Low-temperature effect on GaN film in argon plasma

Daisuke Ogawa, Yoshitsugu Banno and Keiji Nakamura
Department of Electrical and Electronic Engineering, Chubu University, Kasugai, Japan
E-mail: d_ogawa@isc.chubu.ac.jp

Keywords: plasma processing, gallium nitride, photoluminescence, plasma-induced damage

Abstract
This journal article shows the effect of low temperature for gallium nitride (GaN) film in an argon plasma. Our first observation showed that the evolution of photoluminescence (PL) from the GaN film depends on the temperature of the film during the plasma exposure. The observation showed that the PL emission became approximately 35% of the original PL intensity for no-temperature-controlled (as-is) GaN film, while the emission became approximately 70% for low-temperature-regulated (cold) GaN film. The main difference between the two films was only in the temperature range during plasma exposure, but the temperature difference between pre- and post-plasma was almost the same for the two films. Then, we did ex situ x-ray photoelectron spectroscopy (XPS) analysis to investigate whether or not there was a difference in the depth profile of elements in the films. As a consequence, we concluded that the reduction of thermal energy during a plasma exposure could regulate the opportunities for the species transfer in the film, which can minimize the evolution of GaN film during the plasma process.

1. Introduction

Gallium nitride (GaN) is one of the semiconductor materials that have stimulated industries due to the success of the blue light-emitting diodes. However, the application of GaN is not only for illuminations or optical devices but also for power-electronic devices with the use of the wide bandgap (3.4 eV) [1–3]. The techniques of miniaturization and integration for semiconductors realize even more powerful and smaller devices in the future.

In fabricating GaN devices, plasma processing plays an important role to achieve anisotropic etching and deposition [4–6]. However, plasma-induced damage (PID) is sometimes problematic as the size of devices gets smaller and smaller [7, 8]. Mostly, the damage is referred such as due to bombardments of high energy ions [9–11], due to dust generated during a plasma processing [12–14], due to electromagnetic radiation from plasma [15], and due to local charges causing stress on a wafer [8, 16, 17], and redirecting charged species to fabricate at undesired locations [18]. GaN also possibly has the kinds of damages [19–22] so that the damage needs to be paid attention in some fabrications. Unfortunately, damage evolution during plasma processing for GaN has minimum knowledge due to much fewer experiences than damage evolution for silicon-based semiconductors. Therefore, it is essential to know the phenomena and mechanisms during plasma processing for GaN to future applications.

We have made in situ monitoring of GaN films to observe the degree of damage during the plasma exposure with the photoluminescence (PL) spectrum [23–25]. The PL spectrum tends to develop from the original spectrum as the plasma exposure time increases due to the elevation of the surface temperature and the PID. Our previous work found that the evolution of PL intensities occurs during plasma exposure, and the evolution of the two intensities, at both near-band-edge (NBE: 350–380 nm) emission and blue luminescence (BL: 400–480 nm) band, indicates the degree of the PID during a plasma processing [23]. The temperature of GaN indeed affected the PL intensity, but the PL evolution by PID was much more effective than the PL evolution by the temperature elevation [24].
Although the PL evaluation is possible even in a temperature elevation, the substrate temperature should still affect the surface condition of GaN during plasma processing because the chemical reaction strongly depends on the temperature, as referred to the Arrhenius equation \[26, 27\]. There are some reports about the high-temperature effect for a GaN substrate in PID reduction. For example, Kometani \textit{et al.} elevated substrate temperature to maintain the stoichiometry of gallium-nitrogen in GaN by supplying nitrogen species from the plasma \[28\]. However, there is a limited number of reports about the low-temperature effect for the GaN substrate. Talking about the low-temperature for the silicon substrate, Tachi \textit{et al.} and Dussart \textit{et al.} independently reported a plasma-processing for silicon substrate at a cryogenic temperature \[29, 30\]. As noticed, a low-temperature effect during exposure of low-pressure plasma is mainly for silicon, but not for GaN. Therefore, it is worthwhile to study the low-temperature effect of plasma exposure for GaN because the importance of GaN processing increases, and also, the miniaturization of the GaN device progresses year by year.

