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Thermal Profiles within the Channel of Planar Gunn Diodes using Micro-particle Sensors

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***Abstract*—The paper describes the use of a novel micro-particle sensor (∼3 μm diameter) and infra-red (IR) microscopy to measure the temperature profile within the active channel (typically 3 μm length and 120 μm width) of planar Gunn diodes. The method has enabled detailed temperature measurements showing an asymmetrical temperature profile along the active width of these devices. The asymmetrical temperature profile suggests a similar behaviour in the channel current density, which may contribute to the lower than expected RF output power.**

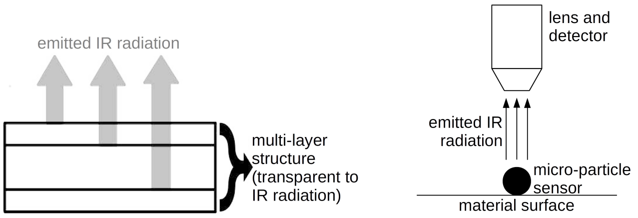
***Index Terms*—Infrared measurements, temperature measurement, Gunn devices, planar objects.**

I. INTRODUCTION

THERE have been recent advances in developing a millimetric wave planar Gunn diode [1] which can be easily integrated into Microwave Monolithic Integrated Circuits (MMICs). The heat is dissipated inside the channel region of these devices, but the expected thermal characteristics are currently untested. An improved thermal understanding of the temperature distribution inside the channel region will enhance further understanding of the operation of these devices. This paper presents a novel thermal measurement, which uses a known high emissivity (up to 0.7), carbon based micro-particle sensor in conjunction with conventional infra-red (IR) microscopy to measure the temperature distribution [2], [3]. The micro-particle sensor enables more accurate point temperature measurements on any material, including semiconductors and low emissivity metals and has been successfully used for measuring the temperature distribution on membrane hot-plates for miniature gas sensors [4].

A. IR Temperature Measurements on Semiconductors

Semiconductors such as gallium arsenide (GaAs) and indium phosphide (InP) are transparent to IR radiation and are used in fabrication of planar Gunn diodes [5]. The transparency leads to anomalous surface emissivity, as thermal radiation is detected from more than just the top surface of the semiconductor (Fig. 1a), leading to errors in the measured surface temperature. Traditionally to overcome this problem, a black coating (paint) was used. However, this method will spread the heat within the coating, reducing the measured peak temperatures. The spherical (∼3 μm diameter) micro-particle sensor has a low thermal mass with negligible heat spreading, and can be positioned wherever the temperature is required to be measured (Fig. 1b); making it ideal for IR temperature measurements, both on semiconductor regions (transparent to IR) and gold metal contacts (low-emissivity, ∼0.1).



(a) Multi-layer IR emission of transparent semiconductors [3].

(b) Emitted IR radiation from a micro-particle [3].

Fig. 1: Emitted IR radiation of (a) semiconductors and (b) micro-particle sensors.

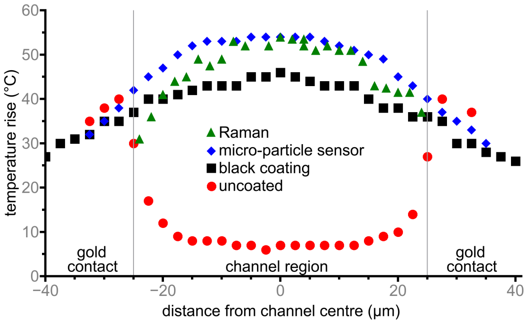


Fig. 2: Plot comparing the measured temperature rise of a GaN TLM structure from a conventional (uncoated) IR temperature measurement with measurements using a black paint coating, a micro-particle sensor, and Raman thermal spectroscopy [3], [6].

The temperature profile (Fig. 2) along the channel length of a TLM structure fabricated on AlGaN/GaN semiconductor was measured using a micro-particle sensor, conventional IR and black coating. These three methods gave different temperatures

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across the semiconductor, but similar temperatures on the gold contacts. A comparative measurement has been made using Raman thermography [6], which gave similar peak temperatures in the central semiconductor region as the micro-particle sensor.

