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

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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 (UV LEDs) emitting at 265 nm is investigated. A two-step plasma etching process with a first rapid etching using BCl_3/Cl_2 gas mixture and a second slow etching step using pure Cl_2 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} Ωcm^2 are obtained on Si-doped $Al_{0.65}Ga_{0.35}N$ 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 Cl_2 or a mixture of Cl_2 and BCl_3 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 BCl_3/Cl_2 and Cl_2 gases at low power to reduce crystal damage

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near the surface [15–17]. Previously, our group described the effects of Cl_2 plasma etching and various post etching treatments of n-$Al_{0.75}Ga_{0.25N}$ 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-step etch process including a final etching with Cl2 at low RF power will be shown to provide the a smooth surface and the a 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 6 μm. Subsequently the AlGaN-based heterostructure is deposited comprised of a 900 nm thick $Al_{0.76}Ga_{0.24}N$:Si current spreading layer, a 100 nm $Al_{0.76}Ga_{0.24}N$:Si/$Al_{0.65}Ga_{0.35}N$:Si transition layer, 200 nm $Al_{0.65}Ga_{0.35}N$:Si contact layer, a threefold 5 nm $Al_{0.62}Ga_{0.38}N$:Si/1.4 nm $Al_{0.48}Ga_{0.52}N$ multiple quantum well active region, a 10 nm $Al_{0.85}Ga_{0.15}N$ and 25 nm $Al_{0.75}Ga_{0.25}N$:Mg electron blocking heterostructure and a 230 nm thick GaN:Mg contact layer [19]. In addition, for n-contact optimization studies, single $Al_{0.65}Ga_{0.35}N$:Si contact layers were grown with a thickness of 500 nm.

Test structures for determining the specific n-contact resistance using the transmission line measurement (TLM) were fabricated using photolithography and ICP-RIE etching in a Sentech SI500 system. All etchings were performed with BCl_3 and Cl_2 at 20 °C and a pressure of 1 Pa. The gas flow ratio of BCl_3 and Cl_2, the ICP power, the RF power, and the bias voltage were varied. The etched surfaces were examined by scanning electron microscopy (SEM). Etch masks made of photoresist were removed after plasma etching using a standard remover and the samples were then cleaned with piranha solution. Prior to the deposition of the n-contact metal stack, the plasma-etched surfaces were wet-chemically cleaned for 30 s in HCl/H_2O (1:1), rinsed for one minute in de-ionized water and spin-dryed under nitrogen. Thereafter, a metal layer stack of V(15 nm)/Al(120 nm)/Ni(20 nm)/Au(40 nm) was deposited by electron-beam evaporation and structured by a lift-off process. The spacings between the TLM contacts were 10 μm, 15 μm, 20 μm, 25 μm, and 30 μm, respectively. The contacts were annealed at 750 °C in nitrogen ambient for 30 s using a rapid thermal annealing (RTA) furnace. Current-voltage (I–V) measurements were performed at room temperature.

Selected wafers were processed to LEDs. Therefore, p-contacts were fabricated by depositing Pt (30 nm) and annealing at 500 °C under nitrogen for 5 min. A SiN_x passivation layer was deposited by plasma enhanced chemical vapor deposition followed by the deposition of the metal bond pads. The fabricated chips are of 1 mm $\times$ 0.6 mm size with an active emitter area of 0.15 mm^2. The light output power was measured on-wafer at room-temperature using a calibrated Si photodiode.

3. Results and discussion

Figure 1(a) shows the etch rates of n-$Al_{0.65}Ga_{0.35}N$:Si as a function of the ratio of the BCl_3 and Cl_2 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 BCl_3. This effect can be attributed to the higher dissociation threshold energy of BCl_3 than Cl_2 which requires a higher ICP power. With a fixed ICP power, an increased ratio of BCl_3 in the total gas flow reduces the amount of available radicals thus hindering the etch rate [10]. In addition, $AlCl_x$ which is less volatile than $GaCl_x$ 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 $AlCl_x$ relies on the physical bombardment by the plasma. To increase the AlGaN etch rate when using a gas flow ratio of 4:1 BCl_3/Cl_2, 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 Cl_2 and (b) 4:1 BCl_3/Cl_2. With the pure Cl_2 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 BCl_3 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 BCl_3 based gas which generates heavier ions [10]. Furthermore, the previously observed fence is less pronounced due to the preferred etching of oxides by BCl_3. 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

