



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Bespalova, Kristina; Nieminen, Tarmo; Gabrelian, Artem; Ross, Glenn; Paulasto-Kröckel, Mervi

In-Plane AIN-based Actuator: Toward a New Generation of Piezoelectric MEMS

Published in: Advanced Electronic Materials

DOI: 10.1002/aelm.202300015

Published: 01/08/2023

Document Version Publisher's PDF, also known as Version of record

Published under the following license: CC BY

Please cite the original version: Bespalova, K., Nieminen, T., Gabrelian, A., Ross, G., & Paulasto-Kröckel, M. (2023). In-Plane AlN-based Actuator: Toward a New Generation of Piezoelectric MEMS. *Advanced Electronic Materials*, *9*(8), Article 2300015. https://doi.org/10.1002/aelm.202300015

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.



Optimizing Interface Conductivity in Electronics



E*₩*IDENT

OLYMPUS

WILEY

The latest eBook from Advanced Optical Metrology. Download for free.

Surface roughness is a key parameter for judging the performance of a given material's surface quality for its electronic application. A powerful tool to measure surface roughness is 3D laser scanning confocal microscopy (LSM), which will allow you to assess roughness and compare production and finishing methods, and improve these methods based on mathematical models.

Focus on creating high-conductivity electronic devices with minimal power loss using laser scanning microscopy is an effective tool to discern a variety of roughness parameters.





In-Plane AIN-based Actuator: Toward a New Generation of Piezoelectric MEMS

Kristina Bespalova,* Tarmo Nieminen, Artem Gabrelian, Glenn Ross, and Mervi Paulasto-Kröckel

A novel design that utilizes aluminum nitride (AIN) piezoelectric thin films deposited on vertical surfaces for lateral motion and sensing is a step toward emerging multi-axial microelectromechanical systems (MEMS). This work demonstrates the fabrication process and potential applications of an in-plane moving piezoactuator. The actuator is excited using the inverse piezoelectric effect of the AIN thin film grown on the vertical surfaces of a Si cantilever. Lateral motion of the actuator is enabled when a voltage is applied between the top and bottom electrodes of the device, which are highly doped Si and titanium nitride thin film. The motion of the actuator is captured using scanning electron microscope.

1. Introduction

3D motion indicates unhindered finite motion in x, y, and z-axis direction, where x, y-axis (lateral) is in the plane of the device, and z-axis is in the out-of-plane (vertical) direction. Compact actuators, that can implement full 3D motion on micro- and nanoscale, are complex to design and fabricate. Microelectromechanical systems (MEMS) that enable 3D sensing and actuation frequently combine several devices. Each of these devices performs motion in one direction only, therefore, such MEMS usually hold a large space on a chip.^[1] Attempts to create small-size coupled 3D-moving device lead to a growing cross-axis sensitivity between different channels or so-called "mechanical crosstalk". Moreover, such MEMS usually have complex structure and low electromechanical coupling.^[1] Mechanical crosstalk together with a low sensitivity bring a degradation of the output signal, making MEMS of this type ineffective.

The development of a novel architecture for 3D motion in MEMS and nanoelectromechanical systems (NEMS) would open

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aelm.202300015

DOI: 10.1002/aelm.202300015

breaking prospects for a fabrication of state-of-the-art devices and technologies. Enhanced design not only brings opportunities for more accurate inertial sensing in autonomous vehicles or augmented and virtual reality systems but also for new types of MEMS/NEMS to the research field. For example, multiaxial motion on the nanoscale introduces new approaches to nanoswitches of complex design, optical beam steering devices, and gyroscopes.^[2–3] Moreover, nanoscale 3D motion can play a pivotal role in addressing the issue of multifunctional nanomanipulators that

move and configure nanosized particles, cells, and other biological objects.^[4] In addition, compact 3D MEMS would introduce novel inertial MEMS with superior accuracy and high functional density meaning large number of devices located on small surface area. For example, piezo half tuning fork MEMS gyroscope demonstrated in the work by Gabrelian et al.^[3] would require only 0.00846 mm² while other demonstrated gyroscopes with similar sensitivity occupy from 2 to 72 mm².

