High-Resolution Thermoreflectance Imaging of GaN Power Microwave Transistors

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Abstract—This paper presents CCD based thermoreflectance measurements of surface temperatures with submicron spatial resolution and 50 ns temporal resolution. The measurement results and methodology for 10-finger GaN transistor are presented. The principles of the thermoreflectance technique are explained, 20x magnification steady-state temperature measurements of the drain and source metals and 60x magnification transient temperature measurements of the gate metal and the GaN channel regions are presented. Steady-state peak temperatures of 106.5°C on the drain metal and 89.6°C on the source metals are observed. A temperature change of 89.8°C within the first 0.2 µs duration of the electrical pulse is measured. A peak GaN channel temperature change of 121.4°C is recorded after 19.7 µs duration of the drain electrical pulse.

Keywords—Thermoreflectance, thermal measurements.

I. INTRODUCTION

The growing demand for high-frequency, high-power, and highly efficient electronic devices has been driving the microelectronic industry towards short gate lengths with many transistors in parallel to generate high powers. Since the junction temperature increases in relation to the high power density operation, the resulting heat dissipation limits the performance and reliability of such devices. To optimise the performance and reliability an understanding of the thermal behaviour of these systems is required. Extensive studies have shown that the temperature distribution in integrated structures is not spatially uniform [1]. The localized hot-spots often determine the peak operating temperature of a power transistor, even though the average die temperature may be significantly lower. Investigating self-heating for such devices requires a versatile thermal imaging technique that combines precise temperature resolution, nanosecond temporal resolution and submicron spatial resolution.

Several thermography methods are used to measure semiconductor materials and devices. The infrared (IR) technique, which is non-contacting, is perhaps the most widely used method for thermal characterization of high-power microwave transistors [2]. By using IR microscopy, the temperature can be acquired from the top surface of the device or from the backside through the chip substrate. Most IR microscopes operate in the 3 µm to 5 µm range, and produce spatial resolution on similar scale. Systems working in near infrared (NIR) wavelengths can achieve spatial resolution down to 1 µm [3]. Transient infrared imaging has been demonstrated with 20 µs temporal resolution using internal camera shuttering [4].

Raman thermography is another non-contacting technique, which is based upon the dependence of temperature on the phonon frequency. The spatial resolution offered by Raman is improved over IR but unfortunately requires longer time to perform the measurement. Its spatial resolution is determined primarily by the size of the focused laser spot used and the method of scanning the laser. Spatial resolution of less than 1 µm has been demonstrated [5].

The thermoreflectance technique is based on measuring the relative change in the reflectivity of a surface as a function of temperature. The spatial and temporal resolutions can be as low as 250 nm and 800 ps, respectively [6]. Temperature resolution of 10 mK can be achieved for relatively short data acquisitions times as compared to the other thermography techniques. This method is suitable for a wide range of materials, making it ideal for thermal characterization of semiconductor devices.

This paper presents an overview of the foundations of the thermoreflectance thermography method, the experimental measurement set-up and measurements of a GaN high electron mobility transistor (HEMT).

II. PRINCIPLES OF THERMOREFLECTANCE

Measurements of reflectance due to temperature modulation have been widely used since the 1960s to study the band structures in semiconductors [7]. Recently, the thermoreflectance imaging method has been extended to measure temperatures in ICs, micro-scale, and nano-scale devices. The first order relationship between the change in reflectivity due to a change in temperature is,

\[
\frac{\Delta R}{R_0} = \left( \frac{1}{R_0} \frac{\delta R}{\delta T} \right) \Delta T = C_{tr} \Delta T
\]

where \(\Delta R\) is the change in reflectivity, \(R\) is the reflected light, \(C_{tr}\) is the thermoreflectance calibration coefficient and \(\Delta T\) is the change in temperature. The thermoreflectance coefficient is typically of the order of \(10^{-5}\) to \(10^{-2} \text{ K}^{-1}\) and is dependent on the sample material and the wavelength of the illumination source. Once \(C_{tr}\) is obtained, the measurement of the temperature variations can be determined from the reflectivity change of the device. During the temperature measurement the device temperature is varied using a function generator to turn on and off the device. Since the thermoreflectance coefficient is very small for most materials of interest, a lock-in technique is employed to enhance the signal-to-noise ratio and achieve good temperature resolution. Furthermore, calibration for each
material is required to determine the wavelength that yields the maximum reflectance change signal. The calibration method consists of heating the sample using an external thermoelectric (TE) heating stage and a micro-thermocouple to record the induced temperature change. The sample is heated at two distinct temperatures where the reflectance distribution of the surface is measured. By measuring the change in reflectance, the thermoreflectance coefficient can be calculated at each location across the sample surface. Once the calibration has been performed the device-under-test (DUT) is placed under a microscope and illuminated by a narrowband source. To extract the thermoreflectance change from the background noise, the image is averaged over many thermal excitation cycles. The thermoreflectance image is then converted to a map of surface temperature by scaling each pixel of the image by its corresponding material thermoreflectance response.

