Electrochemical etching of AlGaN for the realization of thin-film devices

Downloaded from: https://research.chalmers.se, 2020-02-01 07:54 UTC

Citation for the original published paper (version of record):
Bergmann, M., Enslin, J., Yapparov, R. et al (2019)
Electrochemical etching of AlGaN for the realization of thin-film devices
Applied Physics Letters, 115(18): 182103-
http://dx.doi.org/10.1063/1.5120397

N.B. When citing this work, cite the original published paper.
Electrochemical etching of AlGaN for the realization of thin-film devices

Cite as: Appl. Phys. Lett. 115, 182103 (2019); https://doi.org/10.1063/1.5120397
Submitted: 17 July 2019. Accepted: 15 October 2019. Published Online: 30 October 2019

Michael A. Bergmann, Johannes Enslin, Rinat Yapparov, Filip Hjort, Björn Wickman, Saulius Marcinkevičius, Tim Wernicke, Michael Kneissl, and Åsa Haglund

COLLECTIONS

F This paper was selected as Featured

ARTICLES YOU MAY BE INTERESTED IN

12 GHz spontaneous optical bandwidth tunnel junction light-emitting transistor
Applied Physics Letters 115, 181102 (2019); https://doi.org/10.1063/1.5124959

Effect of hydrogen derived from oxygen source on low-temperature ferroelectric TiN/Hf0.5Zr0.5O2/TiN capacitors
Applied Physics Letters 115, 182901 (2019); https://doi.org/10.1063/1.5126144

High power surface emitting InGaN superluminescent light-emitting diodes
Applied Physics Letters 115, 171102 (2019); https://doi.org/10.1063/1.5118953
Electrochemical etching of AlGaN for the realization of thin-film devices

Michael A. Bergmann,1,a) Johannes Enslin,2 Rinat Yapparov,3 Filip Hjort,1 Björn Wickman,4 Saulius Marcinkevičius,3 Tim Wernicke,2 Michael Kneissl,2 and Åsa Haglund1

AFFILIATIONS
1Department of Microtechnology and Nanoscience, Chalmers University of Technology, 41296 Gothenburg, Sweden
2Institute of Solid State Physics, Technische Universität Berlin, 10623 Berlin, Germany
3Department of Applied Physics, KTH Royal Institute of Technology, 16440 Kista, Sweden
4Department of Physics, Chalmers University of Technology, 41296 Gothenburg, Sweden

a)michael.bergmann@chalmers.se

ABSTRACT
Heterogeneously integrated AlGaN epitaxial layers will be essential for future optical and electrical devices like thin-film flip-chip ultraviolet (UV) light-emitting diodes, UV vertical-cavity surface-emitting lasers, and high-electron mobility transistors on efficient heat sinks. Such AlGaN-membranes will also enable flexible and micromechanical devices. However, to develop a method to separate the AlGaN-device membranes from the substrate has proven to be challenging, in particular, for high-quality device materials, which require the use of a lattice-matched AlGaN sacrificial layer. We demonstrate an electrochemical etching method by which it is possible to achieve complete lateral etching of an AlGaN sacrificial layer with up to 50% Al-content. The influence of etching voltage and the Al-content of the sacrificial layer on the etching process is investigated. The etched N-polar surface shows the same macroscopic topography as that of the as-grown epitaxial structure, and the root-mean square roughness is 3.5 nm for 1 µm x 1 µm scan areas. Separated device layers have a well-defined thickness and smooth etched surfaces. Transferred multi-quantum-well structures were fabricated and investigated by time-resolved photoluminescence measurements. The quantum wells showed no sign of degradation caused by the thin-film process.

AlGaN is used in a variety of devices for different applications such as ultraviolet C (UVC) light-emitting diodes (LEDs) for water purification and high-electron mobility transistors (HEMTs) for high power applications. By separating the device layers from their substrates, the device performance can be improved and more advanced device concepts can be realized such as thin-film flip-chip LEDs, vertical-cavity surface-emitting lasers (VCSELs) with double dielectric distributed Bragg reflectors, high-quality microring resonators, photonic crystal resonators, and HEMTs on efficient heat sinks or flexible substrates. However, achieving lift-off of AlGaN device layers from the substrate has proven to be challenging.

