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Investigation of the low-temperature AlGaN interlayer in AlGaN/GaN/AlGaN double heterostructure on Si substrate

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Abstract

A low-temperature (LT) AlGaN interlayer is inserted in the Al0.1Ga0.9N back barrier layer of an Al0.2Ga0.8N/GaN/Al0.1Ga0.9N double heterostructure grown on a 150 mm Si substrate. It is found that the 21-nm-thick LT-AlGaN interlayer plays an important role in stress relaxation and dislocation reduction of the Al0.1Ga0.9N back barrier layer, especially for screw dislocation reduction. In addition, a buffer breakdown voltage higher than 600 V is achieved, which is much higher than those of conventional heterostructures. These results demonstrate the effectiveness of combining the LT-AlGaN interlayer and the Al0.2Ga0.8N/GaN/Al0.1Ga0.9N double heterostructure on a Si substrate to increase the breakdown voltage for high-power applications.

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Fig. 1. (a) Schematic diagram of the Al0.2Ga0.8N/GaN/Al0.1Ga0.9N double heterostructure on Si substrate with the inserted LT-AlGaN interlayer and (b) cross-sectional TEM image of the whole epitaxial layer structure.
H₂ was used as the carrier gas. The growth sequence is as follows: an 800-nm-thick transition layer consisting of AlN and multi-AlGaN layers was first grown on the Si substrate, which was followed by the growth of a 1-µm-thick Al₀.₁Ga₀.₉N back barrier layer. In the subsequent growth of the 2-µm-thick Al₀.₁Ga₀.₉N back barrier layer, a thin LT-AlGaN interlayer was inserted between two 1-µm-thick Al₀.₁Ga₀.₉N back barrier layers. The growth was completed after the growth of a 90-nm-thick GaN channel layer and a 30-nm-thick Al₀.₂Ga₀.₈N top barrier layer. For the buffer breakdown voltage comparison, two conventional structures, namely, an Al₀.₂Ga₀.₈N/GaN single heterostructure with a LT interlayer and an Al₀.₂Ga₀.₈N/GaN/Al₀.₁Ga₀.₉N double heterostructure without a LT interlayer, were grown on the same transition layer. Details of the epitaxial growth of these two control samples can be found in our previous work.¹⁹

During the epitaxial growth, the wafer temperature, reflectance, and wafer curvature were in situ-monitored using a Laytec EpiCurve® TT system. The structure and composition of each layer were characterized by secondary ion mass spectrometry (SIMS), high-resolution X-ray diffraction (HRXRD), and weak-beam dark-field TEM.

In order to further confirm the buffer quality of the two conventional structures and the proposed structure, the buffer breakdown voltage characteristics of these samples were measured using Agilent B1505A. The isolation regions were defined by Cl₂-based dry etching. The electrodes of a Ti/Al/Ni/Au multilayer metal were deposited using an electron beam evaporator, followed by rapid thermal annealing at 800 °C for 60 s under N₂ atmosphere. The contact resistances of these samples were in the range of 0.5–0.6 Ω mm based on the transmission line model method. The gate metal of Ni/Au was deposited as a Schottky gate electrode using an electron beam evaporator. An off-state breakdown voltage was measured on the proposed structure sample to prove the real advantages of the fabricated device. The gate width (W), gate length (Lg), gate-to-drain spacing (Lgd), and gate-to-source spacing (Lgs) were 100, 1, 4.5, and 1.5 µm, respectively.

Previously, Fritze et al. investigated the impact of LT-AlGaN interlayer thickness on the stress and crystalline quality of the GaN-on-Si structure.²¹ It was found that the role of the LT-AlGaN interlayer was to introduce additional compressive stress to compensate for the tensile stress generated in the thick epilayers. On the basis of this concept, it is expected that a similar benefit will be obtained by adding a LT-AlGaN interlayer into the thick Al₀.₁Ga₀.₉N back barrier layer of the Al₀.₂Ga₀.₈N/GaN/Al₀.₁Ga₀.₉N double heterostructure.

The stress evolution during the Al₀.₁Ga₀.₉N back barrier layer growth can be observed from the in situ wafer curvature measurement. Figure 2 shows the results of the in situ measurements of temperature, reflectance, and wafer curvature obtained with a Laytec EpiCurve® TT system during the growth of the Al₀.₂Ga₀.₈N/GaN/Al₀.₁Ga₀.₉N double heterostructure. The first Al₀.₁Ga₀.₉N back barrier layer was grown under a compressive stress (negative curvature). It was attributed to the larger in-plane lattice constant of Al₀.₁Ga₀.₉N than of the transition layer. However, if the first Al₀.₁Ga₀.₉N back barrier layer is thicker than 1 µm, this compressive stress will be relaxed with dislocation formation and converted to tensile stress. A LT-AlGaN interlayer was inserted in the middle of the 2-µm-thick Al₀.₁Ga₀.₉N back barrier layer in order to prevent this stress transition. The inserted LT-AlGaN interlayer was grown at 750 °C for 180 s. A negative curvature trace was observed during the growth of the Al₀.₁Ga₀.₉N back barrier layer with the insertion of the LT-AlGaN interlayer, which indicates that an effective compressive stress was induced by this LT-AlGaN interlayer.

