Curvature evolution of 200 mm diameter GaN-on-insulator wafer fabricated through metalorganic chemical vapor deposition and bonding

Abdul Kadir; Wang, Yue; Lee, Kenneth E.; Tan, Chuan Seng; Chua, Soo Jin; Fitzgerald,
Eugene A.; Zhang, Li; Lee, Kwang Hong

2018

Zhang, L., Lee, K. H., Abdul Kadir., Wang, Y., Lee, K. E., Tan, C. S., . . . Fitzgerald, E. A. (2018).
Curvature evolution of 200 mm diameter GaN-on-insulator wafer fabricated through
metalorganic chemical vapor deposition and bonding. Japanese Journal of Applied
Physics, 57(5), 051002-. doi:10.7567/JJAP.57.051002

<https://hdl.handle.net/10356/90142>

<https://doi.org/10.7567/JJAP.57.051002>

© 2018 The Japan Society of Applied Physics. All rights reserved. This paper was published
in Japanese Journal of Applied Physics and is made available with permission of The Japan
Society of Applied Physics.

Downloaded on 26 Apr 2023 20:13:50 SGT

Curvature evolution of 200 mm diameter GaN-on-insulator wafer fabricated through MOCVD and bonding

Li Zhang^{1,*}, Kwang Hong Lee¹, Abdul Kadir¹, Yue Wang¹, Kenneth E. Lee¹, Chuan Seng Tan^{1,2}, Soo Jin Chua^{1,3} and Eugene A. Fitzgerald^{1,4}

¹*Singapore-MIT Alliance for Research and Technology, Low Energy Electronic Systems, 138602, Singapore*

²*Nanyang Technological University, School of Electrical and Electronic Engineering, 639798, Singapore*

³*National University of Singapore, Department of Electrical and Computer Engineering, 117576, Singapore*

⁴*Massachusetts Institute of Technology, Department of Materials Science and Engineering, Cambridge, MA, 02139, U.S.A.*

*E-mail: zhangli@smart.mit.edu

Crack-free 200 mm diameter N-polar GaN-on-insulator (GaN-OI) wafers are demonstrated by the transfer of MOCVD-grown Ga-polar GaN layers from Si(111) wafers onto SiO₂/Si(100) wafers. The wafer curvature of the GaN-OI wafers after the removal of the original Si(111) substrate is correlated with the wafer curvature of the starting GaN-on-Si wafers and the voids on the GaN-on-Si surface evolve into cracks on the GaN-OI wafers. In crack-free GaN-OI wafers, the wafer curvature during the removal of the AlN nucleation layer, AlGaIn strain-compensation buffer layers and GaN layers is correlated with the residual stress distribution within individual layers in the GaN-OI wafer.

1. Introduction

Over the last few years, the integration of GaN and Si CMOS in both electronic and optoelectronic applications has become a strong motivation for GaN-on-Si research.¹⁻³⁾ Choosing Si over sapphire or silicon carbide as the substrate for GaN in the integrated platform is for two main reasons. The first is the availabilities of 200 mm diameter substrates and automated fabrication facilities in the existing Si foundries which simplify the scale-up of the production from research laboratories to manufacturing facilities. The other reason is the mature Si substrate removal and wafer bonding process at 200 mm substrate size. Various forms of the integrated Si CMOS + III-V-on-Si wafers including CMOS + GaN wafers have been demonstrated by the double bonding and layer transfer of the CMOS layers onto the III-V-on-Si device wafers by our group.⁴⁾

The mature substrate removal and bonding technologies are also explored extensively to open new avenues in advanced device options in discrete GaN-on-Si devices.⁵⁻⁸⁾ Often, the device orientation in the as-grown Ga-polar GaN-on-Si can be modified by wafer bonding to realize N-polar HEMTs and flip-chip LEDs. This is made possible by the flip-chip bonding of the as-grown Ga-polar devices to a handle Si wafer followed by a removal of the original Si(111) substrate and some parts of the GaN and its $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{AlN}$ buffer layers to expose the device layers. However, most the work in this area has been carried out on small substrates ($\ll 200$ mm diameter) in which the strain evolution in the process of bonding and removal of buffer layers was difficult to measure or the curvature change did not affect the device fabrication significantly. However, similar to the growth of 200 mm GaN-on-Si wafers, it is expected that the wafer curvature and the residual strain will play an important role in when wafer bonding processes are carried out using a 200 mm GaN-on-Si wafer. Additionally, in order to achieve high yield and reproducible device processing at 200 mm substrate, the wafer bow of the final GaN-OI wafer must be $< 50 \mu\text{m}$. As a result, we attempt to create a thin N-polar GaN layer on 200 mm-diameter $\text{SiO}_2/\text{Si}(100)$ wafer by bonding the 200 mm Ga-polar MOCVD grown GaN-on-Si to a $\text{SiO}_2/\text{Si}(100)$ handle wafer to investigate the curvature evolution in this paper.