In this journal article, we conducted some investigations of the evolution of low-temperature-regulated (cold) GaN film in argon plasma with a comparison of the no-temperature-controlled (as-is) GaN film. The series of the following investigations is informative and fundamental for future applications and researches for GaN processing. This journal article focuses on a plasma generated with argon because argon gives only physical effects from plasma, such as ion bombardments and radiations. Of course, it is still far from an application stage yet, but the series of experiments with argon species gives an idea to monitor the low-temperature effect during plasma processing. Other molecular gas, such as N$_2$, H$_2$, Cl$_2$, etc requires more complex analyses so that we here report the effect of low-temperature with argon gas first and leaving the effect with other gases for future work.

2. Experimental condition

Figure 1 shows a reactor to investigate the low-temperature effect of GaN in an argon plasma. This reactor chamber is homemade, mainly consisting of a quartz tube (outer diameter is 120 mm, and its height is 100 mm). The gas pressure during a process was 10 Pa with a flow of argon gas (99.9995% purity) at 15 sccm. (The base pressure is $10^{-4}$ Pa with this system.) A one-turn coil around the quartz tube produces a plasma with a radio frequency power supply (GreenTec, HFS-025-P, 2.5 kW) and a matching box (Pearl Kogyo, ZDK-916S) operating of the frequency at 13.56 MHz modulated with a square wave (500 Hz, 50% duty cycle).

We placed a sample holder inserted from the top of the reactor chamber, as seen in figure 1. Here, a GaN film (Powdec; 2 μm thickness on a sapphire substrate, silicon doped n-type GaN) was attached to the bottom of the sample holder with a piece of double-sided polyimide tape. Note that the films utilized in this journal article have

![Figure 1](image-url)
3. Experimental results

3.1. Low-temperature effect: photoluminescence (PL) spectrum from a GaN film

Figure 2 shows the evolution of the PL spectrum from a GaN film before plasma exposure (pre-plasma) and after plasma exposure (post-plasma) to find the low-temperature effect. Note that the spectrum in pre-plasma for the cold GaN (figure 2(b)) was the spectrum taken in a vacuum chamber without liquid nitrogen. Also, note that we took a spectrum of post-plasma when the temperature of GaN films turned to the temperature close to room temperature in a vacuum. It is because the intensity of the PL spectrum depends on the temperature of the GaN film, as seen in our previous article [25]. Therefore, it is necessary to equalize temperature as close as possible to make a fair comparison for both as-is GaN and cold GaN spectra to explicit that the evolution is due to plasma exposure for both spectra. Although the temperature of post-plasma did not reach the same temperature as the temperature of pre-plasma, the spectrum of the post-plasma was close enough to the original spectrum according to regular observations. Figure 2(a) is the evolution of the spectrum for as-is GaN film and figure 2(b) is the evolution of the spectrum for cold GaN film.

As seen in the figures, the two temperature conditions of plasma exposure differentiate PL evolution from pre- to post-plasma. The main difference was the total PL intensities, an integrated value of the PL intensity from 300 to 660 nm. For the as-is GaN film, the total intensity decreased to 35% of the original total intensity. On the other hand, for the cold GaN film, the intensity decreased to 71% of the original total intensity, where the PL property of the GaN film remained better. This result was promising that the reduction of temperature during a plasma exposure maintains at least the optical property of GaN film.

In addition to the total intensities, the evolution of PL intensity depends on the wavelength. In particular, when focusing on NBE emission and yellow luminescence (YL: 480–700 nm) bands [23], the intensities tended to decrease after argon plasma exposure in either case of the as-is or the cold GaN film. However, the evolution of the intensity at the BL band depends on the temperature during plasma exposure. The intensity tends to increase for as-is GaN film, while the intensity tends to stay almost the same for cold GaN film. In fact, the same kind of observation was in our early experiment [25].