MEMS devices that employ piezoelectric effect for actuation (piezoactuators) have several strengths due to direct electromechanical coupling, small size, and small voltage that can be applied for driving. No high voltage drive or DC bias is required for the excitation of piezoactuators because an output signal is proportional to the change in stress.^[5] Moreover, piezoelectricbased MEMS (piezoMEMS) are less sensitive to the stiction, which is common for comb drive devices. Fabrication techniques for the out-of-plane moving piezoactuators have been thoroughly demonstrated previously,^[5–9] while the design for structures that implement 3D motion remains difficult to fulfill. One of the main challenges in the fabrication of a coupled 3D piezoMEMS device is the generation of the lateral motion. In-plane piezoactuator must have a piezoelectric layer with certain crystallographic orientation deposited on the vertical surfaces of a moving cantilever and a suitable electrical connection to this layer. The crystallographic orientation of the piezoelectric material must be chosen thus to maximize the piezoelectric effect capability. Twisting or tilting cannot be considered as a pure lateral motion, because in this case a vertical motion component still exists. Thus, design development for laterally driven piezoelectric-based actuators is becoming a pivotal link to fabrication of novel compact 3D piezoMEMS.

Aluminum nitride (AlN) is a well-known, lead-free, piezoelectric material. Using AlN thin films grown on vertical surfaces

K. Bespalova, T. Nieminen, A. Gabrelian, G. Ross, M. Paulasto-Kröckel School of Electrical Engineering, Department of Electrical Engineering and Automation Aalto University Tietotie 3, Espoo 02150, Finland E-mail: kristina.bespalova@aalto.fi

^{© 2023} The Authors. Advanced Electronic Materials published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.



2199 160x, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/aetm.202300015 by Aalto University, Wiley Online Library on (08/08/2023). See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

www.advelectronicmat.de





Figure 1. a) Schematic illustration of AIN crystal lattice, c-axis direction assigned. AIN films sandwiched on vertical Si surface between TE and BE: b) c-axis oriented textured and c) AIN films with no preferential orientation.

of Si cantilever one can get naturally bimorph and highly symmetrical structures, which can provide greater robustness and energy efficiency to the system.^[10] Laterally moving AlN-based actuator could have a small static amplitude, which can be utilized for nanoscale measurements, switching, and manipulation.

In this work, piezoelectrically driven AlN-based in-plane actuator is introduced for the first time. The fabrication process of the actuator is easily compatible with mass production and the structure can be used as a platform for a wide range of devices from energy harvesters and compact gyroscopes to nanoswitches and manipulators.^[3,11] In the Section 2 of this paper the AlN growth on the vertical surfaces and concept of the device fabrication are discussed. Section 3 contains detailed fabrication flow of the device and description of the characterization methods. Section 4 includes results and discussion on AlN microstructure, finite element analysis (FEA) simulation of the piezoactuator performance, and demonstration of the motion of the piezoactuator. The paper is concluded in the Section 5.

2. Concepts

2.1. AIN Growth on Vertical Surfaces

Deposition of AlN thin films on planar surfaces is already quite well optimized and studied process for out-of-plane motion.^[12] But 3D piezoMEMS would require piezoelectric thin films on high aspect ratio structures of patterned substrates to achieve lateral motion. Metals and oxides grown on vertical surfaces have already been integrated into some MEMS devices and moreover can be used, for example, in through silicon vias.^[13-15] Mean-

while, the deposition of piezoelectric films on vertical surfaces is much more challenging task and still not fully investigated for AlN. AlN thin films must meet certain criteria for piezoMEMS fabrication to gain the most effective movement in the in-plane direction.

First, the films should be conformal all over the surface determined for the deposition, i.e., have uniform thickness without gaps or pinholes. Unproportionally thin films increase chance of the dielectric breakdown and limit the maximum drive voltage. Second, AlN films must have good crystal quality and keep c-axis orientation perpendicular to the vertical surface of the device. c-axis oriented AlN with a large grain size and a narrow X-ray diffraction (XRD) rocking curve (XRC) around the (0002) reflection exhibit best piezoelectric properties.[11] The importance of the right orientation of AlN films on the vertical surfaces for the efficient work of a device is determined by the non-centrosymmetric wurtzite structure of AlN along c-axis or parallel to [0001] direction, as shown in Figure 1a. Thus, electric field should be aligned parallel to the c-axis of AlN for the maximum efficiency of the electromechanical coupling. Figure 1b demonstrates an example when textured caxis oriented AlN film is deposited on vertical surface of Si. The majority of the grains of the film have c-axis orientation perpendicular to vertical surface of Si. Thus, when the electric field is applied, the total deformation of the film is proportional to the applied voltage. The piezoelectric effect in AlN is averaged over all the grains, therefore reduction in crystal quality and orientation results in a reduction in electromechanical coupling and performance of the device, respectively. The effect of untextured polycrystalline AlN is demonstrated in Figure 1c.

Adv. Electron. Mater. 2023, 2300015

ADVANCED SCIENCE NEWS

www.advancedsciencenews.com

ADVANCED LECTRONIC MATERIALS

www.advelectronicmat.de

Table 1. Reported data on AIN deposited on vertical surfaces.

