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Reduction of reverse-bias leakage current in GaN-based Schottky-type light-emitting diodes by surface modification using the aluminum facepack technique

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We investigated the reduction of the large reverse-bias leakage current in GaN-based Schottky diodes using the aluminum facepack technique, which involves the evaporation of aluminum onto the nitride surface, the subsequent oxidation of the Al film in air, and its removal by a wet-etching technique. The reduction of the reverse-bias leakage current was due to the mask effect of the facepack, which reduced the number of dislocation-related leakage current paths. This reduction leads to the enhancement of quantum efficiency in Schottky-type light-emitting diodes.

1 Introduction

GaN-based Schottky-type light-emitting diodes (ST-LEDs) are cost-effective devices that can be integrated in devices such as flat display panels (FDPs) [1-3]. We have reported the reverse-bias operation of GaN-based ST-LEDs in the UV spectral region [1]. Although the device structure of these ST-LEDs is similar to that in a previous report (tunneling metal-insulator-semiconductor (MIS) or metal-oxide-semiconductor (MOS) LEDs) [4, 5], we successfully achieved a reverse-bias operation [1] with ten times higher quantum efficiency using ST-LED devices. However, the reverse-bias leakage current in GaN-based Schottky-type devices remains an obstacle for their application to LEDs because the leakage leads to the reduction of external quantum efficiency. Thus, reduction of the reverse-bias leakage current is a technical issue in the development of GaN-based UV ST-LEDs. The reverse-bias leakage is also a crucial issue in their application to GaN-based Schottky diodes and field-effect transistors.

Many techniques for the reduction of leakage current have been reported. The techniques can be classified into two types. One aims to reduce the number of surface leakage paths on III-V nitrides [6] and the other aims to reduce the number of leakage paths due to threading dislocations (TDs) [7]. Kotani *et al.* [6] have reported that the evaporation of aluminum onto an AlGaN surface and its subsequent annealing in vacuum reduces the number of surface leakage paths due to oxygen impurities, which leads to the reduction of reverse-bias leakage current in the Schottky contact. However, the process was based on an *in situ* process, which is not suitable for the fabrication of cost-effective devices. In this paper, we report an *ex situ* technique involving the annealing of an Al film evaporated onto AlGaN or GaN for the formation of the Schottky contact. The mechanism of the leakage reduction is also discussed.

2 Experimental procedures

Hexagonal $Al_{0.1}Ga_{0.9}N$ and GaN layers grown on (0001) sapphire substrates by conventional radio-frequency plasma-assisted molecular beam epitaxy (RF-MBE) [8] were used for the device fabrication. AlN buffers were used for the growth. The thickness of the layers, which was were Si-doped layers and had an electron concentration of $1x10^{18}$ cm^{-3}, was approximately 1 μm. The facepack technique was adopted to modify the surfaces of the layers for the formation of Schottky contacts. This technique is similar to a previously reported technique [6] but is an *ex situ* process. First, the layers were cleaned using buffered hydrogen fluoride (BHF) to remove their surface oxides, as

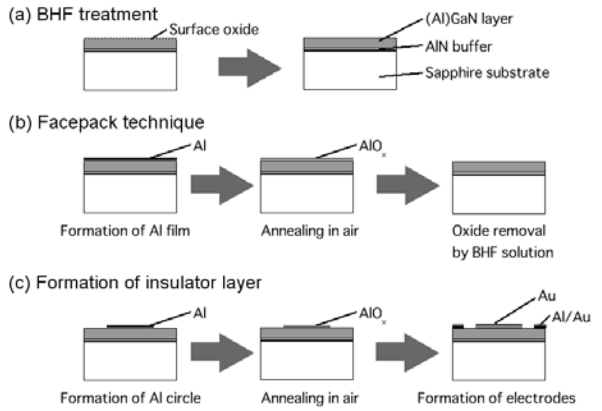

Figure 1 Fabrication process of AlGaN or GaN-based MOS LEDs.

