TiO_2 Thin Film Transistor by Atomic Layer Deposition

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ABSTRACT

In this study, TiO_2 films were deposited using thermal Atomic Layer Deposition (ALD) system. It is observed that as-deposited ALD TiO_2 films are amorphous and not suitable as TFT channel material. In order to use the film as channel material, a post-annealing process is needed. Annealed films transform into a polycrystalline form containing mixed anatase and rutile phases. For this purpose, devices are annealed at 475°C and observed that their threshold voltage value is 6.5^V, subthreshold slope is 0.35 V/dec, I_{on}/I_{off} ratios $2.5x10^6$ and mobility value is 0.672 $cm^2/V.s$. Optical response measurements showed that devices exhibits decent performance at ultraviolet region where TiO_2 has band to band absorption mechanism.

Keywords: Atomic Layer Deposition, Thin Film Transistors, Titanium Dioxide, Transparent Electronics

1. INTRODUCTION

TiO_2 is a very interesting semiconductor due to its wide bandgap and functional optical properties such as optical transparency and photocatalytic activity. Adjustable doping concentration characteristic of TiO_2 thin films is very attractive in terms of electronic applications. Undoped, in our case: as-deposited/unannealed, TiO_2 has a very high dielectric constant (~100) and behaves like an insulator; on the other hand, doped TiO_2 films, which correspond to annealed films at a temperature higher than 300°C for this study, behave like a wide-bandgap semiconductor.[1] As a result, flexible and transparent TFT's can be built using TiO_2 films either as the dielectric layer or as the channel layer by observing the doping concentration of the film.[2] As we preferred in our experiments, ALD technique can be chosen for TiO_2 channel layer deposition owing to very important advantages of the system like accurate thickness control, good conformality and reproducibility. Electrical characteristics of TiO_2-based TFT's shown in literature are summarized in Table 1.

Table 1. TiO_2-channel TFT characteristics reported in the literature

Reference No	Phase of TiO_2 film	Threshold Voltage (V)	I_{on}/I_{off}	μ_{sat} ($cm^2/V.s$)
3	Amorphous	3.8	10^3	0.087
	Anatase	2.3	10^4	10.7
4	-	7.5	$1.45x10^2$	0.03
5	Single crystal rutile	-	10^4	10.7
6	-	-8.5	$2x10^2$	3.2
	After N_2O treatment	7.4	$4.7x10^5$	1.64
7	Anatase	-	10^5	0.3
8	Amorphous	-4.05	$2.7x10^5$	0.063

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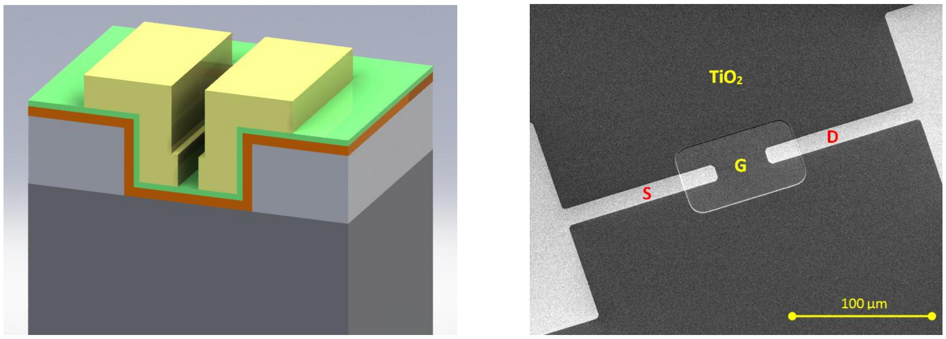
2. DEVICE FABRICATION

Devices are fabricated on highly doped (0.010-0.018 ohm-cm) p-type (111) Si wafer. After chemical cleaning of wafer, 210-nm-thick SiO_2 layer is deposited for isolating devices from each other. Active areas are patterned by photolithography and etched with BOE solution. 30-nm-thick Al_2O_3 and 18-nm-thick TiO_2 layers are deposited in a single ALD step. ALD is performed using the Cambridge Nanotech Inc., Savannah 100 system. The precursors used in the experiments are tetrakis(dimethylamido)titanium(IV) (TDMAT) and milliQ water (H_2O). TDMAT (99.999%) is purchased from Sigma Aldrich Chemical Co. The TDMAT precursor is kept at 75°C. Nitrogen is used as the carrier gas with the flow rate of 20 sccm. The deposition temperature of TiO_2 and Al_2O_3 layers are 150°C and 250°C respectively.
The processing cycle consists of a 0.1 s TDMAT pulse, 1 min for purging, 0.015 s H_2O pulse and 1 min for purging. After TiO_2 deposition, devices are annealed at 475°C for 1 h in air environment.



