NOVEL INFRA-RED (IR) THERMAL MEASUREMENTS ON GaAs MICRO-COOLERS

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Abstract

Electronic devices are shrinking in size and new materials, for example gallium nitride (GaN) are being introduced, resulting in higher dissipated power densities. Therefore, new and novel technologies are required to remove the heat and to thermally characterise the devices.

A particular example of a device that will require these thermal management technologies is the gallium arsenide (GaAs) planar Gunn diode [1] which is being developed for millimetre-wave and terahertz (THz) frequencies, and in which the dissipated power density will be very high (approximately 10^6 W/cm^2).

This paper will review preliminary thermal and electrical characterisation of a GaAs electro-thermal micro-cooler with the aim of its integration with the planar Gunn diodes, thus increasing the efficiency of the latter.

The thermal characterisation of these electro-thermo coolers brings its own set of unique measurement problems. A comparative temperature measurement has been developed using infra-red (IR) thermal microscopy and novel micro-particle sensors [2]. The measurement technique will be described in detail and preliminary measurements on simple superlattice electro-thermal GaAs micro-coolers will be presented.

Introduction

Gunn Diodes

The Gunn diode is an electronic device that can be used as a high frequency microwave source by utilising the negative resistance characteristic of a two valley semiconductor, for example gallium arsenide (GaAs). The negative differential resistance of a Gunn diode is shown in Figure 1, where the current is plotted against the supplied voltage across the

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diode. The traditional, vertical, Gunn diode manufactured by e2v technologies [3] can be used as a DC to microwave converter, to fundamental frequencies approaching 60 GHz.

In recent years the vertical Gunn diode has been largely superseded by the microwave transistor, which can be easily included in microwave monolithic integrated circuit (MMIC) technology, unlike the vertical Gunn diode. The idea of a planar Gunn diode has been considered by many, almost as soon as the Gunn effect was discovered [4], but only recently Khalid et al. at the University of Glasgow [1] have realised a planar Gunn diode, which has the potential of being integrated in MMIC technology. Very high frequency of operation has been obtained (>158 GHz [5]), determined by the distance between the planar cathode and anode contacts (Figure 2). By extracting the second or third harmonic, it may be possible to use the planar Gunn diode as a frequency source towards terahertz frequencies [6].

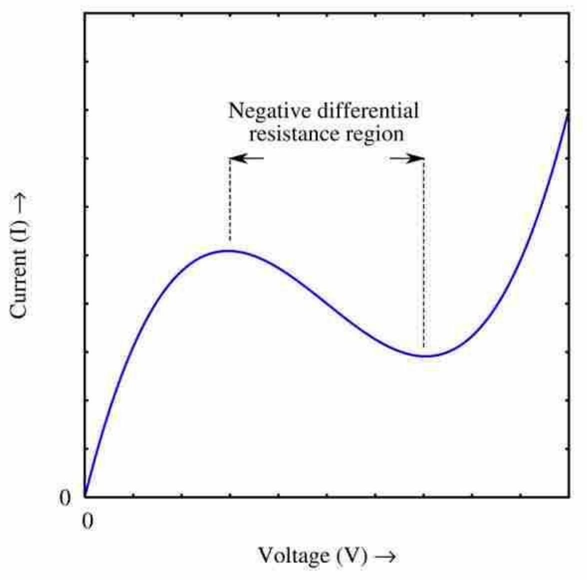

Fig. 1: Approximate Gunn VI characteristic, showing the negative differential resistance region