Until now, most substrate removal attempts for AlGaN-based optical devices have focused on laser induced lift-off. AlGaN-based thin-film ultraviolet (UV) LEDs have been fabricated by either laser lift-off of GaN or AlGaN to remove the substrate. Thermal decomposition of GaN is an established process, but a GaN sacrificial layer does not allow for the growth of AlGaN device layers on top with a high crystalline quality due to the lattice mismatch, leading to cracking of the AlGaN layer and thus strongly limiting the aluminum content and layer thickness. Using a sacrificial layer of AlGaN instead would ensure a high crystalline quality of the device layers. However, the decomposition of AlGaN yields rigid aluminum residues that are difficult to remove. In addition, strained epitaxial layers have a tendency to crack when exposed to elevated temperatures during laser irradiation. Additionally, laser lift-off creates rough surfaces and it is not possible to accurately control the thickness. Therefore, it is not an optimal method for optical devices such as VCSELs and microring resonators that require low scattering losses and precise control of modal properties, i.e., the membrane thickness.

A promising method to achieve GaN and AlGaN membranes with a low surface roughness and epitaxially defined thickness is doping-selective electrochemical etching of sacrificial GaN layers. This technique has been used to realize various thin-film devices like AlGaN-based HEMTs, AlGaN-based microring resonators, and
piezoelectric energy harvesters. Depending on the doping concentration in the GaN sacrificial layer and the applied voltage during the electrochemical etching, the sacrificial layer can either be completely etched or porosified. To enable AlGaN-based devices with a high crystalline quality and high aluminum content, the sacrificial layer should be of AlGaN rather than GaN to avoid strain relaxation and formation of threading dislocations. There are so far only a few reports on porosification of AlGaN by electrochemical etching. In this work, we demonstrate electrochemical etching of AlGaN with an Al content of up to 50% and investigate the dependence of the morphology of the sacrificial layer after the etching on the applied etching voltage and the Al-composition. Furthermore, we show the usability of this method for the realization of thin-film devices by the transfer of a multi-quantum-well (MQW) containing structure and the optical characterization of the transferred device layers.

The epilayer layers were grown on a relaxed n-doped Al<sub>x</sub>Ga<sub>1-x</sub>N:Si pseudosubstrate with a doping level of [Si] = 2 × 10<sup>19</sup> cm<sup>-3</sup> on top of a c-plane AlN/sapphire substrate by metal organic vapor phase epitaxy in a close coupled showerhead reactor. This n-doped template ensures a uniform electrochemical etching across the sample by spreading the current. On top of the template, a 225 nm n-Al<sub>x</sub>Ga<sub>1-x</sub>N etch stop layer with a reduced doping of [Si] = 0.5 × 10<sup>18</sup> cm<sup>-3</sup> was grown to prevent etching of the doped template. The next layer is a 130 nm n-Al<sub>x</sub>Ga<sub>1-x</sub>N layer, which serves as the sacrificial layer with a doping level of [Si] = 2 × 10<sup>19</sup> cm<sup>-3</sup> and an Al-composition x = [11%, 27%, 39%, 50%] for four different samples. The doping level was the same in all samples and was chosen to be as high as possible while still ensuring a high layer quality, to achieve a large etch selectivity between the sacrificial layer and the etch stop layers. The last layer on top of the sacrificial layer is an unintentionally doped Al<sub>x</sub>Ga<sub>1-x</sub>N layer with a thickness of 580 nm for the samples with an Al-composition x = [27%, 39%, 50%] in the sacrificial layer and 1900 nm for the samples with an Al-composition of x = 11% in the sacrificial layer. High resolution X-ray diffraction investigations of the grown samples show pseudomorphically grown sacrificial layers and Al<sub>x</sub>Ga<sub>1-x</sub>N:Si layers on top of the pseudosubstrate for all sacrificial layer compositions.