Figure 3 shows a quantitative comparison with the PL intensity evolution ratio for (a) as-is GaN film and (b) cold GaN film. Here, we defined the PL intensity evolution ratio by calculating the PL intensity at the post-plasma divided by the PL intensity at the pre-plasma with the use of the values shown in figure 2. As seen in the figures, the intensity at the NBE emission decreases approximately 70% of the original intensity after plasma exposure. This decrease occurs in either as-is or cold GaN film. This result indicates that plasma exposure, more or less, tends to decrease the intensity at the NBE emission.

The low-temperature effect appeared in the BL and YL bands. For as-is GaN film, a plasma exposure dramatically increased the intensity in the BL band to be doubled, but dramatically decreased the intensity in the YL band down to 20% of the original intensity. On the other hand, for cold GaN film, a plasma exposure kept almost the same intensity for the BL band and decreased the YL band down only to 75% of the original intensity. The results at the two temperature conditions indicate that a plasma exposure dramatically gives the evolution of the intensity in BL and YL bands without temperature regulation. In contrast, plasma exposure limitedly gives
the evolution in BL and YL bands with low-temperature regulation. The BL and YL bands relate to the intermediate energy states by impurities and vacancies etc [35] so that low temperature during the plasma exposure avoids the evolution of the energy states better than no temperature regulation does.

One of the possible reasons to make the difference of the evolutions can be due to the combination of the thermal energy in GaN and the energy given by argon plasma. Argon plasma gives extra energy with ion bombardments, energetic metastable, and ultraviolet radiation in addition to the thermal energy already existing in a GaN film. As seen in the Arrhenius equation, there should be activation energy to make a chemical reaction, which herein indicates the degradation of the PL property of GaN film. The summation of heat and energy supplied from the plasma likely exceeded the activation energy in the case with no-temperature regulation but did not exceed in the case with low-temperature regulation. The consequence of this reaction will be discussed later in x-ray photoelectron spectroscopy (XPS) analysis.

3.2. Temperature evolution during the plasma-processing

Figure 4 shows the temperature evolution during argon exposure for (a) as-is GaN and (b) cold GaN. Note that the temperature shown here was the temperature at the very location of the tip of the thermocouple. However, it does not mean that the temperature has the spatial distribution on the GaN surface because the sample was in the vacuum, and has contact only with the sample holder. This experimental system has a fair flux of heat gain and loss in the plane so that the temperature here expresses the very top surface temperature of the GaN film. In these figures, closed circles indicate the duration when the plasma was on, and open circles indicate the duration when the plasma was off. Also, the time in these graphs started when argon plasma turned on because the definition shows how effective the plasma exposure was to the film evolution. The initial temperature was 25 °C for as-is GaN film and −114 °C for cold GaN film. As seen in the figures, the temperature kept increasing in either condition of as-is or cold GaN film during the plasma was on. This temperature elevation was mainly due to ion bombardments transferring energy to the surface of GaN film as heat [36]. Here, the aluminum plate covering...
the thermocouple is firmly attached to the GaN film so that the temperature here expresses the temperature at the GaN surface.

The temperature evolution for as-is GaN film monotonically decreases because there was no heat source without plasma so that the heat diffuses to the surroundings, finally reaching room temperature. In contrast, the temperature evolution for the cold GaN film also monotonically decreased approximately to 60 min, trying to reach the initial temperature. However, the temperature curve has an inflection point and then started to increase to reach room temperature due to the evaporation of liquid nitrogen.

