

Plasma-enhanced atomic layer deposition of tungsten oxide thin films using (tBuN)₂(Me₂N)₂W and O₂ plasma

Citation for published version (APA):

Balasubramanyam, S., Sharma, A., Vandalon, V., Knoops, H. C. M., Kessels, W. M. M., & Bol, A. A. (2018). Plasma-enhanced atomic layer deposition of tungsten oxide thin films using (tBuN)₂(Me₂N)₂W and O₂ plasma. *Journal of Vacuum Science and Technology A*, 36(1), Article 01B103. <https://doi.org/10.1116/1.4986202>

DOI:

[10.1116/1.4986202](https://doi.org/10.1116/1.4986202)

Document status and date:

Published: 13/01/2018

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Plasma-enhanced atomic layer deposition of tungsten oxide thin films using $(^t\text{BuN})_2(\text{Me}_2\text{N})_2\text{W}$ and O_2 plasma

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

Citation: *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* **36**, 01B103 (2018); doi: 10.1116/1.4986202

View online: <http://dx.doi.org/10.1116/1.4986202>

View Table of Contents: <http://avs.scitation.org/toc/jva/36/1>

Published by the [American Vacuum Society](#)



Instruments for Advanced Science

Contact Hiden Analytical for further details:

W www.HidenAnalytical.com

E info@hiden.co.uk

CLICK TO VIEW our product catalogue



Gas Analysis

- › dynamic measurement of reaction gas streams
- › catalysis and thermal analysis
- › molecular beam studies
- › dissolved species probes
- › fermentation, environmental and ecological studies



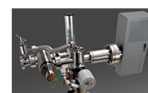
Surface Science

- › UHV TPD
- › SIMS
- › end point detection in ion beam etch
- › elemental imaging - surface mapping



Plasma Diagnostics

- › plasma source characterization
- › etch and deposition process reaction
- › kinetic studies
- › analysis of neutral and radical species



Vacuum Analysis

- › partial pressure measurement and control of process gases
- › reactive sputter process control
- › vacuum diagnostics
- › vacuum coating process monitoring

Plasma-enhanced atomic layer deposition of tungsten oxide thin films using $({}^t\text{BuN})_2(\text{Me}_2\text{N})_2\text{W}$ and O_2 plasma

Shashank Balasubramanyam,^{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

(Received 2 June 2017; accepted 24 August 2017; published 13 September 2017)

The growth of tungsten oxide (WO_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_3 thin films using the metalorganic precursor bis(tertbutylimido)-bis(dimethylamido)-tungsten and O_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_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/cm³ 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 classifies them as multifunctional for several applications. Among them, tungsten oxide (WO_3) has been of particular interest for electrochromic,^{1–4} gas-sensing,^{5,6} and catalytic^{7,8} applications. In particular, WO_3 is extensively studied for electrochromic applications such as smart windows for automobiles and buildings.^{9,10} Electrochromic WO_3 based auto-dimming rear view mirrors for automobiles are commercially available.¹¹ Recently, WO_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.^{12–14} Furthermore, WO_3 is being utilized in the synthesis of two-dimensional transition metal dichalcogenide (2D-TMD) such as tungsten disulfide (WS_2) through sulfurization of the oxide.^{15,16} The application of WO_3 thin films for solar cells and 2D-TMD synthesis are particularly gaining a lot of interest lately.

WO_3 has been previously deposited using a wide range of deposition techniques including evaporation,^{17,18} sputtering,^{19,20} sol-gel deposition,^{21,22} chemical vapor deposition (CVD),^{23,24} and atomic layer deposition (ALD).^{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_3 thin