II. Gunn Diodes

The planar Gunn diode (Fig. 3) consists of an active channel, where the narrow length (anode-cathode separation) determines the operating frequency and the channel width the current magnitude, and therefore the RF output power. To date, these devices have given low RF output power, restricting the potential applications. For example, AlGaAs based planar Gunn diodes with 4 μm channel lengths have shown fundamental frequencies between 25 and 29 GHz and RF output powers of 1 to 11 μW [8]. While a state-of-the-art $In_{0.53}Ga_{0.47}As$ planar Gunn diode with a 1.3 μm channel length gave a fundamental frequency of 164 GHz [9] and with a 0.6 μm channel length 307 GHz [1], the respective RF output powers were 100 and 28 μW. In this paper AlGaAs planar Gunn diodes with ohmic anode and cathode contacts and channel lengths of 4 and 3 μm were used (Gunn devices A and B respectively), enabling a ~3 μm diameter micro-particle to be positioned in the channel. The IR microscope was a Quantum Focus Instrument's Infrascope II fitted with a ×25 objective, giving a maximum spatial thermal resolution of 2.5 μm, which represents the limit to diameter of the micro-particle.

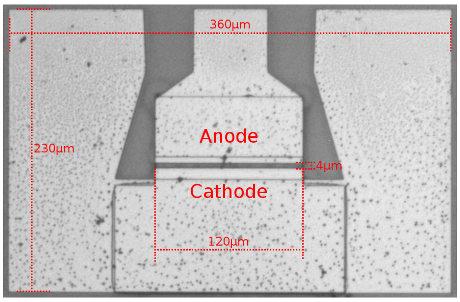

Fig. 3: Optical image of a planar Gunn diode showing the basic structure with a 4×120 μm channel. [7]

A. Manipulating a Single Micro-particle

A Scientifica micro-manipulator was used to position and move a single 3 μm diameter micro-particle sensor in the channel (Fig. 4). The planar Gunn was biased to the chosen voltage, and the micro-particle temperature measured. The micro-particle was then repositioned, the Gunn diode rebiased (at the same bias voltage and current), and temperature of the micro-particle remeasured. This process was repeated, at the constant DC input power, for as many positions as required to build up the temperature profile along the channel.

The planar Gunn diode contact geometry enables the current to flow across the whole channel width, with some expected current spreading at the channel edges (edge-effects). By measuring the temperature profile along the channel width and assuming the diode thermal impedance remains constant, the temperature profile (ΔT is temperature rise) will give an indication of current density (J_i) distribution along the channel width, where $J_i = \Delta T \cdot \mathrm{c} \cdot V \cdot k_{ijk}$, c is a constant, V is the applied Gunn bias voltage and k_{ijk} is a thermal conductivity tensor. Therefore, the peak temperature at the channel centre will correspond to maximum current density, with cooler temperatures corresponding to lower current density (end-effects) at the channel edges.

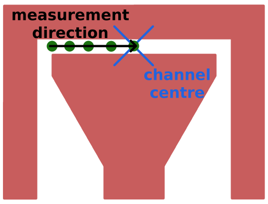

Fig. 4: Schematic showing measurement direction in relation to the Gunn diode contacts for temperature profiles made with a manipulated micro-particle sensor [3].

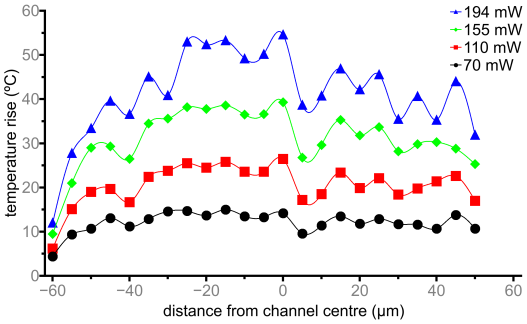

Fig. 5: Asymmetrical temperature profile along the channel of Gunn-A, a planar Gunn diode with a 4 μm long and 120 μm wide channel [3].

