Low resistance n-contact for UVC LEDs by a two-step plasma etching process

H K Cho1, J H Kang1, L Sulmoni2, K Kunkel1, J Rass1, N Susilo2, T Wernicke2, S Einfeldt1 and M Kneissl1,2

1 Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Str. 4, 12489, Berlin, Germany
2 Technische Universität Berlin, Institute of Solid State Physics, Hardenbergstr. 36, EW 6-1, 10623, Berlin, Germany

E-mail: hyunkyong.cho@fbh-berlin.de

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Abstract
The impact of plasma etching on the formation of low-resistance n-contacts on the AlGaN:Si current spreading layer during the chip fabrication of ultraviolet light-emitting diodes (UVC LEDs) emitting at 265 nm is investigated. A two-step plasma etching process with a first rapid etching using BCl3/Cl2 gas mixture and a second slow etching step using pure Cl2 gas has been developed. The etching sequence provides smooth mesa side-walls and an n-AlGaN surface with reduced surface damage. Ohmic n-contacts with a contact resistivity of 3.5 × 10−4 Ωcm2 are obtained on Si-doped Al0.65Ga0.35N layers and the operating voltages of the UVC LEDs were reduced by 2 V for a current of 20 mA.

Keywords: light emitting diode, plasma etch, ohmic contact, low resistance n-contact, high Al mole fraction n-AlGaN, operating voltage

(Some figures may appear in colour only in the online journal)

1. Introduction
AlGaN-based deep ultraviolet light-emitting diodes (UV LEDs) are promising devices that could replace mercury discharge lamps in various applications including sterilization, water purification, medical diagnostics, phototherapy, and UV curing [1–3]. However, to achieve devices with a high wall plug efficiency, low operating voltages and consequently low contact resistances are required. Due to low electron affinity and to the strong Al-N bond of AlGaN with high Al mole fraction, ohmic contacts are difficult to realize [4, 5]. Moreover, a buried n-AlGaN layer needs to be exposed by plasma etching before the n-contact metal stack can be deposited. Plasma etching can potentially roughen the surface, change the stoichiometry of the AlGaN materials, and damage the crystal structure [6].

All these effects are known to influence the performance of the electrical contact. Various types of dry etching techniques have been used for etching mesa structures in group-III nitride LEDs or laser diodes, e.g. reactive ion etching (RIE), electron cyclotron resonance plasma, and inductively coupled plasma (ICP). ICP-RIE with Cl2 or a mixture of Cl2 and BCl3 as the chemically reactive gases is the most commonly employed method [7–10]. For etching AlGaN with high Al mole fraction in UV LEDs, achieving a sufficiently high etch rate is a further issue because of the strong bond energy between aluminum and nitrogen atoms and the high affinity of aluminum to oxidation [11, 12]. The etch rate can be easily increased by increasing the radio frequency (RF) power during the RIE process. However, a high RF power results in high energy ions which bombard the surface and potentially generate crystal defects [13, 14].

Recently, a two-step plasma etching process has been reported for GaN which involves a final etch step with BCl3/Cl2 and Cl2 gases at low power to reduce crystal damage...
near the surface [15–17]. Previously, our group described the effects of Cl2 plasma etching and various post etching treatments of n-Al0.75Ga0.25N surfaces on their chemical composition [18].

In this study, we report on the effects of the BCl3 to Cl2 gas flow ratio and RF power during the ICP-RIE plasma etching of n-Al0.65Ga0.35N:Si on the etch rate and the smoothness of fabricated mesa edges. A two-stepetch process including a final etching with Cl2 at low RF power will be shown to provide a smooth surface and the low resistivity for vanadium-based contacts deposited thereon. UVC LEDs with an emission wavelength of 265 nm featuring the optimized two-step etching process exhibit lower operating voltages. To the best of our knowledge, this is the first report of the successful use of a two-step etching process in the processing of UVC LEDs. The approach described contributes to gradually increasing the low efficiency of UVC LEDs and to improve the still limited applicability of the components.

2. Experimental

UVC LED heterostructures with a target emission wavelength of 265 nm were grown by metal-organic vapor phase epitaxy on (0001) c-plane sapphire substrates. A 500 nm AlN layer on sapphire was patterned into stripes by photolithography and dry etching and then laterally overgrown with AlN to a total thickness of 600 nm. A 900 nm thick Al0.65Ga0.35N:Si was deposited and the UVC LED heterostructure with different gas flow ratios: (a) pure Cl2, (b) 4:1 BCl3/Cl2, and (c) pure BCl3. The etch rate increases steadily up to the maximum applied RF power 100 W. This effect is attributed to the increased ion energy with higher RF power which enhances the ion-assisted etching and consequently the etch rate.

3. Results and discussion

Figure 1(a) shows the etch rates of n-Al0.65Ga0.35N:Si as a function of the ratio of the BCl3 and Cl2 flow rates. Etching was performed at an ICP power of 200 W, an RF power of 60 W and a fixed total gas flow. The etch rate decreases with increasing amount of BCl3. This effect can be attributed to the higher dissociation threshold energy of BCl3 than Cl2 which requires a higher ICP power. With a fixed ICP power, an increased ratio of BCl3 in the total gas flow reduces the amount of available radicals thus hindering the etch rate [10]. In addition, AlCl3 which is less volatile than GaCl3 is known to form on the etched surface of high-aluminum mole fraction AlGaN [11]. With a fixed process temperature of 20 °C, the removal of AlCl3 relies on the physical bombardment by the plasma. To increase the AlGaN etch rate when using a gas flow ratio of 4:1 BCl3/Cl2, the RF power has been varied at a constant ICP power of 200 W. The results are shown in figure 1(b). The etch rate increases steadily up to the maximum applied RF power 100 W. This effect is attributed to the increased ion energy with higher RF power which enhances the ion-assisted etching and consequently the etch rate.

