Plasma-enhanced atomic layer deposition of tungsten oxide thin films using \((t\text{BuN})_2(\text{Me}_2\text{N})_2\text{W}\) and \(\text{O}_2\) plasma

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Plasma-enhanced atomic layer deposition of tungsten oxide thin films using $(\text{tBuN})_2(\text{Me}_2\text{N})_2\text{W}$ and $\text{O}_2$ plasma

Shashank Balasubramanyam, Akhil Sharma, Vincent Vandalon, Harm C. M. Knoops, Wilhelmus M. M. (Erwin) Kessels, and Ageeth A. Bol

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Plasma-enhanced atomic layer deposition of tungsten oxide thin films using (\textsuperscript{1}BuN)\textsubscript{2}(Me\textsubscript{2}N)\textsubscript{2}W and O\textsubscript{2} plasma

Shashank Balasubramanyam,\textsuperscript{a) Akhil Sharma, and Vincent Vandalon
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Harm C. M. Knoops
Oxford Instruments Plasma Technology, North End, Bristol BS49 4AP, United Kingdom

Wilhelmus M. M. (Erwin) Kessels and Ageeth A. Bol
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

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The growth of tungsten oxide (WO\textsubscript{3}) thin films by atomic layer deposition (ALD) offers numerous merits including atomic-scale thickness control at low deposition temperatures. In this work, the authors have developed and characterized a new plasma-enhanced ALD process for WO\textsubscript{3} thin films using the metalorganic precursor bis(tertbutylimido)-bis(dimethylamido)-tungsten and O\textsubscript{2} plasma as coreactant over a wide table temperature range of 100–400 °C. The influence of deposition temperature on the growth behavior and film properties is investigated comprehensively. The WO\textsubscript{3} ALD process developed in this work yields relatively high growth per cycle values which vary from ~0.7 Å at 100 °C to ~0.45 Å at 400 °C, as-determined by in situ spectroscopic ellipsometry. Rutherford backscattering spectrometry (RBS) measurements revealed a mass density of 5.9 g/cm\textsuperscript{3} and near stoichiometric film composition (O/W = 2.9). Both RBS and x-ray photoelectron spectroscopy measurements confirmed no detectable C as well as N impurity incorporation. Grazing incidence x-ray diffraction measurements indicated that the films deposited at 400 °C were polycrystalline in nature. © 2017 American Vacuum Society. [http://dx.doi.org/10.1116/1.4986202]

I. INTRODUCTION

Transition metal oxides exhibit interesting electrical, optical, and mechanical properties which classify them as multifunctional for several applications. Among them, tungsten oxide (WO\textsubscript{3}) has been of particular interest for electrochromic,\textsuperscript{1–4} gas-sensing,\textsuperscript{5,6} and catalytic\textsuperscript{7,8} applications. In particular, WO\textsubscript{3} is extensively studied for electrochromic applications such as smart windows for automobiles and buildings.\textsuperscript{9,10} Electrochromic WO\textsubscript{3} based auto-dimming rear view mirrors for automobiles are commercially available.\textsuperscript{11} Recently, WO\textsubscript{3} thin films (i.e., having 5–10 nm thickness) have attracted interest as a highly transparent hole-selective contact for c-Si solar cells.\textsuperscript{12–34} Furthermore, WO\textsubscript{3} is being utilized in the synthesis of two-dimensional transition metal dichalcogenide (2D-TMD) such as tungsten disulfide (WS\textsubscript{2}) through sulfurization of the oxide.\textsuperscript{15,16} The application of WO\textsubscript{3} thin films for solar cells and 2D-TMD synthesis are particularly gaining a lot of interest lately.