Figure 1(a) shows the sample design that was used for the electrochemical etching series. The sample fabrication started with dry etching of via holes with a diameter of 10 μm in a 7 × 9 array with a pitch of 400 μm using chlorine-based inductively coupled plasma reactive-ion etching (ICP-RIE) into the current spreading layer to fully expose the sacrificial layer. To apply a bias voltage to the sample during the electrochemical etching, a V/Al/V/Au (15/80/20/95 nm) contact to the n-AlGaN current spreading layer was formed using e-beam evaporation and lift-off. The n-contact was annealed at 700 °C in a N<sub>2</sub> atmosphere to reduce the contact resistance. In the last step, the top surface of the formed mesa structure was protected with a 1.3-μm thick S1813 photoresist. Electrochemical etching was performed using a BioLogic SP-300 potentiostat in a three-electrode setup as illustrated in Fig. 1(b). The electrolyte, 0.3 M nitric acid, was constantly stirred during the etching process using a magnetic stir bar. A constant positive potential was applied to the AlGaN sample, which served as the working electrode (WE) relative to a Ag/AgCl reference electrode (RE) and a graphite rod that was used as the counter electrode (CE) to regulate the current flow. The applied etching voltages were +15 V, +20 V, +25 V, and +30 V relative to the Ag/AgCl reference electrode. During the etching, no intentional heating or illumination was used. The exposed part of the sample was the via array and the edge of the 5 mm × 10 mm sample. Etching currents were in the low milliampere range [see Fig. 1(c)] and showed a similar trend to that reported in previous works. After the etching process, the samples were rinsed with de-ionized water and left to dry in air.

Figure 2 shows an optical microscopy image of a sample with a sacrificial layer containing 11% Al after electrochemical etching for two and five minutes at 30 V vs Ag/AgCl ref. In Fig. 2(a), the bright circular areas depict the parts where the sacrificial layer is etched. As seen, the lateral etching that is initiated in the via holes proceeds isotropically. Therefore, the etch front area increases, and with that, also the current increases [compare Fig. 1(c)]. However, the etching current also contains contributions from etching at the sample edge.

![Figure 1](image1.png)

**Figure 1.** Schematic of (a) the AlGaN sample structure, (b) the three-electrode setup used for the electrochemical etching, and (c) etching current vs time for etching an Al<sub>0.11</sub>Ga<sub>0.89</sub>N sacrificial layer at 30 V.

![Figure 2](image2.png)

**Figure 2.** Top view optical microscopy image of the sample with an Al<sub>0.11</sub>Ga<sub>0.89</sub>N sacrificial layer after electrochemical etching at 30 V for (a) 2 min and (b) 5 min.
Eventually, the etch fronts merge and a continuous air gap is formed [see Fig. 2(b)].

The morphology of the sacrificial layer after electrochemical etching was studied in the cross-sectional view utilizing scanning electron microscopy (SEM). Figure 3 shows the cross section of four samples, all having the same sacrificial layer with an Al content of 50%, but etched at different voltages. Only the sacrificial layer was etched, whereas the etch stop layers on top and bottom are not affected, i.e., not porousified. Considering that all three epitaxial layers in each sample have the same Al content, this confirms the doping dependent etch selectivity of the electrochemical etching process. A similar etch selectivity has previously been reported for GaN.10 The morphology of the sacrificial layer after the etching depends on the applied etching voltage. Complete etching was achieved for a sacrificial layer with an Al-content of 50% using an etching voltage of 30 V, as seen in the SEM image, which shows a continuous airgap and smooth etched surfaces. An etching voltage of 25 V yielded an almost completely removed sacrificial layer with few residues [see Fig. 3(b)]. Etching voltages of 20 V and 15 V, on the other hand, resulted in a porous sacrificial layer. Figures 3(c) and 3(d) show that the average pore diameter is larger at the higher voltage. The dependence of the etching rate, including the pore diameter on the applied etching voltage is similar to previous studies for GaN.10 In addition to the morphology dependence such as surface states in the semiconductor, interface charges,7 the influence of the Al content was investigated. Based on the morphology of the sacrificial layer after etching, all samples were categorized into complete etching of the sacrificial layer or porous etching. Figure 4 shows the dependence of the etching type on the Al content of the sacrificial layer and the applied etching voltage. The absolute values of the required bias voltage also include the different voltage drops at the contact and in the sample structure, which could not be quantified. The lateral etch rate was calculated based on optical microscopy images. It is on average around 40 μm/min for all samples for which the sacrificial layer is completely etched, except samples with an Al content of 50% in the sacrificial layer for which the rate was around 18 μm/min. The etch rate was lower in the samples where the sacrificial layer only got porousified with an etch rate below 10 μm/min. The correlation of the aluminum content of the sacrificial layer and the required etching voltage is due to the working principle of electrochemical etching, which is based on the generation of holes (h+) at the AlGaN/electrolyte interface. These holes oxidize AlGaN at the interface, and the oxidized material can be dissolved by the electrolyte. Based on the oxidation states of Al and Ga17 and previous works,5,28 the following reaction equation is proposed:

\[
2\text{Al}_x\text{Ga}_{1-x}\text{N} + 6\text{h}^+ \rightarrow 2x\text{Al}^{3+} + 2(1 - x)\text{Ga}^{3+} + \text{N}_2.
\]