films for solar cells and 2D-TMD synthesis. However, there are only a few reports on ALD of WO_3 in the literature. Tägtström *et al.* have reported a WO_3 ALD process using *in situ* generated oxyfluorides as precursor and H_2O as coreactant.²⁵ However, controlling the *in situ* generated oxyfluoride species was difficult. Dezelah *et al.* utilized a metalorganic precursor $\text{W}_2(\text{NMe}_2)_6$ and H_2O in an ALD process which resulted in W_2O_3 films with trivalent tungsten, instead of WO_3 .²⁶ Malm *et al.*²⁷ and Nandi *et al.*²⁸ investigated the ALD growth of WO_3 using the hexacarbonyl precursor $\text{W}(\text{CO})_6$ and O_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.²⁷ Furthermore, an initial incubation delay of around 200 ALD cycles was reported.²⁷ Mamun *et al.*³⁰ and Zhang *et al.*³¹ have also reported a GPC of 0.2 Å using the same hexacarbonyl precursor $\text{W}(\text{CO})_6$ and H_2O . Recently, Song *et al.* utilized a plasma-based ALD process for WO_3 using $\text{WH}_2(\text{iPrCp})_2$ and O_2 plasma, in their attempt to synthesize 2D- WS_2 nanosheets by sulfurizing WO_3 layers.¹⁶ Their WO_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 WOCl_4 precursor and H_2O to deposit WO_3 by ALD. They observed that WO_3 grew on the surfaces of select substrates but the film growth was limited as WO_3 did not appear to grow on itself.²⁹ The metalorganic precursor bis(tertbutylimido)-bis(dimethylamido) tungsten, $({}^t\text{BuN})_2(\text{Me}_2\text{N})_2\text{W}$, used in this work has been previously used to

^{a)}Electronic mail: s.balasubramanyam@tue.nl

deposit WO₃ by ALD using H₂O as coreactant.^{8,29,32} 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.^{8,32} Further, Bergum *et al.* have reported a CVD-type of growth for substrate temperatures above 350 °C for this process.²⁹ 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 WN_x ALD process have resulted in very low levels of carbon impurities (< 2 at. %).³⁶ 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 $\sim 10^{-6}$ Torr. A detailed description of the ALD reactor can be found in an earlier work of the group.³⁷ 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 material⁵² compares the actual substrate temperature and the deposition temperature (table temperature). Throughout this work, the

TABLE I. Overview of process parameters for the plasma-enhanced ALD of WO₃ from (tBuN)₂(Me₂N)₂W and O₂ plasma.

| | |
|---|-----------------------|
| Deposition temperature | 100–400 °C |
| Chamber wall temperature | 100–120 °C |
| Bubbler temperature | 50 °C |
| Precursor line temperature | 70 °C |
| Chamber base pressure | 10 ⁻⁶ Torr |
| Pressure during precursor dosing | 30 mTorr |
| Pressure during coreactant exposure | 15 mTorr |
| Precursor dosing | 3 s |
| Precursor purge time | 5 s |
| Preplasma time | 2 s |
| Coreactant O ₂ plasma exposure | 3 s |
| Coreactant purge time | 5 s |
| O ₂ plasma power | 250 W |

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 a (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 ~ 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 α 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 α 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 WO₃ film thickness as a function of number of ALD cycles for the investigated deposition temperatures as-determined by *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

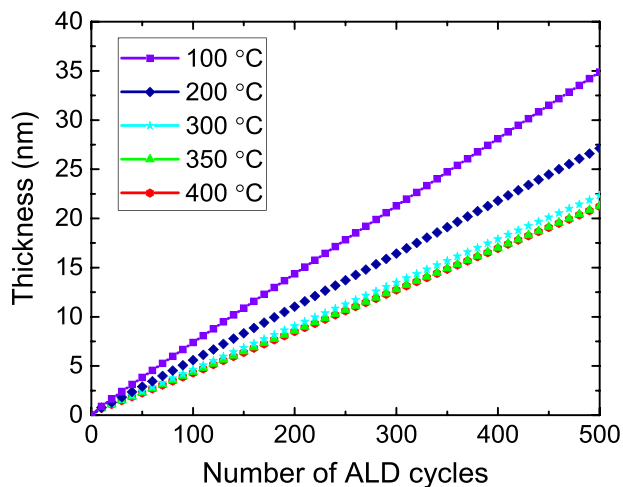


FIG. 1. (Color online) WO₃ film thickness in progression of number of ALD cycles for deposition temperatures ranging from 100 to 400 °C, as-determined by *in situ* SE.

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 O₂ plasma exposure time was fixed at 4 s while varying the precursor dosing and for the O₂ plasma saturation curves [Fig. 2(b)], the precursor dosing time was fixed at 4 s while varying the O₂ 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 O₂ 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 (≥ 5 s) precursor doses [Fig. 2(a)] and O₂ 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.