III. EXPERIMENTAL SET-UP

Thermoreflectance measurements were carried out on the high power microwave transistor, as shown in Fig. 1, using the Microsanj NT220B system, as shown Fig. 2. The analysed device was produced in the Leonado S.p.A. GaAs/GaN foundry.

The schematic of the thermoreflectance measurement set-up used to obtain the temperature distributions across the GaN HEMT is shown in Fig 3. The measurement system uses a CCD camera to capture the change in the intensity of the reflected light on each pixel of the image. The CCD camera approach enables easy variations of the probing light (to maximise $C_{tr}$ coefficient) and the measurement procedure is relatively fast [8]. Either a light emitting diode (LED) or a tunable light source can be used as the illumination source. The temporal resolution of 50 ns can be achieved using the CCD based measurement system. The microscope objective is equipped with 5x, 20x, 60x and 100x magnifications that enable thermal measurements of the metal surfaces as well as the channel and gate regions.
IV. THERMOREFLECTANCE MEASUREMENT RESULTS

A. Thermoreflectance calibration

A calibration of the drain, source and gate metals was performed using the tunable light source in order to find the LED wavelengths at which the $C_{tr}$ is optimal. The thermoreflectance coefficient response as a function of the wavelength sweep between 450nm-560nm is shown in Fig. 4.

In order to detect a temperature change of 1°C, it is necessary to detect a reflectance change of 1 part in 100 to 1 part in 100,000 [9]. The metallizations material exhibits maximum $C_{tr}$ values around LED wavelengths of 520 nm and 480 nm. It was concluded that the calibrated material is gold due to very similar $C_{tr}$ vs LED wavelength behaviour previously shown in [9]. The temperature profile of the 10 finger GaN HEMT was obtained using a 530 nm LED, as previous studies have shown that the temperature variation for this material is best captured at this wavelength [9]. The temperature extraction of the channel region has been performed using illumination source at 365 nm wavelength.

B. Thermoreflectance measurements

The steady state measurement of the GaN HEMT was obtained using the 20x magnification. The lower magnification is required to obtain the temperature distribution across the entire device. During DC operation a bias of 28 V on the drain and -2 V on the gate was used resulting in picture of the temperature distributions across the HEMT is shown in Fig 5.

Fig. 5. Temperature distribution for the drain and source metals at 20x magnification. The black dashed line is a line cut where the temperatures were obtained for Fig. 7.

Fig. 6. Image series at 1.8 $\mu$s, 4.8 $\mu$s and 95 $\mu$s showing the heat spreading for a 100 $\mu$s drain pulse.

Fig. 7. Temperature distribution graph for all drain and source metals obtained at 20x magnification.

The black regions between the drain and the source metals are unresolved as they require higher magnifications.

Figure 7 shows the temperature distributions across for all drain and source metals. The thermal measurement was performed at 22 °C base temperature. The temperatures across the drain metals are $\approx$ 15 °C hotter than the source metals. The peak drain metal temperature is recorded at 106.5 °C and the peak source metal temperature at 89.6 °C. Transient temperature measurements at 20x magnification for a 100 $\mu$s electrical pulse are shown in Fig 6. The image series shows the heat spreading once the device is turn on. Although not shown here, the images can be combined into a movie to see the transient heating of the entire die.

The transient thermoreflectance measurements were performed at 60x magnification to capture the gate metal and the channel region. The GaN HEMT was biased with a 20 $\mu$s pulse on the drain terminal at 10% duty cycle and -2.5 V on the gate port at the centre. The full transient response for the two middle gate fingers is shown in Fig. 8. The thermoreflectance measurement was obtained at 100°C base temperature. After 200 ns of the drain electrical pulse the temperature rises to
189.8°C on the two measured GaN channel regions. The peak temperature of 221.4°C is recorded 0.3 µs before the device turn-off. The CCD image overlaid with the temperature across the channel region is shown in Fig. 9. The GaN channel region has a width of ≈ 1 µm. These measurements were obtained using an LED wavelength of 365 nm with 0.7 numerical aperture (NA). As a result, the achieved spatial resolution was 260 nm.

V. Conclusion

Thermoreflectance thermography was successfully employed to measure the temperature distributions across a ten finger GaN HEMT. Both DC and pulsed operation was thermally investigated. Steady state temperature distributions of the drain and source metals and transient temperature of the channel regions have been measured. Steady-state of metallization regions and transient of the channel region temperature measurements have been successfully acquired using the thermoreflectance method.

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References