The temperature elevation during the plasma exposure was almost the same for both conditions of as-is and cold GaN films. The temperature during the plasma exposure was approximately from 25°C to 180°C for as-is GaN film and from −120°C to 25°C for cold GaN film. It is decent to consider here that the energy from the plasma was the same in both conditions because we made the experimental conditions as equalized as possible, and the temperature elevation was almost the same in both conditions, as seen in figure 4. Therefore, the main difference between the two conditions was only the temperature range during plasma exposure.

One might notice that a constant temperature would be better, in particular, to investigate the threshold temperature where the plasma most effectively affects to change GaN spectrum. Unfortunately, due to the limitation of our equipment condition, we currently have poor heat transfer from the sample holder to GaN, as seen in figure 4(b) (~2.5°C min⁻¹ after post-plasma). However, this journal article shows the temperature range that is effective for plasma exposure, as seen in figures 2 and 4. The evolution due to plasma exposure was significant in a temperature range from 25°C to 180°C, but the evolution was not very significant in the temperature range from −120°C to 25°C.

Even in this circumstance, a result in figure 2 is still valuable in the point of informing the effect of low-temperature during the plasma process because gallium in GaN desorbs approximately at 400°C and nitrogen in GaN desorbs approximately at 600°C to 800°C [37]. Our temperature range here was still below such temperature range so that it is not necessary to consider the deformation of GaN due to temperature. Furthermore, there might be a concern that low temperature affected the evolution of the film due to de-gas, contamination reduction, grain boundary improvements etc. In fact, our usual experiment shows that the
intensity of the spectrum tends to be lower for a GaN sample with plasma exposure than a GaN sample without plasma exposure even with similar temperature history. It means that plasma added further evolution on the thermal effect on a GaN sample, and the evolution was more significant to as-is GaN film than cold GaN.

3.3. Low-temperature effect: element distribution in a GaN film
We also performed x-ray photoelectron spectroscopy (XPS; Ulvac, Versa Probe CU) to analyze the evolution of the GaN film by argon plasma from the aspect of the evolution of the elemental distribution. The XPS utilized here has a sputtering function so that the argon ion beam (4 keV, 7 mA in 4 mm²) achieves the sputtering rate at \( \sim 12 \text{ nm min}^{-1} \). Note that the GaN films after a plasma exposure were passing in the ambient air when transferring them to the XPS machine.

Figure 5 shows that the XPS spectra in Ga3d range, (a) pristine GaN film, (b) as-is GaN film during argon plasma, and (c) cold GaN film during argon plasma. Also, the figures show depth profiles of the spectrum at four different depths (top surface, 1.2 nm depth, 2.4 nm depth, and 3.6 nm depth; the depths were estimated values according to our measurement of sputtering, \( \sim 600 \text{ nm in 50 min} \). The values were under the assumption that the sputtering rate was constant in-depth. This assumption is a little rough, but decent enough because gallium nitride and oxide have similar mechanical properties [38–40]).

As seen in the figures, all GaN films have a peak at 20.7 eV at the very top surface, which is an indication of gallium oxide [41]. In particular, the spectrum of the pristine GaN film developed a lot somewhere between the top surface (0.0 nm) and the depth at 1.2 nm, which means that our pristine GaN film (or an original GaN film) has a native-oxide layer with the thickness thinner than 1.2 nm. Then, a peak observed in all GaN films shifts to lower binding energy, and it finally reaches 19.7 eV, which is an indication of gallium nitride, approximately by the depth at 3.6 nm.

Firstly, when making a comparison between (a) pristine GaN film and (b) as-is GaN film during argon-plasma exposure, the two GaN films have different depth profiles. As described in the previous paragraph, the
pristine GaN film had a thin oxidized layer only in the vicinity of the top surface. Meanwhile, the plasma-exposed as-is GaN film had a thicker oxidized layer because the binding energy of a peak was approximately 20.7 eV at the very surface, and then the energy of a peak gets lower as the depth increases. In particular, at the depth 1.2 and 2.4 nm, the binding energy of a peak was between the peak for gallium oxide (20.7 eV) and the peak for gallium nitride (19.7 eV). The binding energy of the peak indicates that the peak consists of the convolutions of the two peaks of gallium oxide and gallium nitride, which means that both oxygen and nitrogen

