A Vanadium Dioxide Microbolometer in the Transition Region for Millimeter Wave Imaging

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***Abstract*—This paper presents the design of a new class of microbolometer that exhibits high responsivity for passive imaging arrays (camera) at millimeter wave (mmW) band. The main objective is to exploit the non-linear behavior of phase-change material (PCM) vanadium dioxide (VO_2) by biasing the sensor at the transition cliff (~68 °C). Simulated results together with calculations show high responsivity of 7.5×10^3 V/W and low noise equivalent power (NEP) of 6.1 pW/√Hz. The corresponding response time of the proposed microbolometer is 376 µs. Two orders of magnitude improvement in device performance as compared with the state-of-the-art sensors is the direct result of both suspension in air by micro-electro-mechanical systems (MEMS) microfabrication processing as well as the sharp change in resistivity of VO_2 in its transition region.**

Keywords—Millimeter wave (mmW) imaging, microbolometer, phase-change material (PCM), vanadium dioxide (VO_2)

I. Introduction

Millimeter wave (mmW) imaging technologies are of significant interest in various applications such as non-destructive testing, biomedical spectroscopy and security screening, because mmW is able to penetrate opaque materials. A mmW camera can detect mmW radiation from a scene and create an image. Among the various methods to measure object radiation, microbolometers are a promising candidate with the advantages of wideband operation, low cost and monolithic fabrication with read-out integrated circuits (ROIC). Microbolometers usually consist of an active material whose electrical resistance changes with temperature caused by radiation absorption. To improve the sensitivity of the microbolometer, it is desired that the active material has large thermal coefficient of resistance (TCR). Traditional microbolometers employ linear materials with small TCR such as nickel, titanium and platinum. Phase-change materials (PCM) such as vanadium dioxide (VO_2), whose electrical resistance change several orders of magnitude in the metal-insulator transition (MIT) region, are also utilized in the design of microbolometers. Despite its large TCR in MIT region, most of the designs are operating in the semiconducting phase of VO_2 for infrared operation [1]. In one previous design intending to utilize MIT region, the responsivity was not significantly improved mainly because of the low quality and large hysteresis of their VO_2 thin films [2]. In this paper, we present a high responsivity mmW (60-90 GHz) microbolometer that utilizes the MIT region of VO_2 by biasing near its phase transition cliff (68 °C). In addition, the overall performance of the proposed microbolometer [3] is further enhanced by suspension using micro-electro-mechanical systems (MEMS) technique.

II. Design

A. Microbolometer Physics

A microbolometer can absorb electromagnetic radiation irradiated from objects leading to temperature change, resulting in resistance change of active material. The provided resistance change will further be processed by ROIC. The performance of a microbolometer can be characterized in terms of responsivity and noise equivalent power (NEP). Responsivity [V/W] is defined as the output voltage divided by the input radiation power irradiated to a microbolometer, and is expressed as [4]

$$\Re = I_b R_b \alpha \left| \frac{R_{th}}{1 + j2\pi f R_{th} C_{th}} \right| \quad (1)$$

where I_b is the bias current, R_b is bolometer resistance, R_{th} is the thermal resistance, C_{th} is the thermal capacitance, f is frequency of signal modulation, and α is TCR defined as $\alpha=dR/(R\cdot dT)$. The transient response can be expressed as $R_{th}C_{th}$. NEP [W/√Hz] is a function of responsivity and noise expressed as $NEP=S_n/\Re$, where S_n is the total noise voltage from the bolometer including several sources: Johnson, phonon and *1/f* [4]. As described in (1), the responsivity is directly proportional to TCR, therefore the selection of high TCR materials is advantageous. VO_2 is employed in our design due to its sharp resistance change in the MIT region. The measured resistivity and calculated TCR for our fabricated 80-nm-thick VO_2 films are shown in Fig. 1. Our

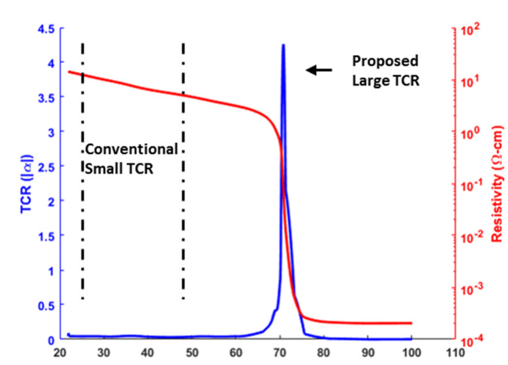

Fig. 1. Measured resistivity and calculated TCR versus temperature.

