A Low Power, Low Cost Infra-red Emitter in CMOS Technology

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***Abstract*— In this paper we present the design and characterisation of a low power low cost infra-red emitter based on a tungsten micro-hotplate fabricated in a commercial 1.0 µm SOI-CMOS technology. The device has a 250 µm diameter resistive heater inside a 600 µm diameter thin dielectric membrane. We first present electro-thermal and optical device characterisation, long term stability measurements, and then demonstrate its application as a gas sensor for a domestic boiler. The emitter has a DC power consumption of only 70 mW, a total emission of 0.8 mW across the 2.5 to 15 µm wavelength range, a 50% frequency modulation depth of 70 Hz, and excellent uniformity from device to device. We also compare two larger emitters (heater size of 600 µm and 1800 µm) made in the same technology that have a much higher infra-red emission, but at the detriment of higher power consumption. Finally we demonstrate that carbon nanotubes can be used to significantly enhance the thermo-optical transduction efficiency of the emitter.**

***Index Terms*— IR Emitter, Tungsten, Gas sensor, SOI, CMOS**

I. Introduction

THERE is a growing need for miniature InfraRed (IR) emitters for Non Dispersive Infra-Red (NDIR) sensing and spectroscopy applications. A micro-bulb is typically used as the IR source in such applications. Micro-bulbs have the advantage of being extremely cheap, but they suffer from several significant disadvantages. Firstly, they have high power consumption (typically several 100 mW), secondly they are bulky compared to a silicon die and thirdly, most importantly have a limited emission at mid to high IR wavelengths above 5 - 6µm due to optical absorption by the outer glass – wavelengths that are needed for certain gases (e.g. ethanol). Finally, micro-bulbs have typically large tolerances on the exact heater position, and the heating element is linear rather than almost a point source; these properties lead to a non-optimal optical arrangement.

As a result there are a number of reports in the literature on the fabrication of silicon based IR emitters. These typically consist of a micro-heater embedded within a dielectric membrane that is thermally isolated from the silicon substrate. Electrical current is applied to the heater, which raises the region to a temperature as high as 700 ^{0}C, and hence emits radiation in the IR range. For example, [1] describes two devices based on a platinum heater embedded within a membrane consisting of silicon dioxide and silicon nitride. One of the devices is a full membrane structure formed by back-side bulk silicon etching, while the other is a suspended membrane structure, formed by a front-side silicon etch. Other similar devices based on platinum have also been described elsewhere [2-7], whilst [8] describes a device based on gallium arsenide (GaAs). However, these devices are not compatible with CMOS processes, as platinum cannot be used in CMOS, while GaAs needs completely different processing and is also much more expensive than silicon.

Devices based on doped *polysilicon* heaters have been described by [9-10], whereas [11-14] describe designs based on doped *single-crystal* silicon heaters. [15] reports on various materials for IR heaters at very high temperatures (800 ºC – 1000 ºC), including platinum, single-crystal silicon, and doped tin oxide. [16-17] report the use of a commercial CMOS process for fabrication, with [16] using polysilicon as a heater material, and [17] using a single-crystal silicon heater with aluminium to form electrical connections between the heater and connections outside the membrane. However, polysilicon is known to suffer from long-term stability problems at high temperatures (over 300 ºC) [18]. Single-crystal silicon is more stable, but it has a relatively high sheet resistance that makes it difficult to design a micro-heater for low voltage operation (below 3 V). Tin oxide also has high resistance, and is not easily integrated in a CMOS process.

In this paper we present a CMOS IR emitter based on tungsten metallization. Tungsten is an interconnect metal found in some high temperature CMOS processes, and is reliable at high temperatures up to 600 °C. This allows a stable IR emitter to be designed and fabricated while having all the advantages of CMOS – very low cost in high volume, excellent device reproducibility and the possibility of a wide range of integrated

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circuitry.

Previously [19] we have reported the use of tungsten as micro-hotplates for resistive and calorimetric gas sensing. In this paper we present a device made in the same technology but designed as an IR emitter. In particular, the heater area has been increased to improve the IR emission at the expense of power consumption. We present the electro-thermal and optical characterization of the device, and demonstrate its use within an NDIR sensor for CO_2 detection and hence application in a domestic gas boiler.

II. Device Design and Fabrication

The device was designed as a 250 µm diameter resistive tungsten micro-heater embedded within a 600 µm circular dielectric membrane. A temperature sensing p-n diode made of thin silicon is embedded within the membrane below the heater. A NFET is also integrated on the chip to drive the heater. The chip size is 1160 µm × 1060 µm – about 1 mm^2.

The IR emitters were fabricated in a commercial 1.0 µm SOI-CMOS process followed by a back-side Deep Reactive Ion Etching (DRIE) to form a thin membrane. The CMOS process used for the devices is a high temperature process that uses tungsten metallization instead of aluminium as the interconnect metal.