Growth method	Reference	Height/depth of the vertical surface and aspect ratio	Thickness on the sidewalls	0002 XRC, FWHM [°]	Orientation
PVD	R Tabrizian et al. ^[24–26]	20 µm	1. 220 nm 2. 458 nm	1. 1.65° 2. 1.95°	Grains are tilted to the sidewall surface normal 1. 38° 2. 30°
	M.Ramezani et al. ^[33-35]	20 µm	ND in the text. Roughly 800 nm from SEM bar	ND	Grains tilted with respect to the sidewall surface 41° and 53°
MOCVD	E. Österlund et al. ^[28]	100 μm, 1:1	160–40 nm, top to bottom	1.7°	c-axis of AIN are normal to vertical Si (111) planes
	V. Kuryatkov et. al. ^[27]	1–4 μm	100–80 nm, top to bottom	ND	c-axis of AIN are normal to vertical Si (111) planes
ALD	E. Österlund et al. ^[31]	100 μm, 1:1	Varies over the vertical surface from 100 to 126 nm	ND	Films are crystalline but lacking c-axis orientation
	X.Liu, et al. ^[32]	5.1 μm from SEM bar, 35:1	Varies over the vertical surface from 16.5 to 23.2 nm	ND	Suggesting a preferred (002) orientation

It was previously confirmed that the tilt of AlN grains affects piezoelectric response in sputtered AlN films significantly.^[15–21] It is also worth adding that AlN cannot be poled in the same way as ferroelectric materials, thus orientation of AlN films can be controlled only by growth parameters.

Table 1 summarizes reported data on AlN deposited on high aspect ratio structures. Physical vapor deposition (PVD) of AlN and mainly sputtering does not require matching substrate lattice or high deposition temperatures.^[12] Therefore, the fabrication process of the device can be unlimited in the choice of electrode materials and substrates. But, at the same time, sputtering is a line-of-sight method that lacks conformal coverage when the deposition occurs on patterned substrates and sputtering tool has no wafer tilting option.^[22-23] Also, in sputtering the crystal orientation of the film depends on the tilt angle between the target and the substrate. Earlier works report on the uniform thickness of the AlN films sputtered on vertical surfaces, though AlN grains tilt to the vertical surface normal is large.^[24-26] Additionally, the structures demonstrated in these works do not have a large aspect ratio and the device's body is formed in such a way that there is no shadowing effect, which is not always possible.

Previous research has established that metalorganic chemical vapor deposited (MOCVD) AlN deposition on patterned Si (110) substrates demonstrates strong c-axis orientation perpendicular to Si (111) but lacking thickness uniformity.^[27–28] However, the thickness of the MOCVD AlN films on the vertical surfaces decreases a lot over the growth area and the films are usually thicker on the top part of the structure which is closer to the showerhead of the reactor. There are several reasons of poor conformality of the MOCVD AlN films grown on vertical surfaces: low temperature, high pressure, and insufficiently fast access of precursors to the bottom of the trench (when the deposition is for wafers with cavities). Also, MOCVD AlN films often have pinholes even

when grown on planar surfaces.^[29] Moreover, for AlN, the temperature required for the growth is over 1000 °C, which is limiting materials that can be used in fabrication, for example as a bottom electrode. Additionally, high-temperature deposition results in large residual stresses in the films after the deposition. Furthermore, when using MOCVD, the crystal growth of the films depends on the substrate orientation a lot. This is mainly crucial for patterned substrates, where structures are formed by diverse etching methods and their surface is might not be ideally smooth. Consequently, a rough surface with a mismatching crystal lattice will result in the misorientation of AlN grains. Despite some of the limitations of this method, when the surface of the substrate is thoroughly prepared for the growth, MOCVD AlN films keep c-axis orientation and have higher crystal quality in general, when compared to other deposition methods.

High conformality is the main advantage of the atomic layer deposition (ALD) process compared to other CVD and PVD methods. Even though ALD is time-consuming and quite costly process, it has no analogs because of its repeatability, large area uniformity, low-temperature deposition possibilities, and stress-free films.^[30] However, previously achieved ALD AlN films had quite weak piezoelectric response due to existing of randomly oriented grains in addition to the preferentially [0001] oriented grains.^[31–32] Also, a strong relationship between underlying layer and AlN orientation has been reported.^[31]

In this work, MOCVD was used as a method for AlN deposition because of its superior capability for the growth of highquality textured c-axis oriented AlN on vertical surfaces.

2.2. Concept of the Device

A schematic illustration of the working principle and a concept of the in-plane motion of the actuator are shown in **Figure 2**.



ADVANCED ELECTRONIC MATERIALS

www.advelectronicmat.de

www.advancedsciencenews.com

(a) (b) Cantilever's motion when voltage applied between TE and BE Si cantilever Top electrode (TE) AIN thin films

Figure 2. Illustration of the device performance.

