Thermal measurement a requirement for monolithic microwave integrated circuit design

Richard Hopper, Christopher Oxley
Faculty of Computing Sciences and Engineering (CSE), De Montfort University,
Leicester, UK
rhopper@dmu.ac.uk.

The thermal management of structures such as Monolithic Microwave Integrated Circuits (MMICs) is important, given increased circuit packing densities and RF output powers. The paper will describe the IR measurement technology necessary to obtain accurate temperature profiles on the surface of semiconductor devices. The measurement procedure will be explained, including the device mounting arrangement and emissivity correction technique. The paper will show how the measurement technique has been applied to study the thermal performance of gallium arsenide (GaAs) MMIC configurations and also to GaAs Gunn diodes.

Introduction

High operating temperatures can reduce the RF performance and decrease the mean time to failure of MMICs [1]. Thermal modelling can be used to predict the junction temperature of individual devices making up the circuit. However, thermal models are not always accurate, as thermal constants, for example, the thermal boundary resistance, are often unknown. Also, as the complexity of the circuit increases thermal interaction between the components becomes more difficult to specify. Experimental temperature measurements are therefore necessary for both specifying difficult parameters and model validation.

A number of thermal measurement techniques will be discussed, which include: Raman spectroscopy, Atomic Force Microscopy (AFM) and infrared (IR) thermal microscopy. Infrared thermal microscopy is a powerful technique, enabling non-invasive 2-D surface temperature measurements to be rapidly made on microwave devices, in both wafer and package forms. An IR thermal microscope facility has now been established at De Montfort University, employing a Quantum Focus (QFI) instrument with state of the art spatial resolution of around 2.5 μm in the 2 - 5 μm wavelength band, see Figure 1.

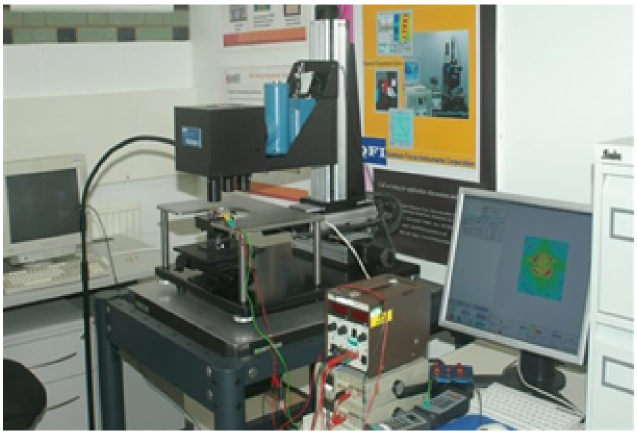


Figure 1: IR thermal microscopy facility at De Montfort University.

Temperature measurement techniques

A large number of temperature measurement techniques exist. These can be grouped into three main categories: electrical, physical contacting and optical. Electrical techniques exploit an electrical temperature sensitive parameter of a device. For example, the forward voltage of a Schottky junction as found in a High Electron Mobility Transistor (HEMT). If this temperature dependence is understood, electrical measurements can be used to establish the junction temperature [2]. A limitation with electrical techniques is they can only be used to give a single average junction temperature and cannot be used to detect hotspots or generate two dimensional temperature maps across structures with multiple heat sources, such as on MMICs.

Another group of temperature measurement techniques are physical contacting methods. These rely on the transfer of thermal energy from the surface of interest to a sensor, such as a thermocouple probe, or to temperature sensitive particulates i.e. liquid crystals. The optical properties of temperature sensitive liquid crystals can be used to determine the operating temperature of a semiconductor device [3]. Temperature measurements can also be made using Atomic Force Microscopy (AFM), which employs a scanning thermal probe to enable two-dimensional mapping. Measurements made using AFM have achieved sub micrometer resolutions [4], although surface topology can give rise to some measurement error.

Optical techniques make use of a temperature dependent optical property of a material. Raman spectroscopy is an optical technique used to measure phonon scattering in semiconductor materials [5]. It can be applied to make single point temperature measurements. For large area two-dimensional surface temperature mapping, IR thermal microscopy can be used [1]. Infrared thermal microscopy is a non-contact technique, utilising naturally emitted infrared radiation from a sample, resulting in a real time thermal image.