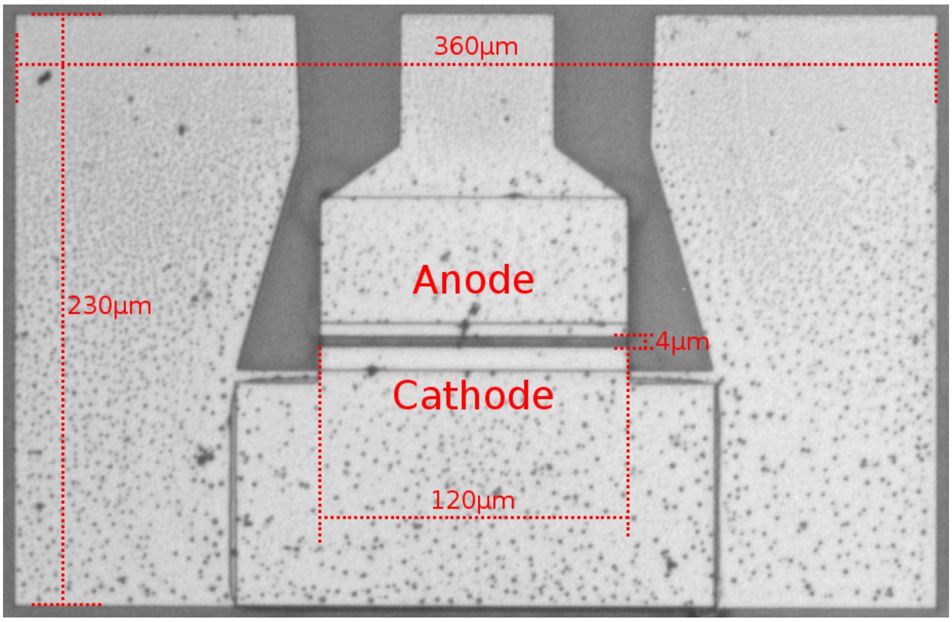

Fig. 2: Planar Gunn Diode with a 4x120 μm channel, fabricated at University of Glasgow

To obtain the RF power performance from the planar Gunn devices it will be necessary to extract heat and this paper will describe solid state coolers which are being designed for integration with the Gunn diode. There are two approaches; *a*) miniature pumped gas/liquid refrigerators [7, 8]; and *b*) thermoelectric coolers [9], the latter will be the approach described in this paper.

The Electro-thermal Micro-cooler

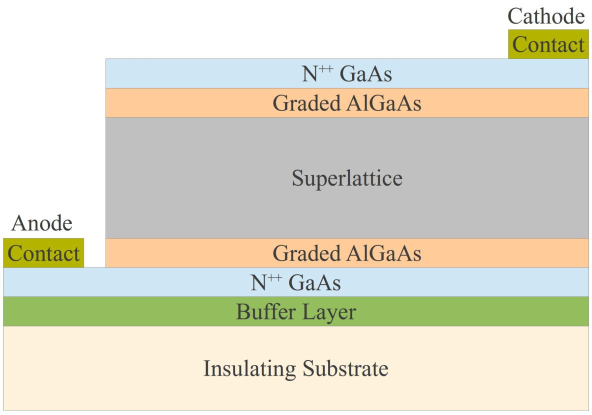

Fig. 3: Basic layer structure of AlGaAs/GaAs superlattice micro-coolers to be characterised

A GaAs cooler has been developed and fabricated at the University of Glasgow. The cooler comprises of, from top to bottom (Figure 3) a n^{++} GaAs contact layer, graded aluminium gallium arsenide (AlGaAs), 100 periods of a $Al_{0.1}Ga_{0.9}As/Al_{0.2}Ga_{0.8}As$ superlattice, graded AlGaAs, and n^{++} GaAs contact layer, grown by molecular beam epitaxy (MBE) on a 600 μm thick GaAs semi-insulating substrate. Electrical contact is made by low resistance metallised ohmic cathode and anode contacts. The superlattice reduces phonon transport, providing a thermal barrier between the top cold cathode and the bottom warm anode contacts. The cooler structures are defined by mesa etching, which enables a large number of different cooler geometries as well as TLM test cells (measuring the contact specific resistance, ρ_c) to be fabricated on the same process wafer.

The performance of the cooler can be approximated by equation (1).

$$\mathrm{Q_C} = ST_C I_{opt} - (0.5\mathrm{R_S} + \mathrm{R_{TC}})I_{opt}^2 \tag{1}$$

Where $\mathrm{Q_C}$ is the maximum cooling power; S is the Seebeck coefficient; T_C is the temperature of the cold contact; I_{opt} is the optimum current; $\mathrm{R_S}$ is the resistance of the superlattice; and $\mathrm{R_{TC}}$ is the resistance of the top cooled contact.

In steady state:

$$\frac{\Delta \mathrm{T_{max}}}{R_{th}} = ST_C I_{opt} - (0.5\mathrm{R_S} + \mathrm{R_{TC}})I_{opt}^2 \tag{2}$$

Where $\Delta\mathrm{T_{max}}$ is the maximum temperature difference between the bottom heated contact (T_H) and the top cooled contact (T_C); and R_{th} is the thermal resistance of the cooler.

If current is further increased the cooling reduces as the contact ohmic heating, $(0.5\mathrm{R_S} + \mathrm{R_{TC}})I^2$ starts to dominate. By using a superlattice to increase the thermal resistance between the bottom and top contacts the flow of backward heat can be minimised.