WO\textsubscript{3} has been previously deposited using a wide range of deposition techniques including evaporation,\textsuperscript{17,18} sputtering,\textsuperscript{19,20} sol-gel deposition,\textsuperscript{21,22} chemical vapor deposition (CVD),\textsuperscript{23,24} and atomic layer deposition (ALD).\textsuperscript{8,16,25–35} Growth of thin films via ALD has gained increasing popularity over the last few decades because of its ability to deposit ultrathin uniform films with precise thickness control and its low temperature growth possibility. These merits of ALD are particularly valuable for the application of WO\textsubscript{3} thin films for solar cells and 2D-TMD synthesis. However, there are only a few reports on ALD of WO\textsubscript{3} in the literature. Tägtström et al. have reported a WO\textsubscript{3} ALD process using in situ generated oxyfluorides as precursor and H\textsubscript{2}O as coreactant.\textsuperscript{25} However, controlling the in situ generated oxyfluoride species was difficult. Dezelah et al. utilized a metalorganic precursor W\textsubscript{2}(NMe\textsubscript{2})\textsubscript{6} and H\textsubscript{2}O in an ALD process which resulted in W\textsubscript{2}O\textsubscript{3} films with trivalent tungsten, instead of WO\textsubscript{3}.\textsuperscript{26} Malm et al.\textsuperscript{27} and Nandi et al.\textsuperscript{28} investigated the ALD growth of WO\textsubscript{3} using the hexacarbonyl precursor W(CO)\textsubscript{6} and O\textsubscript{3}. This process was characterized by relatively low growth per cycle (GPC) values of ~0.2 Å for temperatures below 250 °C, and for temperatures above 250 °C, the precursor decomposes thermally which leads to carbon impurity incorporation in the films.\textsuperscript{27} Furthermore, an initial incubation delay of around 200 ALD cycles was reported.\textsuperscript{27} Mamun et al.\textsuperscript{30} and Zhang et al.\textsuperscript{31} have also reported a GPC of 0.2 Å using the same hexacarbonyl precursor W(CO)\textsubscript{6} and H\textsubscript{2}O. Recently, Song et al. utilized a plasma-based ALD process for WO\textsubscript{3} using WH\textsubscript{2}(iPrCp)\textsubscript{2} and O\textsubscript{2} plasma, in their attempt to synthesize 2D-WS\textsubscript{2} nanosheets by sulfurizing WO\textsubscript{3} layers.\textsuperscript{16} Their WO\textsubscript{3} ALD process yielded a high GPC of ~0.9 Å at 300 °C with the formation of substoichiometric tungsten oxide (O/W = 2.4). Bergum et al. investigated the application of WOCI\textsubscript{4} precursor and H\textsubscript{2}O to deposit WO\textsubscript{3} by ALD. They observed that WO\textsubscript{3} grew on the surfaces of select substrates but the film growth was limited as WO\textsubscript{3} did not appear to grow on itself.\textsuperscript{29} The metalorganic precursor bis(tertbutylimido)-bis(dimethylamido)tungsten, (\textsuperscript{1}BuN)\textsubscript{2}(Me\textsubscript{2}N)\textsubscript{2}W, used in this work has been previously used to

\textsuperscript{a)Electronic mail: s.balasubramanyam@tue.nl
deposit WO₃ by ALD using H₂O as coreactant. This process offers a high GPC of ~1 Å at 350 °C, but relatively small GPC values (<0.2 Å) were observed for temperatures below 300 °C. Further, Bergum et al. have reported a CVD-type of growth for substrate temperatures above 350 °C for this process. From these literature reports, it is evident that there is interest to develop a WO₃ ALD process with all of the following attributes: (1) high GPC (>0.2 Å), (2) low impurity incorporation, (3) wide temperature window, and (4) stoichiometric film composition (WO₃).

In this study, we report a plasma-enhanced ALD process for tungsten oxide thin films using (tBuN)₂(Me₂N)₂W and O₂ plasma over a wide table temperature range of 100–400 °C. The application of plasma can provide the advantage of acceptable growth rates and improved material properties such as high film density as well as low impurity content at lower deposition temperatures. Also, previously, it has been demonstrated that usage of the metalorganic precursor (tBuN)₂(Me₂N)₂W along with N₂, H₂/N₂, and NH₃ plasmas for a WN₃ ALD process have resulted in very low levels of carbon impurities (<2 at. %). Here, we provide a detailed study on the tungsten oxide ALD process and the material properties of the as-deposited material. The influence of deposition temperature on GPC, chemical composition, stoichiometry, and optical properties of the resulting WO₃ films is investigated.

II. EXPERIMENT

In this section, the process conditions for film deposition are discussed and followed by a description of the techniques used to characterize the deposited film and related equipment used.

A. Film deposition

WO₃ thin films were deposited in a FlexAL ALD reactor from Oxford Instruments, equipped with an inductively coupled plasma (ICP) source. The reaction chamber is equipped with a turbomolecular pump which enables to reach a base pressure of ~10⁻⁶ Torr. A detailed description of the ALD reactor can be found in an earlier work of the group. Prior to deposition, the reactor walls were preconditioned with 300 ALD cycles of Al₂O₃ and 300 ALD cycles of WO₃ itself. All depositions were performed on c-Si substrates (2 × 2 cm) with a thin native oxide layer (~1.5 nm) unless mentioned otherwise. The starting substrates were subjected to an O₂ plasma pretreatment (10 s) in the ALD reactor in order to remove any surface contamination using the same plasma conditions as during deposition.

