Infra-Red Thermal Measurement on a Low Power Infra-Red Emitter in CMOS Technology

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Abstract: This paper presents high temperature characterisation of a novel infra-red (IR) emitter chip based on CMOS technology, using IR thermal microscopy. The performance and reliability of the thermal source is highly dependent on the operating temperature and temperature uniformity across the micro-heater which is embedded within the silicon dioxide membrane. To date, the accuracy of the IR measurement has been limited by the optical transparency of the semiconductor material forming the membrane, which has poor emissivity compared to a black-body source. In this paper, a high emissivity micro-particle sensor is used improve the accuracy of the temperature measurements. IR measurements on the emitter chip were validated with reference to temperature measurements made using an electrical technique where good temperature uniformity across the membrane heater was found.

1. Introduction

This paper reports on the use of infra-red (IR) thermal microscopy to thermally characterise a novel CMOS IR micro-emitter. The emitter is based on tungsten metallization technology, which allows operation to high temperatures [1]**.** IR microscopy has been used to form 2D real time thermal maps of the miniature micro-heater which is an integral part of the IR micro-emitter. The thermal maps can be used to further understand the temperature uniformity across the micro-heater and identify hot-spots which may lead to early stage failure of the device.

There is a commercial drive for miniature mid-IR emitters, for use in Non-dispersive Infra-red (NDIR) gas sensing and spectroscopy applications [2]. Presently, many of these applications use a glass micro-bulb as the IR source. Although the micro-bulb can be manufactured at low cost, it has a number of disadvantages, which include; (i) high power consumption (typically > 0.5 W) [3], (ii) bulky in comparison with the silicon chip IR emitter, and (iii) limited to IR emission in the mid to long IR wavebands due to optical absorption by the glass envelope. A number of methods have been used for the fabrication of miniature silicon based IR emitters [4, 5], many based on propriety Micro-Electro-Mechanical Systems (MEMS) processing technologies.

Tungsten is an interconnect metal found in some high temperature CMOS processes and enables the design and fabrication of a stable IR source, having all the advantages of CMOS technology, which include very low manufacturing cost in high volume, excellent device reproducibility and the feasibility of integration with a wide range of electronic circuitry. The MEMS emitter consists of a tungsten heater (800 µm diameter) embedded within a silicon dioxide membrane (1200 µm diameter), passivated with silicon nitride. The membrane is only 5 µm thick and thermally isolates the heater from the substrate, ensuring efficient heating, fast thermal transient response and low power consumption. The emitter utilises a plasmonic structure to enhance IR emission, which is formed by a geometric arrangement of metallic dots in a metal layer which has previously been reported [6]. Two tungsten metal layers form the plasmonic structure and the heating element, respectively. Silicon oxide layers are used as inter-layer dielectrics. The membrane was formed using Deep Reactive Ion Etching (DRIE) of the silicon substrate with the first silicon dioxide layer acting as an etch stop. The chip structure was fabricated using a 1.0 µm CMOS process at a commercial foundry [6]. The die size is 1.76mm × 1.76 mm. Electrical power is applied to the micro-heater element which increases its temperature to over 500 °C. The thermal source emits IR radiation over a broad spectrum of wavelengths (2.5 µm to 15 µm) [3].

IR thermal microscopy enables non-contact temperature measurements to be made on devices under bias. It utilises naturally emitted IR radiation from the sample, resulting in a real time 2D (two dimensional) thermal image [7]. The technique has been used to study the thermal performance of a number of different types of electronic devices, including: Gallium Arsenide (GaAs) field effect transistors (FETs), Monolithic Microwave Integrated Circuits (MMICs), Radio Frequency (RF) power amplifiers and micro-heaters [8].

