Improved Infrared Temperature Measurement of RF Devices

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Abstract
The paper describes the infrared (IR) thermal measurement facility at De Montfort University and the use of the facility to make IR temperature measurements on RF devices. Some of the limitations with conventional IR measurements will be described; including effects related to the low emissivity and optical transparency of materials.

A novel method for improving the accuracy of IR temperature measurements has been developed. By measuring the level of IR radiation emitted by high emissivity micro-particles, placed in isothermal contact with an electronic device, an indirect estimate of its surface temperature can be obtained. The paper will show how the IR "micro-particle" technique has been used to make improved IR temperature measurements on the gallium arsenide (GaAs) Gunn diode and gallium nitride (GaN) high electron mobility transistor (HEMT).

1. Introduction

The thermal characterisation of microelectronic RF devices to obtain a good estimate of the junction temperature is very important to optimise both performance and reliability. Infrared (IR) thermography is a powerful technique for performing non-invasive 2D temperature measurements across a device [1]. The technology has significantly improved over the last decade, resulting in a state-of-the-art spatial resolution of approximately 3 µm.

While conventional IR imaging has many applications, the technique suffers from temperature errors which occur when low emissivity metals and optically transparent semiconductor materials are studied [2]. Although a high emissivity coating can be sprayed onto such materials, the coating can cause heat spreading, distorting the measured temperature profile. Additionally, the coating also damages the device and visually obscures areas for inspection.

A novel technique has recently been developed to improve the accuracy of IR temperature measurements made on electronic devices [3]. The new technique employs radiative carbon micro-particles, which are placed in isothermal contact with areas of the device under study. Infrared measurements made on the micro-particles can be used to obtain an improved estimate of a device's surface temperature, eliminating the need for conventional high emissivity coating. The paper will show how the IR micro-particle technique has been used to obtain temperature measurements on a GaAs Gunn diode and an aluminum gallium nitride/gallium nitride (AlGaN/GaN) HEMT.

2. IR Thermography

The spectral distribution of emitted radiation from an ideal IR black body source, at a number of different temperatures, is shown in Figure 1. Infrared radiation is most intense in the 2 – 20 µm waveband, where most passive IR detectors are designed to operate.

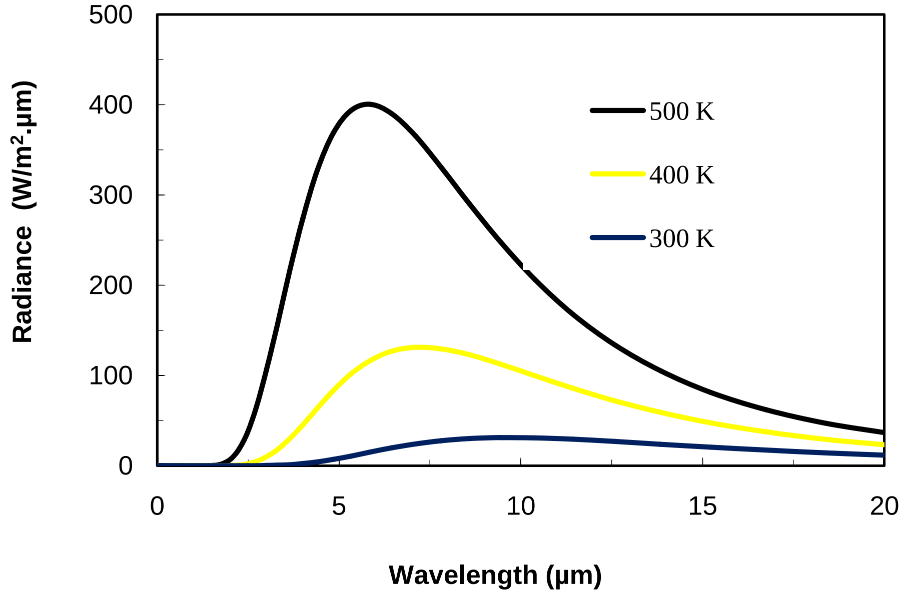


Figure 1: Spectral distribution of emitted IR radiation from an ideal black body source.