The power used to drive the cooler is $\mathrm{Q_p}$:

$$\mathrm{Q_p} = S\Delta \mathrm{T} I + (\mathrm{R_{TC}} + \mathrm{R_S} + \mathrm{R_{BC}})I^2 \tag{3}$$

Where R_{BC} is the bottom contact resistance of the cooler.

The unloaded coefficient of performance (COP) is:

$$\mathrm{COP} = \left(\frac{\mathrm{Q_C}}{\mathrm{Q_p}}\right) 100\% \tag{4}$$

To thermally characterise these devices the temperature difference between the top cooled and bottom heated contacts is measured.

$$\Delta \mathrm{T} = R_{th}[ST_C I - (0.5\mathrm{R_S} + \mathrm{R_{TC}})I^2] \tag{5}$$

IR Thermal Microscopy

Infra-red (IR) thermal microscopy is a contact-less measurement technology, however, the accuracy of the temperature measurement is dependent on accurately knowing the surface emissivity ($\mathrm{e_s}$) at the point of the thermal measurement. Many materials, which include semiconductors, are transparent to IR radiation and therefore, when making a surface emissivity measurement, radiation is captured by the microscope from the back and front faces of the semiconductor as well as from any interface layers (Figure 4). Also, many materials have a low surface emissivity (<0.1) for example gold and therefore radiation emitted by the contact can be a similar level to reflected background radiation. With reference to the micro-coolers (Figure 3) it can be seen that the measurements are on gold contacts with a low emissivity and a semiconductor material, which is transparent to IR. These factors are further aggravated as the expected temperature difference is approximately 1 °C between the contacts of a micro-cooler based on GaAs [10]. To overcome these problems an IR micro-particle sensor technology was used. This technique was developed at De Montfort University [11, 2] and uses particles with a high and known surface emissivity to measure the surface temperature at the point the sensor is placed on the device. The technique does not require the measurement and computation of the surface emissivity of the device and the measurement is completely independent of the device's material properties. The spatial resolution of IR microscopy is not compromised by this technique, provided micro-particle sensors have a diameter greater than 3 μm, the diffraction limit of the IR microscope. Unlike high emissivity paint coating, the micro-particle sensor causes minimal heat spreading and can be removed from the device, leaving it undamaged.