The required holes (h+) are generated by Zener tunneling from the valence band to the conduction band and/or avalanche breakdown in the depletion region.19 The influence of the Al content on the Fermi level is negligible due to a similar donor ionization energy.19 Assuming a fixed redox level for the electrolyte, the built-in potential increases with the increasing Al content because the electron affinity decreases.20 Accordingly, the depletion region width in the semiconductor increases with the increasing Al content. To achieve tunneling from the valence band to the conduction band, the applied bias voltage including the built-potential has to exceed the bandgap. Therefore, the required bias voltage for the tunneling depends on the valence band edge position, which is consequently larger for the higher Al content. Further, the required bias voltage is also influenced by additional factors such as surface states in the semiconductor, interface charges,7 potential drop in the Helmholtz layer of the electrolyte, and geometrical factors in the setup, which reduce the conductivity of the electrolyte, which is beyond the scope of this work.

Fabricated membranes were investigated utilizing atomic force microscopy (AFM) to obtain the topography of the etched surface and photoluminescence (PL) to measure the membranes’ optical properties. The membranes were picked up using a thermal release tape on a Si carrier to access the etched N-polar side. Figure 5(a) shows the structure of the as-grown sample with 27% Al, and Fig. 5(d) shows an AFM scan of its top surface. The sample structure for the transferred membrane is illustrated in Fig. 5(b), an optical microscopy image of the transferred membrane is shown in Fig. 5(c), and an AFM image of the etched (N-polar) surface is shown in Fig. 5(e). Both AFM scans show the same macroscopic topography mainly dominated by large hillocks typical for AlGaN growth.17 Thus, the epitaxially defined morphology is conserved in the etching process. 1 μm × 1 μm AFM scan areas yield a root-mean square roughness of 3.5 nm after the electrochemical etching [see the inset of Fig. 5(e)].

To investigate that transferred devices are not affected by the electrochemical etching process, MQW structures were grown, underetched, transferred, and characterized. A 4 μm thick relaxed silicon doped Al0.37Ga0.63N pseudosubstrate34,35 with a Si concentration of 2 × 1018 cm−3 was grown. This was followed by a 130 nm thick Al0.37Ga0.63N/Si sacrificial layer.
layer with a Si-concentration of $2 \times 10^{19} \text{cm}^{-3}$, embedded into a 500 nm thick $\text{Al}_{x}\text{Ga}_{1-x}\text{N}:\text{Si}$ layer with a reduced Si-concentration of $0.5 \times 10^{19} \text{cm}^{-3}$. The Al content in the sacrificial layer was chosen as low as 37% to maximize the contrast to the surrounding layer but high enough to be transparent for the emitted light for on-wafer testing. On top of that, a $\text{Al}_{x}\text{Ga}_{1-x}\text{N}:\text{Si}$ current spreading layer for barriers with an Al-content of 30%. Subsequently, an $\text{Al}_{0.75}\text{Ga}_{0.25}\text{N}$ electron blocking layer and a Mg-doped $\text{AlGaN}/\text{AlGaN}$ superlattice are grown. Finally, the structure was capped by a 20 nm thick $\text{GaN:Si}$ contact layer [see Fig. 6(b)].

The epitaxial layers were patterned into circular mesas using ICP-RIE etching, and a Pd layer with a Si-concentration of $3 \times 10^{19} \text{cm}^{-3}$, embedded into a $\text{SiO}_{2}$ layer to prevent parasitic electrochemical etching, and a Ti/Au (10/30 nm) bonding layer using thermocompression bonding at 300 °C [see Fig. 6(b)].