Wafer bonding, especially with 200 mm wafers, imposes a stringent requirement on the wafer bow of the GaN-on-Si wafer. A reproducible bonding process in the 200 mm diameter usually requires the bow not to exceed $50 \mu\text{m}$. Acceptable post-growth wafer bow in the MOCVD grown GaN-on-Si wafers is achieved by the balancing of compressive stress generated by the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ buffer layers during growth and the tensile stresses generated by both the Si δ -doping layer as well as the coefficient of thermal expansion

(CTE) mismatch between the nitride epilayers and the Si substrate upon cooling down from the growth temperature. Inevitably, inhomogeneous post-growth residual strain within the III-nitride layers will cause wafer curvature changes if portions of them are removed during the creation of the GaN-OI wafer. Additionally, the stress state of the final thin N-polar GaN layer affects the device performance, and the wafer bow of the GaN-OI wafer has to satisfy the requirements for any subsequent bonding steps (e.g. for the formation of CMOS + GaN wafers). In this paper, we investigate the curvature evolution and strain evolution in the GaN layer during the entire process of creating GaN-OI wafers.

2. Experimental methods

Five GaN-on-Si templates, each consisting of an AlN nucleation layer, a 5-step graded AlGaIn buffer, and a μ -GaN layer with a Si δ -doping layer inserted intermediately, are grown on 1 mm thick 200 mm diameter Si(111) wafers. The Si δ -doping layers of different durations are employed to obtain different post-growth wafer curvatures. A negative curvature indicates a concave wafer bow (wafer edges curved upwards relative to the center), while a positive curvature indicates a convex wafer bow. The summary of the growth condition and post-growth wafer curvature in GaN-on-Si wafers is listed in Table I. The wafer curvature decreases as the duration of the Si δ -doping layer is increased.⁹⁾

500 nm of SiO₂ was deposited on each GaN-on-Si wafer by plasma-enhanced chemical vapor deposition (PECVD). To reduce the surface roughness in preparation for wafer bonding, the SiO₂ is planarized by chemical mechanical planarization (CMP) to a thickness of 250 nm after thermal densification of the PECVD SiO₂ at 600 °C in N₂. 50 nm of Si₃N₄ is then deposited on the SiO₂ layer to minimize the interface void formation at the bonding interface that occurs with direct SiO₂-SiO₂ bonding.¹⁰⁾ The same PECVD SiO₂ deposition, CMP process, and Si₃N₄ deposition are carried out on a 725 μ m thick 200 mm diameter Si(100) wafer. The curvature of the Si(100) substrate is -0.9km^{-1} and the curvature of the Si₃N₄/SiO₂/Si(100) wafer is 3.5 km^{-1} . We have found that as long as the curvature of the Si₃N₄/SiO₂/Si(100) wafer stays within the range of $\pm 10/\text{km}$, high quality bonding can be achieved.

Both bonding Si₃N₄ surfaces of the two wafers are activated with an O₂ plasma, followed by rinsing with deionized water and then spin dried. After post-bonding annealing, the Si(111) substrates from the GaN-on-Si wafer are then removed by a combination of mechanical grinding and wet etching in Hydrofluoric/Nitric/Acetic (3:2:5) Acid (HNA) solution with a protective coating layer (BrewerBOND[®] 305 from Brewer Science) on the

Si(100) side at room temperature. The etch rate of the Si(111) in the HNA solution is $\sim 8 \mu\text{m}/\text{min}$.