Figure 5. XPS spectra in the range of Ga3d for four different depths; (a) pristine GaN film, (b) as-is GaN film during argon-plasma exposure, and (c) cold GaN film during argon-plasma exposure.
exist from the top surface to the depth at 2.4 nm. One might consider the formation of GaO₂Nₓ after this plasma processing. The composition is indeed possible to be in the plasma-exposed GaN. Remember that there is no oxygen flow during plasma exposure. This result indicates that some oxygen species in a native oxide layer diffused into a deeper level during plasma exposure. Furthermore, plasma-processed as-is GaN film has the lowest peak intensity at the top surface in any other peaks. This low intensity was an indication of the decomposition of some GaN in plasma-processed as-is GaN. However, the temperature during plasma processing for as-is GaN film from 25°C to 180°C. The temperature seems too low for the decomposition of GaN, according to data shown in [42]. This result indicates that plasma added the energy over the heat existing in the GaN film, which was equivalent to several hundreds of degrees in this case. Therefore, the overall results convince us that a plasma exposure to a GaN film tends to induce native-oxygen atoms to diffuse into GaN film approximately to 2–3 nm deeper level, and some GaN decomposed.

Secondly, when making another comparison between (a) pristine GaN film and (c) cold GaN during argon-plasma exposure, the two samples have similar depth profiles in their spectrum. This result confirms the low-temperature processing affects to avoid the evolution in terms of material composition due to argon-plasma exposure. One might indicate that even lower temperatures might reduce evolution better according to our observation. However, such observation is not complete yet due to our technical difficulty. The investigation of the evolution by plasma with an even lower temperature will be future work. At this point, we conclude that low temperature is effective in avoiding the evolution of chemical composition due to plasma exposure in addition to optical evolution, as seen in figure 2.

As seen in the results of the low-temperature effect on PL evolution and depth profile, pristine film and cold GaN film during argon-plasma exposure have similar characteristics in PL property and a depth profile of elements. On the contrary, pristine GaN film and as-is GaN during argon-plasma exposure are different in both PL property and a depth profile of elements. The XPS analysis here showed that the element distribution evolved approximately down to 3 nm, which was ~7% of the skin depth of the incident illumination. However, the illumination exponentially decades so that the effective contribution of elemental evolution to PL emission is approximately 11% according to the summation ratio of illumination intensity at 3 nm over 45 nm. Remember that the PL evolution was 71% for as-is GaN and 35% for cold GaN in figure 2. Considering that the difference was approximately 35%, it is decent to consider that the effective contribution of elemental evolution was not trivial.

In particular, the two measurements indicate that the increasing BL band the decreasing YL band (as seen in figure 2(a)) can be due to a diffusion of oxygen in the vicinity of the GaN surface (as seen in figure 5(b)). Oxygen species work as shallow donors, which affect electronic transitions relating to the BL band [43–45]. Remember that plasma exposure evolved NBE intensity down to 75% for both as-is and cold GaN, as seen in figure 3. On the other hand, the evolutions in BL and YL bands were different in as-is and cold GaN. Both bands relate to impurities and crystal structure etc, and our XPS analysis showed that the two samples have a difference in oxygen distribution in the vicinity of the GaN surface. According to these circumstances, it is decent to consider that evolution occurs in the two bands rather than NBE. Indeed, high energy bombardments can give opportunities to evolve the crystal structure on the surface of GaN that can cause the evolution of PL properties. At this point, we did not investigate the crystal structure of plasma-processed GaN for either as-is or cold GaN. Here, we assume that the same crystal structure for plasma-processed as-is and cold GaN. As a result, the new energy states increase the number of electronic transitions relating to the BL band, and then decrease the number of the optical-emitting transitions which used to occur for the PL emission at the YL band. Therefore, these experiments shown above suggest that it is a good idea for a plasma-processing GaN film to maintain the temperature less than room temperature during plasma processing.