Table I summarizes the utilized processing conditions. Depositions were performed at different temperatures by varying the temperature of the table from 100 to 400 °C. The actual substrate temperatures [as-determined by in situ spectroscopic ellipsometry (SE) and thermocouple measurements] were lower than the deposition temperatures (commonly referred to as table temperature) due to poor thermal contact in vacuum. Table S1 in the supplementary material compares the actual substrate temperature and the deposition temperature (table temperature). Throughout this work, the deposition temperatures are used for discussion unless mentioned otherwise. The reaction chamber wall temperature was set to 120 °C for all deposition temperatures except for depositions at 100 °C for which the wall temperature was set to 100 °C as well. The liquid precursor (tBuN)₂(Me₂N)₂W (99% purity, Sigma Aldrich) was stored in a bubbler maintained at 50 °C and was bubbled into the reaction chamber using Ar (100 sccm) as a carrier gas to enhance precursor delivery. The precursor delivery line to the reaction chamber was heated to 70 °C to prevent any possible precursor condensation.

A standard ALD recipe (Table I) was utilized to perform depositions in this work unless mentioned otherwise. The saturated precursor dosing was fixed at 3 s, and a chamber pressure of 30 mTorr was maintained during the precursor dosing step. A preplasma time of 2 s was used to stabilize the O₂ gas flow into the ICP source. The saturated coreactant O₂ plasma exposure was fixed at 3 s. The plasma power was fixed at 250 W, and a chamber pressure of 15 mTorr was maintained during the plasma exposure step. After the respective ALD half cycle, Ar gas (100 sccm) was used to purge the reaction chamber for 5 s, resulting in a chamber pressure of 30 mTorr.

B. Film analysis

In situ SE was used to monitor the growth of ALD WO₃ films using a rotating compensator ellipsometer (RCE) of type M2000U from J.A. Woollam, Inc. Ellipsometric spectra were recorded after every ten ALD cycles in the high accuracy mode over a wavelength range of 245–1000 nm. An optical stack model was used to translate the raw ellipsometric spectra into film thickness and optical parameters (n, k) by utilizing the COMPLETEEASE software. The optical stack model (from bottom to top) consisted of (1) Si substrate modeled by Si Temp JAW (Temp Library) material model, (2) ~1.5 nm native oxide modeled by NTVE_JAW material model, and (3) a WO₃ layer whose dielectric functions were parameterized by using the Tauc-Lorentz oscillator. The thickness and optical constants of the WO₃ layer were obtained using the following fitting methodology: In the recorded SE spectral range (245–1000 nm), tungsten oxide films are transparent for wavelengths from 400 to 1000 nm and thus, a Cauchy dispersion equation was used to extract
the thicknesses of the respective films in this range. Using these thickness values, the optical constants were then determined by using the B-spline material model over the entire recorded SE spectra (245–1000 nm). For this fitting, a bandgap of \( \sim 3.1 \) eV (Refs. 38 and 39) was assumed, and an initial value of 2.1 was chosen for refractive index which was obtained from the Cauchy dispersion model at the largest wavelength (1000 nm). Subsequently, the optical constants were parameterized using the Tauc-Lorentz oscillator.

To investigate the chemical composition of the as-deposited films, x-ray photoelectron spectroscopy (XPS) was performed using a Thermo Scientific KA1066 spectrometer with monochromatic Al K\( \alpha \) x-rays having an energy of 1486.6 eV. Also, Rutherford backscattering spectrometry (RBS) and elastic recoil detection (ERD) measurements were done to determine the composition, stoichiometry, and mass density. The RBS and ERD measurements were done by Detect 99 B.V Eindhoven, The Netherlands, using a 1.9 MeV He\(^+\) beam. The respective areal densities of the constituent elements were determined by simulations. To investigate the crystallinity and crystal structure, grazing incidence x-ray diffraction (GI-XRD) measurements were performed using a PANalytical X'Pert Pro MRD system which utilized a Cu K\( \alpha \) x-ray source (\( \lambda = 1.54 \) Å). The surface roughness was investigated using a NT-MDT Solver P47 atomic force microscope (AFM).

