TiO₂ Thin Film Transistor by Atomic Layer Deposition

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ABSTRACT

In this study, TiO₂ films were deposited using thermal Atomic Layer Deposition (ALD) system. It is observed that as-deposited ALD TiO₂ 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., Ion/Ioff ratios 2.5x10⁶ and mobility value is 0.672 cm²/V.s. Optical response measurements showed that devices exhibits decent performance at ultraviolet region where TiO₂ has band to band absorption mechanism.

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

1. INTRODUCTION

TiO₂ 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 TiO₂ thin films is very attractive in terms of electronic applications. Undoped, in our case: as-deposited/unannealed, TiO₂ has a very high dielectric constant (~100) and behaves like an insulator; on the other hand, doped TiO₂ 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 TiO₂ 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 TiO₂ channel layer deposition owing to very important advantages of the system like accurate thickness control, good conformality and reproducibility. Electrical characteristics of TiO₂-based TFT’s shown in literature are summarized in Table 1.

Table 1. TiO₂-channel TFT characteristics reported in the literature

<table>
<thead>
<tr>
<th>Reference No</th>
<th>Phase of TiO₂ film</th>
<th>Threshold Voltage (V)</th>
<th>Ion/Ioff</th>
<th>μsat (cm²/V.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Amorphous</td>
<td>3.8</td>
<td>10⁵</td>
<td>0.087</td>
</tr>
<tr>
<td></td>
<td>Anatase</td>
<td>2.3</td>
<td>10⁴</td>
<td>10.7</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>7.5</td>
<td>1.45x10⁴</td>
<td>0.03</td>
</tr>
<tr>
<td>5</td>
<td>Single crystal rutile</td>
<td>-</td>
<td>10⁴</td>
<td>10.7</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-8.5</td>
<td>2x10⁷</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>After N₂O treatment</td>
<td>7.4</td>
<td>4.7x10⁵</td>
<td>1.64</td>
</tr>
<tr>
<td>7</td>
<td>Anatase</td>
<td>-</td>
<td>10⁵</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>Amorphous</td>
<td>-4.05</td>
<td>2.7x10⁵</td>
<td>0.063</td>
</tr>
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</table>

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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 SiO2 layer is deposited for isolating devices from each other. Active areas are patterned by photolithography and etched with BOE solution. 30-nm-thick Al2O3 and 18-nm-thick TiO2 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 (H2O). 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 TiO2 and Al2O3 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 H2O pulse and 1 min for purging. After TiO2 deposition, devices are annealed at 475°C for 1 h in air environment.

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

Analysis on TiO2 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 TiO2 films and films annealed at 475°C, all diffraction peaks can be indexed to the anatase and rutile phases of TiO2.

![Figure 2. XRD patterns of TiO2 films showing anatase and rutile phases.](image)
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.](image)

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 TiO₂ 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.
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 $C_{ox} = \varepsilon_o \varepsilon_r t_{ox}$, where $t_{ox}$ and $\varepsilon_r$ denote the thickness of ALD-deposited Al₂O₃ 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

<table>
<thead>
<tr>
<th>Annealing Temperature (°C)</th>
<th>Threshold Voltage (V)</th>
<th>Ion/Ioff Ratio</th>
<th>Subthreshold Slope (V/dec)</th>
<th>Mobility (cm²/V.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>475</td>
<td>6.5</td>
<td>2.5x10⁶</td>
<td>0.35</td>
<td>0.672</td>
</tr>
</tbody>
</table>

Spectral responsivities of fabricated TiO₂ 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. TiO₂ has a wide band gap (anatase 3.2 eV and rutile 3.0 eV). The spectral responsivity measurements of our TiO₂ TFTs, given in Figure 6, exhibits decent performance at ultraviolet region where TiO₂ has band to band absorption mechanism.
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 5. Spectral responsivity measurement setup.](image)

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 TiO2 TFTs for various VDS (drain-to-source bias) while constant VGS (gate to source bias) of 0 V.](image)

![Graph showing spectral responsivity measurements for various VDS values.](image)

Figure 6. Spectral responsivity measurements of our TiO2 TFTs for various VDS (drain-to-source bias) while constant VGS (gate to source bias) of 0 V.

**ACKNOWLEDGMENT**

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**REFERENCES**