The starting SOI wafer is a 6” wafer with a 1 µm buried silicon dioxide layer, and 0.25 µm thin silicon layer. The wafer is then processed by standard CMOS processes such as ion implantation, gate oxide formation and polysilicon deposition. Silicon dioxide is deposited as the dielectric material, followed by alternate layers of tungsten interconnect and more silicon dioxide. A tungsten interconnect layer is used to form the micro-heater and a heat spreading plate, while the thin silicon layer forms the temperature sensing diode and the heater drive NFET. Next, a silicon nitride layer is deposited on the wafer for passivation. Finally, a back-side DRIE step defines the membrane area. The total membrane thickness is ca. 5 µm, which consists mostly of silicon dioxide and a 0.5 µm passivation layer of silicon nitride on top. The tungsten layer is 300 nm thick. Figure 1 shows a photograph of the fabricated chip, while figure 2 shows a schematic cross-section of the device and its different elements.

III. Electro-thermal Characterisation

Extensive electro-thermal characterisation was performed on the micro-hotplates. First, the temperature coefficient of resistance of the heater metallization, and the diode voltage drop as a function of temperature were measured. A wafer was put on a high temperature chuck, and the temperature stepped up to 300 °C. At each temperature step the tungsten resistance and the diode forward voltage at a bias of 65 µA were measured. To calibrate the tungsten a similar structure as the heater was used, but with 4-wire connections to allow accurate measurement of the resistance. The temperature coefficient of both the tungsten and the diode were determined. The tungsten was found to have a linear temperature coefficient of resistance (TCR1) of 2.05×10^{-3} K^{-1} and a quadratic temperature coefficient of resistance (TCR2) of 0.3×10^{-6} K^{-2}, while the diode had a voltage coefficient of –1.3 mV/K.

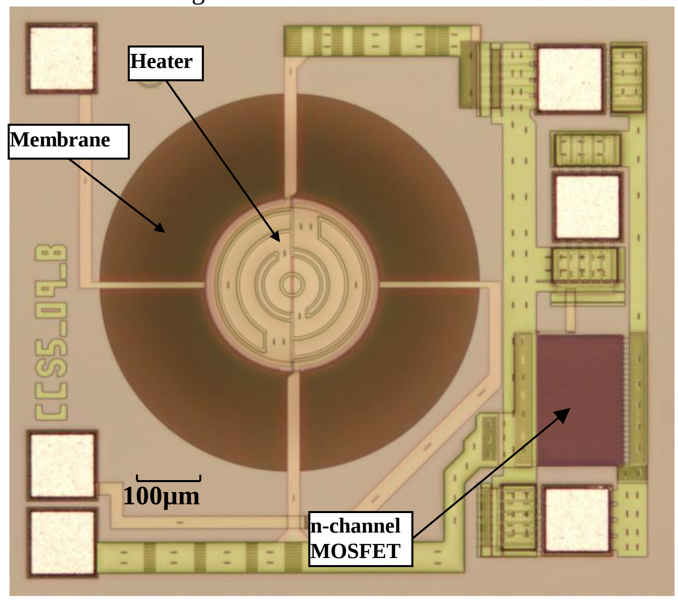

Fig. 1. Photograph of fabricated IR emitter chip (1.16 mm × 1.06 mm) with integrated FET drive.

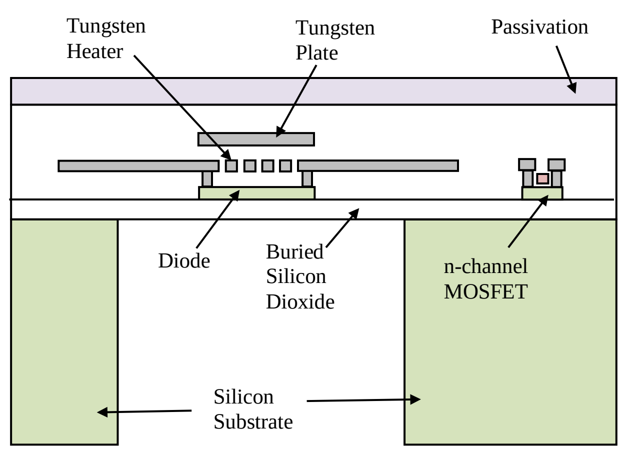

Fig. 2. Schematic cross-section of the IR emitter with the n-channel MOSFET (pad openings not shown).

The power consumption of the devices was then measured by electrically biasing the heater at different power levels and measuring the change in heater resistance to determine the heater temperature. Figure 3 shows the power consumption of the device for 5 devices taken across a wafer. The device needs low power (70 mW) to reach 600 °C. The curves are nearly identical for each of the chips showing excellent reproducibility from device to device. The diode can also be used as a temperature sensor instead of the tungsten heater, however it was found to become inaccurate above 550°C[20].