The device can be a cantilever structure with AlN thin film sandwiched between the top (TE) and bottom (BE) electrodes on the vertical walls of the Si cantilever, as shown in Figure 2a. When an electric field is applied, the crystal lattice of AlN deforms due to the charge separation along the c-axis, which empowers the in-plane motion of the cantilever as demonstrated in Figure 2b.

Deposition of piezoelectric AlN on the lateral surfaces is required to acquire 3D motion. Additional TE/AlN films might be placed on the top of lateral surface of the cantilever in a similar way as shown in **Figure 3a**. Thus, AlN on the top of the cantilever enables out-of-plane motion when applying voltage on the top electrode (TE2 in Figure 3a) and in-plane motion is possible when applying voltage to the sidewall drive electrodes (TE1 and TE3 in Figure 3a). The piezoelectric effect is inverse, so piezoactuator can be transformed into energy harvester by adding proof mass to the free end of the cantilever as shown in Figure 3b. The harvested energy output can be maximized if the harvesters are placed in an array.

For the fabrication of piezoelectric actuators and harvesters, silicon-on-insulator (SOI) wafer can be used as a starting platform. Cantilevers can be formed in a device layer of SOI, and a handle wafer can be etched through for the devices' release at the end of the fabrication process.

In this paper, special terminology is used to describe different parts of the device during the fabrication. All parts of the piezoactuator are shown in **Figure 4**. As was mentioned in



Figure 3. Illustration of the multiaxial MEMS device performance: a) 3D piezoactuator, b) multiaxial energy harvester.

www.advancedsciencenews.com

CIENCE NEWS





Figure 4. Designation of the main parts of the device on the schematic illustration of the structure.

the chapter AlN growth on vertical surfaces, in this work MOCVD was used for the deposition of AlN films. MOCVD requires high temperatures for high-quality AlN growth. Hence, to avoid utilization of high-melting-point metals, SOI wafers with highly doped device layer were used. Highly doped Si operates as a substrate for the cantilever formation and BE simultaneously.

Cavities-first approach is a contemporary idea that was integrated into the fabrication flow of the piezoactuator. Such approach requires that cavities in the device layer of SOI are formed prior to thin film deposition, while conventional fabrication paths operate with thin films deposited on planar surfaces followed by cavity etching and element release. The area between cavities forms future cantilevers, as shown in Figure 4b. Si-bridge area separates two cantilevers and provides isolation between future TEs on the left and right side of a cantilever. **Figure 5** shows SEM micrographs of the released piezoactuators.

3. Results and Discussion

3.1. Conformality and Microstructure Analysis of AIN

Table 2 presents the results obtained from high-resolution XRD scan on MOCVD AlN/Si(111) structures. As can be seen from the table, AlN films are high-quality crystalline with c-axis orientation. In the work by Österlund et al.,^[28] was demonstrated that c-axis oriented growth of MOCVD AlN on blank Si (111) wafers indirectly indicates that AlN films keep c-axis orientation when grown on vertical surfaces with surface roughness 2.0 ± 1.4 nm using the same growth parameters. Thus, same deposition parameters were used for AlN growth on the vertical surfaces of the piezoelectric cantilever.

The measured profiles of the AlN film on vertical sidewalls showed that the thickness of the film decreases from 750 to 166 nm from the top to bottom of the cantilever's wall after 7000 s of growth. AlN films thickness profile remains same for



Figure 5. SEM micrographs of the fabricated device.

SCIENCE NEWS _____ www.advancedsciencenews.com

www.advelectronicmat.de

			2θ–ω		0002	2 XRC
Growth time, [s]	Thickness, [nm]	2θ (°)	FWHM, [°]	d, [Å]	ω [°]	FWHM, [°]
1860	300	36.1	0.11	2.48	18.02	1.320
3600	500	36.1	0.06	2.48	18.17	0.470
7000	1000	35.8	0.22	2.50	17.92	0.445

Table 2. High resolution XRD results of AlN films grown on the blank Si(111) substrates.

both types of samples: when the deposition is on patterns etched in ICP-RIE and KOH, as shown in **Figure 6**. EBSD results, as shown in **Figure 7**, demonstrate that the AlN film retains its crystal quality and c-axis texture on vertical sidewalls only for samples with KOH-etched cavities, while AlN grown on samples with dryetched cavities has poor crystal quality.

