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SOI CMOS MEMS Infra-Red Thermal Source with Carbon Nanotubes Coating

A. De Luca[a]*, M.T. Cole[a], R.H. Hopper[b], S.Z. Ali[b], F. Udrea[a,b], J.W. Gardner[c], W.I. Milne[a,d]

[a]*Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, CB3 0FA, Cambridge, United Kingdom*
[b]*Cambridge CMOS Sensors Ltd, Cambridge, Deanland House, Cowley road, CB4 0GU, Cambridge, United Kingdom*
[c]*School of Engineering, University of Warwick, CV4 7AL, Coventry, United Kingdom*
[d]*Kyung Hee University, Dept. of Inform. Display, Seoul, 1 Hoegi-dong, Dongdaemun-gu, 130-701, Seoul, South Korea*

Abstract

This abstract presents the development of a Silicon-on-Insulator (SOI) CMOS micro-electro-mechanical (MEMS) micro-hotplate based infra-red (IR) light source employing a vertically aligned multi-walled carbon nanotubes (VA-MWCNTs) emission layer. Chips were batch fabricated using a standard SOI CMOS process with tungsten metalization followed by a deep reactive ion etching (DRIE) post-CMOS process. VA-MWCNTs were grown at the chip level with a proven *in-situ* technique. The CNTs coated devices were compared with uncoated devices. Herein we discuss the device performance in terms of power dissipation, beam collimation, thermal transient times, integrated emitted radiation and emitted radiation spectral profile.

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Keywords: Thermal source; Micro-hotplate; Carbon-nanotubes; Silion-on-insulator; CMOS, MEMS.

* Corresponding author. Tel.: +44(0)1223748311; fax: +44(0)1223748348.
E-mail address: ad597@cam.ac.uk

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1. Introduction

Recently, the demand for miniaturized, low-cost, highly-selective and long lifetime carbon dioxide gas sensors has significantly increased due to the increase in affordable mobile consumer electronics. Non-dispersive-infra-red (NDIR) spectroscopy [1] is believed to be a promising sensing technique, due to its intrinsically high-selectivity and mechanical robustness. Nevertheless, issues related to size and cost of traditional systems must be resolved before wide-scale adoption. CMOS technologies are certainly one very attractive route for the fabrication of the main components of an NDIR sensor (IR source and IR detector), since they permit aggressive size reductions and low-cost/high-volume production. Unfortunately, CMOS compatible materials often have poor emissive and absorptive properties [2]. In [3], we demonstrated CO_2 detection can be significantly improved by the inclusion of a CNTs ad-layer and that the emitter is surprisingly stable up to a working temperature of 500°C. Herein we present a new IR source design with improved performance and we carry out an extensive analysis of its characteristics.

2. IR thermal source design and fabrication

The IR thermal source (chip size 2.4 mm × 2.4 mm) was designed using the CADENCE Virtuoso design platform and fabricated in SOI CMOS technology, in a commercial foundry. In **Fig. 1a**, an optical micrograph of the developed IR thermal source is shown. A schematic cross section of the SOI CMOS MEMS technology is depicted in **Fig. 1b**. High temperature tungsten metallization was used as the resistive material for the micro-heater and the interconnects. Tungsten was chosen due to its very high melting point (> 3400 °C) and lower susceptibility to electromigration when compared to aluminum or polysilicon. The micro-heater has a circular multi-ring structure with a diameter of 1.4 mm, embedded within an ~ 5 µm thick, 2mm diameter dielectric membrane released by a post-CMOS DRIE process. During this fabrication step, the buried oxide layer acts as an effective etch-stop. The DRIE process allows for the realization of nearly vertical side-walls, thereby permitting aggressive miniaturization. The circular design of the membrane allows for uniform intrinsic stress distribution at the membrane's edge. The membrane thermally isolates the micro-heater from the substrate, allowing temperatures in excess of 600 °C to be reached in the heater area. Si_3N_4 is used as passivation layer. Several devices were wedge-bonded onto TO5 packages, to allow *in situ* (only on the heater area) VA-MWCNTs growth [4]. First, a bilayer catalyst Al/Fe (10/1 nm) was DC magnetron sputtered and the micro-hotplate was employed as the micro-reactor, allowing VA-MWCNTs to grow (at 700 °C for 10 min) by thermal chemical vapor deposition (T-CVD) in a 4% H_2:C_2H_2 atmosphere at 25 mbar. MWCNTs growth was subsequently verified by optical microscopy and scanning electron microscopy.