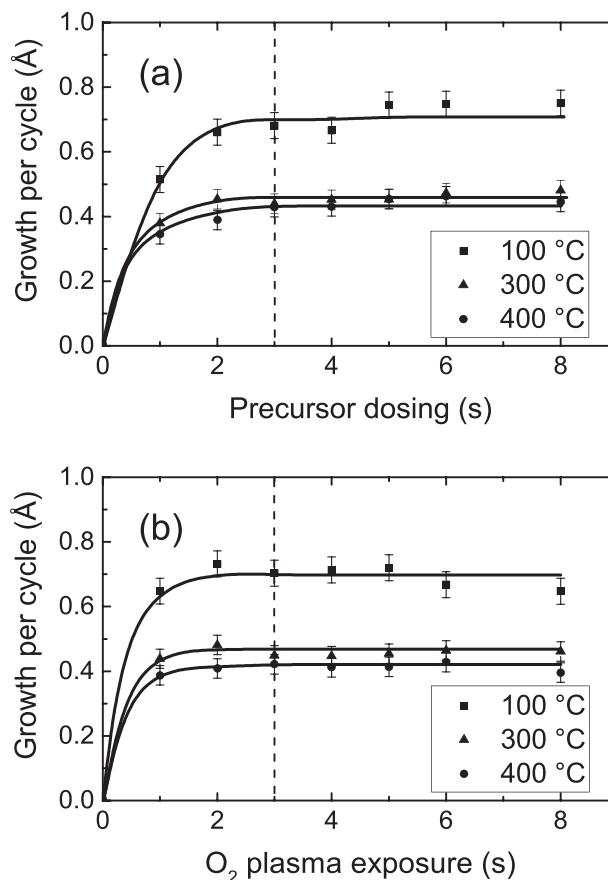


FIG. 2. Saturation curves: GPC as a function of (a) precursor dosing and (b) O₂ plasma exposure, for deposition temperatures of 100, 300, and 400 °C. The dotted lines indicate the respective chosen precursor/O₂ plasma saturation times (3 s) for the WO₃ ALD process. The solid lines serve as guide to the eye.

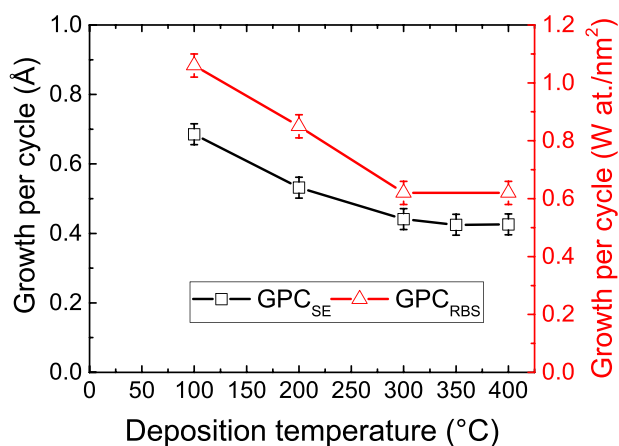


FIG. 3. (Color online) GPC in terms of (1) thickness: as-determined by *in situ* SE (GPC_{SE}—left axis) and (2) deposited W atoms/nm²: as determined by *ex situ* RBS (GPC_{RBS}—right axis), for the investigated deposition temperatures. GPC_{SE} (squares) was calculated by averaging the respective slopes in Fig. 1, for the last 100 out of 500 ALD cycles. GPC_{RBS} (triangles) was calculated by dividing the total number of deposited W atoms/nm² by the total number of ALD cycles.

Figure 3 compares the GPC in terms of (1) thickness: as-determined by *in situ* SE (GPC_{SE}—left axis) and (2) number of W atoms/nm²: as-determined by RBS (GPC_{RBS}—right axis), for the investigated deposition temperatures. The GPC_{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 Å at 100 °C to ~ 0.45 Å at 300 °C and then stabilized at ~ 0.45 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 °C.