### III. RESULTS AND DISCUSSION

#### A. Film growth and uniformity

Figure 1 shows the WO\(_3\) film thickness as a function of number of ALD cycles for the investigated deposition temperatures as-determined by \textit{in situ} SE. For all temperatures, 500 ALD cycles were performed on the starting substrates. As seen from Fig. 1, the thickness incremented linearly with number of ALD cycles for all temperatures without any nucleation delay. This thickness increment decreased with increasing temperature in the investigated temperature range (100–400 °C).

Figures 2(a) and 2(b) show the saturation curves for the precursor dosing and plasma exposure steps, respectively, for various temperatures (100, 300, and 400 °C). For the precursor saturation curves [Fig. 2(a)], the O\(_2\) plasma exposure time was fixed at 4 s while varying the precursor dosing and for the O\(_2\) plasma saturation curves [Fig. 2(b)], the precursor dosing time was fixed at 4 s while varying the O\(_2\) plasma exposure. ALD saturating behavior was observed over the entire temperature range for both precursor and plasma half-cycles. Also, a decrease in GPC with increasing temperature was observed for both the half-reaction steps. In Fig. 2(a), the GPC was already in the region of saturation for a corresponding precursor dosing time of 3 s independent of temperature. For the O\(_2\) plasma saturation in Fig. 2(b), the GPC also exhibited a saturating behavior starting from 3 s for all investigated temperatures. A small nonideal component might be present at 100 °C for longer (\( \geq 5 \) s) precursor doses [Fig. 2(a)] and O\(_2\) plasma exposure times [Fig. 2(b)]. Note: The saturation curves were repeated three times to calculate the average GPC value, the standard deviation, and thereby the respective error bars.
Figure 3 compares the GPC in terms of (1) thickness: as-determined by in situ SE (GPC\textsubscript{SE}—left axis) and (2) number of W atoms/nm\textsuperscript{2}: as-determined by RBS (GPC\textsubscript{RBS}—right axis), for the investigated deposition temperatures. The GPC\textsubscript{SE} (squares) was calculated by taking the average of the respective slopes for the last 100 out of 500 ALD cycles in Fig. 1. As seen in Fig. 3, GPC decreased significantly from \(0.7\ \text{Å} \) at 100 \(^\circ\text{C}\) to \(0.45\ \text{Å} \) at 300 \(^\circ\text{C}\) and then stabilized at \(0.45\ \text{Å} \) for higher temperatures. Increasing the purge time to 10 s from the standard purge time of 5 s had no effect on the GPC. This was verified at 200 \(^\circ\text{C}\).

Samples with thickness of \(\sim 20\ \text{nm}\) were utilized for RBS measurements. GPC\textsubscript{RBS} (triangles) was calculated by dividing the total number of deposited W atoms/nm\textsuperscript{2} by the total number of ALD cycles. As seen from Fig. 3, GPC\textsubscript{RBS} decreased from \(1 \ \text{W at/nm}^2\) at 100 \(^\circ\text{C}\) to \(0.6 \ \text{W at/nm}^2\) at 300 \(^\circ\text{C}\) and then stabilized at \(0.6 \ \text{W at/nm}^2\) for higher temperatures, which is analogous to the trend exhibited by GPC\textsubscript{SE}. Similar results have been reported for O\textsubscript{2} plasma-enhanced ALD processes for Al\textsubscript{2}O\textsubscript{3} (Refs. 40–42) as well as SiO\textsubscript{2} (Refs. 43 and 44) (utilizing metalorganic precursors) where, the decrease in GPC with temperature have been attributed to a reduction of –OH surface reactive groups due to thermally activated dehydroxylation reactions. These processes reported in literature are similar to our WO\textsubscript{3} ALD process and the GPC decrement with temperature from 100 to 300 \(^\circ\text{C}\) in our case can also be due to surface dehydroxylation. The fact that the GPC does not decrease further and stabilizes at temperatures above 300 \(^\circ\text{C}\) suggests that the observed GPC values can result from a combined effect of reduced –OH surface reactive group density\textsuperscript{44} and a transition toward polycrystalline growth which is shown later in the GI-XRD diffractogram (Fig. 7).

