Infrared Physics & Technology 71 (2015) 127–130

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Temperature coefficient of resistance and thermal conductivity of Vanadium oxide 'Big Mac' sandwich structure

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HIGHLIGHTS

- V_xO_y multilayer thin film structure was sputtered for microbolometer applications.
- Synthesized V_xO_y thin films were annealed at a temperature of 300 °C.
- Best achieved TCR was found to be −2.57%/K for 40 min annealed samples.
- Thermal conductivity of V_xO_y was measured using Photo-thermal deflection technique.
- Thermal conductivity of V_xO_y films ranged from 2 W/m K to 5.8 W/m K.

ARTICLE INFO

Article history:
Received 5 December 2014
Available online 25 March 2015

Keywords:
Vanadium oxide
Thermal conductivity
Photo-thermal deflection
Temperature coefficient of resistance
Microbolometer

ABSTRACT

In this paper, we synthesize and characterize a thin film thermometer structure for infrared microbolometers. The structure is composed of alternating multilayers of Vanadium pentoxide (V_2O_5), 25 nm, and Vanadium (V), 5 nm, thin films deposited by rf magnetron and dc magnetron sputtering respectively and annealed for 20, 30 and 40 min at 300 °C in Nitrogen (N_2) atmosphere. The best achieved temperature coefficient of resistance (TCR) was found to be −2.57%/K for 40 min annealed samples. Moreover, we apply, for the first time, the photo-thermal deflection (PTD) technique for measuring the thermal conductivity of the synthesized thin films. The thermal conductivity of the developed thin films reveals an increase in thermal conductivity from 2 W/m K to 5.8 W/m K for as grown and 40 min annealed samples respectively.

1. Introduction

Microbolometers are the most commonly used pixel element detectors in uncooled thermal imaging systems. Vanadium oxide (V_xO_y) and Amorphous Silicon (a-Si) are the most widely employed thermometer materials in microbolometer-based uncooled IR cameras and in particular, V_xO_y-based microbolometers are employed in the majority of thermal imaging cameras existing in the market [1]. The main advantages of Vanadium oxide (V_xO_y) thin films in such applications are their suitable pixel resistance for matching to CMOS readout integrated circuits [2], their simple low cost fabrication methods, and their high temperature coefficient of resistance (*TCR*). Temperature coefficient of resistance *TCR* quantifies the amount of change in resistance as a function of a given temperature change. *TCR* is given by:

$$TCR = \frac{1}{R}\frac{dR}{dT} \quad (1)$$

where R is the microbolometer resistance at temperature T. A high *TCR* yields a desirable high voltage responsivity R_v where the voltage responsivity is given by [3]:

$$R_v = \frac{I_b \cdot R \cdot TCR \cdot \eta}{G\sqrt{1+\omega^2\tau^2}} \quad (2)$$

where I_b is the microbolometer bias current, η is the optical absorptance in the microbolometer, G is the thermal conductivity of the

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http://dx.doi.org/10.1016/j.infrared.2015.03.006
1350-4495/© 2015 Published by Elsevier B.V.

microbolometer, ω is the modulation frequency and τ is the time constant of the microbolometer.

Sputter deposition is favorable amongst other techniques in synthesizing V_xO_y thin film thermometers for its low cost and simplicity. The synthesis process of the V_xO_y thin film, however, needs to be CMOS compatible by maintaining a low processing temperature, usually lower than 350 °C, in order to prevent the damage of underlying CMOS readout integrated circuits. The synthesis processes targets a mixed phase of V_xO_{yx} aiming for a high *TCR* and low resistivity. The most famous technique is reactive pulsed dc sputter deposition in mixed Argon/Oxygen (Ar/O_2) plasma [4–7]. Another notable technique that was introduced for synthesizing mixed phase V_xO_y is by utilizing a multilayer structure of $V_2O_5/V/V_2O_5$ where V_2O_5 is formed from dc sputter deposited V in mixed Ar/O_2 plasma and the whole structure is post-deposition annealed in O_2 atmosphere [8,9].

In this paper we present the fabrication and characterization of a novel V_xO_y mixed phase thin film five-layer 'Big Mac'-like sandwich structure based on alternating V_2O_5 and V layers. Additionally, despite the crucial importance of measuring the thermal conductivity values of the synthesized V_xO_y thin film in modeling the performance of a microbolometer and estimating its R_v and τ, yet very limited experimental data is available in the literature for VO_2 [10] and data is completely missing for mixed phase V_xO_y. The Photo-thermal deflection (PTD) technique is used for the first time to measure the room temperature thermal conductivity of the developed mixed phase V_xO_y thin films.