3. Results and discussion

NDIR spectroscopy is based on the principle that the vibrational and rotational frequencies are particular to given molecules providing a specific and characteristic signature. These phases are responsible for the absorption of specific wavelengths in the IR window. A NDIR sensor relies on *(i)* a light source to generate IR radiation, which is partially absorbed by the target gas, as postulated by the Beer-Lambert law; *(ii)* an optical filter, which spectrally selects the wavelengths of interest; and *(iii)* an IR detector, which detects the radiation transmitted through the filter. The detector output can then be correlated to the gas concentration *via* a calibration procedure. A thermal source is an electro-thermo-optical transducer. The electro-thermal transduction is performed *via* Joule heating in a resistive component (i.e. the micro-hotplate). The thermal energy is then partially dissipated through the membrane by conduction, and partially through the ambient *via* convection. Typical power vs. temperature curves for the proposed thermal source are presented in **Fig. 2a**, for both coated and uncoated devices. VA-MWCNTs grown only on the heater area do not offer a thermal bridge between the "hot zone" and the substrate, thus no extra conduction losses are present. The remainder energy accounts for the functional and measureable optical component *via* radiation. In **Fig. 2b** the response of a commercial thermopile (Heimann HMS J21 with a 3µm - 6µm optical filter) is shown to

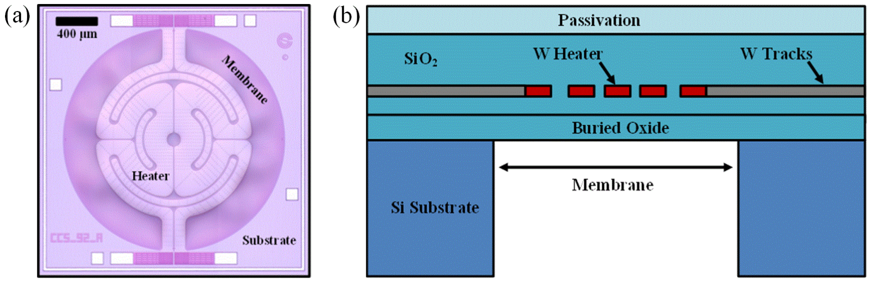

Fig. 1. Optical micrograph of SOI CMOS MEMS IR source (chip size: 2.4 mm × 2.4 mm); (b) SOI CMOS MEMS technology cross section (not to scale).

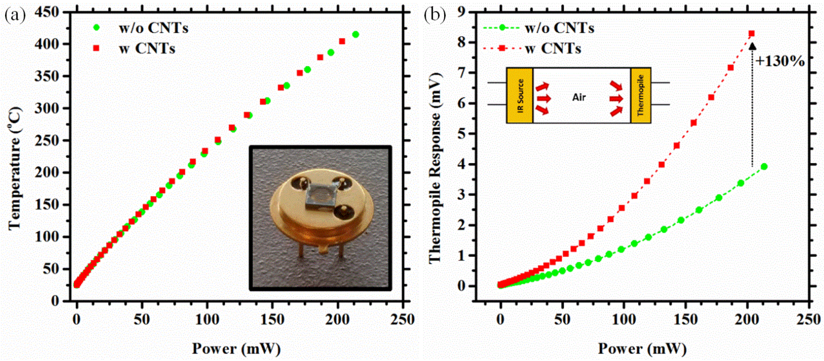

Fig. 2. (a) IR source average heater temperature vs. DC power dissipation. *Inset*: Optical photograph of TO5 packaged IR source; (b) Thermopile response vs. IR source power dissipation. *Inset*: Schematic depiction of NDIR setup.

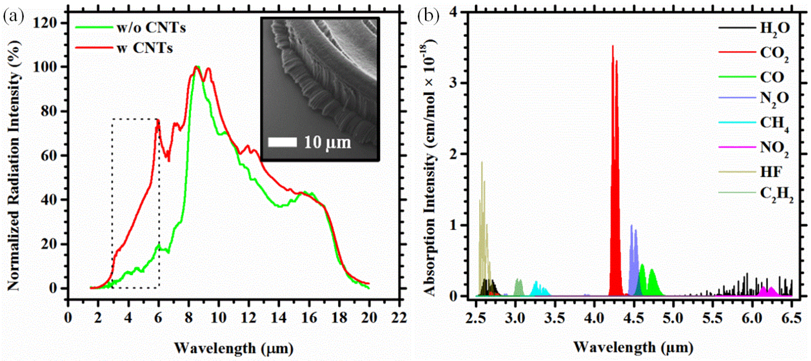

Fig. 3. (a) IR source normalized radiation intensity as a function of wavelength for a heater average temperature of 400 °C. *Inset*: SEM image of the VA-MWCNTs at the heater edge / membrane interface; (b) Absorption fingerprints of gases of interest in the range 3μm - 6μm (data from HITRAN2008 database).