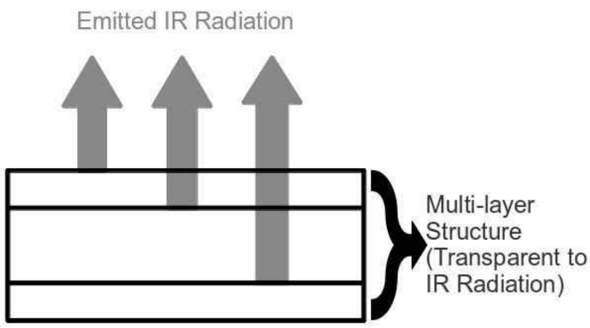

Fig. 4: Multi-layer IR emissions for transparent materials

Thermal Measurements of the Micro-cooler

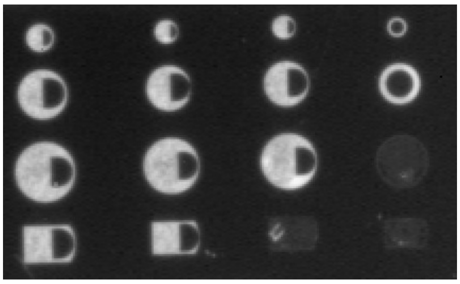

Fig. 5: Selection of micro-coolers on wafer

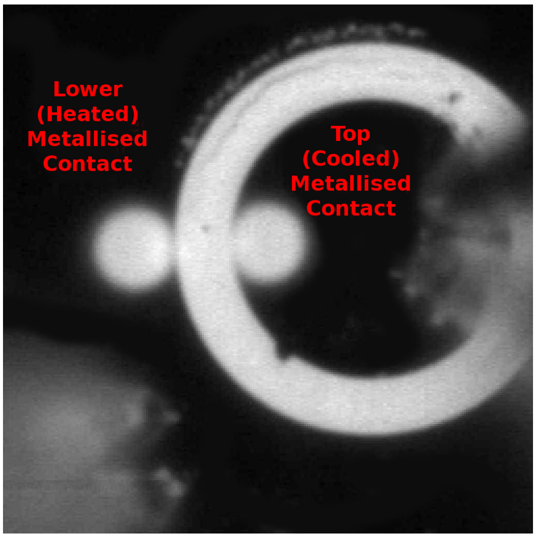

Fig. 6: 10 μm micro-particles on a micro-cooler

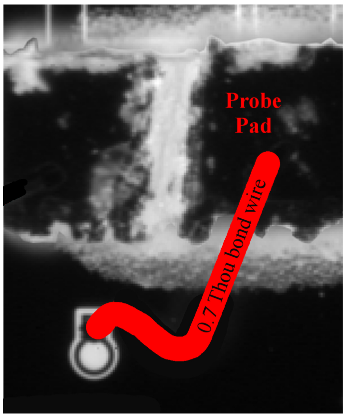

Fig. 7: Thermally isolated micro-cooler

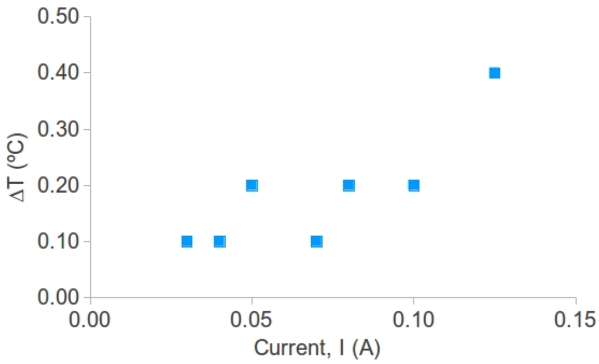

Fig. 8: Cooling (ΔT) against bias current for cooling in Figure 6

The miniature GaAs based thermal coolers were fabricated with areas from approximately 450 to 125,000 μm^2 and the mesa heights were 3 μm (Figure 5). The coolers were biased using miniature DC bias probes, which were found to thermally load the top cooled contact when a current was drawn. To minimise this effect, the top contact was bonded using a 0.7 thou diameter gold wire between the cooler top contact and an alumina stand-off, Figure 7. The gold bond wire enabled electrical connection to the cold top contact, while thermally isolating the probe from the cooler. Micro-particle sensors were placed on the top and bottom contacts of the cooler. The particles were approximately 10 μm diameter and provided a minimal thermal loading, compared with miniature thermocouples. Figure 6 shows the micro-sensors placed on the contacts. Thermal measurements were made on the GaAs based coolers and a maximum cooling temperature of around 0.4 °C was achieved, at an ambient of 120 °C (Figure 8).

The micro-coolers contain many thin layers semiconductors underneath the metal contacts, this creates a vertical variation in the wafer's sheet resistance. A standard transmission line method (TLM) measurement may not give an accurate result for the specific resistance of the contact (ρ_c). Therefore, for this work ρ_c was calculated using the Reeves and Harrison TLM measurement [12], which takes into account the vertical variation in sheet resistance. Measurements from a number of wafers are given in Figure 9.

Improvements to the micro-cooler's performance can be made. These include reduction of contact resistance, as well as increasing thermal resistance of the micro-cooler by increasing the number of periods of the superlattice, however, this is constrained by the fabrication technology and wafer cost. Further improvements can also be obtained by raising the ambient temperature of the cooled contact, when integrating with the Gunn diode, the cooled contact will be close to the junction temperature (∼170 °C) of the diode. The Seebeck coefficient may also be increased by considering alternative material based coolers, for example InGaAs/InP.

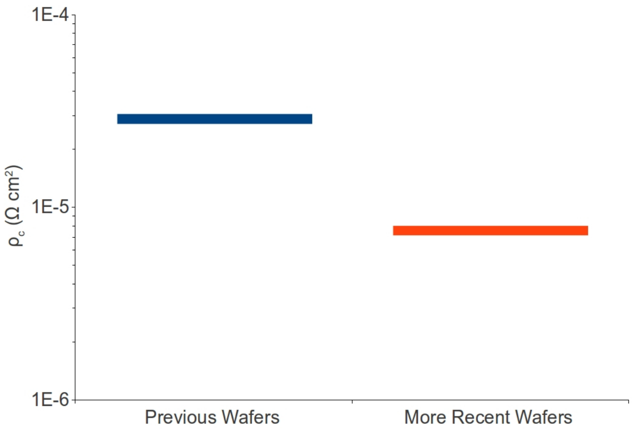

Fig. 9: Improved specific contact resistance on more recent wafers

Acknowledgements

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