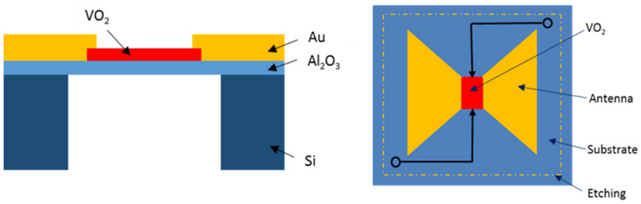

Fig. 2. Cross-section and top view of the microbolometer.

films exhibit $>9\times10^4$ resistivity change between dielectric and conducting states which is among the largest values reported in the literature. The TCR of VO_2 can be up to 4.2/K around the transition region, which is $>10^3$ times larger than metallic materials (normally 0.1%-0.3%/K). In this study, we propose to exploit nonlinear behavior of VO_2 film by biasing the sensor around the phase change cliff. A small temperature increase will translate to significant change in resistivity around the cliff, therefore the sensitivity of the mmW sensor is greatly improved.

B. Microbolometer Structure

A schematic of the proposed VO_2 microbolometer is shown in Fig. 2. It is coupled and matched to a wideband antenna (bow-tie dipole) and ROIC. The chosen alumina (Al_2O_3) buffer layer will have two functions. First, it facilitates lattice-matched growth and phase change property. Second, it serves as a membrane for suspending the VO_2 sensor and to achieve a robust structure. Thermal resistance (isolation) of the bolometer can be improved as compared to traditional on-substrate designs.

III. Results

COMSOL Multiphysics is used to investigate the performance of the sensor with width, length, and thickness of 50, 10, 0.08 µm, respectively. The geometry is predefined to the antenna impedance of around 200 Ω. The bolometer is simulated in thermal and electrical domains. Initial temperature is set to 293.15K, and electric current bias is applied to VO_2 to increase the temperature to the phase transition cliff. The concept of thermal resistance improvement is shown in Fig. 3 where the out-of-plane temperature of the biased sensor changes rapidly across the gap. Results for the transient response of Fig. 4 show response time of 376 µs with 1mA current bias. Performances of the micobolometer are calculated for responsivity and NEP based on the procedure we described previously, with I_b=1 mA, R_b=268 Ω, $R_{th}=2\times10^5$ K/W, and f= 6 KHz. The performance

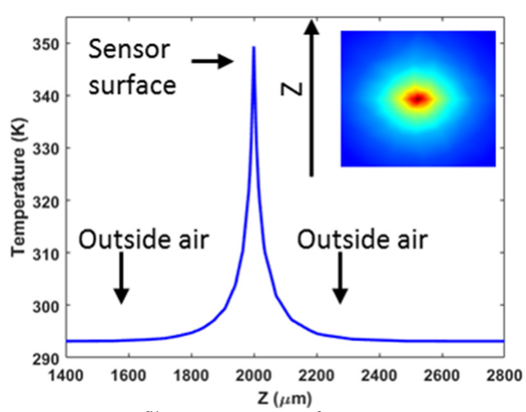

Fig. 3. Temperature profile across sensor surface.

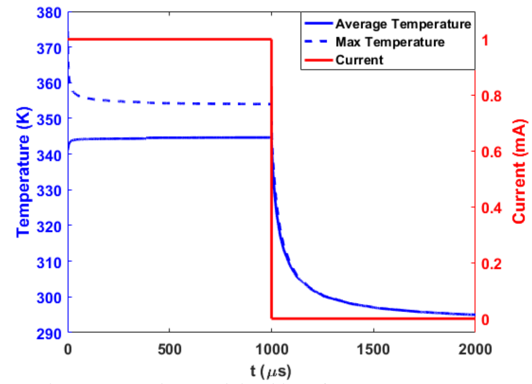

Fig. 4. Dynamic response when applying bias of 1 mA.

TABLE I. COMPARISON OF MICROBOLOMETERS

	Dimension (µm²)	*Responsivity (V/W)*	*NEP (pW/√Hz)*
This work	10×50	7.5×10^3	6.1
[4]	0.6×20	315	14
[5]	10×30	61.5	85

results are shown in Table I. Lower NEP is mainly achieved by enhancements to the responsivity.

IV. Conclusion and Future Work

A highly sensitive mmW microbolometer operating in MIT region of VO_2 is presented. The sensor is biased to the transition region of VO_2 (~68°C), where its TCR is more than 10^3 times larger than conventionally used linear materials. Due to significant enhancement to thermal resistance and responsivity (7.5×10^3 V/W) of the detector, low NEP in the order of 1 pW/√Hz is achievable. Electromagnetic simulation of the antenna coupled bolometer and fabrication process will be presented in the conference. The proposed VO_2 microbolometer with high sensitivity and fast response will be expanded into an array for a mmW imaging system.

Acknowledgment

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