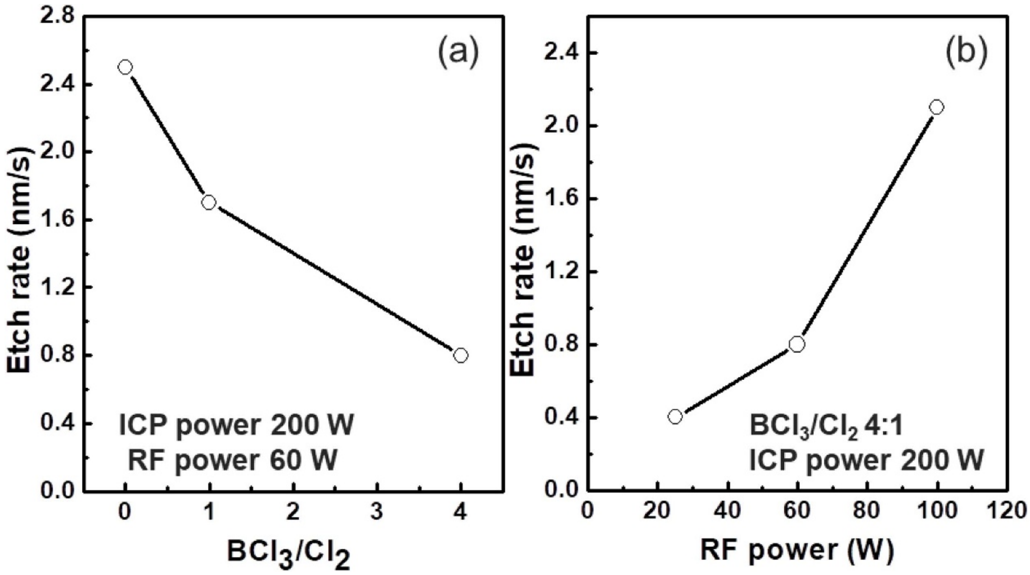

Figure 1. Etch rates of n- $Al_{0.65}Ga_{0.35}N$:Si as a function of (a) the ratio of BCl_3 and Cl_2 flow rates using a constant ICP power of 200 W, an RF power of 60 W, and a bias voltage of −100 V, and (b) the RF power using a ratio of the gas flow rates BCl_3/Cl_2 of 4:1, and an ICP power of 200 W.

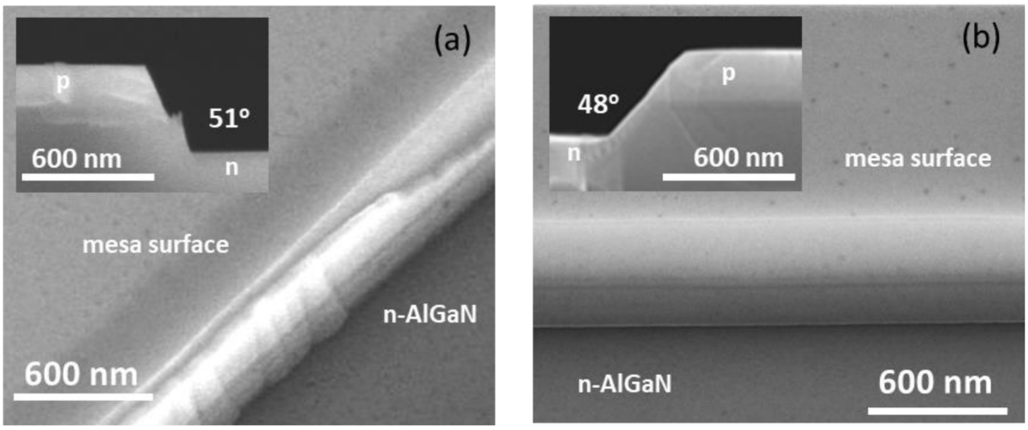

Figure 2. Bird's eye view SEM micrographs of the etched mesa edge of a UVC LED with (a) Cl_2 and (b) a BCl_3/Cl_2 gas mixture of 4:1 and using an ICP power of 200 W, an RF power of 100 W, and a bias voltage of −200 V. Inset: corresponding cross section SEM micrographs with inclination angles of the mesa side walls.

micrographs for pure Cl_2 plasma and for BCl_3/Cl_2 gas mixture of 4:1, respectively (insets in figure 2).