IR measurement technique

Infrared thermal microscopy involves the measurement of naturally emitted infrared radiation from the surface of a semiconductor device, such as an MMIC. Materials on the surface of the semiconductor device can vary in ability to emit infrared radiation. A ratio known as ‘emissivity’ is used to characterise the efficiency of a surface to emit infrared radiation, compared to a black body source. Accurate emissivity mapping is crucial to enable the actual surface temperature of the powered device to be obtained. Emissivity values associated with a semiconductor device can vary widely, with values of around 0.1 for metals and higher values (>0.5) for some semiconductor materials.

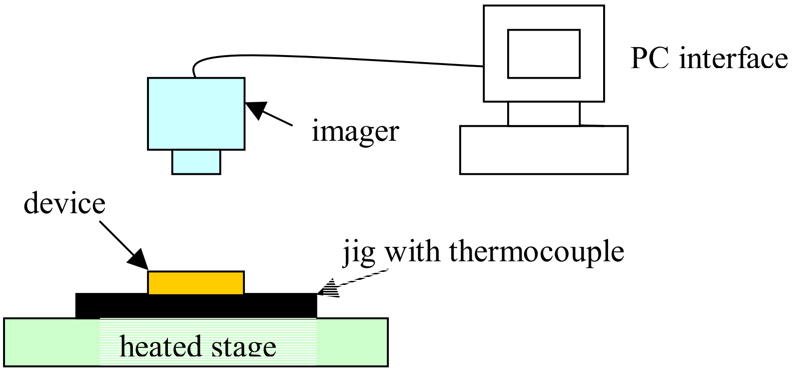


Figure 2: IR temperature measurement arrangement.

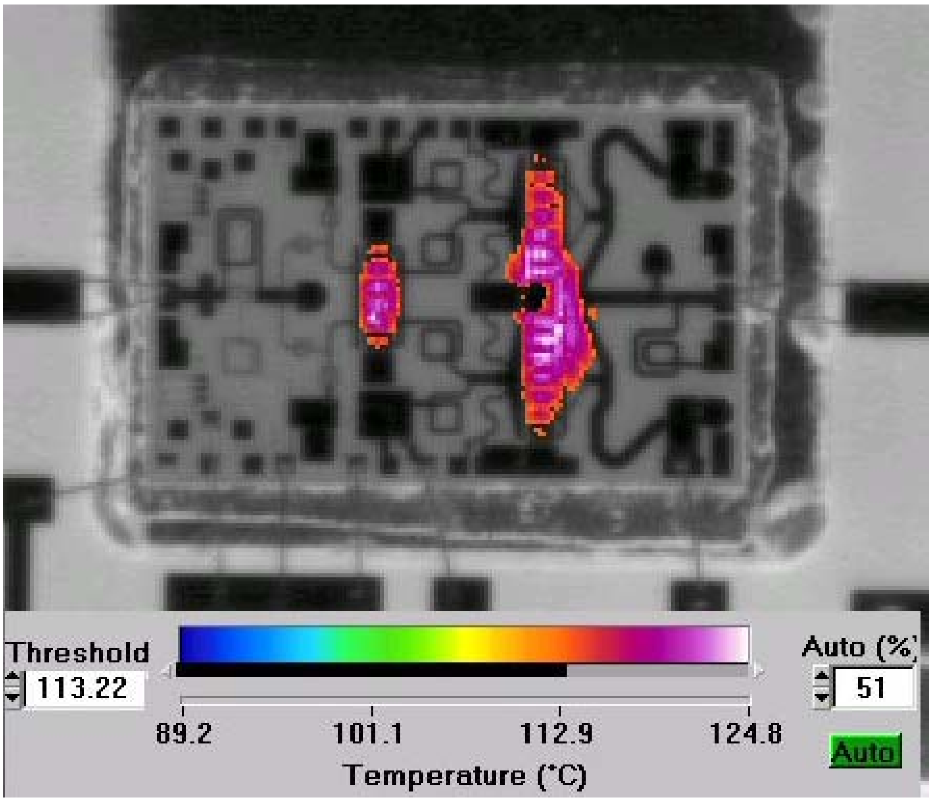
The emissivity of the surface of a device can be found by performing radiance measurements on an un-powered sample, heated to different ambient temperatures [6]. For measurement purposes, the sample is mounted on a jig containing a thermocouple which is placed on Peltier heated stage; the temperature is measured using the thermocouple, see Figure 2. The heated stage allows the temperature of the sample to be controlled precisely. Radiance measurements can then be made using an infrared imager linked to a computer. The emissivity measurement procedure involves measuring the change in emitted radiation level from a sample due to a known change in temperature. Emissivity (e) can be calculated using expression (1)