(a) (b)

Figure 1. (a) Schematic view and (b) SEM image of devices.

Analysis on TiO_2 thin films showed that anatase inclusions are formed in the amorphous film which then transform into crystalline phase by additional treatments like annealing. In our work, XRD and XPS measurements are performed in order to analyze the effect of annealing on mixed phases forming the film. Figure 2 shows the XRD analysis of amorphous TiO_2 films and films annealed at 475°C, all diffraction peaks can be indexed to the anatase and rutile phases of TiO_2.

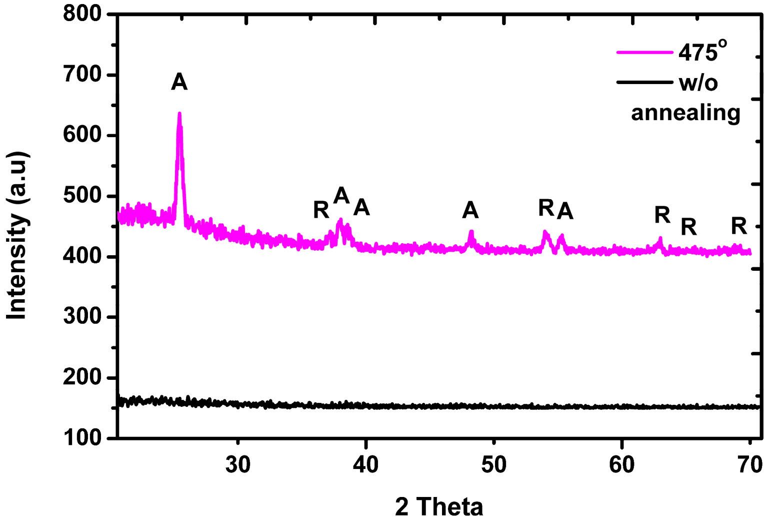
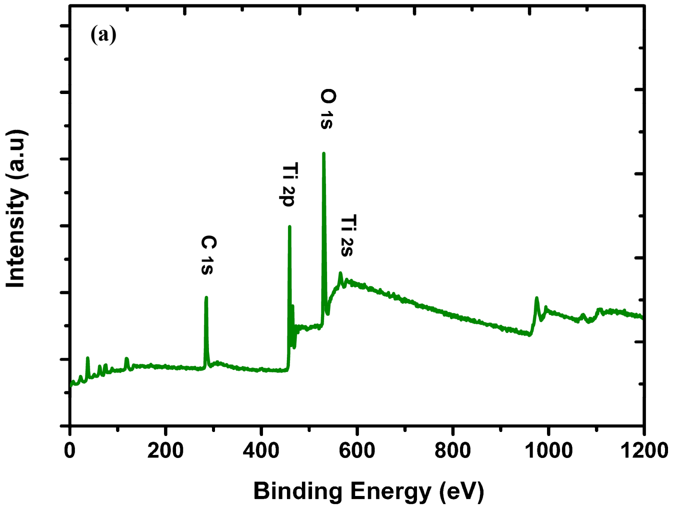


Figure 2. XRD patterns of TiO_2 films showing anatase and rutile phases.

According to Rietveld quantitative analysis, TiO_2 films annealed at 475°C contains 98.81% anatase and 1.19% rutile phases. XPS survey-scan spectra analyses were run to show the exact chemical composition of films, results are shown in Figure 3 (a). All XPS spectral peaks are fitted with Thermo Scientific Avantage 5.50 software. The C 1s spectral line is standardized to 285.0 eV and the O 1s and Ti 2p spectra are adjusted to this energy. Figure 3 (b) shows narrow scan of O 1s. According to results, we have two peaks at O1s spectra which indicate O-H and Ti-O bonds. O-H bond exists due to the absorbance of H coming from water precursor [9].