To investigate the optical properties of the active region, room temperature PL measurements were performed using a Ti:sapphire laser with an emission wavelength of 275 nm and an average power of 1.2 mW (spot diameter of 50 μm) at a repetition rate of 80 MHz and a pulse duration of 140 fs. The PL spectrum for the as-grown and transferred MQW structures is shown in Fig. 6(c). The CW spectra for the as-grown and transferred MQW structures are presented normalized because of the different excitation conditions. A redshift in the peak wavelength is seen from 309 nm for the as-grown MQW structure to 311 nm for the transferred MQW structure. This shift of 2 nm could be caused by small local variations in the Al-composition and thickness over the sample, residual strain in the epitaxy, and process induced strain. To further quantify any potential process related degradation of the active region, the carrier lifetime for the as-grown MQW structure and the transferred MQW structure was compared by time-resolved PL measurements. Time-resolved PL excitation was performed in a similar manner to the time-integrated PL measurements. For detection, a spectrometer and a streak camera operating in the synchroscan mode were used. The excitation wavelength of 275 nm assured that carriers were generated mainly in the MQW region. PL decay times in the QWs of the as-grown and lifted-off MQW structures were $340 \pm 30$ ps and were not affected by the lift-off process. This confirms that the electrochemical etching and transfer process do not influence the quality of the QWs and, hence, are an appropriate process for fabrication of devices based on free-standing membranes.

In conclusion, we have demonstrated a method to laterally etch a sacrificial layer of $\text{AlGaN}$ and thereby separate a device layer stack from the substrate with a well-defined thickness and smooth etched surface. We have shown complete removal of an $\text{AlGaN}$-layer with an Al-content of up to 50% using electrochemical etching. The required bias voltage to achieve complete etching increases with the increasing Al-composition in the sacrificial layer. Etched surfaces show an RMS roughness of the N-polar AlGaN surface of 3.5 nm for 1 μm thick barriers with an Al-content of 30%. Subsequently, an $\text{Al}_{0.75}\text{Ga}_{0.25}\text{N}$ electron blocking layer and a Mg-doped $\text{AlGaN}/\text{AlGaN}$ superlattice are grown. Finally, the structure was capped by a 20 nm thick $\text{GaN:Si}$ contact layer [see Fig. 6(b)].

The project was financially supported by the Swedish Foundation for Strategic Research, the Swedish Energy Agency, the Swedish Research Council (Project Nos. 2016-04686 and 2018-00295), the German Federal Ministry of Education and Research (BMBF) within the “Advanced UV for Life” project, and the
Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center “Semiconductor Nanophotonics” (SFB 787).

REFERENCES

1. H. Amano, Y. Baines, E. Beam, M. Borgia, T. Bouchez, P. R. Chalker, M. Charles, K. J. Chen, N. Chowdhury, R. Chu, C. D. Santi, M. M. D. Souza, S. Decoutere, L. D. Cioccio, B. Eckardt, T. Egawa, P. Fay, J. J. Freedman, L. Guido, O. Hberlen, G. Haynes, T. Heckel, D. Hemakumara, P. Houston, J. Hu, M. Hua, Q. Huang, A. Huang, S. Jiang, H. Kawai, D. Kinzer, M. Kuball, A. Kumar, K. B. Lee, X. Li, D. Marcon, M. Mrz, R. McCarthy, G. Meneghesso, M. Meneghini, E. Morvan, A. Nakajima, E. M. S. Narayanan, S. Oliver, T. Palacios, D. Piedra, M. Plissontier, R. Reddy, M. Sun, I. Thayne, A. Torres, N. Trivellini, V. Ureni, M. J. Uren, M. V. Hove, D. J. Wallis, J. Wang, J. Xie, S. Yagi, S. Yang, C. Youtsey, R. Yu, E. Zanoni, S. Zeltner, and Y. Zhang, “The 2018 GaN power electronics roadmap,” J. Phys. D 51, 163001 (2018).

2. M. K. Kelly, O. Ambacher, R. Dimitrov, R. Handschu, and M. Stutzmann, “Optical process for liftoff of group III-nitride films,” Phys. Status Solidi A 159, R3–R4 (1997).

3. H. K. Cho, O. Krüger, A. Külberg, J. Rass, U. Zeimer, T. Kolbe, A. Knauer, S. Einfeldt, M. Weyers, and M. Kneissl, “Chip design for thin-film deep ultraviolet LEDs fabricated by laser lift-off of the sapphire substrate,” Semicond. Sci. Technol. 32, 121T01 (2017).

4. H. Yoshida, Y. Takagi, M. Kuwabara, H. Amano, and H. Kan, “Entirely crack-free ultraviolet GaN/AlGaN laser diodes grown on 2-in. sapphire substrate,” Jpn. J. Appl. Phys., Part 1 46, 5782–5784 (2007).