The transient thermal response time of the heater was also measured by pulsing the heater and measuring the temperature using the diode. Figure 4 shows a 10-90% rise time of 10 ms, and fall time of 25 ms. Lastly the NFET on the chip was tested. The circuit formed by the NFET and heater is shown in the inset in figure 5. The VDD was held at a constant voltage and the gate voltage varied up to 3 V. This was repeated for different values of VDD and the results are shown in figure 5, which shows the gate switching the device on and off. Using an NFET means that the control circuitry doesn't need to provide the drive current, but instead controls by changing the gate voltage. Integrating it on the same chip reduces overall system cost, and because of good thermal isolation the NFET is not heated when the micro-hotplate is in operation, although ambient temperature changes can affect it.

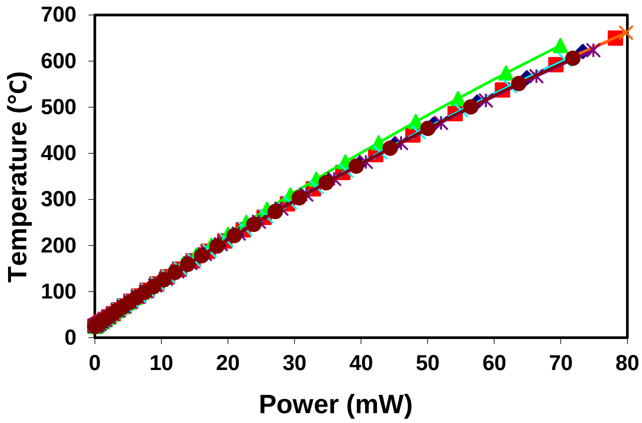

Fig.3. Power consumption curve of the IR emitter at different temperatures measured for 5 devices across a wafer.

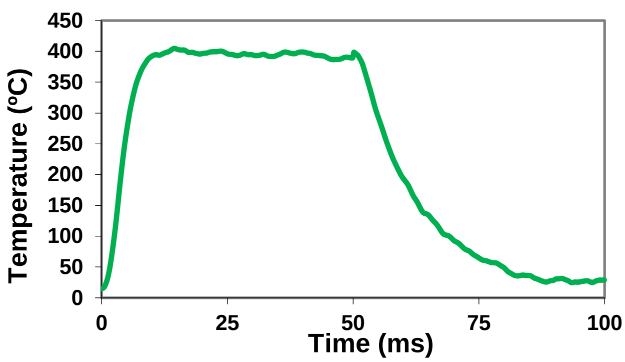

Fig.4. Transient heat up and cool down time of the IR emitter. The 10-90% response time is 10 ms for heating up, and 25 ms for cooling down.

IV. Optical Characterisation

Infrared measurements were then performed to test the optical characteristics of the device. The chip was packaged onto a TO39 header and placed in a 6 cm aluminium tube (9mm diameter) in front of a thermopile IR detector (Heimann HMS-J21 with a 4.26 µm band pass filter, with 90 nm half-pass band width). Figure 6 shows the change in detector signal as the IR emitter was heated up.

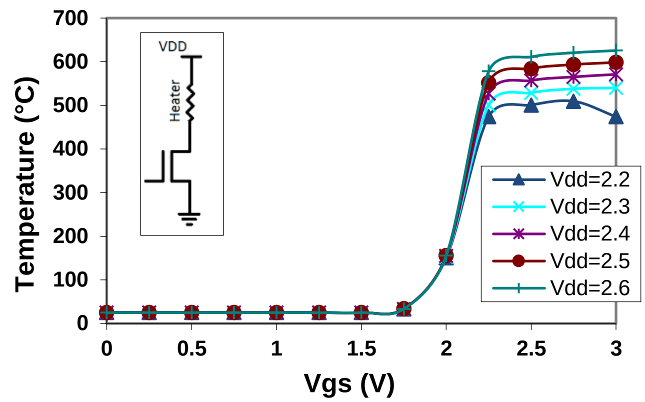

Fig.5. The NFET characteristics when used to switch the heater on/off.

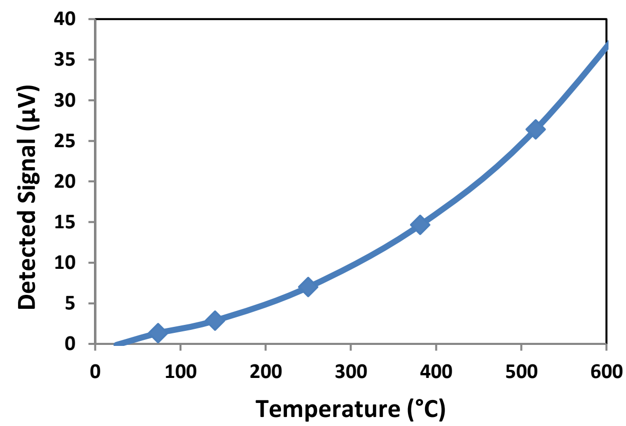

Fig.6. The response of an IR detector as the micro-hotplate on the IR CMOS emitter chip is slowly heated up.

A. *Frequency Response*

The frequency response was measured by using a high frequency lead selenide photoconductive detector (Hamamatsu P9696-02) in an aluminium tube. The emitter was electrically pulsed at different frequencies at 50 % duty cycle, and the detector signal was measured. Figure 7 shows the measured frequency response, showing a 50 % response at 70 Hz.

