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Broadband infrared absorber based on a sputter deposited hydrogenated carbon multilayer enhancing MEMS based CMOS thermopile performance

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Abstract: Absorber optical coating with maximised broadband infrared absorptance is described, deposited using pulsed DC sputter deposited hydrogenated carbon. Application to MEMS CMOS thermopile device wafers is demonstrated with thermopile device output voltage increased 220%.

1. Introduction

Thermopile infrared (IR) detectors are extensively applied to the sensing elements of non-contact infrared thermometers, non-dispersive infrared (NDIR) gas detectors and uncooled thermal imagers [1]. As shown in the following figure the thermopile chip consists of a silicon substrate, supporting layers, passivation layers, thermopile and absorber.

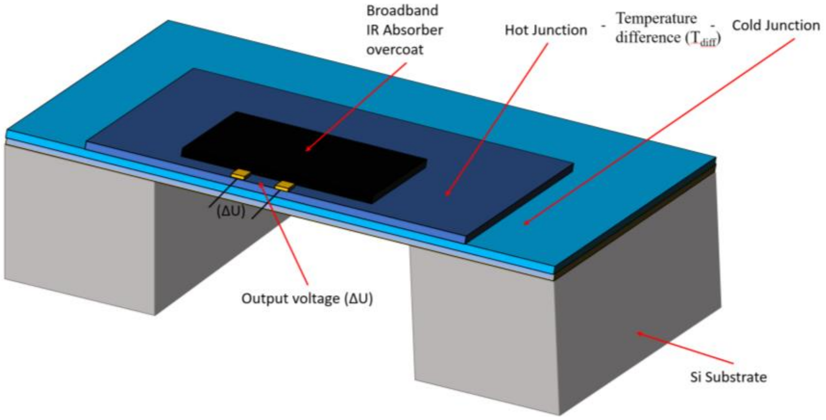

Fig. 1. Thermopile chip structure with deposited broadband absorber coating.

A temperature difference occurs between the hot and cold junctions (T_{diff}) when IR radiation is applied to the thermopile IR detector. Based on the Seebeck effect [2], the thermopile converts the temperature difference between the hot and cold junctions into an output voltage (ΔU) with the absorber critical in enhancing performance of the thermopile chip. Silicon, a primary substrate material, is used in many microelectromechanical systems (MEMS) based thermopile devices due to its low cost and complementary metal oxide semiconductor (CMOS) (semiconductor wafer) processing compatibility [3].

A porous metal (named "metal black", such as gold-black, silver-black, and platinum-black) is typically used as an absorber, with excellent absorption properties (> 90%) and broadband IR absorption [4, 5]. However, these porous metals are easily destroyed by contact, difficult to pattern and not compatible with CMOS because the dendritic and soft structures also make them too fragile for standard techniques like lithography and etching. Furthermore, their preparation process is much more complicated and cost is relatively high. A silicon nitride (Si_3N_4) or silica (SiO_2) layer or $SiO_2/Si_3N_4/SiO_2$ sandwich film structure is also often used as the IR absorber of thermopile chip (termed a "membrane" layer), however provides low IR absorption and narrow absorption range [6-8].

This paper provides a new CMOS compatible durable broadband absorber (BBA) multilayer optical coating based on hydrogenated carbon, overcoming shortfalls of the “metal black” and “Si_3N_4/SiO_2 multilayer” absorber approaches. Deposition utilises pulsed DC sputtering of carbon with controlled hydrogenation during sputtered carbon deposition. Combining a broadband absorption carbon layer (non-hydrogenated) with a low absorption anti-reflective (hydrogenated carbon) overcoat provides high broadband (2.5-20µm) IR absorption (>90%) with minimal IR reflection. The deposition process involves room temperature pulsed DC deposition of carbon with controlled introduction of hydrogen during the carbon deposition [9,10], thereby enabling control of the spatial absorption distribution through the carbon coating and achieving optimized combination of reduced reflectance and maximized absorption.

2. Theory & Modelling

Temperature difference (see Fig 1 $T_{diff)}$) occurs between the hot and cold junctions when infrared radiation is applied to the thermopile IR detector, and it will be transformed into an output voltage (see Fig 1 ΔU) according to the Seebeck effect [2].

The ΔU for a thermopile is calculated from [2]

$$\Delta U = NT_{diff}\,|\,\alpha_A - \alpha_B| = NT_{diff}\alpha_{AB} \qquad (1)$$

Where N is the number of serially interconnected thermocouples, α_A and $\boldsymbol{\alpha_B}$ are respectively the absolute Seebeck coefficients for materials A and B, and $\alpha_{AB}=|\alpha_A-\alpha_B|$ is the relative Seebeck coefficient T_{diff} between hot and cold junctions can be expressed as equation 2 [10] -

$$T_{diff} = \frac{\eta P_o}{G_{th}} \qquad (2)$$

Where η and G_{th} are the infrared absorptance of material and the total thermal conductivity of detector respectively. Incident power is P_0. Substituting 2 into 1 demonstrates output voltage (ΔU) $\propto$ absorptance (η).