3. Results and discussion

3.1 Curvature evolution GaN-OI wafers after bonding and the removal of the original Si(111) substrates

The cross-sectional SEM image of GaN-OI wafer D after the removal of the Si(111) substrate is shown in Fig. 1. The polarity of the III-nitride layers are flipped from Ga(Al)-polar to N-polar, thus the front surface of the wafer is now the AlN surface that was previously at the as-grown wafer's AlN/Si interface. The wafer curvature of the starting GaN-on-Si wafers and the corresponding GaN-OI wafers after the removal of the original Si(111) substrates are plotted in Fig.2. The GaN-on-Si wafers exhibit wafer curvatures from -17.5 to $+9.2 \text{ km}^{-1}$, while the GaN-OI wafers exhibit wafer curvatures from -8.6 to -61.9 km^{-1} . The curvature of a given wafer is always defined with the III-nitride layers on top of the respective substrates (i.e. Si(111) for the GaN-on-Si wafers and Si(100) for the GaN-OI), where positive (negative) curvature indicates a convex (concave) bowing. Thus, the transfer of the III-nitride epilayers from the Si(111) substrate to the Si(100) substrate is expected to lead to a change in sign of the curvature. When the Si(100) (handle) wafer is bonded to the GaN-on-Si wafer, the wafers are flattened, and the Si(100) wafer effectively applies biaxial stress to the epitaxial III-N layers that is in opposition to the existing biaxial stress (from growth and CTE mismatch during cooldown) in the GaN-on-Si wafer. Subsequently, when the original Si(111) is removed, the source of the original biaxial stress is removed, and thus the III-nitride epilayers will now be under the biaxial stress imparted by the Si(100) handle wafer, which is of opposite sign to the original biaxial stress from the Si(111) wafer. This results in a change in the sign of the curvature, assuming no plastic deformation occurs. However, the change in the sign of curvature is not observed in wafer E whose curvature changes from -17.5 to -61.9 km^{-1} . The red line in Fig. 2 is obtained by assuming that the isotropic membrane forces exerted by the III-nitride layers on the substrates are maintained after deposition of bonding dielectrics, wafer bonding and Si(111) substrate removal. As the deposited bonding dielectric layers on both the GaN-on-Si and Si(100) handle wafers are identical and under compression, we have made the simplifying assumption for the following analysis that the stresses in the ensemble bonding dielectric layers effectively cancel out. According to the Stoney formula, $\kappa = \frac{6f}{M_s h_s^2}$ where κ is the wafer curvature, f is the isotropic membrane force on the

substrate, and M_s and h_s are the biaxial elastic modulus and thickness of the substrate, respectively, the expression $\frac{\kappa_{\text{GaN-OI}}}{\kappa_{\text{GaN-On-Si}}} = -\frac{M_{s(111)}h_{s(111)}^2}{M_{s(100)}h_{s(100)}^2} \approx -2.42$ relating the starting GaN-on-Si and final GaN-OI wafer curvatures is obtained when the III-nitride layer from the GaN-on-Si with 1000 μm -thick Si(111) substrate is inverted and transferred to the 725 μm -thick Si(100) substrates. The curvature changes after the transfer of the III-nitride layers in wafers A, B, C and D are relatively accurately predicted by the derived expression whereas Wafer E deviates by about -100 km^{-1} .

The surface morphology, as examined under a Nomarski microscope, of GaN-on-Si wafers A, C and E, and their corresponding GaN-OI wafers, are shown in Fig.3 (a-c). Wafers A and C show smooth surfaces without crack lines after the growth and after the transfer of the III-nitride layers to the Si(100) substrates as illustrated Fig. 3 (d) and (e). However, surface pits are found on GaN-on-Si wafer E due to the incomplete coalescence of the 1.4 μm u -GaN with the 240 s Si δ -doping layer. Si δ -doping creates a partial SiGa_3N_3 antisurfactant layer on the GaN surface. The actual coverage is determined by the duration of the Si δ -doping.¹¹⁾ GaN islands regrow in the regions of the GaN surface which are still revealed and coalesce after a certain thickness. Usually there is an increase in the coalescence thickness of the GaN layer when duration of the Si δ -doping is increased. Crack lines with both of their ends terminating at the surface pits were observed on GaN-OI wafer E as illustrated Fig. 3(f). We believe the plastic relaxation in the GaN layer caused by these cracks lines is responsible for the large deviation between the predicted and measured wafer curvature in wafer E since the Stoney equation is derived under fully elastic deformation conditions. These observations indicate that starting GaN-on-Si wafers with minimum wafer curvature and void-free surfaces are necessary in the fabrication of the GaN-OI wafers with minimal surface cracks and wafer curvature.