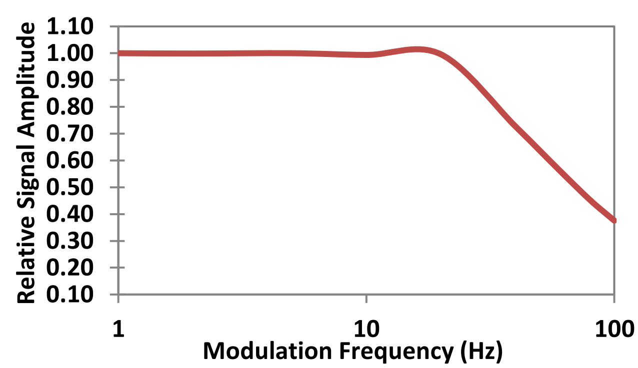

Figure 7: Frequency response of the IR CMOS emitter.

B. *FTIR Measurements & Calculation of Radiance*

The spectral response of the IR emitters was measured using an FTIR system (FTS-2000 FTIR spectrometer with UMA 600 FT-IR Microscope). Reflectivity measurements were made over an IR waveband of 2.5 - 15 µm to estimate the emissivity of the heater which for an opaque body is given by $e = 1 - r$, where e is the emissivity and r is the reflectivity. The FTIR system was calibrated using a gold plate (near perfect reflector). To image the device, the microscope was focused onto the area of the heater using a 15× lens objective. The emissivity spectrum calculated from the reflectivity measurements is shown in figure 8. This wavelength range is similar to that of other devices found in literature, however the emissivity is low (< 0.4) at wavelengths below 7 µm, but is fairly high (> 0.5) at wavelengths above 8 µm. The spectral response is dominated by the properties of the silicon dioxide and silicon nitride layers which form the membrane.

Based on these results the total emission from the device was estimated. The emission of a blackbody at different wavelengths is given by Planck's law [21]:

$$I = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

Where, c is the speed of light, λ is the wavelength, k is Boltzmann's constant, h is Planck's constant, T is the absolute temperature of the radiating surface, and I is the radiated power per unit area per unit solid angle per unit wavelength.

Our device is considered as a grey body. Its radiance can be estimated using the radiance of a perfect blackbody corrected by its effective emissivity. Figure 9 shows the spectral radiance of a perfect blackbody at 600°C against the spectral radiance of our device operated at 600°C estimated by multiplying the figure 8 profile with the blackbody curve.

Integrating under the curve in figure 10 gives the radiance of the emitter which is 2.59×10^3 W m^{-2} sr^{-1}. For a Lambertian emitter the relationship between the radiance and radiant emittance is given by [19]:

$$W = \pi N$$

Where W is the radiant emittance (emission per area), and N is the radiance (emission per area per solid angle). Calculating the radiant emittance and multiplying by the heater area (for a circular heater of 250 µm diameter) gives an emission of 0.4 mW of power within the wavelength range of 2.5to 15 µm.

The emitter will radiate both above and below the membrane, and also some IR emission will occur in the membrane area outside the heater region. So the total emitted power is estimated to be twice this value – at 0.8mW. The input power at 600 °C is a lot more – 70 mW, but much of it is lost as thermal conduction through to the substrate, and heat loss through air.

A comparison is given in Table 1 this device and other devices reported in literature. Our device is on the lower scale in terms of size and power consumption, and average for temperature and frequency, while being made in CMOS.

V. Gas Sensing Measurements

The device was then tested for use as an NDIR carbon dioxide (CO_2) gas detector in a domestic boiler. The IR emitter was packaged in a TO-5 header and placed in an aluminum tube 5 mm away from a commercial thermopile-based IR detector (Heimann HMS-J21). The detector was packaged with a band pass filter centered at 4.26 µm and a half pass bandwidth of 90 nm (which aligns with the main absorption band for carbon dioxide). A photograph of the tube is shown in figure 10. There are holes to allow the diffusion of air/gas in to the tube. PCBs were mounted on either side to connect the IR emitter and detector. The PCB on the detector side also has an amplification circuit, placed close to the detector to reduce electrical noise pickup. The schematic of the circuit (a two stages amplifier with a total gain of about 4200) is shown in figure 11. The whole system was then placed in a tight fitting chamber and connected to a gas testing system which allows control of dry air, humid air and carbon dioxide.

