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Shkondin, Evgeniy; Alimadadi, Hossein; Takayama, Osamu; Jensen, Flemming; Lavrinenko, Andrei V.

Published in:
Journal of Vacuum Science and Technology A: Vacuum, Surfaces and Films

Link to article, DOI:
10.1116/1.5130176

Publication date:
2020

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):
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Running Authors: Shkondin et al.

Evgeniy Shkondin$^a$)
Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby
National Centre for Nano Fabrication and Characterization (DTU Nanolab), DK-2800 Kgs. Lyngby

Hossein Alimadadi
National Centre for Nano Fabrication and Characterization (DTU Nanolab), DK-2800 Kgs. Lyngby
Danish Technological Institute, DK-8000 Aarhus C, Denmark

Osamu Takayama
Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby

Flemming Jensen
National Centre for Nano Fabrication and Characterization (DTU Nanolab), DK-2800 Kgs. Lyngby

Andrei V. Lavrinenko
Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby

$^a$) Electronic mail: eves@dtu.dk

In this communication, fabrication of high aspect ratio Al$_2$O$_3$/ZnO/Al$_2$O$_3$ nanotubes is reported and morphological changes at elevated temperature are investigated. The structures were made by implementing several fabrication methods, such as deep-UV lithography, atomic layer deposition (ALD), and plasma etch methods. During the fabrication, the ALD deposited Al$_2$O$_3$ and ZnO conformally passivated the prepared Si holes template resulting in the complex coaxial Al$_2$O$_3$/ZnO/Al$_2$O$_3$ pillars. By utilizing several scanning and transmission electron microscopy techniques, it is experimentally
shown that at elevated temperatures, internal voids form in the nanotube due to diffusion of ZnO into surrounding Al₂O₃ and also ZnAl₂O₄ spinel structure forms. Finally, the porous tubes have been isolated from the surrounding silicon core using a conventional isotropic selective Si plasma etch process. The presented approach opens the opportunity to build complex optical metamaterial compositions, for example for a new generation of sensors for gas and biomarker detection.

I. INTRODUCTION

Current progress in optical metamaterials, artificially engineered materials, has emphasized the significance of developing the fabrication approach that would allow patterning high-quality optical materials at the nanoscale. Far-field imaging with super-resolution, materials with hyperbolic dispersion and optical cloaking are only a few examples among many different topics that require the realization of highly ordered, periodic metal-dielectric three-dimensional structures with deep subwavelength feature sizes. The topology of metamaterials and metasurfaces typically consists of an array of nanopillars, trenches, and flat multilayers in the simplest forms. The realization of multi-coaxial cylindrical structures enables the development of new promising materials with extraordinary and exciting responses to light which includes hyperbolic and all-dielectric metamaterials. Additionally, such structures are excellent candidates for a new generation of gas and biological sensors, where the response based on the extremely large surface area of active materials can be enhanced further by hyperbolic light dispersion. One method to change the surface area and tune the optical response is to use solid-state interface diffusion and the associated phenomena such as Kirkendall effect. Different interface reactions have been reported so far, which includes
ZnO-TiO$_2$, ZnO-SiO$_2$, MgO-Al$_2$O$_3$, etc. Recent reports pointed out possible Kirkendall effect in Al$_2$O$_3$/ZnO nanolaminates. During annealing, the diffusion of ZnO into Al$_2$O$_3$ leads to the formation of crystalline ZnAl$_2$O$_4$ spinel. In general, this solid-state reaction is highly sensitive to annealing temperature, annealing time, layer thickness and other parameters.

This work presents a fabrication approach of free-standing high aspect ratio, hollow coaxial nanotubes, where Al$_2$O$_3$/ZnO/Al$_2$O$_3$ coatings exhibit a solid-state diffusion reaction, which transforms ZnO-Al$_2$O$_3$ interfaces into porous ZnAl$_2$O$_4$ spinel nanocrystals. The Kirkendall effect can be used in the realization of a new class of advanced optical metamaterials, where the porous structure inside the tube can significantly increase the surface area facilitating enhanced sensitivity towards analyzed targets.