Figure 2 shows the bird’s eye-view scanning electron microscopy (SEM) micrographs of mesa edges etched in to the UVC LED heterostructure with different gas flow ratios: (a) pure Cl2 and (b) 4:1 BCl3/Cl2. With the pure Cl2 plasma, the sidewalls of the etched mesa structure show a rough surface with an additional fence structure. It is assumed that the fence structure is related to the redeposition of reaction products, most likely oxides, from etching and indicates a high proportion of physical ablation. The rough sidewalls of the etched mesa were observed independent of the ICP power or the RF power (not shown here). This is assumed to be related to crystal damage. When the concentration of BCl3 increases, the mesa sidewalls become smoother and more clearly defined (figure 2(b)). This is probably due to re-deposition effects from sputtering during the plasma etch by using BCl3 based gas which generates heavier ions [10]. Furthermore, the previously observed fence is less pronounced due to the preferred etching of oxides by BCl3. The redeposited layer protects the exposed mesa sidewalls during etching thus resulting in a smoother surface [10, 20, 21]. Images for determining the inclination angles of the mesa edges are shown as insets of figure 2. The gas flow ratio is not impacting the mesa inclination angles as 48° and 51° are measured in cross section SEM
A reasonably high etch rate during plasma etching requires high ICP power, high RF power, and high bias voltage. Unfortunately, plasma-induced damage often results in an etched near-surface of poor quality: generation of point defects such as Ga or N vacancies which can considerably degrade the device performance [22]; alteration of the near-surface stoichiometry through preferential loss of the more volatile element, e.g. N deficiency of the surface and subsequent oxidation [18, 23]; introduction of deep non-radiative compensating centers due to energetic ion bombardment [14, 24]. Therefore, in order to preserve the electrical contact performance of the electrodes deposited on the etched surface, a two-step etching process is proposed here. First, the target etch depth is approached with a high etch rate of 2.1 nm s$^{-1}$ using BCl$_3$/Cl$_2$. Second, possible surface damage is removed using a low etch rate of 0.3 nm s$^{-1}$ using either Cl$_2$ or BCl$_3$/Cl$_2$. This is in agreement with the results for n-contacts on n-Al$_{0.75}$Ga$_{0.25}$N reported in [25]. Accordingly, the second etch step was performed with Cl$_2$ or BCl$_3$/Cl$_2$ at a low RF power of 15 W. The RF power is mainly linked to the physical etching process, i.e. the lower the RF power the smaller the expected surface damage. The ICP power was set to 100 W to ensure a stable plasma discharge at the low RF power.

The I–V characteristics of annealed contacts on plasma-etched n-Al$_{0.65}$Ga$_{0.35}$N surfaces with different gas flow mixtures in the second etch step are shown in figure 3. The I–V curves are non-linear for the case of single-step etching with a BCl$_3$/Cl$_2$ gas mixture of 4:1. When adding a second etch step with BCl$_3$/Cl$_2$ and Cl$_2$, the voltage drop at the contacts decreases. Cl$_2$ plasma is more effective in reducing contact resistivity than BCl$_3$ plasma. An ohmic contact with a contact resistivity of $(3.5 \pm 0.5) \times 10^{-4}$ $\Omega \text{cm}^2$ is found when using pure Cl$_2$ gas in the second etch step. The result supports the idea that the semiconductor surface suffers from either crystalline...
damage or residuals induced by plasma etching which limit the contact performance. Improved contacts can be obtained by reducing this damage or these residuals through final plasma etch step where chemical etching dominates rather than physical etching.

Figure 4 shows the I–V characteristics and the emission spectrum of UVC LEDs fabricated with single-step and two-step etching process. The operating voltage of the devices with the two-step etching is lower than that of the devices with a single-step etching at a constant forward current, e.g. 8.5 V and 11 V at 20 mA, respectively. This finding agrees with the TLM data discussed before and suggests that a significant part of the operating voltage of the devices with a single-etching process drops at the n-contact. Again, the reduced resistivity of the n-contact of the LEDs is attributed to the fact that the surface damage below the metal stack is reduced during the soft final Cl2 plasma etch step.

4. Conclusion

The plasma etching of n-Al0.65Ga0.35N layers was investigated with respect to (i) the performance of V/Al/Ni/Au n-contacts deposited on the etched n-AlGaN surfaces and (ii) the feasibility of implementing the technology in the front-end processing of UVC LEDs emitting at 265 nm. A reasonable etch rate with smooth sidewalls of etched mesas was obtained when using a gas mixture of BCl3 and Cl2 at a low RF power was found to smoothen the surface and resulted in an ohmic n-contact with a contact resistivity of $(3.5 \pm 0.5) \times 10^{-4}$ $\Omega\text{cm}^2$. The developed two-step etching process was successfully applied to UVC LEDs and reduced their operating voltage by 2 V at 20 mA. The superior performance of the n-contacts and the LEDs is attributed to the reduction of surface damage or residuals from plasma etching during the final soft etch step.

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ORCID iDs

H K Cho https://orcid.org/0000-0001-5540-2582
L Sulmoni https://orcid.org/0000-0002-5341-7032
J Rass https://orcid.org/0000-0002-9232-0495
N Susilo https://orcid.org/0000-0002-5583-629X
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