For low deposition temperatures (\(\leq 200^\circ\text{C}\)), the observed GPC values are higher than the GPC values reported in literature. For instance, Malm \textit{et al.} and Nandi \textit{et al.} have reported a GPC of \(\sim 0.2 \ \text{Å}\) at around 200 \(^\circ\text{C}\) using the hexacarbonyl W(CO)\textsubscript{6} precursor, which is lower than the observed GPC value of \(0.55 \ \text{Å}\) in our case.\textsuperscript{27,28} The observed GPC values are also higher compared to the process developed by Liu \textit{et al.} who have reported GPC values of \(<0.2 \ \text{Å}\) using the same precursor ((BuN)\textsubscript{2}(Me\textsubscript{2}N)\textsubscript{2}W and H\textsubscript{2}O for temperatures below 300 \(^\circ\text{C})\textsuperscript{8} The utilization of O\textsubscript{2} plasma as coreactant could be the primary reason for the reasonably higher GPC in our process.

Figure 4 shows the WO\textsubscript{3} thickness uniformity on an 8 in. (200 mm) Si wafer evaluated by mapping the thickness over the whole wafer area, as-determined by SE at room temperature. For this experiment, 350 WO\textsubscript{3} ALD cycles were performed on the 8 in. Si wafer at 200 \(^\circ\text{C}\) with a corresponding GPC of \(<0.55 \ \text{Å}\). The thickness nonuniformity determined by dividing the standard deviation (\(\sigma\)) by the average mean WO\textsubscript{3} thickness, was less than 2.5%. This indicates very good thickness uniformity and the developed WO\textsubscript{3} plasma-enhanced ALD process can potentially be a viable technique for the growth of WO\textsubscript{3} films on large area substrates.

**B. Film characterization**

The WO\textsubscript{3} films of \(\sim 20\ \text{nm}\) in thickness which were deposited at various temperatures (100–400 \(^\circ\text{C}\)) were used to study the film properties including chemical composition, optical properties, and crystallinity. Table II lists the O/W ratio and H content in the as-deposited WO\textsubscript{3} films, deduced from RBS and ERD measurements, respectively, for various deposition temperatures. Typically, tungsten oxide thin films tend to grow substoichiometrically, and the level of oxygen deficiency depends on the type of preparation as well as process conditions.\textsuperscript{35} In our case, the O/W ratio was found to be constant at 2.9 for all investigated temperatures. With respect to previous WO\textsubscript{3} ALD reports, the O/W ratio of 2.9 is comparable to values (i.e., \(< 3\)) reported by Marim \textit{et al.} and is relatively higher than the value (i.e., 2.4) reported by Song \textit{et al.}\textsuperscript{16} The effect of the ambient on the film stoichiometry cannot be ruled out as the samples were stored in air...
prior to RBS/ERD measurements. The H content in as-deposited films decreased from ~11 at. % at 100 °C to ~2.5 at. % at 300 °C and then increased to ~6 at. % at 400 °C. This H content in the films can originate from the ligands of the precursor (a single precursor molecule has 30 H atoms) and/or from the residual water in the ALD reactor and/or from exposure to the ambient.

The mass density of the WO₃ films were deduced from RBS/ERD measurements in conjunction with the WO₃ layer thickness determined from in situ SE measurements. The mass density was found to be ~5.9 g/cm³ throughout the deposition range (100–400 °C), which is lower than the bulk density of WO₃ (7.16 g/cm³). The C and N impurity concentration in the bulk of the films was lower than the RBS detection limit of 3 at. % at 300 °C and 2 at. %, respectively, suggesting a relatively high purity of the as-deposited films.

Figure 5(a) shows the W4f core level spectra of as-deposited WO₃ films (at 100 and 400 °C) acquired by XPS measurements. The measured spectrum was deconvoluted into a doublet and a loss feature. The doublet comprised of a W 4f7/2 peak at 36.1 eV and a W 4f5/2 peak at 38.28 eV, with the peaks having an intensity ratio of 0.75 as well as a difference of ~2.17 eV in their binding energies, which corresponds to the W⁶⁺ oxidation state. The O1s XPS spectra [Fig. 5(b)] comprised of 2 peaks: one at ~531.1 eV, which can be assigned to O bound to W atoms, and a smaller peak at ~532.4 eV, which might originate from O–H bonds or residual water adsorbed on the sample surface.

C as well as N were present on the surface, and their concentration was reduced to negligible amounts upon depth profiling, which involves sputtering of the sample with Ar⁺ ions. Depth profile measurements for W as well as O spectra resulted in reduction of W⁶⁺ to lower oxidation states due to preferential sputtering of O atoms. Therefore, the spectra in Fig. 5 were acquired prior to sputtering to assess the chemical state correctly.