II. EXPERIMENT

A. Fabrication details

The nanopillars were fabricated by combining deep-UV lithography, atomic layer deposition (ALD), and advanced deep reactive ion etching (DRIE) techniques. A similar approach has been developed recently for the fabrication of high aspect ratio Al-doped ZnO pillars, deep trenches made of Al$_2$O$_3$, TiO$_2$, TiN, and ZnO. The method is based on ALD deposition on high aspect ratio silicon structures (mold) with subsequent selective removal of the silicon template, leaving a negative replica of the template structure in the functional material.

ALD is the only technique that can produce such coatings, all other known methods such as pulsed laser deposition, CVD or sputtering suffer from poor step
coverage and non-uniformity\textsuperscript{28}. The use of ALD in combination with a sacrificial silicon mold is a novel method to create high aspect ratio metal oxide structures. Figure 1 shows the fabrication steps in the pillars patterning. Starting from the substrate deep-UV lithography and DRIE template preparation [Figs. 1(a)-1(c)], the fabrication continues with ALD deposition, top layer Ar\textsuperscript{+} ion sputtering and annealing [Figs. 1(d)-1(f)]. The last step is silicon template removal, which was done by an isotropic SF\textsubscript{6} plasma reactive ion etching [Fig. 1(g)]. The success of this procedure is heavily dependent on the ability to etch silicon selectively, without affecting the ALD coatings. It is noteworthy that no distortion of the pillars was observed after template removal in the last step.
Fig. 1. (Color online) Fabrication flow. (a) Silicon-on-insulator (SOI) substrates. (b) Deep-UV lithography. (c) Square lattice holes arrays in the silicon substrate as a template prepared by DRIE. (d) Deposition of Al₂O₃/ZnO/Al₂O₃ using ALD. (e) Sputtering of ALD deposited cap layers. (f) Annealing of the structure at 800 °C. (g) Isolation of pillars by etching of the silicon template.

1. **Si hole array template preparation**

Homemade silicon-on-insulator (SOI) wafers [Fig. 1(a)] were used for the entire fabrication procedure. First, 150 mm (100) Si wafers were selected, and the wafers were RCA cleaned and later oxidized to achieve 200 nm thick SiO₂ in a conventional quartz tube furnace (from Tempress) using a dry oxidation process based on O₂ at 1100 °C. Afterward, 2 µm polycrystalline silicon was deposited on the SiO₂ surface using a low vapor chemical vapor deposition (LPCVD) technique, based on SiH₄ which carried out at 560 °C (furnace from Tempress). Surface roughness was characterized by atomic force microscopy (AFM), which revealed that surface roughness is below 1nm, validating the use of the SOI wafers as a Si template.

A square lattice of holes [Fig. 1(b)] with a diameter of 300 nm and a lattice constant of 400 nm was patterned using deep-UV lithography, on a square chips (1×1 cm²) of SOI wafer. The procedure consists of a bottom antireflective coating (BARC), photoresist coating, exposure, post-bake, and development. To minimize interference effects and promote adhesion, the substrate surface was coated (Süss MicroTec Gamma 2M spin coater) with a 65 nm thick BARC coating (DUV42S-6, Brewer Science, USA) followed by a bake-out at 175 °C for 60 s. Then, a positive photoresist (KRF M230Y, JSR Micro, NV) was spin-coated to a thickness of 360 nm and baked at 130 °C for 90 s.
Next, the SOI wafer with resist coatings was exposed (exposure dose of 860 J/m²) on field sizes of 1×1 cm² (Canon FPA-3000 EX4 DUV stepper). The last lithography step was 90 s post-exposure bake at 130 °C followed by developing in 2.38% tetramethylammonium hydroxide (TMAH) solution for 90 s (Süss MicroTec Gamma 2M developer).