A factor limiting the accuracy of temperature measurements made using IR thermal microscopy is, uncertainty in the determination of the surface emissivity of the sample to be measured. The surface emissivity (ε) characterises the radiative efficiency of a material and is defined as the ratio of emitted IR radiation from a sample to that emitted by a black-body at the same temperature and spectral bandwidth. Most IR thermal microscopes use 2D Focal Plane Array (FPA) detectors, which enables pixel-to-pixel mapping of the surface emissivity, thereby taking into account any non-homogeneity. This approach is particularly important when measuring an electronic device where topology and material may change across the surface. Device surface topology may also give rise to localised reflections which will influence the measured magnitude of the surface emissivity. This is mainly a concern for measurements made on samples with very low surface emissivity and small rapid changes in topology, for example, the narrow channel region of a field effect transistor (FET).

A further problem when measuring the surface emissivity of electronic devices is the optically transparent semiconductor materials, which allow IR radiation from subsurface layers to be collected by the microscope, leading to errors in measuring the surface emissivity [9]. To overcome these limitations, a novel technique has been developed that employs a micro-particle with a known, and high, surface emissivity. The micro-particle is placed in isothermal contact with the device under test. The micro-particle technique has been used to improve the accuracy of single point IR temperature measurements made on optically transparent and highly reflective surfaces [10]. It eliminates the need for a conventional high emissivity coating of black-paint, which is destructive and causes heat spreading across the surface, thereby averaging the temperature of hot-spots. Knowledge of the temperature of hot-spots is vital for assessing the potential failure mechanisms of devices. The micro-particle sensor is small and unlike the paint coating does not cause significant heat spreading, allowing for more accurate point temperature measurements. The particle can also be removed without damaging the device.

A comparison of the temperature results using a micro-particle sensor, conventional IR with and without coating the surface of the device with black paint is shown in [11]. The advantages of the micro-particle sensor technique [12] is clearly seen and was used to measure the surface temperature of the hot-areas on the semiconductor region of the IR micro-emitter chip.

2. Infra-red measurement technique

The surface emissivity mapping of the IR emitter chip, taking into account the background radiation (including reflected radiation from the topology), was measured using an approach described in [9],

$$\varepsilon = [R_{T1}(\lambda) - R_{T2}(\lambda)]/[R_{b1}(\lambda) - R_{b2}(\lambda)] \qquad (1)$$

where $R_{T1}(\lambda)$ and $R_{T2}(\lambda)$ are the IR emission levels at known temperatures T_1 and T_2, and $R_{b1}(\lambda)$ and $R_{b2}(\lambda)$ are the respective equivalent black body emission levels.

For measurement purposes, the IR emitter chip was mounted on an aluminium base-plate, which in turn was mounted on a Peltier heater to control the base-plate temperature. A calibrated K-type thermocouple was embedded in the base-plate to monitor its temperature. The base-plate with the mounted IR emitter chip was positioned underneath the objective of an IR microscope (Quantum Focus Instruments (QFI) infra-red microscope (Infrascope II), as shown in figure 1. The instrument has been modified for high temperature detection (> 500 °C), and has a cooled (77 K) 512 × 512 pixel InSb detector with a maximum spatial resolution of ~3 µm (using a 25× objective), which gives a field of view of 464 µm × 464 µm [13].

To enhance the accuracy of the IR thermal measurements, a single high emissivity (> 0.7) micro-particle sensor (amorphous carbon sphere) of ~15 µm diameter was placed in isothermal contact with the surface of the device to be measured using a Scientifica micro-manipulation probe. Naturally occurring electrostatic and Van-der-Waals forces were used to adhere the micro-particle to the manipulation probe, enabling the single micro-particle to be transferred to the point on the surface of the device under test (DUT) where the temperature was to be measured [14]. Figure 2 shows a schematic of the experimental arrangement. Radiance IR emission from the micro-particle sensor was measured using the IR microscope, thereby providing an improved estimate of the surface temperature.

The surface emissivity of the micro-particle sensor was measured using the two-temperature approach described in [9], where, $T_1 = 65\,°C$ and $T_2 = 95\,°C$. The equivalent black-body radiance level was calculated, and a calibration curve used to read off the temperature.