3.2 Curvature evolution GaN-OI wafers during the removal of the buffer layers

Inductively coupled plasma (ICP) dry etching was used to remove the AlN, AlGaN buffer and part of the GaN layers to access the device layers. The device layers can be as thin as several tens of nanometers in the case of N-polar HEMT or can be a few micrometers thick in the case of a flip-chip LED. Etching gases used in this study are a combination of BCl_3 and Cl_2 (20/10 sccm). The bias power and ICP power were 200 and 500 W, respectively, with a chamber pressure of 1.33 Pa. GaN-OI wafer D was diced into $3 \times 3 \text{ cm}^2$ pieces for this etching study. The etch depths measured by cross-sectional SEM and the surface

roughness measured by AFM over $25 \mu\text{m}^2$ as a function of etch duration is displayed in Fig. 4. The AFM images of the samples with different etch durations are shown in the inset of Fig. 4. The mean etch rate is about 82 nm/min in the AlN and 5-step AlGaIn buffer layers. It is observed that the etch rate tends to increase with decreasing Al-content in the buffer in the N-polar surface. The observed etch rate is 121 nm/min in the GaN layers. The roughness of the N-polar surface of the III-nitride also increases with the etch duration. The rough surface may hinder the fabrication of thin-body HEMT device fabrication and further wafer bonding of the GaN-OI with Si CMOS wafers. We did not try to optimize the ICP etching process conditions on the N-polar surfaces to achieve a smooth N-polar surface in this work, but Waki *et al.* have previously suggested a smooth N-polar surface morphology could be realized with optimized Cl_2/Ar etching.¹²⁾

The entire 200 mm GaN-OI wafer C was then etched in steps according to the etch rate determined from wafer D. The precise lattice parameters of GaN after each etching step were determined from the weighted nonlinear least-square fit of $\frac{1}{d_{hkl}} = \frac{4}{2} \frac{(h^2 + k^2 + hk)}{a^2} + \frac{l^2}{c^2}$ with the symmetric (002), (004), (006) and asymmetric (104), (105), (204) XRD ω - 2θ peaks with a single azimuthal position. The measured wafer curvature and the calculated in-plane strain from the measured in-plane GaN lattice parameter were plotted against the estimated etch depths obtained from wafer D in Fig. 5. There were three times that a change in the direction of curvature was observed, (1) from concave to convex until the maximum curvature of $+9.8 \text{ km}^{-1}$ during the removal of the AlN layer, (2) from convex to concave until the curvature decreases to the minimum curvature of -21 km^{-1} during the removal of the 5-step graded AlGaIn buffer, and (3) from concave to slightly convex during the removal of about $1 \mu\text{m}$ GaN layer. There is a fluctuation in the GaN in-plane strain during the removal of the AlN and AlGaIn layers. However, a clear correlation between the GaN layer thickness and its in-plane strain is observed when both AlN and AlGaIn layers are completely removed. As the GaN layer is removed, the strain in the residual GaN film is changing at a rate of 0.14% per μm . The final GaN-OI wafer has about 400 nm of the GaN layer remaining, with a convex wafer bow of about $20 \mu\text{m}$, and a residual in-plane strain about 0.18% in the GaN layer.

The observed curvature change and in-plane strain variation during the removal of the buffer layers and part of the GaN layer is related to the distribution of residual strain in the GaN-OI wafers. In Table 2, the average composition and average strain values within each layer obtained from both the measured lattice parameters of GaN and the asymmetric (-1-14) reciprocal space map before the ICP removal are listed.¹³⁾ The tensile strain in the AlN layer

is caused by the tensile lattice mismatch and CTE mismatch with the Si substrate. The combination of the compressive lattice mismatch during growth and the tensile CTE mismatch upon cooling down results in the compressively strained AlGa_N layers and slightly tensile strained Ga_N layer. The amount of strain within the AlGa_N and Ga_N layers depends on the amount of the lattice mismatch at each heterointerface, the growth temperature, the thickness of the layers and the threading dislocation densities within each layer.¹⁴⁾ When the strain distributions within the III-nitride layers are known, the curvature changes observed in Fig 5 can be understood. Higher amounts of tensile strain in the III-nitride layers leads to greater negative curvature values (i.e. concave-shaped wafers), while higher amounts of compressive strain in the III-nitride layers leads to greater positive curvature values (i.e. convex-shaped wafers). Thus, during the removal of the tensile-strained AlN and Ga_N layers, wafers tend to become more convex-shaped (i.e. in the direction of positive wafer curvature) as the net compressive strain in the III-nitride layers increases. Conversely, as the compressively-strained AlGa_N buffer layers are removed, the wafers become more concave-shaped (i.e. in the direction of negative wafer curvature).