Samples with thickness of ~ 20 nm were utilized for RBS measurements. GPC_{RBS} (triangles) was calculated by dividing the total number of deposited W atoms/nm² by the total number of ALD cycles. As seen from Fig. 3, GPC_{RBS} decreased from ~ 1 W at/nm² at 100 °C to ~ 0.6 W at/nm² at 300 °C and then stabilized at ~ 0.6 W at/nm² for higher temperatures, which is analogous to the trend exhibited by GPC_{SE}. Similar results have been reported for O₂ plasma-enhanced ALD processes for Al₂O₃ (Refs. 40–42) as well as SiO₂ (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 WO₃ ALD process and the GPC decrement with temperature from 100 to 300 °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 °C suggests that the observed GPC values can result from a combined effect of reduced –OH surface reactive group density⁴⁴ and a transition toward polycrystalline growth which is shown later in the GI-XRD diffractogram (Fig. 7).

For low deposition temperatures (≤ 200 °C), the observed GPC values are higher than the GPC values reported in literature. For instance, Malm *et al.* and Nandi *et al.* have reported

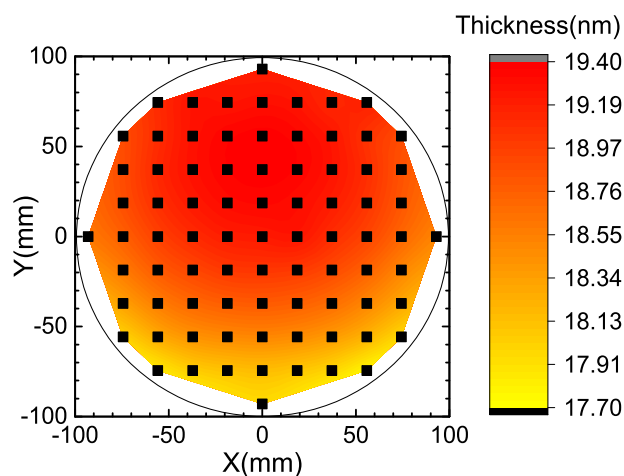


FIG. 4. (Color online) Thickness uniformity of the WO₃ film on an 8 in. (200 mm) Si wafer as-determined by room temperature SE mapping. The WO₃ film was deposited at 200 °C.

a GPC of ~ 0.2 Å at around 200 °C using the hexacarbonyl W(CO)₆ precursor, which is lower than the observed GPC value of ~ 0.55 Å in our case.^{27,28} The observed GPC values are also higher compared to the process developed by Liu *et al.* who have reported GPC values of < 0.2 Å using the same precursor (tBuN)₂(Me₂N)₂W and H₂O for temperatures below 300 °C.⁸ The utilization of O₂ plasma as coreactant could be the primary reason for the reasonably higher GPC in our process.

Figure 4 shows the WO₃ 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 WO₃ ALD cycles were performed on the 8 in. Si wafer at 200 °C with a corresponding GPC of ~ 0.55 Å. The thickness nonuniformity determined by dividing the standard deviation (σ) by the average mean WO₃ thickness, was less than 2.5%. This indicates very good thickness uniformity and the developed WO₃ plasma-enhanced ALD process can potentially be a viable technique for the growth of WO₃ films on large area substrates.

B. Film characterization

The WO₃ films of ~ 20 nm in thickness which were deposited at various temperatures (100–400 °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 WO₃ 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.⁴⁵ In our case, the O/W ratio was found to be constant at 2.9 for all investigated temperatures. With respect to previous WO₃ ALD reports, the O/W ratio of 2.9 is comparable to values (i.e., ~ 3) reported by Marim *et al.*²⁷ and is relatively higher than the value (i.e., 2.4) reported by Song *et al.*¹⁶ The effect of the ambient on the film stoichiometry cannot be ruled out as the samples were stored in air

TABLE II. Important film properties of WO₃ including (1) GPC determined by *in situ* SE, (2) number of deposited W at nm⁻² cycle⁻¹, (3) O/W ratio as well as (4) mass density determined by RBS, and (5) H content determined by ERD measurements, for various deposition temperatures. C and N impurity content in the as-deposited films (bulk) were below the RBS detection limit of 3 and 2 at. %, respectively. The error margins for the respective parameter are indicated along with the first value in each column. No RBS/ERD measurements were performed on the samples deposited at 350 °C.