2. Thin film synthesis and TCR measurements

The structure developed in this work is a multilayer structure composed of alternating layers of V_2O_5 and V with thicknesses of 25 nm and 5 nm respectively. Fig. 1 shows a two dimensional schematic diagram of the developed multilayer structure. The 85 nm multilayer thin film structure was prepared on Quartz substrate. Vanadium pentoxide (V_2O_5) was deposited using rf sputtering of V_2O_5 sputter target with 99.5% purity. RF sputtering of the V_2O_5 layers was performed at 150 W of rf power, 3 mTorr of Ar pressure and a chamber base pressure of 1×10^{-6} Torr. Vanadium (V) layers were immediately deposited in alternation with the V_2O_5 layers using dc sputtering at 150 W of rf power, 3 mTorr of Ar pressure and a chamber base pressure of 1×10^{-6} Torr. The thin film structures were then annealed in a tube furnace at 300 °C in N_2 atmosphere. Flow rate of N_2 gas was 120 ml/min while pressure inside tube was 700 Torr. The thin films were subjected to different annealing times, 20, 30 and 40 min.

For resistance versus temperature measurements, Quartz substrates with deposited V_xO_y thin films were placed on a hot plate. Tungsten probes were made to contact aluminum pads, that were sputter deposited on the V_xO_y thin films, using Cascade Microtech's EP6 probe station micro-positioners. The probes were electrically connected to an Agilent U1251A multimeter for resistance measurements. Moreover, Agilent type-K thermocouple, connected with an Agilent U1251A multimeter, was placed in contact with the substrate adjacent to the deposited thin films and temperature readings were taken. The resistances of the prepared thin films were measured at different temperatures and the results for the

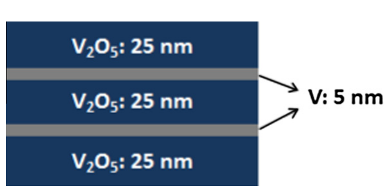

Fig. 1. Schematic diagram of the multilayer sandwich structure.

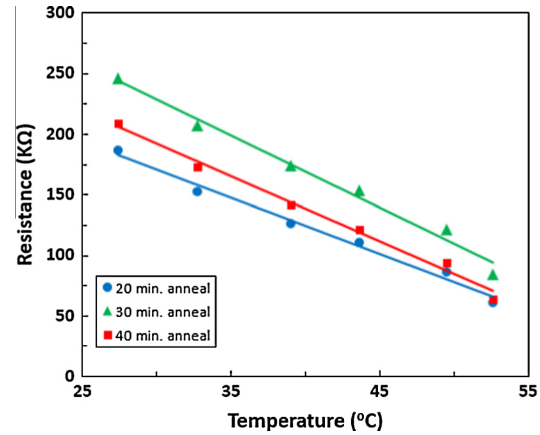

Fig. 2. Resistance vs. temperature plot for the multilayer structure at different annealing times.

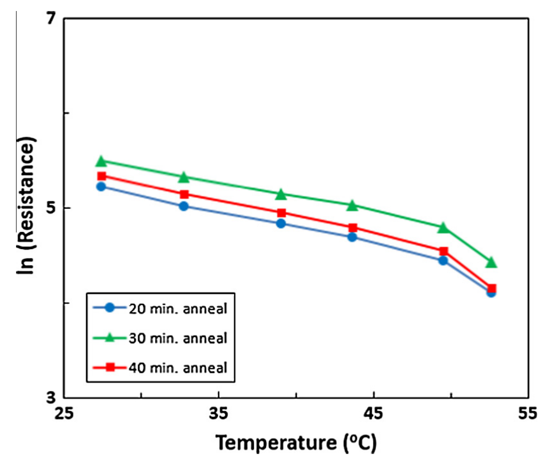

Fig. 3. Ln (Resistance) vs. temperature plot for the multilayer structure at different annealing times.

different samples are shown in Fig. 2 (measurements are only shown for temperatures up to 52.6 °C). In addition, the logarithmic dependence of resistance on temperature is plotted in Fig. 3. The resistance versus temperature measurements indicate a typical behavior for a V_xO_y semiconducting thin film where the resistance decreases as the temperature increases. The evaluated *TCR*s were found to be −2.48%/K, −2.42%/K and −2.57%/K for 20 min, 30 min and 40 min annealed structures respectively. The thin film's high TCR behavior cuts off at a temperature of 52.6 °C where V_xO_y goes to a metallic phase. The observed behavior suggests that the developed thin film structure can also be proposed for optical switching applications [11,12]. The resistivity versus temperature plot for the developed thin films is shown in Fig. 4. The absolute value of *TCR* is observed to be decreasing and resistivity is observed to be increasing as the annealing time of the films was increased from 20 min to 30 min. The *TCR* of the developed thin films is then increased and its resistivity is decreased as the annealing time was increased to 40 min. The observed behavior suggests different phases of V_xO_y to be formed at different annealing times. Extensive material analysis, being the subject of a forthcoming paper, is further needed to analyze the formed phases.

3. Thermal conductivity measurements

Thermal conductivity measurements for the synthesized V_xO_y thin films were performed using PTD technique. PTD is a