5. J. Park, K. M. Song, S.-R. Jeon, J. H. Baek, and S.-W. Ryu, “Doping selective lateral electrochemical etching of GaN for chemical lift-off,” Appl. Phys. Lett. 94, 221907 (2009).

6. T.-H. Chang, K. Xiong, S. H. Park, G. Yuan, Z. Ma, and J. Han, “Strain balanced AlGaN/GaN/AlGaN nanomembrane HEMTs,” Sci. Rep. 7, 6360 (2017).

7. A. W. Bruch, K. Xiong, H. Jung, X. Guo, C. Zhang, J. Han, and H. X. Tang, “Electrochemically sliced low AlGaN optical microresonators,” Appl. Phys. Lett. 110, 021111 (2017).

8. J.-H. Kang, D. K. Jeong, and S.-W. Ryu, “Transparent, flexible piezoelectric nanogenerator based on GaN membrane using electrochemical lift-off,” ACS Appl. Mater. Interfaces 9, 10637–10642 (2017).

9. D. Chen, H. Xiao, and J. Han, “Nanopores in GaN by electrochemical anodization in hydrofluoric acid: Formation and mechanism,” J. Appl. Phys. 112, 064303 (2012).

10. P. Griffin, T. Zhu, and R. Oliver, “Porous AlGaN-based ultraviolet distributed Bragg reflectors,” Materials 11, 1487 (2018).

11. L. Zhang, J. Yan, Q. Wu, Y. Guo, C. Yang, T. Wei, Z. Liu, G. Yuan, X. Wei, L. Zhao, Y. Zhang, J. Li, and J. Wang, “Improved crystalline quality of Al-rich n-AlGaN by regrowth on nanoporous template fabricated by electrochemical etching,” J. Nanophotonics 12, 043509 (2018).

12. K. Xiong, R. Dimitrov, H.-Y. Chen, Z.-J. Yang, T.-L. Tsai, Y.-S. Lin, and C.-F. Lin, “GaN/AlGaN ultraviolet light-emitting diode with an embedded porous AlGaN distributed Bragg reflector,” Appl. Phys. Express 10, 122102 (2017).

13. F.-H. Fan, Z.-Y. Syu, C.-J. Wu, Z.-J. Yang, B.-S. Huang, G.-I. Wang, Y.-S. Lin, H. Chen, C. H. Kao, and C.-F. Lin, “Ultraviolet GaN light-emitting diodes with porous AlGaN reflectors,” Sci. Rep. 7, 4968 (2017).

14. J. Enslin, F. Mehnke, A. Mogilatenko, K. Bellmann, M. Guttmann, C. Kuhn, J. Rass, N. Lobo-Ploch, T. Wernicke, M. Weyers, and M. Kneissl, “Metamorphic AlxGa1-xN on AlN/sapphire for the growth of UVB LEDs,” J. Cryst. Growth 464, 185–189 (2017).

15. C. Zhang, G. Yuan, A. Bruch, K. Xiong, H. X. Tang, and J. Han, “Toward quantitative electrochemical nanomachining of III-nitrides,” J. Electrochem. Soc. 165, E513–E520 (2018).

16. M. Pourbaix, Atlas of Electrochemical Equilibria in Aqueous Solutions (National Association of Corrosion Engineers, 1974), Chap. 4.

17. W. J. Tseng, D. H. van Dorp, R. R. Lieten, P. M. Vereecken, and G. Borghs, “Anodic etching of n-GaN epilayer into porous GaN and its photoelectrocchemical properties,” J. Phys. Chem. C 118, 29492–29498 (2014).

18. R. Collazo, S. Mita, J. Xie, A. Rice, J. Tweedie, R. Dalmaz, and Z. Sitar, “Progress on n-type doping of AlGaN alloys on AlN single crystal substrates for UV optoelectronic applications,” Phys. Status Solidi C 8, 2031–2033 (2011).

19. G. Grabowski, M. Schneider, H. Nienhaus, W. Mchn, R. Dimitrov, O. Ambacher, and M. Stutzmann, “Electron affinity of AlGa1-xN on AlN/natural surfaces,” Appl. Phys. Lett. 78, 2503–2505 (2001).

20. A. Mogilatenko, J. Enslin, A. Knauer, F. Mehnke, K. Bellmann, T. Wernicke, M. Weyers, and M. Kneissl, “V-pit to truncated pyramid transition in AlGaN-based heterostructures,” Semicond. Sci. Technol. 30, 114010 (2015).