3.2. FEA Results

Figure 8 shows FEA simulated results of displacement in-plane direction for cantilevers with varying length and width when the drive voltage is equal to 10 V. The maximum amplitude of the

deflection along the length of the piezoactuator changes significantly with the change of AlN and TE's thickness. It can be seen from Figure 8a, that the maximum displacement for the piezoactuators, that have 300 nm TiN electrode and 1000 nm thick AlN piezolayer is 1.5 times higher than for the actuators of the same geometry with thinner TiN/AlN films. Reduction of the actuator's deflection value happens because of the increase in overall thickness of the structure when deposited thicker AlN and TEs so the cantilever became stiffer and thus more resistant to deformation. Same behavior of the actuator is demonstrated in Figure 8b when increasing the width of the cantilever only. The in-plane deflection increases exponentially when increasing



Figure 6. SEM micrographs of the cross-section of the not released piezoactuator and EDS maps of the non-patterned thin films: a) Cavities formed in ICP-RIE, b) Cavities formed in KOH.



www.advelectronicmat.de



Figure 7. EBSD maps and pole figures of AIN on vertical Si (111) surface. Vertical surface of Si (111) achieved by: a) dry etching in SF6 plasma, b) wet etching in KOH.

cantilever's length. In addition, out-of-plane displacement is negligible to the in-plane displacement, especially for long cantilevers, thus it was not represented on the graphs. Thereby, presented actuator is supposed to perform only lateral motion.

Table 3 summarizes simulated values of eigenfrequency f_r for the piezoelectric actuators obtained for varying length and width of the device. Thus, the required operational frequencies are in the range from 0.024 (0.028) to 1.694 (1.800) MHz.

3.3. Demonstration of the Actuator's Motion

Main fabrication steps of the piezoactuator are shown in **Figure 9**. Detailed fabrication steps described in Experimental Section.

Figure 10a shows general look of the fabricated piezoactuators during motion testing. Figure 10b demonstrates actuators (A1 and A2) in the normal state, i.e., no voltage applied on any of the piezoactuators. In Figure 10c, a 1 Hz sine wave with $V_{DC} = 0$ V bias and $V_{pp} = 20$ V amplitude was applied on the TE of the actuator A2, while BE was grounded. Figure 10c demonstrates that A2 was set in motion since moving objects in the SEM are captured as disjoined parts. At the same time, A1 remained motionless. Also, the amplitude of the motion of A2 strongly depends on the amplitude of the applied signal. The structure can be set in motion selectively, and individual devices are isolated from each other. However, it is noticeable that the motion of A2 is not purely lateral and displacement along the y-axis of the actuator exists.

Table 3. Simulated values of resonance frequency for the actuators with varying length and width.

Length, [nm]	Width, [µm]	Resonance frequency f_r , MHz		
		AlN = 300 nm, TE = 100 nm	AIN = 1000 nm, TE = 300 nm	
200–1100	20	0.732–0.024	0.833–0.028	
	30	1.063-0.035	1.169–0.039	
	40	1.385–0.047	1.491-0.051	
	50	1.694–0.058	1.800–0.062	





Figure 8. Simulated curves. Comparison of the maximum displacement: a) Actuators of the same geometries but with varying length. Displacement is in *x*-axis direction. b) Maximum displacement at varying width of the cantilever.

To find the value of the cantilever's displacement along the x-axis, method that combines series of SEM images of the motion described in the work by Nieminen et al.,^[36] was used. For the calculations combined image formed from the set of 50 micrographs of the structure shown in Figure 10d was used. The calculated displacement of the actuator was 1.4 μ m which is much higher than simulated amplitude of 70 nm.

3.4. Potential Reasons for the Discrepancy between the Simulated and Observed Deflection

The observed displacement for the piezoactuator is $1.4 \mu m$ and differs with the simulated deflection amplitude. As potential reasons for the discrepancy between the simulated and observed deflection, we consider the following influences:

3.4.1. Surface Charge in SEM

Electrical probing in SEM was found to add sources of error in the measurement. For example, the surface charge caused by the electrical actuation might create noticeable motion in the image.

3.4.2. Imperfection of TiN as Electrode Material

TiN has been shown to be used as an electrode material for AlN films previously.^[37–39] However, ALD TiN application as an electrode material for piezoelectric MEMS actuation is not sufficiently covered in literature. TiN interaction with AlN piezoelectric films should be complimentary studied. For example, it has been previously reported that TiN/AlN systems can be unstable at certain conditions,^[40] and affect piezoelectric properties of AlN.^[41–42] As an alternative for TE material, another conventional conductive material should be considered for application, e.g., Al or Mo.

www.advelectronicmat.de

4. Conclusion

In conclusion, this work has demonstrated the fabrication flow for the first AlN-driven in-plane actuator. This work examined the impact of the cantilever's geometry on the maximum displacement amplitude and resonance frequency of the actuator using finite element method simulations. The motion of the fabricated actuators was registered in the SEM.