The total radiated power emitted by a surface is proportional to the fourth power of temperature and can be given by Stefan Boltmann's law

$$W = e\sigma T^4$$

where e is the surface emissivity, T is temperature and σ is the Stefan-Boltzmann constant. The emissivity of a surface characterises its efficiency to emit IR radiation relative to a black body source at the same temperature and over the same spectral range. If the emissivity and emitted radiation level from a surface is known its temperature can be determined. For accurate temperature measurements, the surface emissivity is measured, as its value is dependent on a number of factors, including material type and surface roughness. Emissivity values can vary widely, with values of less than 0.1 on gold and greater than 0.9 on painted surfaces.

The IR microscope system at De Montfort University is shown in Figure 2. The system uses an indium antimonide (InSb) CCD array to obtain 2D temperature profiles on areas from 230 µm – 5 mm square. The microscope detects IR radiation in the 2 - 5 µm waveband and has a spatial resolution of ~ 3 µm.

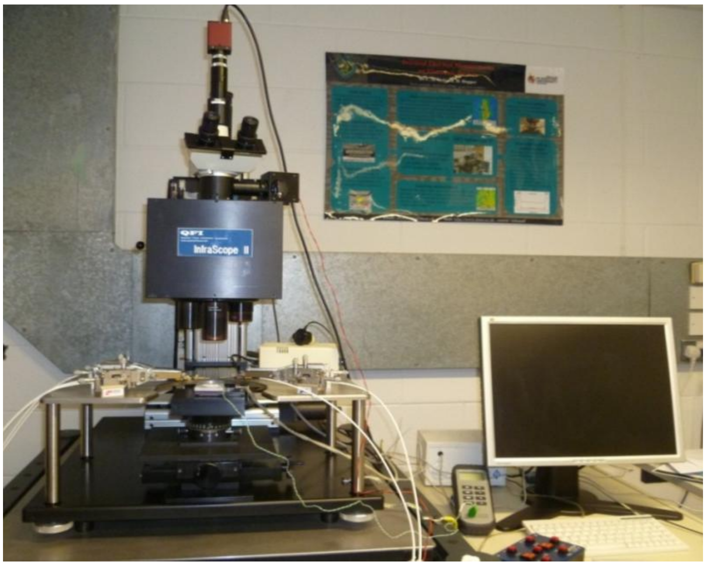


Figure 2: IR microscope system at De Montfort University.

3. Thermal analysis of the GaAs Gunn diode

Gallium arsenide Gunn diodes are widely accepted high frequency microwave sources. In recent years, the graded-gap Gunn diode has been used as a 77 GHz signal source for adaptive cruise control (ACC) [4]. Adaptive cruise control systems are fitted in cars to enable the position and velocity of vehicles travelling ahead to be determined. The system is commonly marketed as a safety feature, enabling a car’s brakes to be automatically applied if an obstacle is detected. The Gunn diode is a critical component to the system and must have a very high reliability. The reliability and performance of the device is known to be adversely affected by high temperature operation, which can be caused by self-heating. Thermal characterisation is required to obtain the peak device operating temperature to ensure longevity of performance.

Device construction

A simplified diagram illustrating the construction of the Gunn diode is shown in Figure 3. The device contains a lightly doped GaAs layer, called the transit layer, contacted top and bottom by two highly doped GaAs contact layers. Within the active device, electrons propagating through the transit layer will be accelerated by an applied electric field. Some of the higher energy “hot electrons” will transfer into the lower mobility state in the conduction band, creating a build-up of slowly moving charge called a ‘domain’. Given an electric field of sufficient strength, the process of domain creation and nucleation is repeated many times, leading to electrical oscillation. Bulk heat generation occurs within the transit layer, as high electric field strengths and current densities exist here.