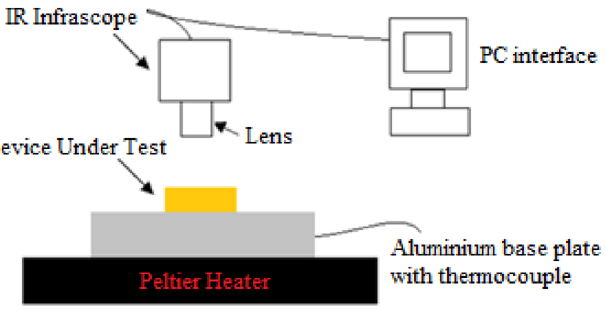


Fig. 1. *Infrared temperature measurement arrangement*

DC probes were used to make electrical contact to the chip, which was biased with a DC power supply (TTI PL303QMD-P Quad-mode). All thermal measurements were made at a base-plate temperature of 80 (+/-0.5) ^{0}C.

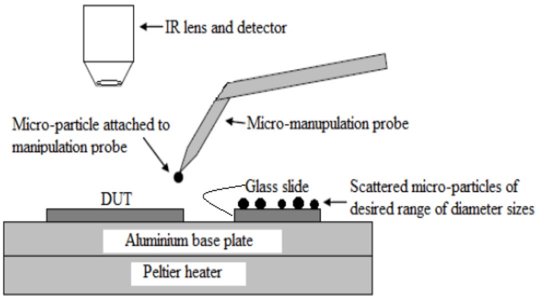


Fig. 2. *Micro-particle manipulation arrangement*

3. Results and discussion

3.1. Conventional IR measurement results

The IR emitter chip was biased over a range of input powers (0 to 240 mW) and for each input power a 2D thermal map of the emitter chip was recorded, using conventional IR microscopy. The peak temperature was identified and plotted as a function of the input power (figure 3). The average temperature of the emitter chip was also calculated using an electrical method [15, 5]. For this approach, the temperature dependent resistance of the heater was measured, taking into account the chip input feed resistance, for each input power. Knowing the temperature coefficients of resistance ($TCR_1 = 9.66 \times 10^{-4}$ K^{-1} and $TCR_2 = 1.0 \times 10^{-12}$ K^{-2} provided by ams sensors UK Ltd) and the heater resistances, the average temperature of the heater was calculated, using expression (2).

$$R = R_0 \left[1 + TCR_1 (T - T_0) + TCR_2 (T - T_0)^2\right] \quad (2)$$

where, T_0 = ambient temperature, T = heater temperature, R = resistance at temperature T and R_0 = resistance at ambient temperature T_0.

The heater temperature calculated using the electrical method (as a function of input power), was compared with the peak temperature obtained by conventional IR measurement (see figure 3). There was good agreement between the temperature readings obtained by both methods.

To investigate the temperature uniformity, thermal maps of 5 emitter chips were measured using conventional IR thermal imaging. A 5× objective lens was used for imaging, giving a field of view of 2.3 mm × 2.3 mm and the spatial thermal resolution was ~10 µm.