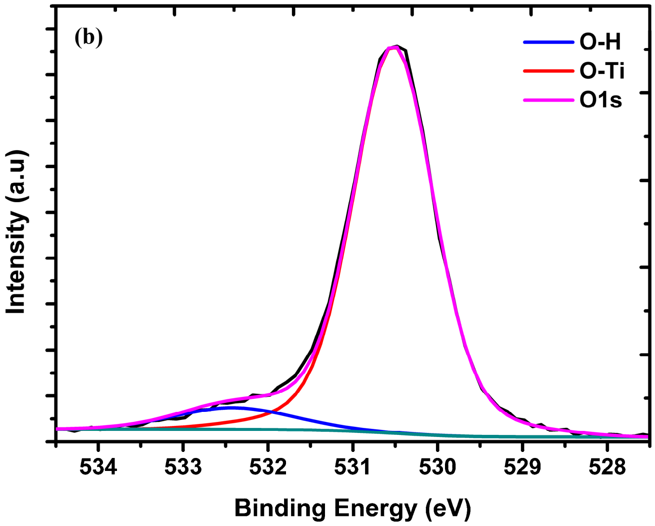
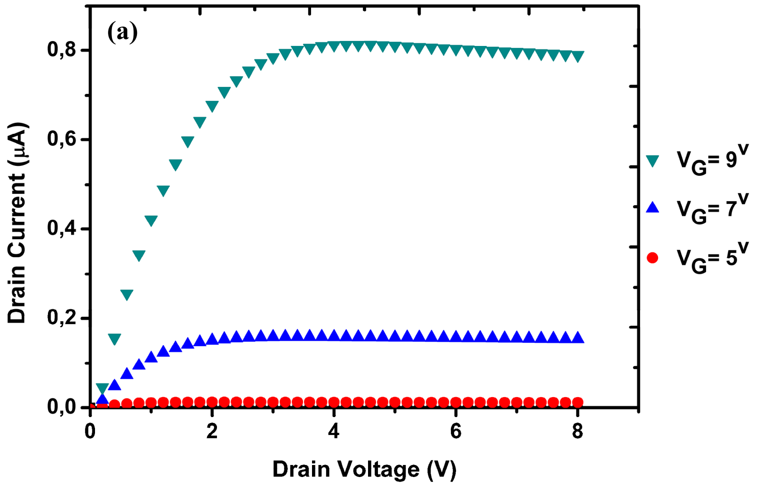


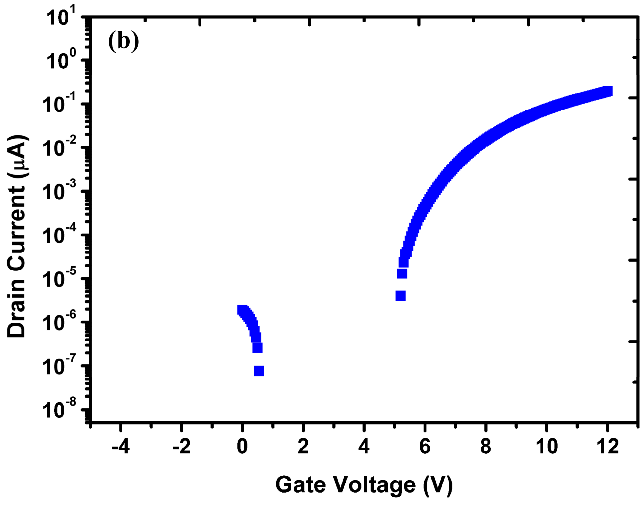
Figure 3. (a) Wide scan survey XPS spectrum of TiO_2 films, (b) narrow scan of O 1s spectra.

Stoichiometric analysis of films annealed at 475°C is obtained by considering both the atomic percentages of O1s and Ti 2p from the survey scan spectra and area ratios of O-H/Ti-O bonds from the detailed analysis of O1s spectra. Ti/O ratio is calculated as 0.5425 after eliminating O-H bonds.

3. RESULTS AND DISCUSSION

Electrical measurements of TiO_2 TFT's are performed with Keithley 4200-SCS parameter analyzer. Figure 4 (a) shows typical $I_D – V_D$ characteristics of devices annealed at 475°C, which has channel dimensions of 50 μm width and 40 μm length; Figure 4 (b) shows typical transfer characteristics of devices after annealing processes.





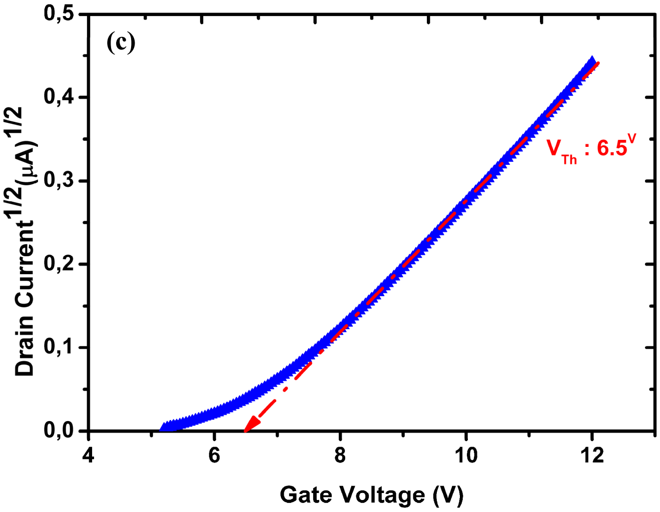


Figure 4. (a) Output characteristics and (b) transfer characteristics of devices annealed at 475°C. (c) ESR method for extraction of threshold voltage value.