The main goal of this work was to demonstrate the completed design of the device that performs lateral motion of the released cantilever utilizing as a drive force piezoelectric properties of AlN thin films deposited on the vertical surfaces. The design of the presented device might be adapted for the fabrication of more complex 3D piezoMEMS. The work will be continued on displacement measurement procedures and design optimization in the future.

5. Experimental Section

Fabrication of the Piezoactuator: Thick 1 μ m wet thermal oxide SiO₂ layer was formed on the device layer and the handle wafer of SOI wafers. Cavities formation in the device layer was implemented using two different approaches: dry and wet etching. Dry etching was conducted using cryo-etching in inductively coupled plasma RIE (ICP-RIE)







Figure 9. Illustration of the fabrication line of the device and picture of the device area with corresponding terms. a) Cavities formation in the device layer of SOI. b) AIN/TiN deposition, patterning, and etching. c) Si-bridge patterning using SU8. d) Si-bridge etching. e) Cantilever's release.



Figure 10. SEM micrographs of two actuators: a) Top view of the piezoactuators. b) No voltage applied. c) Voltage applied only on A2 (20 V, 1 Hz). d) Selectively combined image formed out from the set of 50 microphotographs.

ADVANCED SCIENCE NEWS

www.advancedsciencenews.com

Table 4. Design parameters.

Parameter name	Values	Description	
AIN thickness	300, 1 μm	Thickness of the piezoelectric film on the vertical surfaces of the actuator	
TE (TiN) thickness	100, 300 nm	Thickness of the top electrodes	
L	200 1000 nm	Length of the actuator. Step: 100 nm	
W	20, 30, 40, 50 μm	Width of the actuator	
h	50 μm	Height of the actuator, thickness of the device layer	

Plasmalab 100. Etching was done in sulfur hexafluoride SF₆ (40 sccm) and oxygen O₂ (6 sccm) plasma at -110 °C. Wet etching was implemented in potassium hydroxide (KOH) 40 wt.% aqueous solution at 70 °C for 66 min.

After that, textured AIN films were deposited on patterned substrates using Aixtron 1 × 4" close-coupled showerhead MOVPE. First, the wafer is being annealed for 5 min in hydrogen (H₂) and 10 more minutes in disilane (Si₂H₆) at 1025 °C and 300 mbar reactor pressure. Nitridation was done under ammonia (NH₃) atmosphere for 15 s at 100 mbar and substrate temperature 980 °C. NH₃ gas flow was 15 sccm. Trimethylaluminium (TMAI) and NH₃ were used as precursors for aluminum and nitrogen, respectively. AIN was grown at 1085 °C substrate temperature in pressure of 100 mbar with H₂ carrier gas. V/III ratio was kept 336.05 during both low-temperature (LT) and high-temperature (HT) AIN growth. Substrate temperature setpoint for LT and HT AIN was 980 and 1085 °C, respectively. Crystal quality of AIN films deposited on vertical surfaces formed using different etching approaches was discussed in 3.1. conformality and microstructure analysis of AIN.

On the top of MOCVD AIN, TiN was deposited in ALD reactor Picosun SUNALE R-200 Advanced. The deposition was implemented in thermal mode of the reactor. As precursors titanium tetrachloride (TiCl₄) and TMAI were used. TiCl₄ was used for 0.1 s pulse and 6 s purge under 80 sccm flow. TMAI was used for 0.1 s pulse and 3.6 s purge under 60 sccm flow. Deposition was implemented at 450 °C.

Further, the structure was patterned as shown in Figure 9g,h using thick layer of SU-8 50 for the etching of the Si-bridge area. First, AIN/TiN layers were etched using gas mixture of chlorine (18 sccm) and argon (6 sccm) in ICP-RIE. Then, underlaying Si was etched away using BOSCH-process in STS Deep RIE Etcher. Etching step was done in SF₆ (130 sccm) and O₂ (13 sccm) with coil power $P_{coil} = 600$ W and bias power $P_{bias} = 12$ W. Octafluorocyclobutane (C₄F₈) was used for a passivation step. C₄F₈ gas flow was 85 sccm at $P_{coil} = 600$ W and $P_{bias} = 0$ W.

Hereafter, the wafer was patterned for TE formation, as shown in Figure 9i,j. For TEs formation, AlN/TiN were etched using same procedure as described for Si-bridge etching. Cantilevers were released via through handle wafer DRIE in SF₆/O₂ using same etching conditions as for Si-bridge etching.

Characterization of the Materials and Device Performance: The crystal quality of AlN thin films on blank Si (111) wafers was measured using XRD Rigaku SmartLab. Symmetrical $2\theta-\omega$ and XRC were measured around the 0002 reflection. The thickness of the films was measured using a spectroscopic ellipsometer. For orientation assessment of the films on the sidewalls electron backscatter diffraction (EBSD) method was used.