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 $(3.5 \pm 0.5) \times 10^{-4}$ Ωcm^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

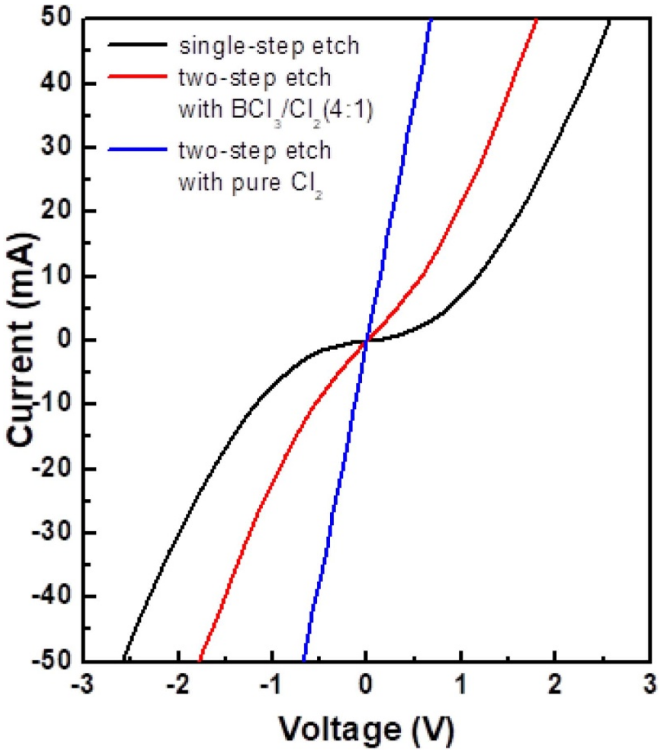

Figure 3. Four-point probe I–V characteristics of annealed V/Al/Ni/Au contacts with an electrode distance of 20 μm on n- $Al_{0.65}Ga_{0.35}N$:Si after single-step etching using BCl_3/Cl_2 gas mixture of 4:1 (black curve), two-step etching using BCl_3/Cl_2 (4:1) (red curve) and Cl_2 (blue curve) in the second etch step.

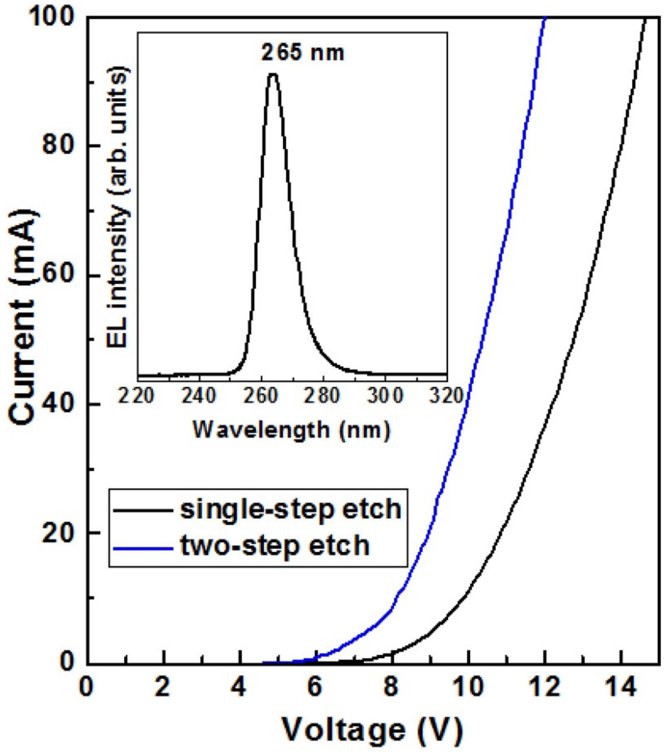

Figure 4. I–V characteristics of UVC LEDs fabricated with single-step etching using BCl_3/Cl_2 gas mixture of 4:1 (black curve) or two-step etching using Cl_2 in the second etch step (blue curve). The inset shows a typical emission spectrum of both LED types at 20 mA (0.15 mm^2). All the measurements were performed on-wafer in continuous wave operation.

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 Cl_2 plasma etch step.

4. Conclusion

The plasma etching of n-$Al_{0.65}Ga_{0.35}N$ 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 BCl_3 and Cl_2 and a sufficient RF power. An additional final etch step with pure Cl_2 at a low RF power was found to smoothen the surface and resulted in an ohmic n-contact with a contact resistivity of $(3.5 \pm 0.5) \times 10^{-4}$ Ωcm^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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