DRIE etching (DRIE Pegasus from SPTS) was completed in a switched Bosch process consisting of cyclic steps of etching and passivation [Fig. 1(c)]. During etching, the wafer chuck was held constantly at 0 °C, and the process pressure was fixed at 10 mTorr. Three main steps were implemented for the Si template fabrication: etching of the BARC layer, high anisotropic silicon etching for template preparation (Table I summarizes the Bosch parameters) and remaining resist plasma ashing. The BARC etch proceeds for 45 s using 40 sccm O₂ plasma with coil and platen powers of 400 W and 20 W, respectively. In the following Bosch process, the depth of the holes was controlled by correcting the number of cycles (85 cycles correspond approximately to 2 μm deep holes). The strict control is less important in this case since etching basically stops when reaching the SiO₂ layer in the SOI substrates. The depth of the holes is limited to the LPCVD deposited Si, which is in this case 2 μm. For deeper profiles which require a thicker Si top layer, a modification of the Bosch process presented in Table I needs to be made, as well. Nowadays, the achievable etch depth is comparable with wafer thickness, as more advanced versions of the Bosch process have been developed. The last phase of template fabrication is the removal of the resist leftovers, which was done using an O₂ plasma for 2 min with the flow of 100 sccm. The coil and platen powers were 800 W and 20 W, respectively. The shape and morphology of the produced Si-holes template
structures were carefully inspected by scanning electron microscopy (SEM, Supra 60VP from Zeiss) in the cross-sectional mode by sacrificing some of the prepared structures. The achieved diameter of the holes is indeed very close to 300 nm despite imperfections in the etching procedure. Prior to the next step (ALD deposition), the prepared Si template hole-array structures received an additional O\textsubscript{2}/N\textsubscript{2} plasma treatment for approximately 20 min in order to eliminate any possible remaining organic residuals from resist coatings and surroundings.

**Table I.** DRIE parameters for template fabrication.

<table>
<thead>
<tr>
<th>Process gas flow (sccm)</th>
<th>Passivation (1.5 s)</th>
<th>Etching (2.75 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{4}F\textsubscript{8}</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>SF\textsubscript{6}</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Powers (W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>Platen</td>
<td>-</td>
<td>40</td>
</tr>
</tbody>
</table>

2. **Atomic layer deposition**

Next, the holes were filled with Al\textsubscript{2}O\textsubscript{3}/ZnO/Al\textsubscript{2}O\textsubscript{3} layers (thicknesses of 50 nm/25 nm/50 nm, respectively) by ALD [Fig. 1(d)]. The deposition was carried in a commercial hot-wall ALD system (Picosun R-200) using diethyl zinc, trimethylaluminum, and water as precursors at 200 °C. The ALD technique is the ideal choice for precise thickness control and conformal deposition of high aspect ratio structures. The recipes used in this work are presented in Tables II and III. Prior to deposition on the Si hole template, the deposition rates of Al\textsubscript{2}O\textsubscript{3} and ZnO were defined by measuring thicknesses of Al\textsubscript{2}O\textsubscript{3} and
ZnO coatings on flat substrates with spectroscopic ellipsometry (VASE, J. A. Woolam Co.). The deposition rate for Al₂O₃ and ZnO at 200 °C was found to be 0.09 nm/cycle and 0.15 nm/cycle, respectively, which is in good agreement with the previously reported values.²⁷,³⁴

**TABLE II. Recipe for one cycle of Al₂O₃.**

<table>
<thead>
<tr>
<th>Precursor</th>
<th>Carrier gas (N₂) flow (sccm)</th>
<th>Pulse time (s)</th>
<th>N₂ Purge (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMA</td>
<td>150</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>TMA</td>
<td>150</td>
<td>0.1</td>
<td>20</td>
</tr>
<tr>
<td>H₂O</td>
<td>200</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>H₂O</td>
<td>200</td>
<td>0.1</td>
<td>20</td>
</tr>
</tbody>
</table>

**TABLE III. Recipe for one cycle of ZnO.**

<table>
<thead>
<tr>
<th>Precursor</th>
<th>Carrier gas (N₂) flow (sccm)</th>
<th>Pulse time (s)</th>
<th>N₂ Purge (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEZ</td>
<td>150</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>DEZ</td>
<td>150</td>
<td>0.1</td>
<td>20</td>
</tr>
<tr>
<td>H₂O</td>
<td>200</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>H₂O</td>
<td>200</td>
<td>0.1</td>
<td>20</td>
</tr>
</tbody>
</table>

3. *Ion beam etching and annealing*

The cap of the ALD layers on top of the structures was removed using Ar⁺ ion milling (Ionfab 300 Plus from Oxford Instrument), thereby exposing the silicon matrix.
between deposited pillars [Fig. 1(e)]. The etching process of ZnO and Al₂O₃ was tuned to approximately 16 nm/min and 3.5 nm/min, respectively, which guaranteed well-controlled top layer sputtering. Prepared samples were annealed (furnace PEO-604 from ATV Technology) at 800 °C for 12 h in an N₂ environment at atmospheric pressure in order to induce diffusion [Fig. 1(f)]. SEM images [Fig. 2(a) and 2(b)] reveal surface morphology before and after the annealing from which it is clearly seen (inset in Fig. 3(b)) that ZnO migrated into Al₂O₃ areas resulting in the formation of large voids.