To investigate the effect of the actuator's geometry on the resonance frequency and deflection value of the device, finite-element-modeling (FEM) was used in "Solid Mechanics" and "Electrostatics" interfaces of COMSOL Multiphysics. Design parameters were taken from **Table 4**. www.advelectronicmat.de

Motion tests of the fabricated actuators were implemented using Imina Technologies nanoprobing station for in situ electrical measurements. Displacement measurements were conducted in Zeiss Supra 40 SEM chamber at the vacuum level.

Acknowledgements

The authors acknowledge Ms. Heli Seppänen for her help with ALD, and Dr. Victor Ovchinnikov for his help with dry etching processing. This work has been carried out as part of ECSEL18 Project NewControl, which received funding within the Electronic Components and Systems For European Leadership Joint Undertaking (ESCEL JU) in collaboration with the European Union's Horizon2020 Framework Programme and National Authorities, under grant agreement no. 826653-2. The authors would like to acknowledge the Innovation Funding Agency Business Finland for their financial support. The authors acknowledge the provision of facilities and technical support of Aalto University at OtaNano Nanomicroscopy Center (Aalto-NMC). K.B. acknowledges support from the HPY Research Foundation, and the Foundation of Electronics Engineers (Elektroniikkainsinöörien Säätiö).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

aluminum nitride, in-plane motion, MEMS, piezoelectric, thin films

Received: January 11, 2023 Revised: March 15, 2023 Published online:

- [1] J. O. Templeman, B. B. Sheil, T. Sun, Sens. Actuators, A **2020**, 304, 111772.
- [2] L. Midolo, A. Schliesser, A. Fiore, Nat. Nanotechnol. 2018, 13, 11.
- [3] A. Gabrelian, G. Ross, K. Bespalova, M. Paulasto-Kröckel, Mater. Today Commun. 2022, 33, 104522.
- [4] A. G. Banerjee, S. K. Gupta, IEEE Trans Autom Sci Eng 2013, 10, 485.
- [5] V. Kaajakari, Practical MEMS: Analysis and Design of Microsystems, MEMS Sensors, Electronics, Actuators, RF MEMS, Optical MEMS, and Microfluidic Systems, Small Gear Publishing, Las Vegas 2009.
- [6] L. Huang, W. Li, G. Luo, D. Lu, L. Zhao, P. Yang, X. Wang, J. Wang, Q. Lin, Z. Jiang, *Microsyst. Nanoeng.* 2022, 8, 38.
- [7] N. Sinha, G. E. Wabiszewski, R. Mahameed, V. V. Felmetsger, S. M. Tanner, R. W. Carpick, G. Piazza, *Appl. Phys. Lett.* **2009**, *95*, 053106.
- [8] R. B. Karabalin, M. H. Matheny, X. L. Feng, E. Defaÿ, G. Le Rhun, C. Marcoux, S. Hentz, P. Andreucci, M. L. Roukes, *Appl. Phys. Lett.* 2009, 95, 103111.
- [9] Ü. Sökmen, A. Stranz, A. Waag, A. Ababneh, H. Seidel, U. Schmid, E. Peiner, J. Micromech. Microeng. 2019, 20, 064007.
- [10] S. Yoshikawa, E. Saarmaa, N. Kottenstette, R. Jacques, J Acoust Soc Am 1998, 104, 1828.
- [11] C. Fei, X. Liu, B. Zhu, D. Li, X. Yang, Y. Yang, Q. Zhou, Nano Energy 2018, 51, 146.