Fig. 5 shows the measured temperature profiles (with 23 micro-particle positions) along the 120 μm wide channel of a 4 μm channel length planar Gunn diode (device A), operated at four bias voltages (2.0, 2.5, 3.0, and 3.5 V) corresponding to constant DC input powers of 70, 110, 155, and 194 mW respectively. The base-plate temperature was 79.2 °C and the maximum temperature rise 56.3 °C, suggesting the device was not thermally limited. At high DC input powers, the profiles show an asymmetrical temperature behaviour with high temperatures in the centre region, cooler temperatures at the edges and superimposed on the profile, rapidly varying temperature (±5 °C) peaks. The rapid temperature variation was identified with having to reposition the probes for each measurement. To minimise probe contact variation, a multiple micro-particle sensor methodology was adopted. Experimental work indicated that multiple micro-particles had little effect on the thermal loading of the device.

B. Multiple Micro-particles

A number of micro-particle sensors were positioned at regular spacing along the width of the planar Gunn (device B) channel. This enabled the bias probes to be positioned only once to make contact with the metallised electrodes, leading to a smoother, but still asymmetrical temperature profile.

Fig. 6 shows 13 micro-particle sensors (∼3 μm diameter) positioned at 10 μm intervals along the 120 μm channel width of Gunn-B. The Gunn diode was biased over a wider range of voltages; 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 V (corresponding to constant DC input powers of 4, 16, 37, 67, 104, 141, 173, and 202 mW respectively). The base-plate temperature was 98.8 °C and the maximum temperature rise was 66.6 °C. The set of temperature profiles (Fig. 7) were similar in shape to those of Gunn-A, but without the rapid temperature variations. For both Gunns A & B, the lower temperature 'end-effects' were a significant percentage of the device width (limiting RF output power); to minimise the effect shaping the contacts could be investigated. As the DC input power was further increased, the temperature profile became more asymmetric, suggesting regions of increased current density (current filaments), which would further limit RF output power. Current filaments have been observed using electroluminescence (EL) [10] with similar geometry devices, and with Schottky contact over-layers more consistent current flow across the width of the device was observed.

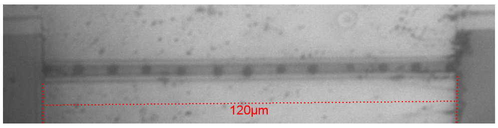

Fig. 6: Optical image of 13 micro-particle sensors placed within the channel of Gunn-B, a planar Gunn diode with a 3 μm long and 120 μm wide channel [3].

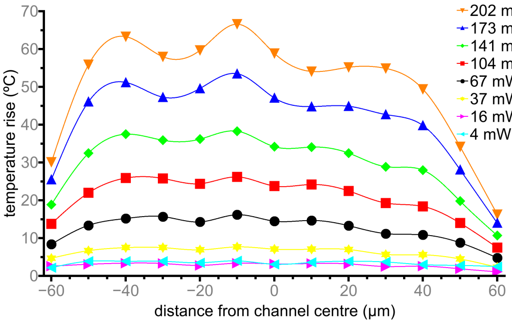

Fig. 7: Asymmetrical temperature profile, with 13 micro-particles, along the channel of Gunn-B, a planar Gunn diode with a 3 μm long and 120 μm wide channel [3].

III. Conclusion

For the first time temperature profiles within the channel of planar Gunn diodes have been measured, using a micro-particle IR thermal measurement technique. These profiles have been achieved using a single micro-particle sensor, manipulated into many positions in the Gunn channel and multiple micro-particle sensors positioned along the Gunn channel. The asymmetrical structure of the temperature profiles suggest a variation in current density across the device width, which may contribute to the poor RF output power observed with current planar Gunn diode structures. The technique enables the exploration of improvements to the design of the planar Gunn diode (for example shaping the contacts towards the ends of the channel) to improve the uniformity of current within the channel. Indeed, the idea of more exotic contact shaping in planar Gunns has been discussed in the literature [11] and this technique will provide a powerful analysis method for such devices.