Extrapolation method is implemented on measured $I_D - V_{GS}$ saturation characteristics of devices to obtain threshold voltage values. Subthreshold slopes are extracted using the formula of $\partial V_{GS} / \partial I_D$. Mobility values of devices are extracted using drain current equation at saturation region:

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{Th})^2$$

Oxide capacitance is calculated using the equation $C_{ox} = \frac{\varepsilon_o \varepsilon_r}{t_{ox}}$, where t_{ox} and ε_r denote the thickness of ALD-deposited Al_2O_3 layer (taken as 9) and its dielectric constant, respectively. Summary of electrical properties is given in Table 2.

Table 2. Electrical characteristics of devices annealed at 475°C

Annealing Temperature (°C)	Threshold Voltage (V)	I_{on}/I_{off} Ratio	Subthreshold Slope (V/dec)	Mobility (cm^2/V.s)
475	6.5	2.5×10^6	0.35	0.672

Spectral responsivities of fabricated TiO_2 with 150 µm x 100 µm device area are measured using characterization setup given in Figure 5. Xenon Arc lamp is used as a wideband light source. Its output is monochromated and mechanically chopped at 400 Hz. Chopped light is focused on fabricated device at normal incidence. Photocurrent between source and drain terminals are measured for various drain to source biases while gate to source voltage is kept constant at 0 V. TiO_2 has a wide band gap (anatase 3.2 eV and rutile 3.0 eV) . The spectral responsivity measurements of our TiO_2 TFTs, given in Figure 6, exhibits decent performance at ultraviolet region where TiO_2 has band to band absorption mechanism.

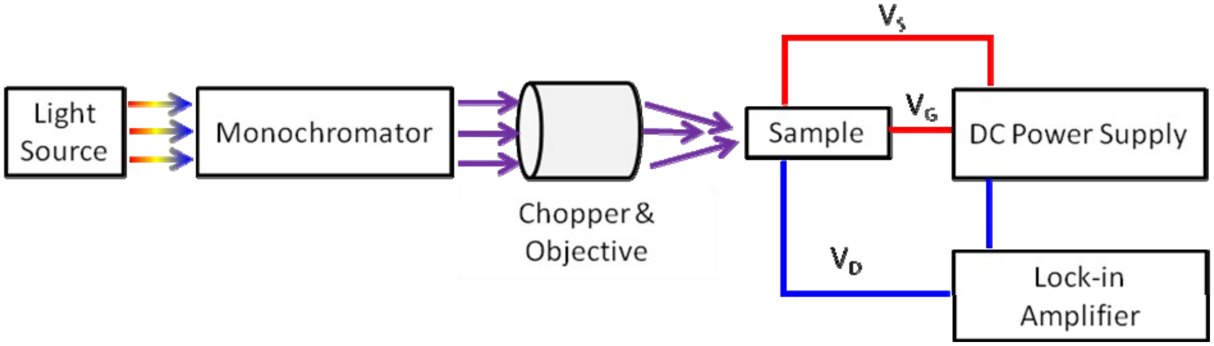


Figure 5. Spectral responsivity measurement setup.

Monochromated and mechanically chopped light is focused on fabricated device from top with normal incidence. The photocurrent between drain and source terminals is measured with lock-in amplifier.

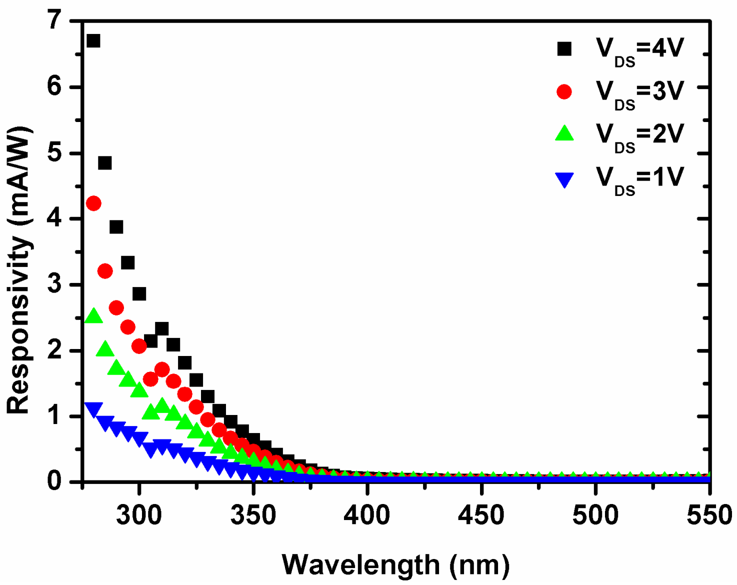


Figure 6. Spectral responsivity measurements of our TiO_2 TFTs for various V_{DS} (drain-to-source bias) while constant V_{GS} (gate to source bias) of 0 V.

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