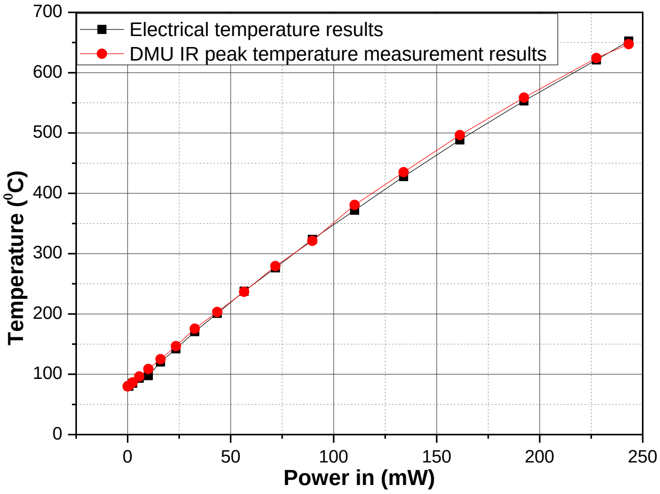


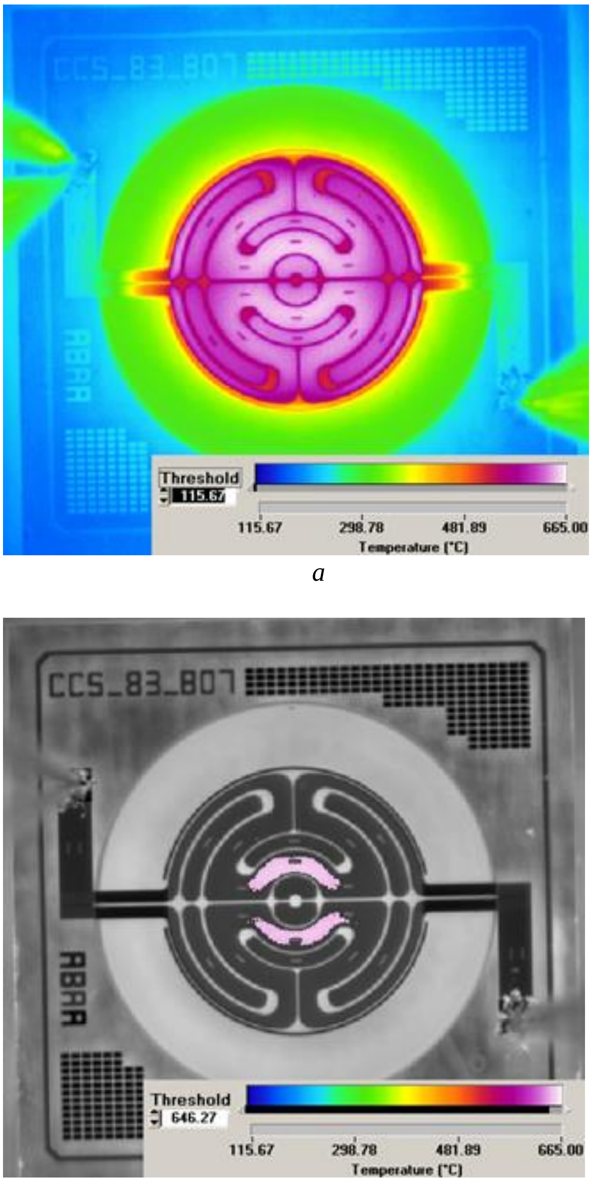
Fig. 3. *Comparison between conventional IR and electrical temperature measurements*

All of the five thermal maps showed good thermal uniformity across the heater of the IR emitter source (an example is shown in figure 4), with a maximum temperature variation across the heater structure of < 20 °C (at highest input power level ~ 240 mW). There is some elevation in temperature in the central ring of the heater structure which is more efficiently thermally insulated from the substrate.

The good thermal uniformity suggests that lumped average operating temperatures obtained using the electrical measurement technique will give a good approximation of device operating temperature.

3.2. IR measurement results using a micro-particle sensor

A micro-particle sensor was used to improve the accuracy of the IR thermal measurement on the thin semiconductor layer of the MEMS heater. A carbon micro-particle sensor (~ 15 µm diameter) was placed using the Scientifica manipulator on the hot area of the heater membrane. The measured surface emissivity of the micro-particle was greater than 0.7 (figure 5). The measured emissivity of the semiconductor layers forming the membrane heater was low (0.3) due to the transparency of the semiconductor layers to IR radiation and high reflectivity of the metal track.



a

b

Fig. 4. *Infra-red thermal images of the IR emitter chip* ***(a)*** Figure showing the thermal uniformity, **(b)** Figure showing the hot spots