$$e = \frac{(R_{s2} - R_{s1})}{(R_{b2} - R_{b1})} \qquad (1)$$

where the change in emitted radiation level from a surface measured at two temperatures t_1 and t_2 is given by (R_{s2}-R_{s1}) and (R_{b2}-R_{b1}) represents the equivalent blackbody change. The emissivity calculation must be performed for each pixel imaged. The two temperature emissivity correction procedure minimises emissivity errors caused by background radiation. Thermal expansion or contraction of the metal jigging holding the sample can result in problems with the radiance measurements becoming misaligned. The thermal expansion coefficient of aluminium is known to be $23.1\ \mu m \cdot m^{-1} \cdot K^{-1}$, and if significant thermal expansion occurs during the procedure, realignment of the detector or sample can be made.

Thermal analysis of a GaAs MMIC

Infrared temperature measurements have been made on a GaAs MMIC RF power amplifier using infrared thermal microscopy. The MMIC structure, on a 1.8 ×2.8 mm die, was eutectic mounted onto a brass package. For measurement purposes, the package was clamped to an aluminium plate containing a thermocouple and secured to the Peltier heated stage of the microscope. A two temperature emissivity correction procedure was used. For temperature measurements, the MMIC amplifier was powered at 4 W DC, the base plate was stabilised at an ambient temperature of 90 °C. Surface temperature measurements were made with a number of different lens objectives attached to the IR microscope



Threshold 113.22

Auto (%) 51

Figure 3: Thermal hotspots on MMIC structure.

Thermal hotspots which occur on the MMIC structure are shown in Figure 3. The image was taken using a × 1 objective and shows an area 4 × 2.5 mm. High temperatures can be seen to occur on the driver and output stage FET structures. A temperature overview, like this, is useful for quickly detecting hotspots and making comparative temperature assessments. The temperature map shows an even level of heating on the two output stage FET structures. As expected, the driver stage is a few degrees cooler in temperature. In some cases, localised high temperature abnormalities have been detected because of voids between the die and mount.

The localized temperature distribution across the channel regions of the FET structures was measured using IR. In an FET, bulk heat generation will occur under the gate, see Figure 4. High electric field strengths and current densities are known to exist in the depletion region. Heat generation will be dynamic and change, according to gate bias level and channel current.

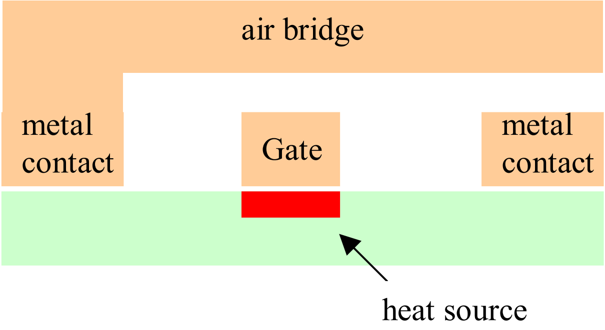
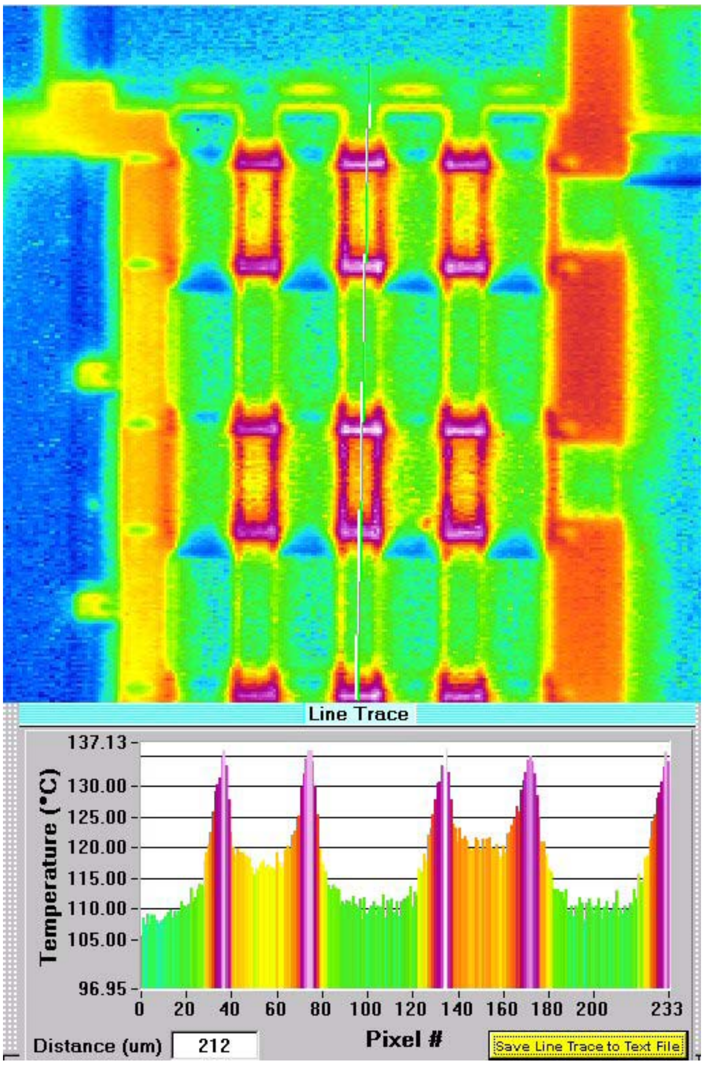