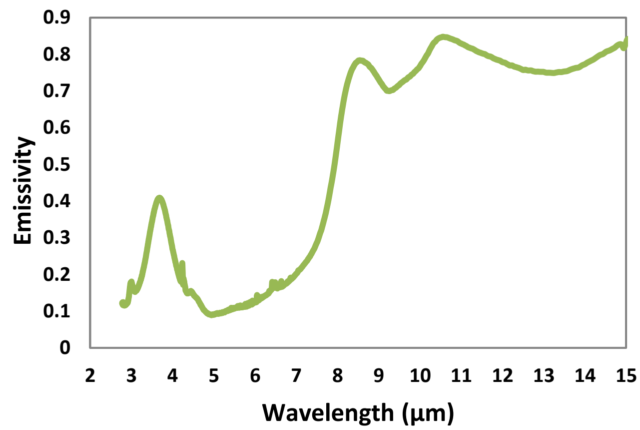

Fig. 8. Emissivity spectrum of the emitter obtained from FTIR reflectivity measurements.

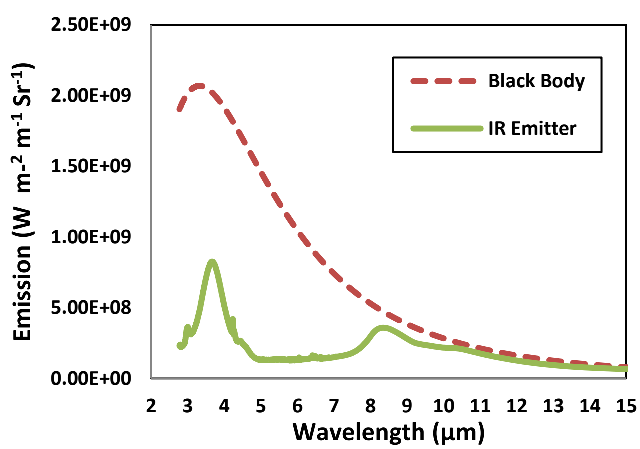

Fig.9. IR emission spectrum of a black body at 600 °C and the calculated value for the emitter at 600 °C.

TABLE I
COMPARISON WITH REPORTED DEVICES

Ref	Heater Type	Size (μm^2)	CMOS Compatible?	Power (mW)	Temperature (°C)	50% Frequency (Hz)
[1]	Pt	2.4×10^4	No	600	550	72
[2]	Pt	2.5×10^5	No	800	-	30
[3]	Pt	2.6×10^6	No	550	800	<50
[4]	Pt	5.4×10^3	No	44	700	230
[5]	Pt	14×10^4	No	241	800	-
[6]	Pt	1×10^5	No	90	450	-
[7]	Pt	-	No	-	212	-
[8]	GaAs	5.8×10^6	No	113	410	-
[9]	Poly Si	3×10^2	Yes	-	1227	
[10]	Poly Si	-	Yes	2632	843	45
[11]	Si	3.1×10^4	Yes	-	700	300
[12]	Si	3×10^4	Yes	-	927	
[13]	Si	5×10^6	Yes	2500	-	
[14]	Si	-	Yes	-	1900	-
[15]	SnO_2	2.3×10^6	No	1000	843	20
[16]	Poly Si	-	CMOS	18.3	334	
[17]	Si	3.3×10^5	CMOS	200	700	20
This Work	W	4.9×10^4	CMOS	70	600	70

Note: the devices denoted as "CMOS" are ones made in an actual CMOS process as opposed to just using materials that are CMOS compatible.

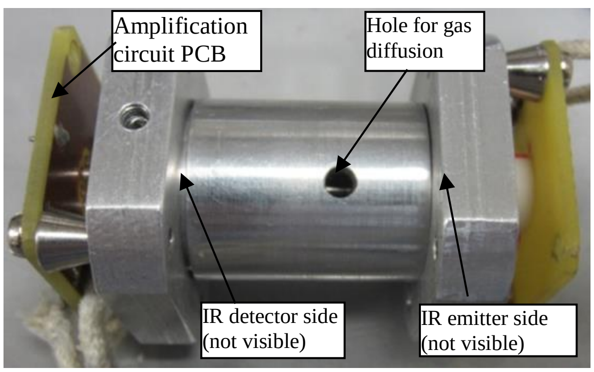

Fig. 10. NDIR sensor tube. Inside there is an IR emitter and detector and a PCB at either end to mount the devices and amplify the detector signal.

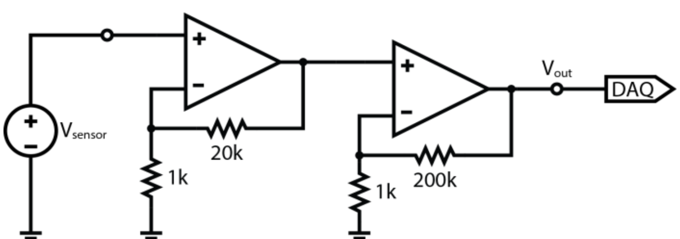

Fig.11. Circuit used to amplify the IR detector signal.

The heater was pulsed at 10 Hz, 50% duty cycle at 600 °C (which results in an average power consumption of approx. 40 mW). The amplified detector signal was measured and recorded using a National Instruments DAQ card. For domestic boilers the CO_2 levels at the exhaust are higher than normal atmospheric concentrations, therefore the testing was done at concentrations of 6-14% by volume. Measurements were performed in dry air as well as 40% humid air.