Essential Macleod optical coating design software [11] was used to model and optimize the thickness of the carbon coating and resulting absorptance. Figure 2 shows modelled performance, demonstrating a factor of 2.2x performance enhancement (average spectral absorptance of coated and uncoated $SiO_2/N_4/SiO_2$ membrane, 93.81% and 42.73% respectively).

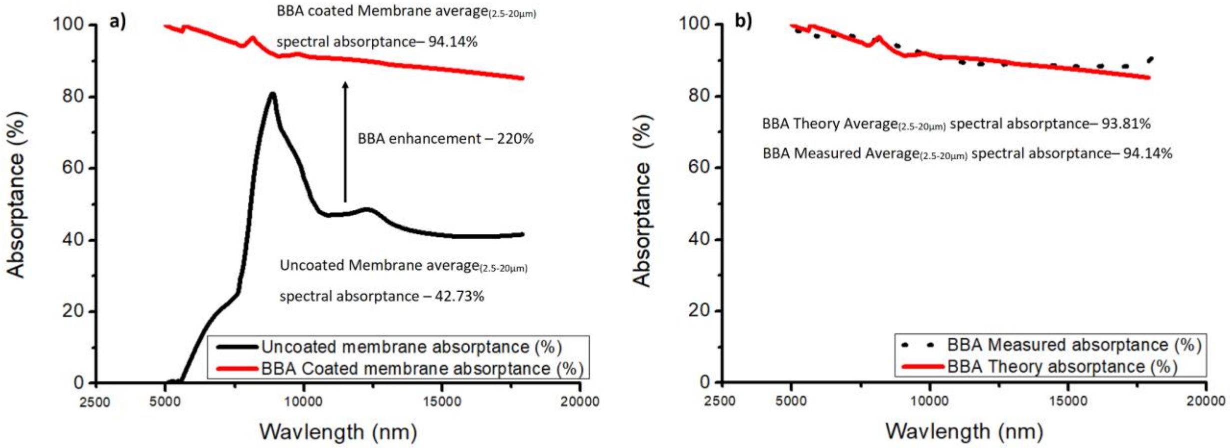

Figure 2a. Modelled absorptance for $Si_3N_4/\ SiO_2$ membrane and BBA overcoated membrane layer (b) comparison of theory and measured BBA coating.

3. Experimental Results

Deposition was carried out using a pulsed DC reactive sputtering process. The deposition system uses a horizontal axis rotating drum in which deposition of each layer can be achieved with multiple passes across a rectangular planar DC magnetron source. Controlled hydrogen introduction is via a high purity hydrogen generator using electrolysis of water [12]. Pulsed DC sputtering is employed to suppress arcing, necessary to ensure required coating cosmetic quality. Deposition conditions provided in following table 1 – primary variables are hydrogen flow, magnetron power and current ranges. All deposition carried out a room temperature.

Table 1: Typical deposition conditions of pulsed DC sputtered hydrogenated carbon

Ar Flow ($sccm^{-1}$)	H_2 Flow ($sccm^{-1}$)	Power (kW)	Current (A)	Voltage (V)	Pulsed DC Frequency (kHz)
100	0 to 3sccms	4	10	400	46

Deposition of the modelled multilayer design was carried out and spectral absorptance shown in Figure 2a, 2b– measurements carried out using a Perkin Elmer 983 spectrophotometer, demonstrating broadband absorptance (average spectral absorptance $_{(2.5\text{-}20um)}$ = 94.14%) used to enhanced output voltage MEMS thermopile chip performance.

Thermopile chip without and with BBA multilayer optical coating underwent output voltage (ΔU) performance testing. Testing coated and uncoated thermopiles utilized a broadband blackbody IR source (2.5 to 20um), exposed to the blackbody IR source and output voltage measured. The output voltage for uncoated and coated thermopile chip results in a 220% increase in response in agreement with modelled prediction.

4. Conclusion

In this work a pulsed DC sputter hydrogenated carbon BBA optical coating was deposited onto MEMS based CMOS thermopile device six inch diameter silicon wafers. The modelled results demonstrate a factor increase of 220% in output voltage between uncoated (average spectral absorptance$_{[2.5\text{-}20um]}$ =42.7%) and BBA coated (average spectral absorptance$_{[2.5\text{-}20um]}$ =94.14%) thermopile device membrane, in agreement with measured voltage output enhancement.

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