other zones (not shown) are 0.99, a quiet accurate measurement for these materials at 20x. The linearity of the zones referred to in Figure 4 is shown Figure 6.

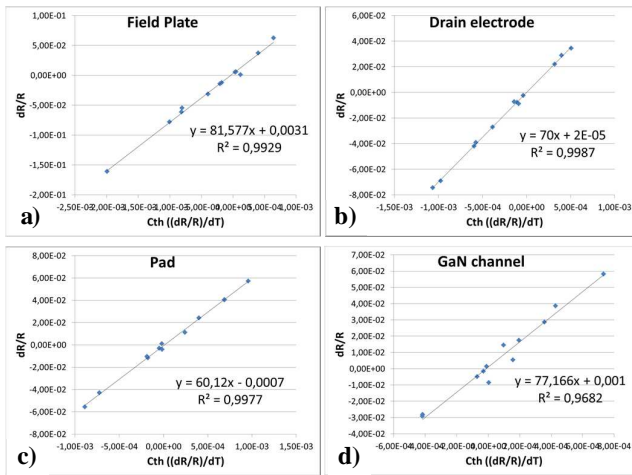


Figure 6: Linearity of C_{th} as function of temperature for Figure 4. (a) Gold of the FP, (b) the drain electrode, (c) the pad and (d) the GaN channel.

The linearity curves from the gold shows quiet accurate values with a correlation coefficient $r^2 = 0.99$. The GaN is a little bit less accurate, perhaps due to some misalignment and the fact that C_{th} values have lower intensity (Figure 1), but the correlation coefficient remains quite good with $r^2 = 0.96$.

IV. CONCLUSION

The Hyperspectral Illumination method has been investigated for an AlGaIn/GaN HEMT with high spatial resolution thermoreflectance imaging. The method used a full band of illumination wavelength from 410 nm to 530 nm in CW mode. Thermal images obtained with this new method significantly reduces the noise and edge effects and permits accurate characterization of several materials with a single image. The linearity shows there is no need to optimize the

measurements with another wavelength or lens. However, the results show that there is some shifted temperature values with the conventional method. We will further investigate the limitations of this method and present this at the conference. Another future step is obtaining imaging results in transient mode.

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