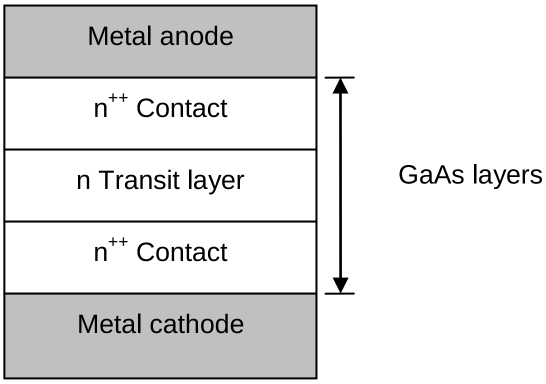


Figure 3: Structure of the GaAs Gunn diode.

A SEM image showing a cross-sectional view of the fabricated Gunn diode is shown in Figure 4. A gold bond wire is used to make electrical contact with a gold top contact, beneath which are the semiconductor layers forming what is termed the mesa. The mesa is cylindrical in shape and has a diameter between 60 – 80 µm and a total thickness of ~ 13 µm. The mesa is attached to a gold integral heatsink (IHS) which is ultrasonically bonded onto a cylindrical copper package to remove heat.

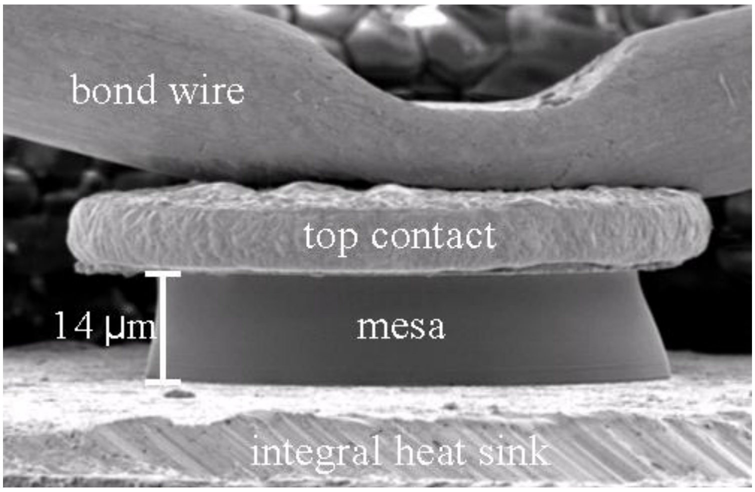


Figure 4: SEM image showing the construction of the Gunn diode.

Thermal measurements

Accurate IR surface temperature measurements cannot be directly made on the GaAs semiconductor layers of the Gunn diode, as these areas are optically obscured and partially transparent to IR radiation. Fortunately, the metal top contact of the Gunn diode is visible; thermal modeling suggests it reaches the peak device operating temperature due to its very close proximity to the active layer. The accuracy of IR temperature measurements made directly on the gold metal contact is poor due its low emissivity of and high reflectance of background radiation. In order to increase the emitted radiation level from metalised areas, a high emissivity, non-conductive, coating (15 – 20 µm thick) can be applied.