Figure 4: The FET structure, showing the heat source.

A temperature map, taken across a number of channel regions of the FET output stage, is shown in Figure 5. A higher magnification a 25× objective was used to measure the image. The air bridge structure partially covers the channel but sufficiently large gaps in the structure allow part of the channel area to be observed. The channel length was 7 µm and the width was 130 µm. In the channel areas, temperature peaks occur around the gate regions, where bulk heat generation occurs. Given the small dimensions of the gate heat source (< 0.5 µm), and the diffraction limited spatial resolution of the instrument (2.5 µm), some temperature averaging will inevitably occur. This temperature averaging needs to be taken into account when comparing the measured results with thermal models.



Distance (um) 212

Figure 5: Temperature map and profile across FET structure.

Thermal analysis of a GaAs Gunn diode

Infrared thermography can also be used to make temperature measurements on discrete devices, for example Gunn diode, bipolar and FET transistors, as well as passive components. Gunn diodes are used to provide the 77 GHz transmit signal [2] in some automotive cruise control (ACC) systems and therefore the reliability of this component is of paramount importance. Knowledge of the junction temperature, particularly over the range of ambient temperatures is required to ensure that the predicted mean time to failure (MTTF) of the component is within specification.

Traditionally the temperature of the diode was monitored using an electrical technique which enabled the average junction temperature to be calculated and is normally expressed as a thermal resistance R_{th} (°C/Watt).

$$R_{th} = \frac{T_j}{W} \qquad (2)$$

T_j is the rise in the diode junction and W is the dissipated power. The electrical method, however, can only be used to give an average junction temperature and cannot be used to give a temperature measurement on the metal top contact (a known point of failure). Infrared temperature measurements were made on a number of Gunn diode samples supplied by e2v Ltd, Lincoln.

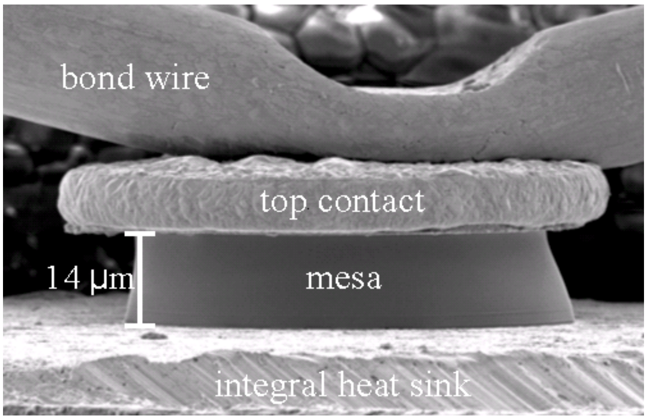


Figure 6: SEM image showing Gunn diode construction.

A scanning electron microscope (SEM) image of the side elevation of a Gunn diode, illustrating its construction, is shown in Figure 6. The semiconductors layers which form the mesa are visible, and include the active junction area of the device (heat source). To remove heat from the semiconductor layers they are bonded to a metal heat sink. Electrical connection is achieved by a gold bond wire connected to the top anode contact. The heatsink is earthed.