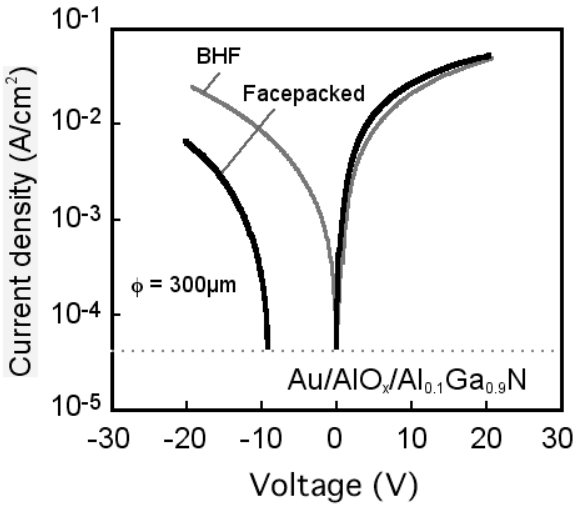

Figure 3 I-V characteristics of AlGaN-based MOS LEDs.

shown in Fig. 1(a). The reduction of the oxygen concentration on the surface was confirmed by x-ray photoelectron spectroscopy (XPS). Next, an Al layer with a thickness of approximately 20 nm was deposited on the surface by vacuum evaporation. The layers were then annealed in air at 750°C and the surface oxides were removed using BHF solution. This sequence was named the facepack technique, which is shown in Fig. 1(b). The aluminum oxide layer was inserted between the Schottky electrodes and nitride layers for the fabrication of MOS LEDs. The oxide insulator layer was fabricated by re-evaporating Al on the surface-modified nitride layer, which was followed by annealing in air. This process is illustrated in Fig. 1(c). A Au electrode was used for the Schottky contact, whose film was formed by vacuum evaporation. The diameter of the circular Au electrode and the window diameter in the ohmic Al electrode were 300 μm and 1 mm, respectively. A schematic drawing of the devices is shown in Fig. 2. The Schottky and ohmic contacts were fabricated on the surface of the devices.

3 Results and discussion

3.1 Reduction of reverse-bias leakage current

Typical current-voltage (I-V) characteristics of the AlGaN-based MOS LEDs are shown in Fig. 3. A reduction of reverse-bias current was observed in the GaN-based MOS LEDs and ST-LEDs, thus clarifying that the aluminum facepack technique is effective for reducing reverse-bias current. The electroluminescence (EL) spectra of GaN-based MOS-LEDs with and without the facepack technique for surface control are shown in Fig. 4. The EL intensity was increased when the facepack technique was employed. Here, the input power was fixed at 750 mW. This means that the difference in the intensity corresponds to that of the external quantum efficiency. A peak-energy difference

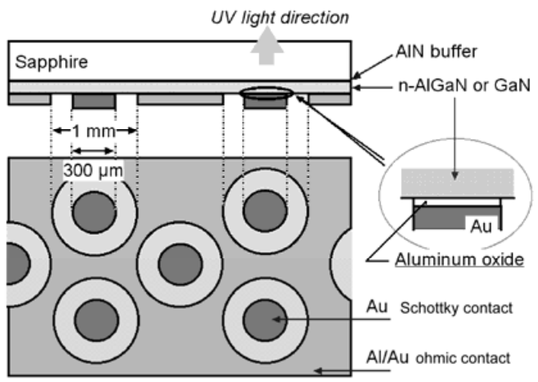

Figure 2 Schematic drawing of the device structure.

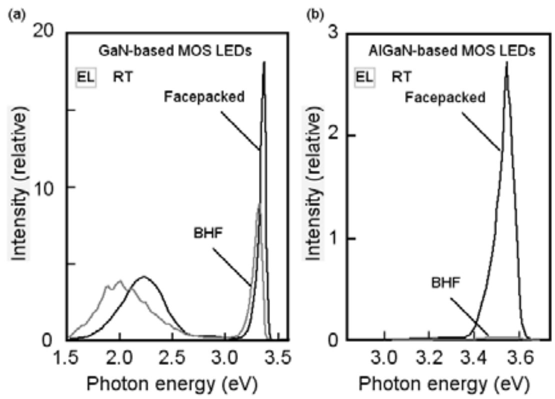

Figure 4 EL spectra of AlGaN- and GaN-based MOS LEDs.