The change in curvature can be modeled by a force-moment balancing model proposed by Olsen and Ettenberg with the strain and thickness information of the individual layers of the Ga_N-OI wafer.¹⁵⁾ The modeled curvature as a function of the etched thickness is plotted in Fig (5). The model predicts the curvature increases (i.e. compressive strain increases) during the removal of the tensile strained AlN layer, the curvature decreases during the removal of the compressively strained AlGa_N layers and it increases again when Ga_N starts to be removed. The model predicts the same curvature evolution as observed in the experiments. However, the magnitude of the curvature change in the model is about 100 to 200% more than the experimental observation. Overestimates by the same model are also observed when the Si(111) substrate of Ga_N-on-Si is thinned down.¹⁶⁾ Overestimation of the curvature in the model originates from the discrepancy between the average and the actual distribution of strain and composition within individual layers. During the growth, the strain relaxation occurs due to the bending of the threading dislocations at the compressively strained Al_xGa_{1-x}N/Al_yGa_{1-y}N ($x < y$) heterointerface.¹⁷⁾ The strain relaxation can be approximated by a function of layer thickness.¹⁴⁾ For the Ga_N-on-Si templates in this study, while there is only a single Ga_N layer schematically, there is a variation in strain in the Ga_N layer, where the material grown earlier (i.e. closer to the AlGa_N buffer layers) is less tensile strained compared to the Ga_N grown later. Thus, for a more accurate prediction of the magnitude of the curvature change using the model, detailed strain variation within each layer, such as the

0.14% μm^{-1} strain gradient within the GaN layer, has to be taken into account. Nonetheless, the current model represents a physical picture of the curvature evolution in the GaN-OI wafers during the buffer removal process. The modeled curvature, measured curvature evolution and measured strain evolution in the GaN-OI wafer indicates different strain engineering buffers during the growth of GaN-on-Si are required in order to achieve low final wafer bow for thin-body N-polar HEMT and flip-chip LED GaN-OI wafers due to differences in the thicknesses of the device layers.

4. Conclusions

In summary, fabrication of crack-free low-curvature 200 mm N-polar GaN-OI from 200 mm Ga-polar GaN-on-Si wafer was explored. The distributions of residual strain within each layer of the GaN-OI wafers govern the curvature evolution during the removal of the buffer layer and GaN layer. The average strain within the GaN is determined by the average residual strain after the epi-growth and its remaining thickness after III-Nitride layer removal.

Acknowledgments

This research was supported by the National Research Foundation Singapore through the Singapore-MIT Alliance for Research and Technology's Low Energy Electronic Systems (LEES) IRG.