be increased by 130% (for a power dissipation of 210 mW), if a device with the proposed emissive layer is employed. This finding is supported by **Fig. 3a**, which shows the spectra of coated and uncoated IR sources measured with a Perkin Elmer Frontier FTIR system. The emission intensity is clearly enhanced for wavelengths < 8 μm. This region of the spectrum is particularly interesting for sensing also other gases in addition to CO_2, as illustrated in **Fig. 3b**. The electrical modulation capabilities of the functionalized emitters were also studied, since

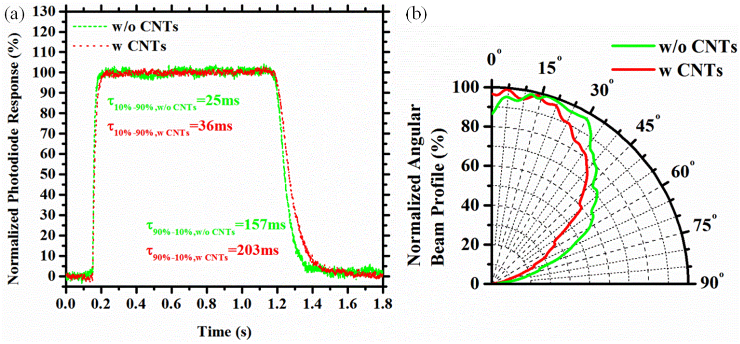

Fig. 4. (a) Normalized transient response of a photodiode under IR source pulsed excitation; (b) IR source normalized angular beam profile.

pulsed emission is an effective route towards power and noise reduction. A 30% degradation of the total thermal transient time ($\tau_{10\%-90\%} + \tau_{90\%-10\%}$) of the coated devices was measured with a fast response IR detector (IG26 PIN photodiode by Laser Components) (**Fig.5**), we believe due to the extra mass of the VA-MWCNTs. Finally, the IR source angular beam profile is shown in **Fig. 4b**. Accurate knowledge of the degree of collimation is of prime importance for the design of micro-IR optical systems to maximize the detector response at a minimised emitter power. The presence of the VA-MWCNTs emission layer has a minimal effect on the beam dispersion with only a slight increase in collimation.

4. Conclusions

We have presented the development of a SOI CMOS MEMS micro-hotplate based IR light source employing a vertically aligned multi-walled carbon nanotubes coating for thermal emission enhancement. Chips were batch fabricated with a standard SOI CMOS process. Tungsten was used as metal for the micro-hotplate and interconnects. A DRIE post-CMOS process step was used to release the membrane. VA-MWCNTs were grown in-house at chip level with a proven *in-situ* T-CVD technique. The CNTs coated devices were evaluated against nascent, uncoated devices. The VA-MWCNTs coating is shown to: *(i)* not degrade the heater power dissipation, *(ii)* slightly improve the beam collimation, *(iii)* increase the total transient time ($\tau_{10\%-90\%} + \tau_{90\%-10\%}$) by 30%, *(iv)* enhance the emitted radiation by 130% at a working temperature of 400°C in the 3µm - 6µm range.

Acknowledgements

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References

[1] J. Hodgkinson, R. Smith, W. O. Ho, J. R. Saffell, and R. P. Tatam, "Non-dispersive infra-red (NDIR) measurement of carbon dioxide at 4.2 µm in a compact and optically efficient sensor," *Sensors and Actuators B: Chemical,* vol. 186, pp. 580-588, 2013.

[2] A. De Luca, M. Cole, A. Fasoli, S. Ali, F. Udrea, and W. Milne, "Enhanced infra-red emission from sub-millimeter microelectromechanical systems micro hotplates via inkjet deposited carbon nanoparticles and fullerenes," *Journal of Applied Physics,* vol. 113, p. 214907, 2013.

[3] A. De Luca, Z. Racz, M. Cole, S. Ali, F. Udrea, J. Gardner, and W. Milne, "In-Situ grown carbon nanotubes for enhanced CO 2 detection in non-dispersive-infra-red system," in *Sensors, 2013 IEEE*, 2013, pp. 1-4.

[4] M. Haque, K. Teo, N. Rupensinghe, S. Ali, I. Haneef, S. Maeng, J. Park, F. Udrea, and W. Milne, "On-chip deposition of carbon nanotubes using CMOS microhotplates," *Nanotechnology,* vol. 19, p. 025607, 2008.