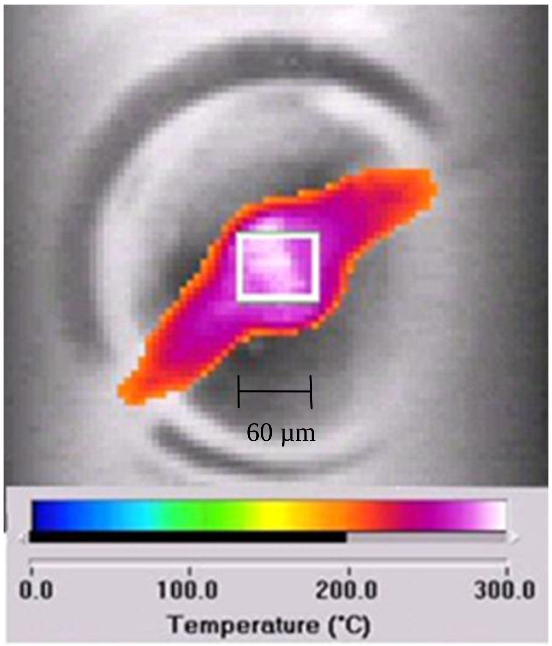
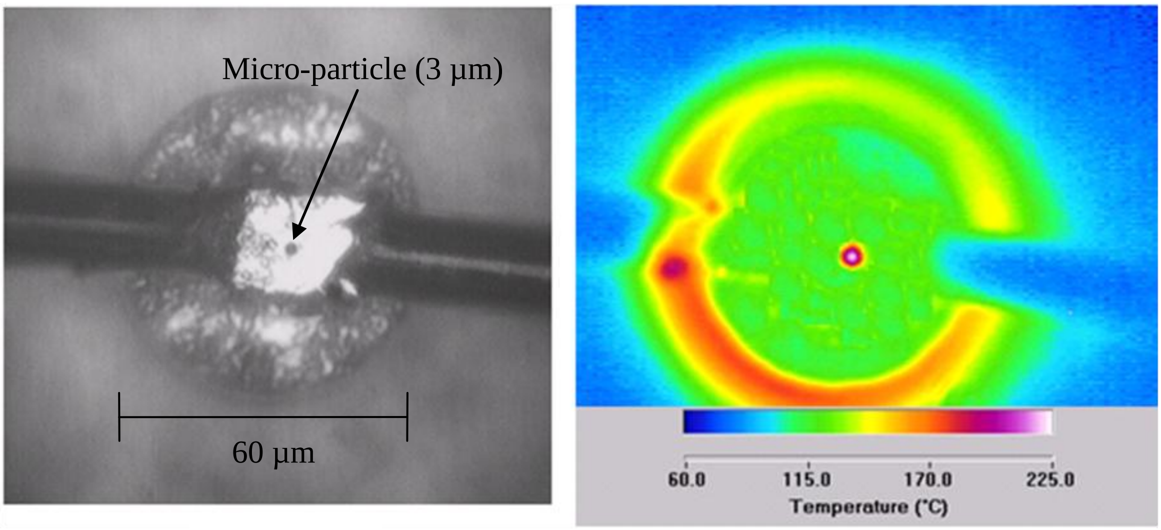


Figure 5: Typical IR temperature image measured on the coated top contact of the electrically powered GaAs Gunn diode. × 5 magnification. Power = 6 W, $T_{ambient}$ = 80 ºC.

A typical IR temperature image of the coated top contact of the electrically powered Gunn diode is shown in Figure 5. Areas of high temperature have been superimposed onto an unpowered radiance image. Infrared thermal microscopy provides a convenient tool for rapidly obtaining the temperature profile on the coated metallised structure, enabling the extraction of the peak operating temperature.



a **b**

Figure 6: a) Optical image (× 20 magnification) showing a carbon micro-particle (3 µm diameter) deposited on the gold top contact of the Gunn diode. **b)** IR temperature image of the micro-particle on the device (Power level = 4 W).

A problem with high emissivity coating is that it damages the device. In order to avoid coating, infrared temperature measurements can be made on a high emissivity carbon micro-particle placed in isothermal contact with the top metal contact of the Gunn diode. Optical and IR temperature images showing a micro-particle (3 µm diameter) deposited onto the top contact are shown in Figure 6. The micro-particle was deposited using a manipulation technique developed at the university.

A QFI IR microscope, with a 25 × lens objective, was used to make temperature measurements on the micro-particle. A graph showing the measured temperature rise on the device, obtained over a range of power levels, is shown in Figure 7. For comparison, the results of conventional IR measurements made on the uncoated and coated metal top contact are also shown in Figure 7. The micro-particle measurements show far higher operating temperatures than the IR measurements made directly on the uncoated metal surface. Accurate IR temperature measurements cannot be made directly on the metal surface, as it has a very poor emissivity < 0.1 and is highly reflective of background radiation. Conventional IR temperature measurements were also made on a high emissivity (0.9) paint coating applied to the top contact, also see Figure 7. Reasonable agreement (± 5 °C) exists between the coated and IR micro-particle temperature results. In this case, heat spreading through the coating is thought to be minimised because the coated structure is large and physically isolated. However, the coating damages the device, whereas the deposited micro-particle sensor can be removed after the measurement by immersing the device in a water bath.