4. Summary and conclusions

This article showed the low-temperature effect on a GaN film during argon-plasma exposure according to the observations with PL emission from the film and with the depth profile of elements measured by XPS measurements. First of all, we observed the difference in the evolution of PL intensity in pre-plasma and post-plasma for as-is and cold GaN films (figure 2). The result showed that the PL property for cold GaN film remained well even after argon-plasma exposure. Then, we numerically discussed the intensity of PL in the three different wavelength ranges (NBE, BL, and YL) as well (figure 3). This analysis revealed that the intensity at the NBE emission decreases by the effect of plasma exposure in either case of as-is or cold GaN film. On the other hand, low-temperature exposure makes some difference in the BL and YL bands. As-is GaN film during plasma exposure dramatically increased the intensity at the BL band and decreased the intensity at the YL band. However, cold GaN film during plasma exposure relatively maintained the PL properties from the original condition. In this case, the temperature range of the low-temperature processing was from −120°C to 25°C.
Finally, we investigated the evolution of elemental distribution in GaN film to make further analysis. Our XPS analysis showed that cold GaN film during plasma exposure maintains the depth profile of elements in a GaN film (figure 4). From the total analysis of PL and XPS measurements, we conclude that low-temperature regulation affects the material property of GaN film after argon-plasma exposure. In this journal article, we focused on the evolution of the depth profile of oxygen in GaN film, but a similar phenomenon can occur even with other species. Therefore, the series of experiments made in this journal article suggests that the low-temperature processing for a GaN film regulates evolutions due to plasma processing.

Acknowledgments

We would like to acknowledge Prof Yoshitaka Nakano, Chubu University, who gave some advice about GaN analysis to make progress on this research.