4. FIB lamella extraction

In order to study structural evolution inside the pillars in details by transmission electron microscopy (TEM), it was necessary to prepare thin lamellae of the pillars cross-section. This was carried out using an in-situ lift out by focus ion beam (FIB) in a SEM (FEI Helios NanoLab 600 Dual Beam system). To study the evolution, two electron transparent lamellae before and after annealing, respectively, were extracted in the cross-section view [Fig. 1(e) and 1(f)] from the bulk sample, transferred and attached to a conventional omniprobe TEM grid. Afterward, the samples were additionally thinned to meet high-resolution TEM investigations. SEM images of both high-quality samples are presented in Fig. 3.
FIG. 2. Fabricated coaxial pillars. (a) Surface directly after IBE etching. The inset shows the clear boundary between ALD deposited Al₂O₃ and ZnO. (b) Sample surface after annealing at 800 °C. The inset shows the magnified image illustrating ZnO migration towards Al₂O₃. (c) Birds-eye-view SEM image of isolated tubes standing on Si/SiO₂ platform.

5. Isolation of pillars by selective template back etch

The last step in tubes fabrication was silicon back etch between structures. This was done by reactive ion etching (RIE) using conventional equipment (RIE, from SPTS) with SF₆ process gas [Fig. 1(g)], where the flow was kept constant at 35 sccm at a substrate temperature of 20 °C. The coil power and process pressure were 30 W and 80 mTorr, respectively. This process proceeds with extreme selectivity towards the deposited ALD layer without any observable damage brought on the coaxial structure. It takes around 3 min to remove the Si core entirely. This etch time is not critical since the process basically stops at the 200 nm thin SiO₂ interlayer of the SOI substrate. Further details regarding the sustainability of the structures in SF₆ plasma environment are given elsewhere⁹, where the fabrication of Al-doped ZnO (AZO) nanotubes with 20 nm thick
walls is described and provided detailed TEM images of side walls. The result of freestanding annealed tubes on the Si/SiO$_2$ surface is presented in Fig. 2(c), where the bird-eye view SEM image shows a well-preserved corner of the tube arrays.

![FIB lamella extracted from the surfaces and attached to the TEM grid.](image)

*Fig. 3. FIB lamella extracted from the surfaces and attached to the TEM grid. (a) From sample before annealing. (b) From sample after annealing.*

**B. Characterization details**

The fabricated isolated coaxial tubes were thoroughly inspected using SEM.

Figure 2 (a) shows SEM images of the fabricated structure at the intermediate stage
shown in Fig. 1(e). The top layer of Al₂O₃/ZnO/Al₂O₃ has been sputtered away, revealing a silicon matrix between coaxial nanotubes. After annealing at 800 °C for 12 hours the morphology of the nanotubes was changed [Fig. 2(b)]. Next, by applying reactive ion etching based on a SF₆ continuous plasma etch, the Si core was removed thus leaving porous free-standing coaxial structures in a periodic pattern on Si/SiO₂ platform [Fig. 2(c)].

Microstructural evolution inside the tubes was studied using several electron microscopy characterization techniques. The methods that have been applied for sample investigation inside a TEM instrument (FEI, Titan 80-300ST, 120 keV) include high-resolution transmission electron microscopy (HRTEM), high angular annular dark-field and annular dark-field scanning transmission electron microscopy, abbreviated as HAADF-STEM and ADF-STEM, respectively. Elemental mapping was performed with energy-dispersive X-ray spectroscopy (EDS) analysis (X-ray spectrometer from Oxford Instrument integrated with the TEM equipment). Selected area electron diffraction (SAED) was carried out on tube samples and conventional X-ray diffraction (XRD) performed to study the crystal orientations of the ALD deposited materials on planar Si (100) surfaces in Bragg-Brentano geometry by a Rigaku SmartLab 3kW diffractometer equipped with Cu Kα X-ray source. The XRD profiles were scanned in steps of 0.002° 2θ/s.