ADVANCED SCIENCE NEWS





www.advelectronicmat.de

- [12] H. Bhugra, G. Piazza, *Piezoelectric MEMS Resonators*, Springer International Publishing, New York, USA 2017.
- [13] W. W. Shen, K. N. Chen, Nanoscale Res. Lett. 2017, 12, 1.
- [14] T. Blanquart, J. Niinistö, M. Gavagnin, V. Longo, M. Heikkilä, E. Puukilainen, V. R. Pallem, C. Dussarrat, M. Ritala, M. Leskelä, *RSC Adv.* 2013, *3*, 1179.
- [15] M. Koyanagi, T. Fukushima, T. Tanaka, Proc IEEE Inst Electr Electron Eng 2009, 97, 49.
- [16] P. Muralt, in Piezoelectric MEMS Resonators. Microsystems and Nanosystems, (Eds.: Bhugra, H., Piazza, G.), Springer, Cham 2017.
- [17] P. Muralt, J. Conde, A. Artieda, F. Martin, M. Cantoni, Int. J. Microw. Wirel. Technol. 2009, 1, 19.
- [18] H. P. Löbl, M. Klee, R. Milsom, R. Dekker, C. Metzmacher, W. Brand, P. Lok, J. Eur. Ceram. Soc. 2001, 21, 2633.
- [19] J. Bjurstrom, D. Rosen, I. Katardjiev, V. M. Yanchev, I. Petrov, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 2004, 51, 1347.
- [20] H. P. Loebl, M. Klee, C. Metzmacher, W. Brand, R. Milsom, P. Lok, Mater. Chem. Phys. 2003, 79, 143.
- [21] S. Mishin, D. R. Marx, B. Sylvia, V. Lughi, K. L. Turner, D. R. Clarke, in *IEEE Symp. Ultrason.*, IEEE, Manhattan, New York 2003, pp. 2028–2032.
- [22] A. L. Thomann, C. Vahlas, L. Aloui, D. Samelor, A. Caillard, N. Shaharil, R. Blanc, E. Millon, *Chem. Vap. Deposition* **2011**, *17*, 366.
- [23] S. M. Rossnagel, J. Vac. Sci. Technol., A 2020, 38, 060805.
- [24] R. Tabrizian, F. Ayazi, in 2011 16th Int. Solid-State Sens., Actuators Microsyst. Conf., IEEE, Manhattan, New York 2011, pp. 1520–1523.
- [25] R. Tabrizian, F. Ayazi, in Proc. 2011 Jt. Conf. IEEE Int. Freq. Control Eur. Freq. Time Forum (FCS), IEEE, Manhattan, New York 2011, pp. 1–4.
- [26] R. Tabrizian, F. Ayazi, in Proc. 2nd International Workshop on Piezoelectric MEMS, Lausanne, 2011.
- [27] V. V. Kuryatkov W, M. P. Feng, J. H. Woo, D. Garcia, H. R. Harris, S. A. Nikishin, M. Holtz, Appl. Phys. Lett. 2010, 96, 073107.

- [28] E. Österlund, S. Suihkonen, G. Ross, A. Torkkeli, H. Kuisma, M. Paulasto-Kröckel, J. Cryst. Growth 2020, 531, 125345.
- [29] W. Tian, W. Y. Yan, J. N. Dai, S. L. Li, Y. Tian, X. Hui, J. B. Zhang, Y. Y. Fang, Z. H. Wu, C. Q. Chen, J. Phys. D: Appl. Phys. 2013, 46, 065303.
- [30] V. Cremers, R. L. Puurunen, J. Dendooven, Appl. Phys. Rev. 2019, 6, 021302.
- [31] E. Österlund, H. Seppänen, K. Bespalova, V. Miikkulainen, M. Paulasto-Kröckel, J. Vac. Sci. Technol., A 2021, 39, 032403.
- [32] T. Nguyen, N. Adjeroud, S. Glinsek, Y. Fleming, J. Guillot, P. Grysan, J. Polesel-Maris, APL Mater. 2020, 8, 071101.
- [33] M. Ramezani, V. V. Felmetsger, N. G. Rudawski, R. Tabrizian, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 2020, 68, 753.
- [34] M. Ramezani, M. Ghatge, R. Tabrizian, presented at 2017 IEEE Int. Electron Devices Meet. (IEDM), Manhattan, New York, December 2017.
- [35] M. Ramezani, M. Ghatge, V. Felmetsger, R. Tabrizian, in 2019 IEEE MTT-S Int. Microw. Symp. (IMS), IEEE, Manhattan, New York 2019, pp. 516–519.
- [36] T. Nieminen, N. Tiwary, G. Ross, M. Paulasto-Kröckel, Micromachines 2023, 14, 698.
- [37] G. F. Iriarte, J. Bjurstrom, J. Westlinder, F. Engelmark, I. V. Katardjiev, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 2005, 52, 1170.
- [38] M. Akiyama, T. Kamohara, N. Ueno, M. Sakamoto, K. Kano, A. Teshigahara, N. Kawahara, *Appl. Phys. Lett.* 2007, *90*, 151910.
- [39] Z. Zhang, B. Gao, Z. Fang, X. Wang, Y. Tang, J. Sohn, H.-S. P. Wong, S. S. Wong, G. Q. Lo, *IEEE Electron Device Lett.* **2014**, *36*, 29.
- [40] C. Stampfl, A. J. Freeman, Appl. Surf. Sci. 2012, 258, 5638.
- [41] H. Y. Lee, S. Y. Lee, K. S. Chang, Ceram. Int. 2019, 45, 22744.
- [42] E. Iborra, J. Capilla, J. Olivares, M. Clement, V. Felmetsger, in 2012 IEEE Int. Ultrason. Symp., IEEE, Manhattan, New York 2012, pp. 2734–2737.