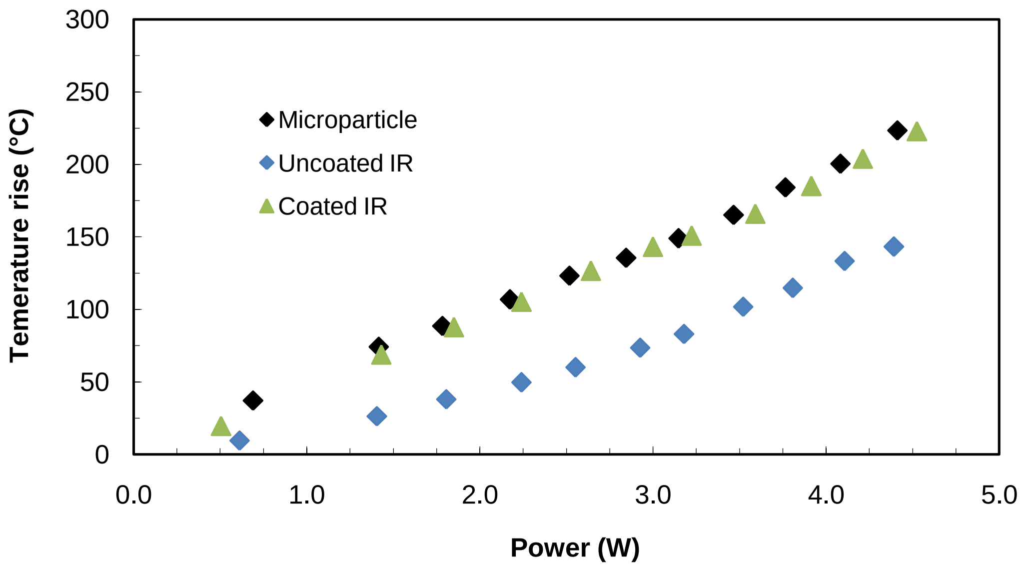


Figure 7: Comparison showing the peak temperature rise measured on the metal top contact of the Gunn diode using the micro-particle and conventional IR techniques.

4. Thermal analysis of the GaN/AlGaN HEMT

Gallium nitride is a wide band-gap semiconductor material with a high breakdown field and peak saturation velocity, making it a particularly interesting material for the manufacture of high power and high frequency transistors for radar and communication applications. Recent work has shown that transistors can operate with output power levels in excess of 10 W/mm of gate width at 10 GHz [5]. Self heating can reduce the electron mobility in the channel region of the device, therefore, decreasing its maximum usable frequency and limiting performance. An GaN/AlGaN high electron mobility transistor (HEMT) has been thermally characterised at De Montfort University using the novel IR micro-particle technique.

Device construction

The GaN/AlGaN HEMT was epitaxially grown on a sapphire substrate, using metal organic vapour phase epitaxy (MOVPE), see Figure 8. It consists of a 25 nm $Al_{0.22}Ga_{0.78}N$ barrier layer on a 2 µm nominally undoped GaN layer, passivated with silicon nitride (Si_3N_4). The channel is connected by two low resistance Ti/Al/Ti/Au based ohmic source and drain contacts. The channel has a length of 5 µm and a width of 40 µm. A metal gate (Ni/Au) is used to modulate current in the channel. The gate length is 0.25 µm. Under electrical bias, heat generation will occur in the channel region, which is only ~ 25 nm below the surface.

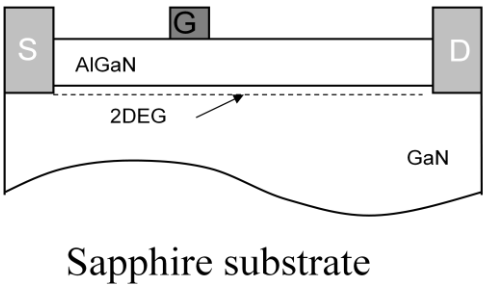


Figure 8: Construction of the AlGaN/GaN HEMT.