III. RESULTS AND DISCUSSION

A. XRD analysis of planar coatings
To investigate crystallinity of the samples before and after annealing the ALD coatings were deposited not only on the Si template [Fig. 1(c)] but also on flat silicon (100) surfaces. These samples have been annealed simultaneously with the tube structures. Figure 4 shows XRD pattern of flat films before and after heat treatment. The annealed samples show the presence of (111) family peaks of ZnAl₂O₄, indicating formation of the cubic spinel structure.³⁵,³⁶ Furthermore, the characteristic peak of the ZnO (002) reflection shifts to a higher 2θ angle, which indicates a reduction of the ZnO lattice constant. This can be attributed to the replacement of the larger Zn²⁺ ions by the smaller Al³⁺ ions in the lattice.⁹,³⁷

![XRD pattern](image)

**Fig. 4.** (Color online) XRD profiles of the flat films containing Al₂O₃/ZnO/Al₂O₃ layers deposited on Si substrates with thicknesses 50 nm, 25 nm, and 50 nm, respectively, before and after annealing. The scan of the sample after annealing indicates the formation of a ZnAl₂O₄ spinel phase as well as a shrinkage of the ZnO crystal lattice in the c-axis direction as a result of heat treatment.

### B. STEM analysis
Figure 5(a-c) shows the initial nanotubes (ca. 300 nm diameter) surrounded by crystalline Si before annealing. The single pillars consist of a polycrystalline ZnO layer between amorphous Al₂O₃ oxide layers, with an empty core [Fig. 5(a)]. A higher magnification image [Fig. 5(b)] reveals that the ZnO layer is assembled from crystals of approximately 25 nm × 10 nm oriented in the radial direction. SAED from a single pillar confirms that ZnO is hexagonal, which is consistent with the XRD result.

Annealed pillars surrounded by crystalline Si exhibit different morphology and microstructure as summarized in Fig. 5(d-f). The single nanowires consist of a porous ZnO layer sandwiched by (Zn-diffused) crystalline ZnAl₂O₄ layers next onto an Al₂O₃ layer [Fig. 5(d)]. The magnified TEM image [Fig. 5(e)] shows the structural evolution as a result of the annealing. The presence of voids in the ZnO region indicates diffusion of ZnO towards the initially amorphous Al₂O₃ layers. Diffraction patterns in SAED [Figs. 5(c) and 5(f)] reveal a big difference between the initial and annealed tubes. The continuous rings of the initial sample, which represent polycrystalline ZnO are transformed into individual spots pattern, which can be interpreted as an increase in grain sizes of remaining ZnO and transformation to a new crystalline ZnAl₂O₄ spinel oxide.
Fig. 5. (a) TEM image of cross-sectional lamella sample showing one individual tube. (b) The corresponding HRTEM image of ZnO interlayer. (c) SAED pattern. (d), (e) and (f) present corresponding results for the annealed sample.

For acquiring further elemental and microstructural information, STEM-HAADF (inner detector diameter, 87.7 mrad), STEM-ADF (inner and outer detector diameter, 9.7 and 41.7 mrad) and STEM-EDS were used. The HAADF and ADF were acquired from the same pillar at the same time. In the HAADF mode, the image contrast is sensitive to the mean atomic number and the specimen thickness, so that higher mean atomic numbers or thicker regions appear brighter. In fact, the brightest contrast in the initial sample [Fig. 6(a)] corresponds to ZnO, which has a heavier element than Al₂O₃ does. In the annealed sample [Fig. 7(a)], the ZnO layer has considerable contrast variation, originating from the presence of voids. The additional two layers of ZnAl₂O₄ that are located on both sides of the ZnO layer appear more clearly in Fig. 7(a). The ZnAl₂O₄...
layers have continuous circular shapes with approximately 20 nm in height and lose image contrast gradually in the outer direction from the ZnO layer. This gradual change and vague phase boundary are also observed in the TEM image [Fig. 5(e)].

The ADF signal [Figs. 6(b) and 7(b)] has a more predominant contribution of diffracted electron beams over specimen thickness or composition. Therefore, the domain-like contrast suggests a polycrystalline structure, where each domain has the same diffracting condition. A uniform contrast would indicate either single crystalline or an amorphous phase. This supports the previous conclusion that the inner and outer shells of Al₂O₃ coatings remain amorphous after annealing, which was also supported by the conventional TEM [Fig. 5(e)]. Nevertheless, apparently, some crystals are extended to the Al₂O₃ region since the ZnAl₂O₄ thickness is almost constant and locally ZnO is missing [Fig. 7(b)]. This means that the diffusion may occur at an earlier stage due to gradual warm-up of the annealing furnace and low temperature (below 800 °C) or quick reaction with a narrow temperature window may take place.