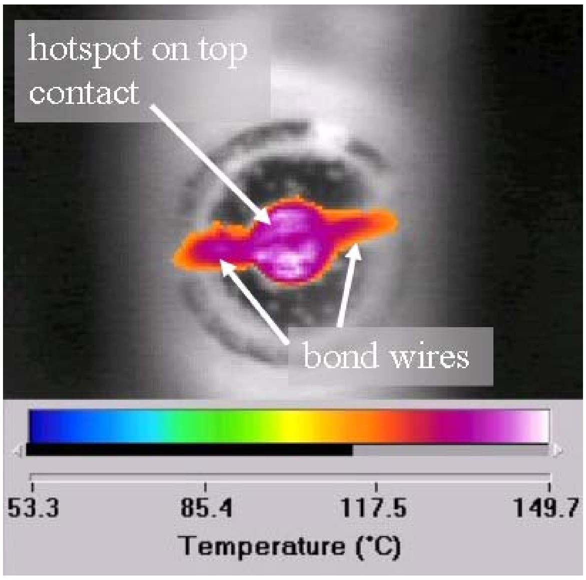


Figure 7: IR temperature profile taken on the top contact of the diode.

Infrared temperature measurements have been made on the top anode contact of the device. A typical measured temperature image, with the device powered at 4 W, is shown in Figure 7. Measurements made on the top contact should give a good indication of the peak operating temperature, as this area sits directly above the semiconductor layers containing the active junction (heat source). Batches of manufactured diodes from the fabrication process were measured over DC operating conditions and the junction temperature monitored, providing valuable process control information. The infrared measuring method would not be used as a line manufacturing test because of the high added cost, but the temperature data can be correlated with the electrical test method, giving a reliable manufacturing process check.

Conclusion

A wide range of techniques exist for performing temperature measurements on semiconductor devices. Infrared thermal microscopy can be used to rapidly obtain two-dimensional temperature measurements on structures such as MMICs. Useful information about the heat distribution across a wide area of the structure can be obtained and also on localised heat sources, such as multi-finger FETs. Infrared temperatures measurements can also be made on discrete devices, such as Gunn diodes. Measurements can be correlated with less demanding techniques which can be used as a process control in manufacturing.

Acknowledgements

The authors would like to acknowledge the EPSRC who part funded this work on grant EP/C511085/1. They would also like to acknowledge e2v Ltd (Lincoln) for their continued encouragement and measurement samples.

References

[1] C. H. Oxley, B. M. Coaker, and N. E. Priestley, “Measured thermal images of a gallium arsenide power MMIC with and without RF applied to the input,” Solid-State Electronics, vol. 47, no. 4, pp. 755-758, April 2003

[2] Mehrotra, Vivek, Boutros, Karim, Brar and Berinder, "Electric-Field Dependence of Junction Temperature in GaN HEMTs," Device Research Conference, 2007 65th Annual , pp.143-144, 18-20th June 2007

[3] K. Azar, and D. Farina, "Measuring Chip Temperatures with Thermochromic Liquid Crystals," Electronics Cooling, 1997

[4] Raphal Aubry, Jean-Claude Jacquet, J. Weaver, Olivier Durand, P. Dobson, G. Mills, Marie-Antoinette di Forte-Poisson, Simone Cassette and Sylvain-Laurent Delage, "SThM Temperature Mapping and Nonlinear Thermal Resistance Evolution With Bias on AlGaN/GaN HEMT Devices," Electron Devices, IEEE Transactions on , vol. 54, no. 3, pp.385-390, March 2007

[5] M. Kuball, J. M. Hayes, M. J. Uren, T. Martin, J. C. H. Birbeck and B. T. Hughes, “Measurement of Temperature in Active High-Power AlGaN/GaN HFETs Using Raman Spectroscopy,” IEEE Electron Device Letters, vol. 23, no. 1, January 2002

[6] P. W. Webb, “Thermal imaging of electronic devices with low surface emissivity,” IEE Proceedings-G, vol. 138, no. 3, June 1991

[7] Hopper, R.H.; Oxley, C.H.; Seddon, R.; Foulger, R.; Priestley, N., "Infrared radiance and temperature measurements on the mesa side of Gunn diodes," Science, Measurement & Technology, IET , vol. 2, no. 1, pp.39-41, Jan. 2008