The signal from the amplifying circuit was analyzed by extracting the peak to peak voltage for each pulse and averaging over 20 samples (2 seconds) to reduce noise. The resulting signal for the measurement in dry air is shown in figure 12. As can be seen there is a clear response to CO_2, however the signal is noisy, and in particularly there seemed to be some 0.05 Hz system noise in the signal. To improve the signal-to-noise ratio, the original signal was averaged over 200 samples (20 seconds) instead of 20 samples, which greatly reduced the noise; however it does have the effect of increasing the effective response time of the sensor. Figure 13 shows the resulting signal, for the measurements with dry and humid air. The results show good response to carbon dioxide, and with the reduced noise the sensor has a resolution of 0.5% CO_2 in the range 6-14%, and there is very minimal effect of humidity. Improved resolution can be obtained by careful alignment of the emitter and detector and using a tube with a smaller diameter to better concentrate the emission onto the detector. The 0.05Hz system noise was likely caused by the implementation circuitry or instrument and not inherently present in the emitter or detector. So better circuit components and shielding would prevent the introduction of this 0.05Hz interference and further improve resolution and response time.

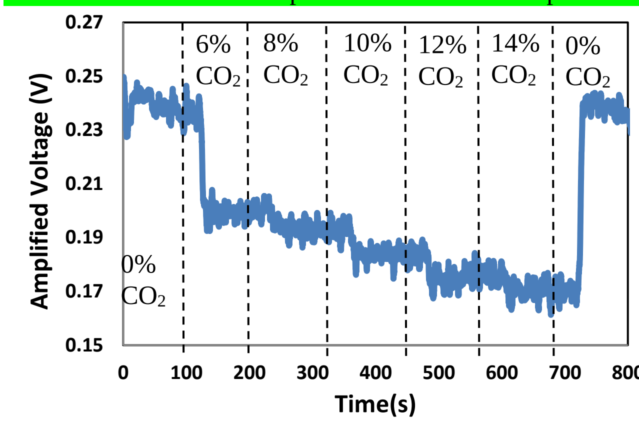

Fig.12. Sensor response to 6-14% by volume of CO_2, with the signal averaged over 2 seconds.

VI. LONG TERM MEASUREMENTS

The devices were tested for long term stability by running them continuously. The chips were put in a long term test board and pulsed continuously at 10 Hz, 50% duty cycle, for 5,000 hours (about 180 million cycles). 5 devices each were pulsed at 500 °C and 600 °C. The resistance of the emitters was monitored and is shown in figure 14.

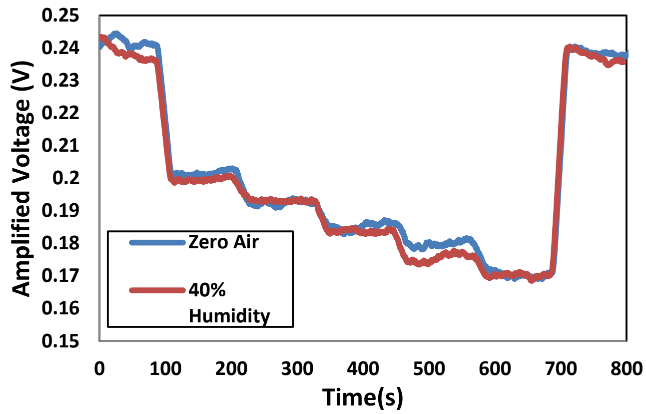

Fig. 13: Sensor response to 6-14% by volume of CO_2 with the signal averaged over 20 seconds to reduce noise. The measurements have been performed with CO_2 in (i) dry air and (ii) 40% humid air.

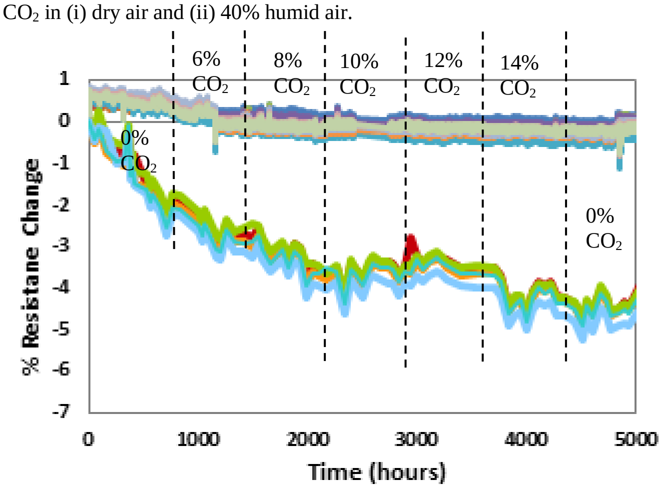

Fig. 14. Long term stability of the emitter operated at 500 °C and 600 °C over a period of 5000 hours and pulsed at 10 Hz.