C. STEM-EDS investigations
Fig. 6. STEM HAADF, ADF and EDS quantitative maps of the initial sample. (a) HAADF image. (b) ADF image. (c) STEM HAADF image of the measured area, (d) - (f) Oxygen, Aluminum, and Zinc elemental maps.

For STEM-EDS analysis, the specimens were tilted to 20° about the horizontal axis for optimal geometry of the spectroscopy and the measured area presented in the tilted HAADF images [Figs. 6(c) and 7(c)]. The quantitative maps of the initial and annealed specimens are presented in Figs. 6(d-f) and 7(d-f), respectively. The annealed tubes show more a homogeneous oxygen distribution and apparent Zn and Al concentration variations (at. %) from the ZnO into the inner and outer directions due to diffusion. In addition to elemental maps presented in Figs. 6 and 7, the carbon signal was detected, which is conventional microscopy contamination and FIB lamella preparation.
Figure 8 shows the EDS quantitative line profile, which gives additional information on chemical distribution and diffusion. The annealing also affects the amorphous outer regions of alumina. Although the majority of the coatings appear to be preserved as the amorphous phase, the composition (Al at.%/O at.%=40/60) is different from that in the initial tubes (Al at.%/O at.%=30/70). This outcome is quite interesting, since the ALD reaction based on water-TMA thermal interaction is expected to provide a stoichiometric Al₂O₃ film. Nevertheless, such high initial content of oxygen in the deposited alumina can be explained by the absorption of water inside the Si template during the ALD process. Post-annealing removes this water leaving the alumina with the predicted ratio (2:3). Moreover, Fig. 8(b) shows characteristic shoulders on Zn, Al and O elemental line profiles of the annealed sample, which is a consequence of the diffusion process (Kirkendall effect). Composition stoichiometry extracted from Fig. 8(b) highly suggest the formation of ZnAl₂O₄ spinel. The thickness of the spinel layer can be estimated from the HAADF image of the annealed sample [Fig. 7(a)] and the chemical composition is provided by EDS [Fig. 8(b)]. Despite the excess of initial Al₂O₃ and ZnO and prolonged annealing, it does not exceed 20 nm. This limitation needs to be addressed in future fabrication designs.
FIG. 7. STEM HAADF, ADF and EDS quantitative maps of the annealed sample. (a) HAADF image. (b) ADF image. (c) STEM HAADF image of the measured area, (d) - (f) Oxygen, Aluminum, and Zinc elemental maps.
IV. SUMMARY AND CONCLUSIONS

To summarize, high aspect ratio arrays of isolated nanotubes were fabricated by combining deep-UV lithography, ALD, and DRIE techniques. The diffusion of ZnO into amorphous alumina was studied by various TEM techniques using FIB extracted lamellas. The work demonstrates a new and generic fabrication method to create and thermally manipulate the inner composition of all-dielectric multilayered nanotubes.
Realized annealed structures clearly show the diffusion of ZnO into surrounding amorphous alumina and partial transformation to crystalline ZnAl₂O₄ spinel structure. It demonstrates that a complex material multilayer can undergo multidirectional diffusion and formation of the prescribed periodic spinel. The total thickness of the ZnAl₂O₄ region is approximately 20 nm.

As for the outlook, further work is needed for understanding the details of the diffusion kinetics. Improved annealing conditions and post-treatment methods need to be developed if fully separated, continuous, and pin-hole free multilayers are required. Additionally, in the ALD deposition step other precursors, such as O₃ need to be considered, to eliminate the presence of absorbed water in the structures and reduce analysis complexity. Further studies on the applications of these transformed nanotubes are in progress.

ACKNOWLEDGMENTS

Firstly, the authors gratefully acknowledge Takeshi Kasama for all the work done on TEM analysis of the prepared structures. Without his help and knowledge, it wouldn't be possible to complete this work. The authors would like to thank process specialists from National Centre for Nano Fabrication and Characterization (DTU Nanolab) M. Keil and E. Khomtchenko for the support related to deep UV lithography. The authors would like to acknowledge Villum Fonden (DarkSILD project No. 11116); Direktør Ib Henriksens Fond, Denmark for financial support.


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