| Deposition temperature (°C) | GPC (Å) | W (at nm ⁻² cycle ⁻¹) | O/W | [H] (at. %) | Mass density (g cm ⁻³) |
|-----------------------------|-------------|--|-----------|-------------|------------------------------------|
| 100 | 0.68 ± 0.03 | 1.06 ± 0.08 | 2.9 ± 0.1 | 11.3 ± 0.8 | 5.8 ± 0.1 |
| 200 | 0.53 | 0.85 | 2.9 | 2.5 | 5.9 |
| 300 | 0.44 | 0.62 | 2.9 | 2.5 | 5.9 |
| 350 | 0.43 | — | — | — | — |
| 400 | 0.43 | 0.62 | 2.9 | 6.2 | 5.9 |

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 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 W4f_{7/2} peak at ~36.1 eV and a W4f_{5/2} 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.^{45,46} 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.¹⁸

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

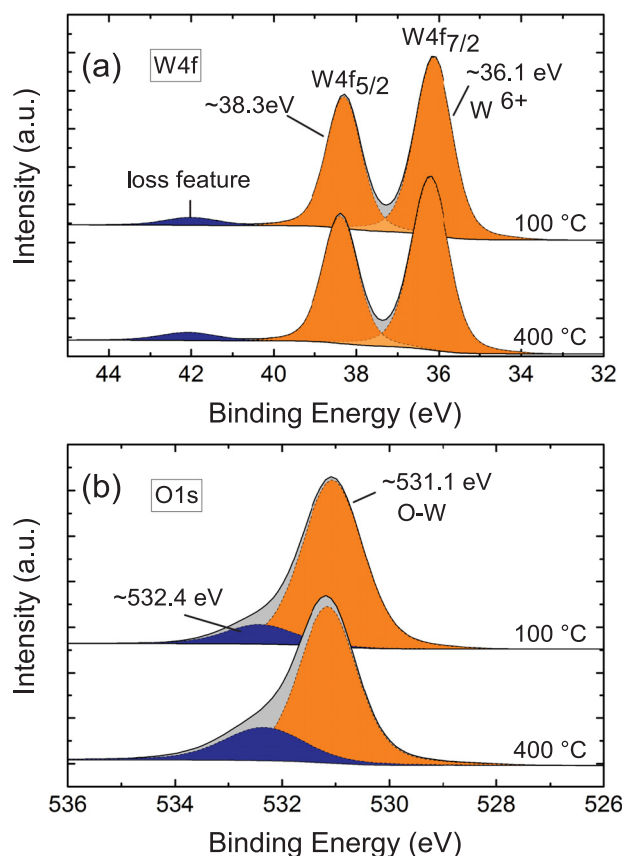


FIG. 5. (Color online) XPS spectra of WO₃ films deposited at 100 and 400 °C. (a) W4f peaks—fitted W4f core level spectra involving a doublet and a loss feature. A W4f_{7/2} peak at ~36.1 eV and a W4f_{5/2} peak at ~38.3 eV constituted the doublet. (b) O1s peaks—fitted O1s core level spectra which includes a peak at ~531 eV corresponding to the valency of W⁶⁺ and another peak at ~532.5 eV which might correspond to residual water adsorbed on the surface.

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 III for various deposition temperatures. As seen from Table III, 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.^{47,48}

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:

$$\alpha h\nu \sim (h\nu - E_g)^n, \quad (1)$$

where α 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.^{2,49} Assuming an indirect transition,^{45,47,50} the band gap for WO₃ can be evaluated by extrapolating the