Thermal measurements

To make the temperature measurements, a carbon micro-particle IR sensor was placed onto the channel region of the transistor structure. Figure 9 shows the carbon micro-particle (3 µm diameter) in the channel region, placed centrally between the source and drain contacts.

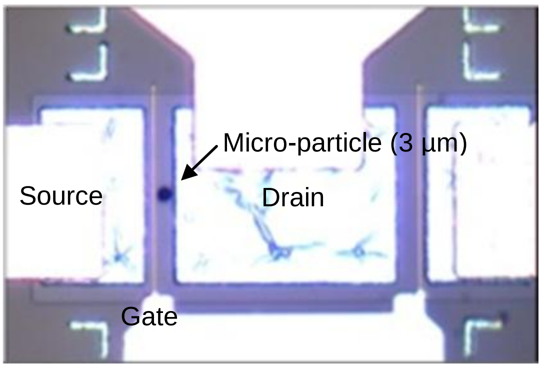


Figure 9: Optical image showing the micro-particle IR sensor (3 µm diameter) placed in the channel region of the AlGaN HEMT.

Infrared temperature measurements were made on the deposited carbon micro-particle using an IR microscope. The micro-particle provides an opaque radiative surface on which low noise IR temperature measurements can be made. In contrast, the semiconductor layers and substrate are transparent to IR radiation. When direct IR measurements are made on these layers, the IR microscope will collect radiation chiefly from the baseplate, therefore, significantly underestimating the true surface temperature. The temperature comparison, shown in Figure 9, clearly shows the advantage of using the novel micro-particle IR technique to record the peak device operating temperature in the channel region.

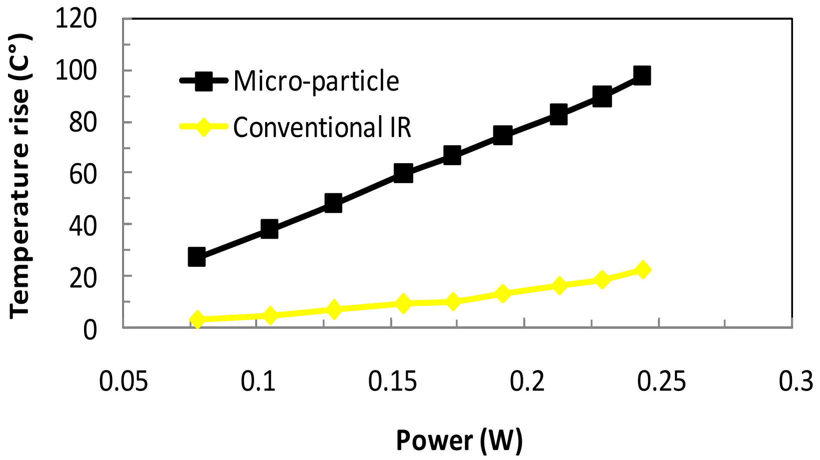


Figure 10: Temperatures measured on the channel region of the AlGaN HEMT using micro-particle and conventional IR techniques.

5. Conclusions

In this paper, we have demonstrated a novel technique which has been used to make improved IR temperature measurements on the GaAs Gunn diode and GaN HEMT. By making IR temperature measurements on high emissivity carbon micro-particles placed in isothermal contact with a device, the temperature errors normally associated with low emissivity and optically transparent semiconductor materials are avoided. The micro-particle technique avoids the need to coat a device with a high emissivity layer, which causes damage and heat spreading. The micro-particle sensors can be physically manipulated and deposited at precise locations. Unlike thermocouple probes, they cause negligible heat loss and are expected to have a high thermal transient response time.

Acknowledgements

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The Gunn diode samples were fabricated by e2v Ltd and the GaN HEMT structures were fabricated by Sheffield University.

References

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