ORCID iDs

Daisuke Ogawa https://orcid.org/0000-0002-3277-5068

References

[1] Pearton S, Abernathy C and Ren F 2006 Gallium Nitride Processing for Electronics, Sensors and Spintronics (London: Springer)
[2] Lin M, Ma Z, Huang F, Fan Z, Allen L and Morkoc H 1994 Appl. Phys. Lett. 64 1003
[3] Vitanov S, Palankovski V, Maroldt S and Quay R 2010 Solid-State Electronics 54 1105
[4] Smith S, Woklen C, Bremser M, Hanser A and Davis R 1997 Appl. Phys. Lett. 71 3631
[5] Gillis H, Chooutov D, Martin K, Bremser M and Davis R 1997 J. Electronic Mat. 26 301
[6] Founta S, Bougerol C, Mariette H, Daudin B and Vennéguès P 2007 J. Appl. Phys. 102 074304
[7] Iswae T et al 2019 Jpn. J. Appl. Phys. 58 SE0802
[8] Shin H and Hu C 1996 Semicond. Sci. Technol. 11 463
[9] Xu S, Qin C, Dao L, Gilbert D, Hou L, Wiesnoski A, Busch E, McGowan R, White B and Weber F 2007 J. Vac. Sci. Technol. B 25 156
[10] Matsuda A, Nakakubo Y, Takao Y, Eriguchi K and Ono K 2010 Thin Solid Films 518 3481
[11] Kazi H and Kelber J 2014 J. Vac. Sci. Technol. A 32 021502
[12] Roth J 2001 Industrial Plasma Engineering: Volume 2—Applications to Nonthermal Plasma Processing (London: CRC Press)
[13] Wang X, Colwell J, Horanyi M and Robertson S 2007 IEEE Trans. on Plasma Sci. 35 271
[14] Tico C, Jepu I, Lungu C, Chiru P, Zarsoschi V and Lunga A 2010 Appl. Phys. Lett. 97 011501
[15] Tatsumi T, Fukuda S and Kadomura S 1994 Jpn. J. Appl. Phys. 33 2175
[16] Liang M, Chang C, Yeow Y and Hu C 1984 IEEE Trans. Electron Dev. ED-31 1238
[17] Martin A 2009 J. Vac. Sci. Technol. B 27 426
[18] Hashimoto K, Hiokosaka Y, Hasegawa A and Nakamura M 1996 Jpn. J. Appl. Phys. 35 3363
[19] Gao X, Pearton S, Zhang A, Dang G, Ren F, Hickman R and Hove J 1999 Appl. Phys. Lett. 75 2569
[20] Hahn Y, Choi R, Hong J, Park H, Choi C and Lee H 2002 J. Appl. Phys. 92 1389
[21] Kawakami R, Inokata T, Tomimaga K and Mukai T 2009 Jpn. J. Appl. Phys. 48 08HF01
[22] Nakano Y, Kawakami R and Niibe M 2017 Appl. Phys. Express 10 116201
[23] Chu M, Nakamura K, Nakano Y, Zhang G and Sugai H 2012 Appl. Phys. Express 5 076201
[24] Chu M, Nakamura K, Nakano Y, Yu S and Sugai H 2012 Appl. Phys. Let. 101 107105
[25] Ogawa D and Nakamura K 2014 IEEE Trans. on Fundamentals and Mat. 134 642
[26] Lieberman M and Lichtenberg A 2005 Principles of Plasma Discharges and Materials Processing 2nd edn (New Jersey: Wiley)
[27] Meister J, Bohm G, Eichentopf T and Arnold T 2009 Plasma Process. Polym. 6 5209
[28] Komnati K, Ishikawa K, Takeda K, Kondo H, Sekine M and Horii M 2013 Appl. Phys. Express 6 056201
[29] Tachi S, Tsujimoto K and Okuda I 1988 Appl. Phys. Lett. 52 616
[30] Dussart R, Tilich T, Lefauchoux P and Boufrichel M 2014 J. Phys. D: Appl. Phys. 47 123001
[31] Paskova P, Schifano R, Paskova T, Malinauskas T, Bergmana J, Monemar B, Figge S and Hommel D 2006 Physica B 376-377 473–76
[32] Zhou S 2006 Physica E 33 394
[33] Chin A, Ahn T, Li H, Vaddiraju S, Bardeen C, Ning C and Sunkar M 2007 Nano Lett. 7 626
[34] Muth J, Lee J, Shmagin I, Kolba R, Casey H, Keller B, Mishra U and DenBaars S 1997 Appl. Phys. Lett. 71 2572
[35] Reschikova M and Morkoc H 2005 J. Appl. Phys. 97 061301
[36] Kim D and Lee Y 1996 Thin Solid Films 283 109
[37] Hattori A, Endo K, Hattori K and Daimon H 2010 Appl. Surf. Sci. 256 4745
[38] Polian A, Grinsditch M and Grzegory I 1996 J. Appl. Phys. 79 3343
[39] Cimalla V, Pezoldt J and Ambacher O 2007 J. Phys. D: Appl. Phys. 40 6386
[40] Pearton S, Ren F and Mastro M 2019 Gallium Oxide Technology, Devices and Applications (Amsterdam: Elsevier)
[41] Li D, Sumiya M, Fuke S, Yang D, Que D, Suzuki Y and Fukuda Y 2001 J. Appl. Phys. 90 4219
[42] Murni Z and Scarry A 1963 J. Chem. Phys. 42 4223
[43] Chung B and Gershenzon M 1992 J. Appl. Phys. 72 651
[44] Niebuhr R, Bachem K, Kaufmann U, Maier M, Merz C, Santic B, Schlottner P and Jürgensen H 1997 J. Electronic Mat. 26 1127
[45] Reschikov M, Morkoc H, Park S and Lee K 2002 Appl. Phys. Lett. 81 4970