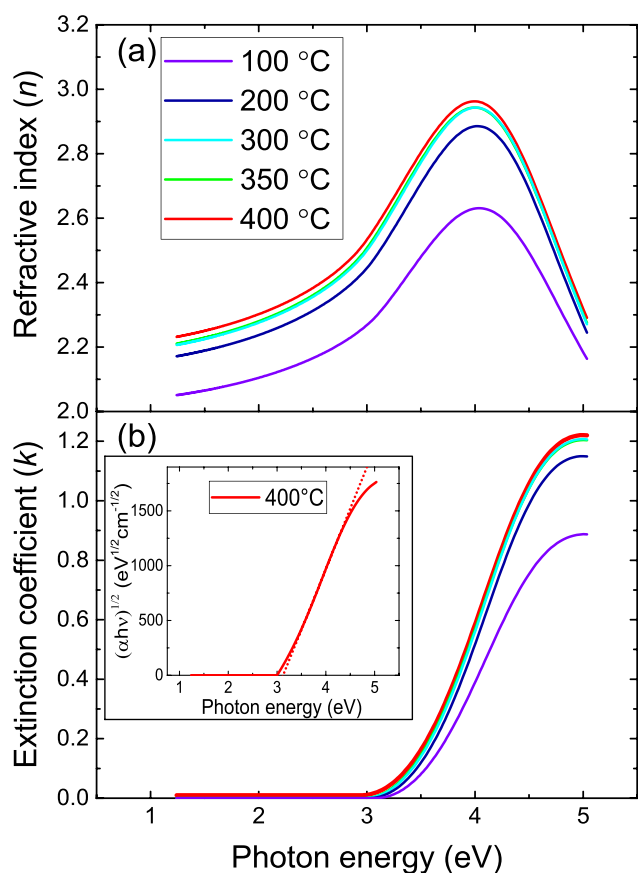


FIG. 6. (Color online) *In situ* SE determined (a) refractive index (n) and (b) extinction coefficient (k) spectra, of the WO₃ films deposited over the temperature range of 100–400 °C. The inset in figure (b) shows the Tauc-plot for the film deposited at 400 °C. The dotted line in the inset indicates the extrapolated linear fit.

linear part of the Tauc plot $[(\alpha h\nu)^{1/2} \text{ vs } h\nu]$ 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 “ α ” was determined from SE measurements.) The observed bandgap values (3.12–3.23 eV) are in agreement with literature values for WO₃ 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

TABLE III. SE determined refractive index n and band gap of the WO₃ films deposited at various temperatures. The refractive index is reported at a corresponding photon energy of 1.96 eV.

| Deposition temperature (°C) | Refractive index (n) | Band gap (eV) |
|-----------------------------|--------------------------|-----------------|
| 100 | 2.10 ± 0.03 | 3.23 ± 0.04 |
| 200 | 2.22 | 3.17 |
| 300 | 2.27 | 3.15 |
| 350 | 2.27 | 3.13 |
| 400 | 2.28 | 3.12 |

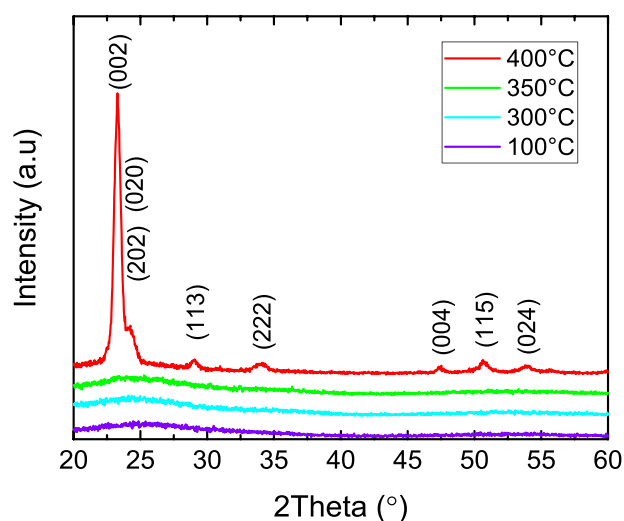


FIG. 7. (Color online) GI-XRD diffractogram of the WO₃ films deposited at various temperatures. For the WO₃ film deposited at 400 °C, the respective peaks are indexed according to monoclinic WO₃.

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 WO₃.^{8,51} 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).

IV. SUMMARY AND CONCLUSIONS

A new ALD process for WO₃ has been developed using (^tBuN)₂(Me₂N)₂W and O₂ plasma over a wide 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 WO₃ 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-WS₂.

ACKNOWLEDGMENTS

The authors acknowledge Jeroen van Gerwen and Cristian van Helvoirt for their technical assistance, Martijn Vos as well as Tahsin Faraz for their valuable suggestions, and

Aileen Omahony from Oxford Instruments for her assistance in uniformity measurements. This work has been supported by the European Research Council (Grant Agreement No. 648787 648787-ALD of 2DTMDs).