Acknowledgment

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References

[1] A. Khalid, G. M. Dunn, R. F. Macpherson, S. Thoms, D. Macintyre, C. Li, M. J. Steer, V. Papageorgiou, I. G. Thayne, M. Kuball, C. H. Oxley, M. Montes Bajo, A. Stephen, J. Glover, and D. R. S. Cumming, "Terahertz oscillations in an In0.53Ga0.47As submicron planar Gunn diode," *J. Appl. Phys.*, vol. 115, no. 11, p. 114502, mar 2014. [Online]. Available: http://aip.scitation.org/doi/10.1063/1.4868705 doi: 10.1063/1.4868705

[2] C. H. Oxley, R. H. Hopper, D. Prime, M. Leaper, G. A. Evans, and A. Levick, "Probe propels IR thermal microscopy to a new level," *Compd. Semicond.*, vol. 17, no. February, pp. 33–36, 2011. [Online]. Available: https://www.compoundsemiconductor.net/article/87689-probe-propels-ir-thermal-microscopy-to-a-new-level.html

[3] J. Glover, "The design and thermal measurement of III-V integrated micro-coolers for thermal management of microwave devices," PhD Thesis, De Montfort University, Leicester, U.K., 2017. [Online]. Available: http://hdl.handle.net/2086/13299 https://www.dora.dmu.ac.uk/handle/2086/13299

[4] R. H. Hopper, I. Haneef, S. Z. Ali, F. Udrea, and C. H. Oxley, "Use of carbon micro-particles for improved infrared temperature measurement of CMOS MEMS devices," *Meas. Sci. Technol.*, vol. 21, no. 4, p. 45107, 2010. [Online]. Available: http://stacks.iop.org/0957-0233/21/i=4/a=045107

[5] A. Khalid, N. J. Pilgrim, G. M. Dunn, M. C. Holland, C. R. Stanley, I. G. Thayne, and D. R. S. Cumming, "A Planar Gunn Diode Operating Above 100 GHz," *Electron Device Lett. IEEE*, vol. 28, no. 10, pp. 849–851, oct 2007. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4317659 doi: 10.1109/LED.2007.904218

[6] R. H. Hopper, "Accurate Temperature Measurements on Semiconductor Devices," PhD Thesis, De Montfort University, Leicester, U.K., 2010. [Online]. Available: http://hdl.handle.net/2086/3315

[7] J. Glover, R. H. Hopper, M. I. Maricar, A. Khalid, D. R. S. Cumming, M. Montes Bajo, M. Kuball, G. M. Dunn, A. Stephen, and C. H. Oxley, "Novel Infra-red (IR) Thermal Measurements on GaAs Micro-coolers," in *ARMMS RF Microw. Soc.*, 2012, pp. 1–7.

[8] M. I. Maricar, "Design of circuits to enhance the performance of high frequency planar Gunn diodes," PhD Thesis, De Montfort University, Leicester, U.K., 2014. [Online]. Available: http://hdl.handle.net/2086/10858

[9] A. Khalid, C. Li, V. Papageorgiou, G. M. Dunn, M. J. Steer, I. G. Thayne, M. Kuball, C. H. Oxley, M. Montes Bajo, A. Stephen, J. Glover, and D. R. S. Cumming, "In0.53Ga0.47As Planar Gunn Diodes Operating at a Fundamental Frequency of 164 GHz," *IEEE Electron Device Lett.*, vol. 34, no. 1, pp. 39–41, jan 2013. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6352833 doi: 10.1109/LED.2012.2224841

[10] M. Montes, G. Dunn, A. Stephen, A. Khalid, C. Li, D. Cumming, C. H. Oxley, R. H. Hopper, and M. Kuball, "Reduction of Impact Ionization in GaAs-Based Planar Gunn Diodes by Anode Contact Design," *IEEE Trans. Electron Devices*, vol. 59, no. 3, pp. 654–660, mar 2012. [Online]. Available: http://ieeexplore.ieee.org/document/6109337/ doi: 10.1109/TED.2011.2177094

[11] N. J. Pilgrim, A. Khalid, C. Li, G. M. Dunn, and D. R. S. Cumming, "Contact shaping in planar Gunn diodes," *Phys. status solidi*, vol. 8, no. 2, pp. 313–315, feb 2011. [Online]. Available: http://doi.wiley.com/10.1002/pssc.201000539 doi: 10.1002/pssc.201000539