Figure 6 compares the (a) dispersion of the refractive index n and (b) extinction coefficient k, of the WO₃ films for various deposition temperatures (100–400 °C). The respective n and k values were determined through SE measurements using the optical model described in Sec. II. As seen in Fig. 6(a), the refractive index varied between 2.05 and 2.95 over the spectral range of 1.2–5 eV. For illustration, the refractive indices at a photon energy of 1.96 eV are listed in Table II for various deposition temperatures. As seen from Table II, the refractive index increased from ~2.1 at 100 °C to ~2.28 for ≥300 °C. These values are in good agreement with refractive index values reported for WO₃ in literature.

The extinction coefficient [Fig. 6(b)] was zero up to ~3.0 eV and then increased toward the absorption edge. This increase in absorption can be attributed to the electronic transitions between the valence and conduction band, related to the bandgap. The absorption can be mathematically expressed by the Tauc relation:

\[ \alpha \propto (h\nu-E_g)^n, \]

where \( \alpha \) is the absorption coefficient, \( h\nu \) is the incident energy of photons, \( E_g \) is the optical bandgap, and the exponent \( n \) which is related to the type of band-gap transition. Typically, \( n = 1/2, 3/2, 2, \) and 3 for transitions corresponding to direct allowed, direct forbidden, indirect allowed, and indirect forbidden, respectively. Assuming an indirect transition, the band gap for WO₃ can be evaluated by extrapolating the
linear part of the Tauc plot \[\left(\frac{\alpha h}{C^2}\right)^{1/2} vs \frac{h}{C^2}\] as shown in Fig. 6(b) inset. The band gap determined using this procedure are listed in Table III for various deposition temperatures. (Note: The absorption coefficient “\(\alpha\)” was determined from SE measurements.) The observed bandgap values (3.12–3.23 eV) are in agreement with literature values for WO\(_3\) films.\(^{45,47,49}\) With respect to deposition temperature, the bandgap decreased marginally from 3.23 eV at 100°C to 3.12 eV for 350°C. Figure 7 shows the GI-XRD spectra of the as-deposited films at 100, 300, 350, and 400°C. The GI-XRD diffractogram of the films deposited at 100 and 300°C was featureless. The AFM images [Fig. S1(a)] also exhibit a featureless and relatively smooth surface at these temperatures. This suggested that the respective films were amorphous. Even though no XRD peaks were observed for the films deposited at 350°C, small crystallite like features were observed in the AFM image [Fig. S1(b)]. This suggested the growth of a partially crystalline film. The presence of multiple peaks at 400°C suggested the growth of a polycrystalline film and the respective peaks could be indexed according to monoclinic WO\(_3\).\(^{5,51}\) The AFM image [Fig. S1(c)] showcased a higher density of the crystallite like features at 400°C in comparison with films deposited at 350°C. This transition from amorphous growth at temperatures below 300°C to polycrystalline film growth at temperatures above 300°C could also explain the GPC stabilization at temperatures above 300°C (Fig. 3).

### Table III. SE determined refractive index \(n\) and band gap of the WO\(_3\) films deposited at various temperatures. The refractive index is reported at a corresponding photon energy of 1.96 eV.

<table>
<thead>
<tr>
<th>Deposition temperature (°C)</th>
<th>Refractive index (n)</th>
<th>Band gap (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.10 ± 0.03</td>
<td>3.23 ± 0.04</td>
</tr>
<tr>
<td>200</td>
<td>2.22</td>
<td>3.17</td>
</tr>
<tr>
<td>300</td>
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<td>3.13</td>
</tr>
<tr>
<td>400</td>
<td>2.28</td>
<td>3.12</td>
</tr>
</tbody>
</table>

**IV. SUMMARY AND CONCLUSIONS**

A new ALD process for WO\(_3\) has been developed using (\(\text{BuN})_2(\text{Me}_2\text{N})\text{W}\) and O\(_2\) plasma over a wide table temperature range of 100–400°C. The influence of deposition temperature on the film growth as well as film properties has been studied comprehensively. The application of oxygen plasma, judicious optimization of process conditions, and the right choice of precursor enabled us to develop a new WO\(_3\) ALD process characterized by (1) a relatively high GPC with very good uniformity, (2) low impurity incorporation, (3) wide temperature window, and (4) near stoichiometric film composition. Due to the relatively high purity of the films and the capability to deposit at low temperatures, the presented process is likely to be suitable for many applications including electrochromic displays, solar cells, and synthesis of 2D-WS\(_2\).

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