- ¹C. G. Granqvist, *Handbook of Inorganic Electrochromic Materials* (Elsevier, Amsterdam, 1995), pp. 19–27.
- ²C. G. Granqvist, *Sol. Energy Mater. Sol. Cells* **60**, 201 (2000).
- ³S. Balaji, Y. Djaoued, A.-S. Albert, R. Z. Ferguson, and R. Bruüning, *Chem. Mater.* **21**, 1381 (2009).
- ⁴C. Yan, W. Kang, J. Wang, M. Cui, X. Wang, C. Y. Foo, K. J. Chee, and P. S. Lee, *ACS Nano* **8**, 316 (2014).
- ⁵J. Polleux, A. Gurlo, N. Barsan, U. Weimar, M. Antonietti, and M. Niederberger, *Angew. Chem. Int. Ed.* **45**, 261 (2006).
- ⁶C. Balázs, L. Wang, E. O. Gouyim, I. M. Szilágyi, K. Sedlacková, J. Pfeifer, A. L. Tóth, and P.-I. Gouma, *J. Eur. Ceram. Soc.* **28**, 913 (2008).
- ⁷Z.-G. Zhao and M. Miyauchi, *Angew. Chem. Int. Ed.* **47**, 7051 (2008).
- ⁸R. Liu, Y. Lin, L.-Y. Chou, S. W. Sheehan, W. He, F. Zhang, H. J. M. Hou, and D. Wang, *Angew. Chem. Int. Ed.* **50**, 499 (2011).
- ⁹C. M. Lampert, *Sol. Energy Mater. Sol. Cells* **76**, 489 (2003).
- ¹⁰D. R. Rosseinsky and R. J. Mortimer, *Adv. Mater.* **13**, 783 (2001).
- ¹¹“Hongwu International Group Ltd.” <http://www.hwnanomaterial.com>.
- ¹²M. Bivour, J. Temmler, H. Steinkemper, and M. Hermle, *Sol. Energy Mater. Sol. Cells* **142**, 34 (2015).
- ¹³L. G. Gerling, S. Mahato, A. Morales-Vilches, G. Masmitja, P. Ortega, C. Voz, R. Alcubilla, and J. Puigdollers, *Sol. Energy Mater. Sol. Cells* **145**, 109 (2016).
- ¹⁴M. Mews, L. Korte, and B. Rech, *Sol. Energy Mater. Sol. Cells* **158**, 77 (2016).
- ¹⁵H. R. Gutiérrez *et al.*, *Nano Lett.* **13**, 3447 (2013).
- ¹⁶J. Song *et al.*, *ACS Nano* **7**, 11333 (2013).
- ¹⁷A. Azens, M. Kitenbergs, and U. Kanders, *Vacuum* **46**, 745 (1995).
- ¹⁸Y. Baek and K. Yong, *J. Phys. Chem. C* **111**, 1213 (2007).
- ¹⁹H. S. Witham, P. Chindaudom, I. An, R. W. Collins, R. Messier, and K. Vedam, *J. Vac. Sci. Technol., A* **11**, 1881 (1993).
- ²⁰R. S. Vemuri, M. H. Engelhard, and C. V. Ramana, *ACS Appl. Mater. Interfaces* **4**, 1371 (2012).
- ²¹P. Judeinstein and J. Livage, *J. Mater. Chem.* **1**, 621 (1991).
- ²²A. Cremonesi, D. Bersani, P. P. Lottici, Y. Djaoued, and P. V. Ashrit, *J. Non-Cryst. Solids* **345–346**, 500 (2004).
- ²³R. U. Kirss and L. Meda, *Appl. Organomet. Chem.* **12**, 155 (1998).
- ²⁴R. G. Gordon, S. Barry, J. T. Barton, and R. N. R. Broomhall-Dillard, *Thin Solid Films* **392**, 231 (2001).
- ²⁵P. Tägtström, P. Martensson, U. Jansson, and J.-O. Carlsson, *J. Electrochem. Soc.* **146**, 3139 (1999).
- ²⁶Dezelah, O. M. El-Kadri, I. M. Szilágyi, J. M. Campbell, K. Arstila, L. Niinistö, and C. H. Winter, *J. Am. Chem. Soc.* **128**, 9638 (2006).
- ²⁷J. Malm, T. Sajavaara, and M. Karppinen, *Chem. Vap. Deposition* **18**, 245 (2012).
- ²⁸D. K. Nandi and S. K. Sarkar, *Energy Procedia* **54**, 782 (2014).