At 600 °C the emitter resistance drifts by about 5% over 5000 hours (corresponding to a 30°C change). At 500 °C the emitter is very stable and the drift is much less ~ 1%. For boilers and most other applications the drift should be less than 2% per year. So to further improve the stability of the IR emission, particularly at 600°C, the device could be driven in constant power mode to keep the operating temperature constant (for applications where the thermal resistance of the device does not change, for example due to large air flow over the emitter).

Change in the optical properties of the membrane materials can also cause a drift in the heater emission. However the membrane materials are silicon dioxide and silicon nitride which are known to be very stable, so any changes in their optical properties are expected to be negligible. Nevertheless testing the stability in an optical system is part of future work.

VII. Optical Performance Enhancement

A. Emissivity Enhancement

To improve the emissivity of the IR emitter it was coated with a layer of carbon nanotubes (CNTs). Details of the CNT growth process are given in [22]. Figure 15 shows a photo of the coated chip. Figure 16 shows the spectral emissivity of the chip with CNTs on the heater area. As can be see the spectral response is near perfect due to the high emissivity of the carbon nanotubes. This is very encouraging and shows that the emission can be greatly improved by using CNTs.

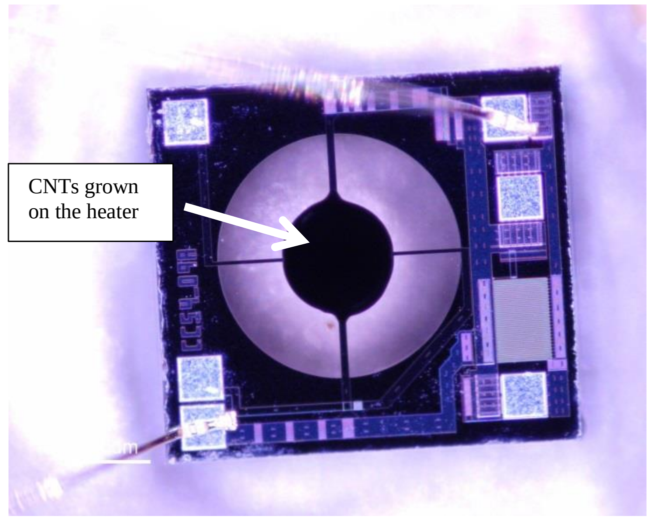

Fig. 15. IR emitter with CNTs grown on the heater area.

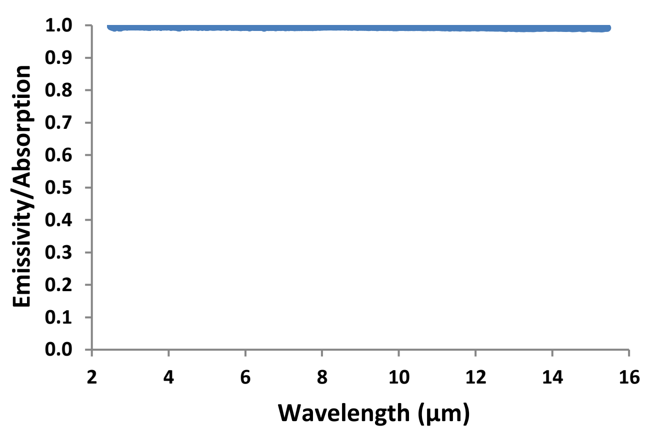

Fig. 16. Calculated emissivity spectrum of the CNT coated emitter obtained from FTIR reflectivity measurements.

B. Larger Emitter Devices

To obtain higher IR emissions two different devices with a larger heater were also fabricated using the same process steps previously described. One has a circular 600 µm diameter heater within a 850 µm membrane and is shown in figure 17. The other has a much larger heater, which is square 1.8 mm ×1.8 mm within a square 2 mm × 2 mm membrane and is shown in figure 18. The corners are rounded to reduce mechanical stresses in these regions.

The emission of these devices was tested with an IR detector and compared to the 250 µm heater. The results are shown in figure 19, and prove that much higher emission can be obtained. However figure 20 shows that the larger devices need much higher power consumption compared to the 250 µm emitter. In addition the 50 % modulation depth of the 600 µm and 1800 µm heater were found to be much lower at 47 Hz and 23 Hz. Therefore it is a trade-off between higher output IR emission and the power consumption and speed depending on the required application.

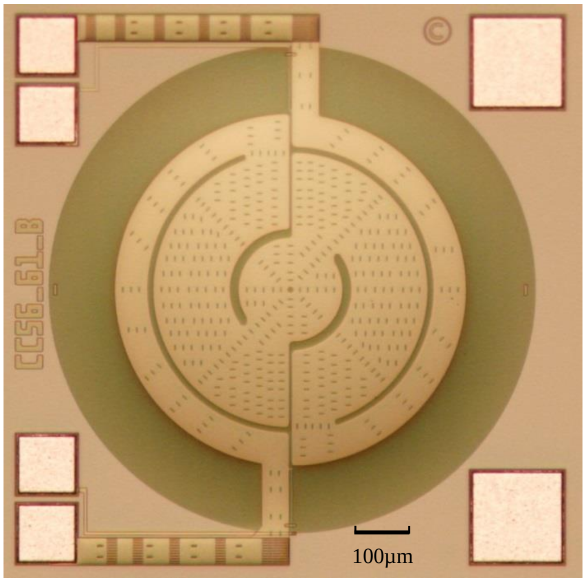

Fig.17. IR emitter with a 600 µm heater on a 850 µm membrane. The chip size is 1.16 mm ×1.16 mm.