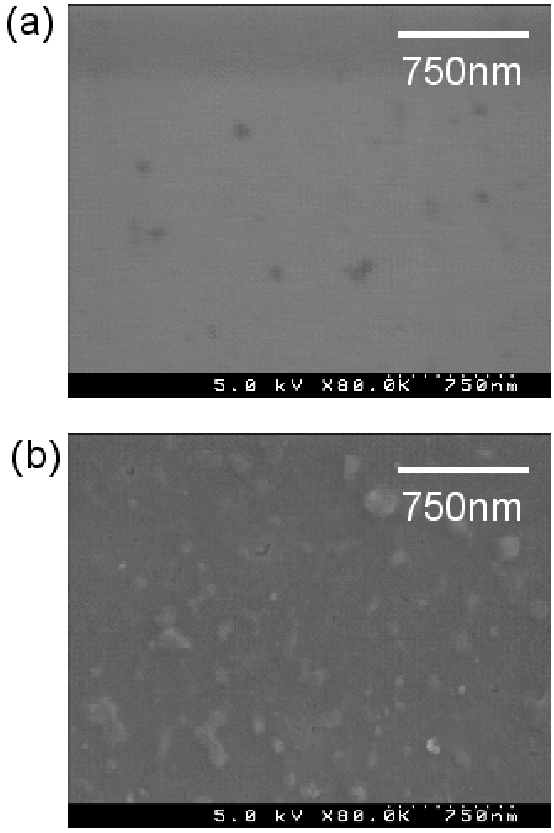

Figure 5 Surface SEM images of AlGaN layers after (a) cleaning by BHF and (b) facepack modification.

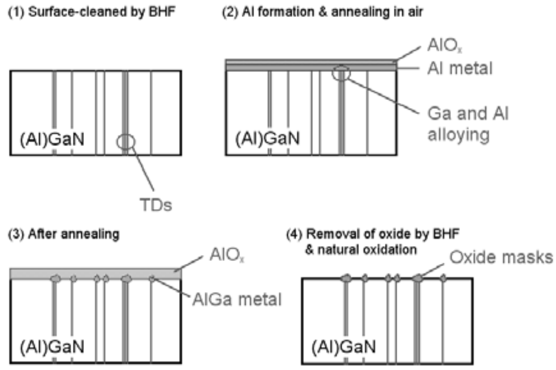

Figure 6 Formation model of aluminum oxide on the TD-related leakage paths.

between the two devices was observed. This was due to the temperature difference of their emission area because of their difference in quantum efficiency [2]. The reduction of reverse-bias leakage current also enables the observation of the EL spectra of the AlGaN-based MOS LEDs (Fig. 4(b)). The devices were typically driven under a forward bias of 18-25 V and a pulsed voltage of 25 ms. The duty ratio of the pulsed voltage was 50%. Although the previously reported external quantum efficiency of the GaN-MOS LED was 5×10^{-3} % (at 77 K) [4], a ten times higher luminescent intensity was achieved at RT in this study.

3.2 Model of leakage current reduction The XPS spectra show that residual aluminum existed on the surface of the GaN layers after the surface modification. The surface oxygen concentrations of the surface-modified GaN and AlGaN layers were higher than those before modification. Furthermore, the surface concentrations of Ga and N on the GaN layers remained almost constant despite the surface modification. This indicates that the residual aluminum is locally attached to the surface of the GaN. To confirm this, SEM images of the layers were observed. Images of (a) the surface of the AlGaN layer cleaned by BHF and (b) that after surface modification by the facepack technique are shown in Fig. 5. TD-related dark spots were observed in (a). On the other hand, some charged particles were observed in (b). We consider that the particles are aluminum oxide. Some of the dark spots in (a) disappeared and charged spots appeared in (b) upon surface modification. We consider that part of the gallium metal around the TDs was replaced with aluminum during the annealing. The aluminum was not etched during cleaning in the BHF process and was oxidized in air to aluminum oxide after cleaning. The aluminum oxide acts as a mask, reducing the number of TD-related leakage paths. This leads to the reduction of the reverse-bias leakage current. A model of oxide formation on the TD-related leakage paths is schematically shown in Fig. 6.

To confirm the validity of the model, the BHF process was performed on the facepacked AlGaN layer and a MOS diode was fabricated from it. The additional BHF process increased the leakage current. This indicates that the aluminum oxides formed on the TD-related leakage paths were removed by the BHF process.

4 Summary The surface modification of GaN-based Schottky diodes using an aluminum facepack technique was investigated. This technique resulted in a decrease in the reverse-bias current. This is due to the mask effect of the facepack reducing the number of dislocation-related leakage current paths. This reduction leads to the enhancement of quantum efficiency in Schottky-type LEDs.

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