- ²⁹K. Bergum, A. Magrasó, H. Fjellvåg, and O. Nilsen, *J. Mater. Chem. A* **2**, 18463 (2014).
- ³⁰M. A. Mamun, K. Zhang, H. Baumgart, and A. A. Elmustafa, *ECS J. Solid State Sci. Technol.* **4**, P398 (2015).
- ³¹K. Zhang, C. McCleese, P. Lin, X. Chen, M. Morales, W. Cao, F. J. Seo, C. Burda, and H. Baumgart, *ECS Trans.* **69**, 199 (2015).
- ³²S. Zhuiykov, L. Hyde, Z. Hai, M. K. Akbari, E. Kats, C. Detavernier, C. Xue, and H. Xu, *Appl. Mater. Today* **6**, 44 (2017).
- ³³N. Li, L. Feng, J. Su, W. Zeng, and Z. Liu, *RSC Adv.* **6**, 64879 (2016).
- ³⁴A. R. Mouat, A. U. Mane, J. W. Elam, M. Delferro, T. J. Marks, and P. C. Stair, *Chem. Mater.* **28**, 1907 (2016).
- ³⁵C. Kastl *et al.*, *2D Mater.* **4**, 21024 (2017).
- ³⁶M. J. Sowa, Y. Yemane, J. Zhang, J. C. Palmstrom, L. Ju, N. C. Strandwitz, F. B. Prinz, and J. Provine, *J. Vac. Sci. Technol., A* **35**, 01B143 (2017).
- ³⁷H. C. M. Knoops, E. M. J. Braeken, K. de Peuter, S. E. Potts, S. Haukka, V. Pore, and W. M. M. Kessels, *ACS Appl. Mater. Interfaces* **7**, 19857 (2015).
- ³⁸A. Subrahmanyam and A. Karuppasamy, *Sol. Energy Mater. Sol. Cells* **91**, 266 (2007).
- ³⁹I. Valyukh, S. Green, H. Arwin, G. A. Niklasson, E. Wäckelgård, and C. G. Granqvist, *Sol. Energy Mater. Sol. Cells* **94**, 724 (2010).
- ⁴⁰E. Langereis, J. Keijmel, M. C. M. van de Sanden, and W. M. M. Kessels, *Appl. Phys. Lett.* **92**, 231904 (2008).
- ⁴¹S. E. Potts, W. Keuning, E. Langereis, G. Dingemans, M. C. M. van de Sanden, and W. M. M. Kessels, *J. Electrochem. Soc.* **157**, P66 (2010).
- ⁴²G. Dingemans, M. C. M. van de Sanden, and W. M. M. Kessels, *Electrochem. Solid-State Lett.* **13**, H76 (2010).
- ⁴³G. Dingemans, C. A. A. van Helvoirt, D. Pierreux, W. Keuning, and W. M. M. Kessels, *J. Electrochem. Soc.* **159**, H277 (2012).
- ⁴⁴S. E. Potts and W. M. M. Kessels, *Coord. Chem. Rev.* **257**, 3254 (2013).
- ⁴⁵D. Gogova, K. Gesheva, A. Szekeres, and M. Sendova-Vassileva, *Phys. Status Solidi* **176**, 969 (1999).
- ⁴⁶C. G. Granqvist, *Handbook of Inorganic Electrochromic Materials* (Elsevier, Amsterdam, 1995), pp. 111–137.
- ⁴⁷K. Muthu Karuppasamy and A. Subrahmanyam, *J. Phys. D: Appl. Phys.* **42**, 95301 (2009).
- ⁴⁸H. Camirand, B. Baloukas, J. E. Klemberg-Sapieha, and L. Martinu, *Sol. Energy Mater. Sol. Cells* **140**, 77 (2015).
- ⁴⁹S. M. A. Durrani, E. E. Khawaja, M. A. Salim, M. F. Al-Kuhaili, and A. M. Al-Shukri, *Sol. Energy Mater. Sol. Cells* **71**, 313 (2002).
- ⁵⁰R. A. May, L. Kondrachova, B. P. Hahn, and K. J. Stevenson, *J. Phys. Chem. C* **111**, 18251 (2007).
- ⁵¹S. Tanisaki, *J. Phys. Soc. Jpn.* **15**, 573 (1960).
- ⁵²See supplementary material at <http://dx.doi.org/10.1116/1.4986202> for (1) comparison between the deposition temperature and the actual Si substrate temperature and (2) AFM images of the WO₃ film.