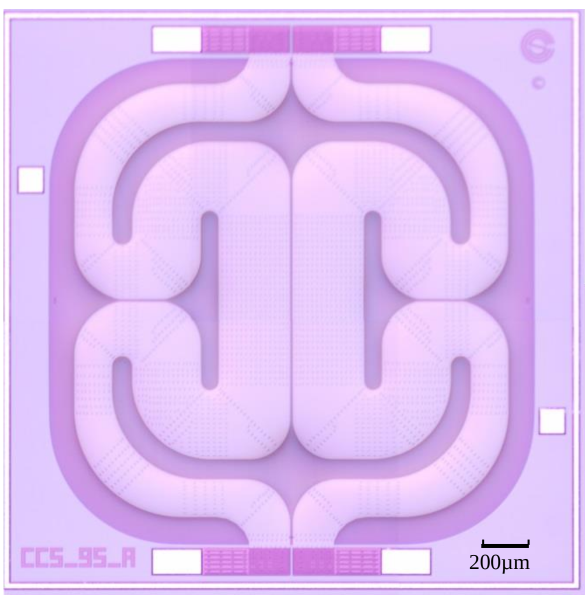

Fig.18. IR emitter with a 1800 µm heater on a 2000 µm membrane. The chip size is 2.56 mm × 2.56 mm.

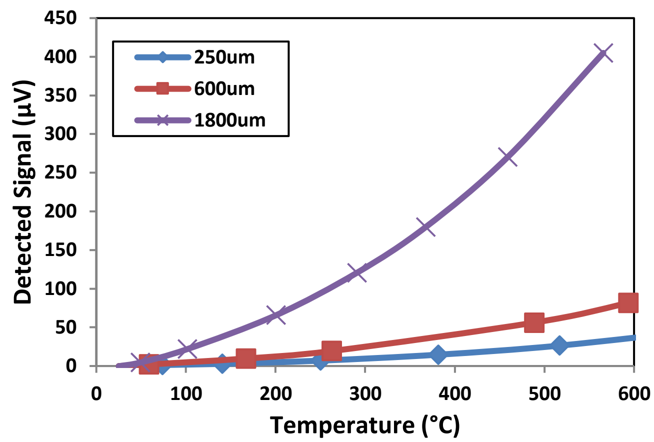

Fig. 19. Relative emission for different sizes of IR emitter, measured using a Heiman thermopile detector with filter at 4.26 µm, and 90 nm half pass band.

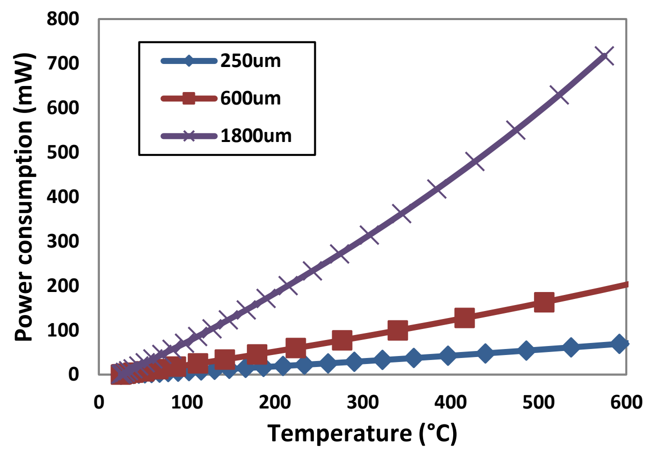

Fig 20. The relative power consumption for each of the different IR emitters.

VIII. Conclusions

In this paper we have fabricated and characterized a low power, low cost CMOS IR emitter based on a tungsten heater. The device is on a 1.16 mm × 1.06 mm chip, has a DC power consumption of only 70 mW, 50% frequency modulation depth of 70 Hz, and optical output power of 0.8 mW. We have also shown the stability of the device over 5000 hours, and a basic setup has been used to demonstrate the use of the device for a carbon dioxide NDIR sensor, which shows a resolution of 0.5% in 6-14% CO_2 concentration range, which is suitable for boiler applications.

The device shows very good emission at wavelengths above 8 µm, and makes it ideal for applications requiring high wavelengths. The emission is low at the wavelengths below 8 µm, but can be greatly improved by coating the device with carbon nanotubes. Further, we have shown that the same technology can be used to fabricate larger IR emitter devices which have much higher IR emissions, but at the cost of higher power consumption. We believe that this technology is very promising as a miniature, low cost, low power IR emitter for NDIR and spectroscopy applications.

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