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Substrate temperature dependent bolometric properties of TiO_{2-x} films for infrared image sensor applications

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ABSTRACT

In this study, we investigated the substrate temperature (T_S) dependent bolometric properties on TiO_{2-x} films for infrared image sensor applications. The film crystallinity was changed from amorphous to rutile phase with increasing the T_S. The decrement of resistivity with temperature in TiO_{2-x} test-devices confirms the typical semiconducting property. All the test pattern devices have linear I-V characteristic performance which infers that the ohmic contact was well formed at the interface between the TiO_{2-x} and the Ti electrode. The resistivity, activation energy (E_a) and the temperature coefficient of resistance (TCR) values of the device samples were decreased up to 200 °C of T_S. The sample deposited at 200 °C had a significantly low 1/f noise parameter and a high universal bolometric parameter (β). However, at the substrate temperature of 250 °C, the E_a, TCR and the 1/f noise values were increased due to increase of the resistivity. The TCR and the 1/f noise values are proportional to the resistivity of TiO_{2-x} films. As a result, the low resistivity of TiO_{2-x} sample deposited at 200 °C is a viable bolometric material for uncooled IR image sensors.

1. Introduction

Semiconducting materials (VO_X, a-Si) are widely accepted for thermal infrared image sensor devices since they exhibit better bolometric properties compared to those of metals and superconductor materials. However, the reproducibility problem of VO_X leads to a loss of yield and increase of cost although it has high TCR and low 1/f noise values [1]. a-Si thin film has a moderate TCR but high 1/f noise, and its fabrication is known to be very difficult [2]. One of the crucial factors that determine the applicability of these oxides is electrical noise. Three types of noise components such as Johnson, Flicker (1/f) and thermal fluctuation noise are arise in a semiconductor material. Among all, the thermal fluctuation noise is sufficiently low in comparison with the other noise components [3]. Therefore, we considered only the Johnson and Flicker noise components as important contributing factors to the bolometer performance. Moreover, the 1/f noise takes special place because it is universal in any conduction media and is the dominant noise component at low frequencies [4]. As a consequence the 1/f noise in a material is of prime importance to get better bolometric properties.

Therefore, recently much research efforts have been focusing on the development of bolometric properties. TiO_{2-x} can be a potential replacement for bolometric materials and has garnered profound interest with a tremendous amount of research due to its virtuous physical and chemical properties [5–9]. Hence, we focused on TiO_{2-x} as a heat-sensitive material for better IR sensor devices. Thin film properties are directly related to the deposition parameters such as the oxygen partial pressure, substrate temperature, and sputtering power [10–12] in the deposition methods and any change in structural parameters may affect electrical characteristics of the devices. The physical, and electrical properties of TiO_{2-x} films can be influenced greatly on the amorphous or crystalline phase of the material by the variation of deposition parameters. It has been previously observed that the variation of substrate temperature has a strong effect on the final crystalline phase of the TiO_2 thin films [13]. Luca et al. [14] have investigated the characteristics of the TiO_2 thin films in terms of amorphous to crystalline phase transitions and the role of oxygen defects.

In earlier, vanadium oxide films-based uncooled microbolometers were demonstrated that the samples required a moderate to high temperature deposition and annealing processes for their high performance [15,16]. One of the possible methods to obtain the information on electrical properties in transition-metal oxides could be the analysis of temperature dependence of resistivity. Therefore, it is necessary to investigate the influence of the deposition/substrate temperature on the film properties which are influenced on the bolometric properties in order to get good device performance. In the present investigation, we aim to specify an optimum fabrication process to obtain the good bolometric

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properties of sputtered TiO_{2-x} films as a function of the substrate temperature. Also, this study directly addresses the improved sensor device properties of sputtered TiO_{2-x} films at different T_S levels in the range of 25–250 °C.

2. Experimental

TiO_{2-x} films were grown at different substrate temperatures (25 °C–250 °C) by RF reactive magnetron sputtering system on p-type Si (100)/SiO_2 wafers by using 4″ pure titanium (99.99%) target. Oxygen and argon were used as reactive and sputtering gases, respectively. The chamber was pumped down to 4×10^{-7} Torr using a turbo molecular pump. The deposition was performed at target-to-substrate distance of 140 mm, sputtering pressure of 2 mTorr and RF power of 300 W for 18 min of constant time. The partial pressure of oxygen was kept constant at 3.4% in all deposited films. Before each deposition, the target was pre-sputtered for 15 min to remove any possible surface contamination.

In order to measure the bolometric properties, the test device was fabricated using UV-lithography by the succeeding routes. At first, silicon nitride (100 nm at 150 °C) was deposited as a hard mask layer on TiO_{2-x} surface using plasma enhanced chemical vapor deposition (PECVD) method. The positive photo-resist material was spin-coated to make the mask pattern. In order to make TiO_{2-x} pattern, the silicon nitride and then TiO_{2-x} layers were etched with buffered oxide etchant and hot H_2SO_4, respectively. After TiO_{2-x} patterning, Ti (at RT, ~100 nm thickness) was deposited on TiO_{2-x} as an electrode material through DC reactive magnetron sputtering. The deposited electrode was patterned in the above process and etched using NH_4OH:H_2O_2:H_2O (1:1:5) etchant. Finally, 100-nm-thick SiO_2 (at 150 °C by PECVD) was deposited as a passivation layer to protect the test device from the environmental factors. The schematic test device is pictured in Fig. 1.