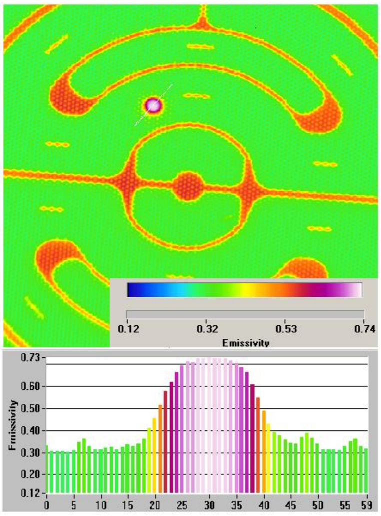


Fig. 5. *Emissivity map of the micro-particle sensor (~ 15µm diameter)*

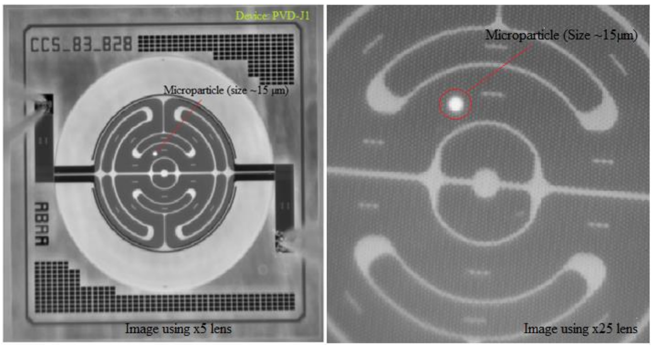


Fig. 6. *IR radiance image showing the micro-particle sensor placed on the heater of the IR emitter chip*

An IR image showing the micro-particle sensor placed on the heater of the chip is shown in figure 6. DC bias was applied to the heater and the temperature of the micro-particle sensor was recorded for each bias point using a 25× objective lens. Figure 7 shows the temperature measured using the micro-particle, and compared with the peak temperature measured using conventional IR at the same x & y coordinate position on the chip. The operating temperature of the chip was measured over the same DC operating power (0 to 240mW). The temperature difference between the micro-particle sensor and the conventional IR measurement was approximately 15 °C. Conventional IR thermal measurements tend to underestimate the device operating temperatures due to uncertainty in the surface emissivity [16]. The micro-particle technique reduces some of the uncertainty in the surface emissivity determination, providing a more exact measurement of surface temperature.

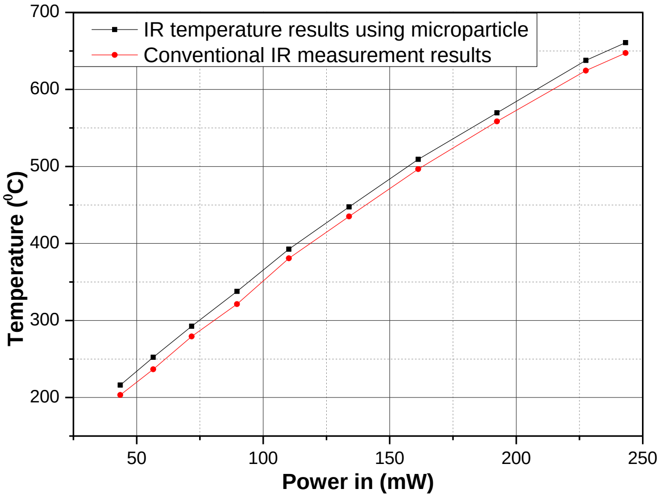


Fig. 7. *Comparison between conventional IR temperature results and measurements made using the micro-particle sensor on the emitter chip.*

4. Conclusion

IR imaging was used to thermally profile the micro-heater of a novel MEMS IR emitter chip, based on tungsten CMOS technology. IR imaging indicates that the micro-heater of the chip has good thermal uniformity and the conventional IR measurements are in reasonable agreement with electrical temperature determination.

Conventional IR thermal measurements underestimate the surface temperature of semiconductor layers due to uncertainties in the surface emissivity. This paper has presented an improved approach for IR thermal measurements, by using a high emissivity micro-particle sensor. It has been shown that the use of a micro-particle IR measurement approach can reduce the uncertainties in the temperature determination due to poor surface emissivity. The micro-particle sensor was used for the first time to make temperature measurements on the hotplate, to a maximum temperature of ~ 665 °C. The results indicate that the conventional IR technique underestimates the peak temperature of hot spots by approximately 15 °C, such underestimation can affect the estimation of device operating life. The approach presented in this paper helps to overcome such uncertainties.

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6. References

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