References

- ¹ E.A. Fitzgerald, K.E. Lee, L. Zhang, C.C. Huang, A. Kadir, S. Bao, Z. Ren, C. Wang, Y. Wang, K.H. Lee, Z.H. Liu, T. Palacios, C.S. Tan, G.I. Ng, and S.J. Chua, *ECS Trans.* **75**, 31 (2016).
- ² E.A. Fitzgerald, K.E. Lee, S.-F. Yoon, S.J. Chua, C.S. Tan, G.I. Ng, X. Zhou, X. Gong, J.S. Chang, L.S. Peh, C.C. Boon, D. a. Antoniadis, S. Yadav, X.S. Nguyen, D. a. Kohen, A. Kumar, L. Zhang, K.H. Lee, Z.H. Liu, S.B. Chain, T. Ge, and P. Choi, *ECS Trans.* **75**, 439 (2016).
- ³ K.E. Lee and E.A. Fitzgerald, *{MRS} Bull.* **41**, 210 (2016).
- ⁴ K.H. Lee, S. Bao, E. Fitzgerald, and C.S. Tan, *Jpn. J. Appl. Phys.* **54**, 30209 (2015).
- ⁵ J.W. Chung, E.L. Piner, and T. Palacios, *IEEE Electron Device Lett.* **30**, 113 (2009).
- ⁶ K.K. Ryu, J.C. Roberts, E.L. Piner, and T. Palacios, *IEEE Electron Device Lett.* **32**, 895 (2011).
- ⁷ N.P. Pham, M. Rosmeulen, Z. Li, D. Sabuncuoglu, and H. Osman, in *2013 IEEE 15th Electron. Packag. Technol. Conf. (EPTC 2013)* (IEEE, 2013), pp. 324–328.
- ⁸ L. Zhang, W.-S. Tan, S. Westwater, A. Pujol, A. Pinos, S. Mezouari, K. Stribley, J. Whiteman, J. Shannon, and K. Strickland, *IEEE J. Electron Devices Soc.* **3**, 457 (2015).
- ⁹ L. Zhang, K.H. Lee, I.M. Riko, C.-C. Huang, A. Kadir, K. Lee, S. Chua, and E. Fitzgerald, *Semicond. Sci. Technol.* **34**, 251123 (2017).
- ¹⁰ K.H. Lee, S. Bao, Y. Wang, E.A. Fitzgerald, and C. Seng Tan, *J. Appl. Phys.* **123**, 15302 (2018).
- ¹¹ T. Markurt, L. Lymperakis, J. Neugebauer, P. Drechsel, P. Stauss, T. Schulz, T. Remmele, V. Grillo, E. Rotunno, and M. Albrecht, *Phys. Rev. Lett.* **110**, 36103 (2013).
- ¹² I. Waki, M. Iza, J.S. Speck, S.P. DenBaars, and S. Nakamura, *Jpn. J. Appl. Phys.* **45**, 720 (2006).
- ¹³ M.A. Moram and M.E. Vickers, *Reports Prog. Phys.* **72**, 36502 (2009).
- ¹⁴ P. Cantu, F. Wu, P. Waltereit, S. Keller, A.E. Romanov, S.P. DenBaars, and J.S. Speck, *J. Appl. Phys.* **97**, 103534 (2005).
- ¹⁵ G.H. Olsen and M. Ettenberg, *J. Appl. Phys.* **48**, 2543 (1977).
- ¹⁶ H.F. Liu, S.B. Dolmanan, L. Zhang, S.J. Chua, D.Z. Chi, M. Heuken, and S. Tripathy, *J. Appl. Phys.* **113**, 23510 (2013).

¹⁷ D.M. Follstaedt, S.R. Lee, A.A. Allerman, and J.A. Floro, J. Appl. Phys. **105**, 83507 (2009).

Figure Captions

Fig. 1. The cross-sectional SEM image shows the GaN-OI wafer with AlN/5-step graded AlGaIn buffer/GaN after the removal of the original Si(111) substrate.

Fig. 2. GaN-on-Si wafer curvatures versus GaN-OI wafer curvatures after the removal of the original Si(111) substrate

Fig. 3. Nomarski microscope images showing the surface morphology of (a-c) GaN-on-Si wafers A, C and E, (d-f) GaN-OI wafers fabricated from wafers A, C and E. The scale bar is 200 μm , and applies to all the images.

Fig. 4. Plot of the etch depths and surface rms roughness measured by cross-sectional SEM and AFM, respectively, versus ICP etch duration. The inset images show the $5 \times 5 \mu\text{m}^2$ AFM surface morphology after etching.

Fig. 5. Plot of the measured wafer curvature, modeled wafer curvature and the measured in-plane strain of the GaN layer versus the estimated etch depth.

Table I. Summary of the growth condition and post-growth wafer curvature in

GaN-on-Si wafers.

wafer	Si δ -doping duration (s)	Wafer curvature (km^{-1})
A	0	+9.2 (convex)
B	120	+2.8 (convex)
C	120	+2.2 (convex)
D	120	+0.7 (convex)
E	240	-17.5 (concave)

Table II. Summary of the thickness, composition, and strain in GaN-OI wafer C before ICP buffer removal.

layer	t(nm)	x(%)	$\epsilon_a(\%)$
AlN	240	-	+0.294
$\text{Al}_x\text{Ga}_{1-x}\text{N-1}$	140	85.6	-0.135
$\text{Al}_x\text{Ga}_{1-x}\text{N-2}$	155	72.6	-0.167
$\text{Al}_x\text{Ga}_{1-x}\text{N-3}$	195	61.2	-0.184
$\text{Al}_x\text{Ga}_{1-x}\text{N-4}$	320	48.4	-0.293
$\text{Al}_x\text{Ga}_{1-x}\text{N-5}$	265	29.1	-0.362
GaN	1400	-	+0.087

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 5.