The thickness of the films was measured using a spectroscopic ellipsometer of M2000D, Woollam model. The crystalline structure of the films was characterized by X-ray diffraction (XRD) with Cu Kα radiation (Rigaku D/MAX-2500 model). Raman spectroscopic studies of the sputtered films were carried out using an ARAMIS high resolution dispersive-Raman spectrometer with an excitation of Ar^+ laser at 514.5 nm. The temperature dependence of resistivity was observed by an I–V measurement with a HP4156A precision semiconductor parameter analyser by varying the sample temperature through a thermo-electric cooler (TEC) in the range of 15 °C–60 °C. The 1/f noise parameter was measured at +3 V bias voltage in an air environment using a low-noise current preamplifier (Stanford Research System, model SR570) and a network signal (spectrum) analyser (Stanford Research System, model SR570) in the range of 1 Hz–100 Hz.

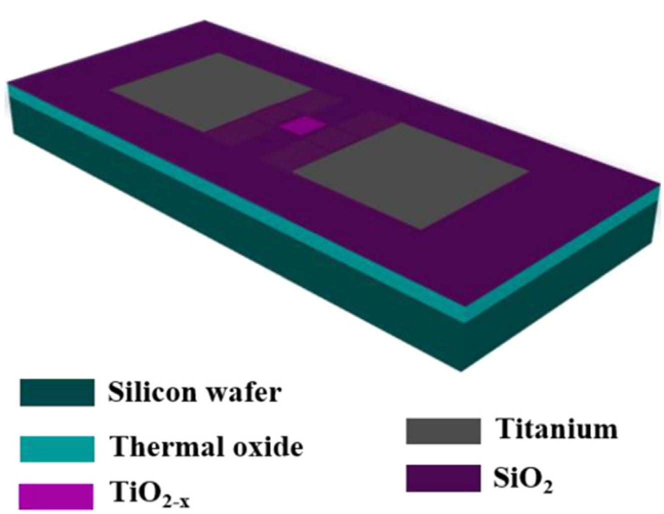

Fig. 1. Schematic view of TiO_{2-x} test device bolometer.

3. Results and discussion

3.1. Variation of thickness

The thickness of the TiO_{2-x} films was found to be decreased from 90.2 (±0.1) nm to 59.8 (±0.1) nm with increasing the substrate temperature from 25 °C to 250 °C, respectively (Table 1). The effect of T_S on the thickness is to a great extent of controversial. Since, some studies have shown that T_S has not any significant influence on thickness [17]. Whereas some others have shown that the thickness either increases or decreases as substrate temperature increases [18,19]. The decrease of thickness with substrate temperature may be the cause of re-evaporation/dissociation of oxygen in the TiO_{2-x} films. Meanwhile, at constant working pressure (2 mTorr), the gas temperature is affected by T_S and it causes to decrease of thickness [20]. Hence, in the present study the thickness was decreased with the substrate temperature.

3.2. Structural properties

The X-ray diffraction patterns of TiO_{2-x} films at different substrate temperatures are shown in Fig. 2. The XRD pattern of room temperature deposited sample cannot display any diffraction peak and suggests that the sample has an amorphous structure. Since, at the time of deposition, the substrate temperature was far below the temperature of Titania crystallization [21]. However, the film structure was changed from amorphous to crystalline (rutile) nature with increasing the substrate temperature. At higher T_S level samples can achieve the sufficient energy to generate crystalline phases since they have sufficient mobility to place them in to lower energy positions [22].

The influence of T_S on the crystallite size (L) of the films was calculated using the Debye-Scherrer's equation ($L = K\lambda/\beta\cos\theta$) [23]. Here, K denotes the Scherrer's constant (K=0.94), λ is the wavelength of the Cu Kα radiation (k=1.54 Å) and β is the full width at half maximum (FWHM) of a Gaussian fit. The crystallite size can't be found for room temperature deposited film due to the amorphous nature of the sample. The average crystallite size of 100 °C, 150 °C, 200 °C and 250 °C substrate temperate deposited films were found to be increased of 12.3 nm, 16.5 nm, 17.4 nm and 18.2 nm (with an accuracy of ±1 nm), respectively. The crystallite size of the films was increased with increasing the substrate temperature. Since, the spices arrived on to the substrate have more kinetic energy at higher substrate temperature which leads to have better crystallization. From the XRD spectra, the peak shift

Table 1
The bolometric properties of TiO_{2-x} device samples at different substrate temperatures.

Sample (T_S) (°C)	Thickness (±0.1 nm)	Resistivity (Ω cm)	E_a (eV)	TCR (−%/K)	1/f noise parameter (k)	β (×10^{13}/$Km^{3/2}$)
25	90.2	0.82	0.19	2.54	3.16×10^{-12}	9.51
100	83.3	0.27	0.18	2.36	1.60×10^{-12}	12.9
150	80.5	0.19	0.17	2.25	7.97×10^{-13}	17.8
200	73.3	0.14	0.16	2.09	3.35×10^{-13}	26.6
250	59.8	0.36	0.17	2.18	1.23×10^{-12}	16.1