In order to investigate the details of each epilayer, the SIMS depth profiles of Al and Ga on the Al₀.₂Ga₀.₈N/GaN/Al₀.₁Ga₀.₉N double heterostructure were analyzed, and the results are shown in Fig. 3. From the depth profiles, increases in the intensities of Al- and Ga-related signals were observed near 1125 nm below the surface. This provides evidence of the existence of the AlGaN interlayer between the two Al₀.₁Ga₀.₉N back barrier layers. From the inset of Fig. 3, a 21-nm-thick LT-AlGaN interlayer can be clearly observed from the TEM image. However, the Al signal is only for qualitative analysis, not for quantitative analysis; further investigation is needed to characterize the Al composition of the LT-AlGaN interlayer.

The Al composition is estimated to be 50% for the LT-AlGaN interlayer as judged from the HRXRD ω–2θ scan data shown in Fig. 4. Owing to the thin interlayer, the intensity of the Al₀.₅Ga₀.₅N(002) peak is low. On the other hand, the Al₀.₁Ga₀.₉N back barrier layer shows a very high peak intensity. The Al₀.₁Ga₀.₉N layer provides a higher band discontinuity that helps prevent the electron leakage from the channel layer. Furthermore, according to the XRD rocking curve, the full-widths at half-maximum (FWHMs) of X-ray rocking curves for the Al₀.₁Ga₀.₉N(002) ω-scan and Al₀.₁Ga₀.₉N(102) ω-scan were 578.6 and 1103 arcsec, re-
respectively. These results indicate that the crystalline quality of the Al$_{0.2}$Ga$_{0.8}$N/GaN/Al$_{0.1}$Ga$_{0.9}$N double heterostructure on Si is comparable to that of the traditional AlGaN/GaN single heterostructure on Si.

The high crystalline quality of this interlayered structure was further confirmed from the cross-sectional TEM images of the heterostructure. The TEM images were taken to observe the dislocation distribution within the epilayers. Figure 5(a) shows the weak-beam dark-field TEM image under the $g = [0002]$ condition. The edge dislocations with a Burgers vector of $b = \frac{1}{3}\langle11\bar{2}0\rangle$ were invisible owing to the $g \cdot b = 0$ criterion. Only screw dislocations with a Burgers vector of $b = \langle0001\rangle$ and mixed dislocations with a Burgers vector of $b = \langle11\bar{2}3\rangle$ were observed. The number of screw dislocations in the upper Al$_{0.1}$Ga$_{0.9}$N back barrier layer was significantly reduced after inserting the LT-AlGaN interlayer. The edge and mixed dislocations are shown in Fig. 5(b) under the $g = [11\bar{0}0]$ condition. Here, the inserted LT-AlGaN interlayer shows less impact on the edge dislocation reduction. In order to enhance the breakdown voltage characteristics, it is necessary to grow a low-dislocation-density film. Hsu et al. and Dadgar et al. also indicated that the screw dislocations were the primary defects causing the decrease in the breakdown voltage.$^{20,21}$ Thus, the LT-AlGaN interlayer acts as a dislocation filter, which is very effective for screw dislocation reduction. This may explain the reason why the breakdown voltage was improved for the Al$_{0.1}$-Ga$_{0.9}$N back barrier with the LT-AlGaN interlayer.

Buffer leakage current measurement is a straightforward method of further evaluating the optimal structure design and material quality. The breakdown voltage of the epitaxial structure was determined by measuring the lateral buffer leakage characteristics across a 20 µm spacing. The buffer leakage currents of the three different epitaxial structures are shown in Fig. 6, which include the samples of (a) an Al$_{0.2}$Ga$_{0.8}$N/GaN single heterostructure with a LT interlayer (total thickness: 3.4 µm), (b) an Al$_{0.2}$Ga$_{0.8}$N/GaN/Al$_{0.1}$Ga$_{0.9}$N double heterostructure without a LT interlayer (total thickness: 2.3 µm), and (c) an Al$_{0.2}$Ga$_{0.8}$N/GaN/Al$_{0.1}$Ga$_{0.9}$N double heterostructure with a LT interlayer (total thickness: 3.0 µm). The breakdown voltage characteristics of the samples from the first two conventional structures were below 400 V, but a breakdown voltage higher than 600 V was obtained from the sample of the Al$_{0.2}$Ga$_{0.8}$N/GaN/Al$_{0.1}$Ga$_{0.9}$N double heterostructure with the LT interlayer. For the double heterostructure, the use of the Al$_{0.1}$Ga$_{0.9}$N back barrier results in a lower...
buffer leakage current. Moreover, the thicker Al$_{0.1}$Ga$_{0.9}$N back barrier with the improved crystalline quality also enhances the buffer breakdown voltage characteristics. On the basis of these advantages, an off-state breakdown voltage higher than 200 V was measured on the fabricated device using the proposed structure with a gate-to-drain spacing of 4.5 µm. This remarkable improvement demonstrates that the double heterostructure with the LT interlayer is an effective structure for high-power electronic applications.

In conclusion, an Al$_{0.2}$Ga$_{0.8}$N/GaN/Al$_{0.1}$Ga$_{0.9}$N double heterostructure on Si with the inserted LT-AlGaN interlayer for breakdown voltage improvement is investigated. According to the SIMS depth profile, the interlayer can be regarded as the AlGaN interlayer. The thickness and Al composition of the LT-AlGaN interlayer as investigated by TEM and XRD are 21 nm and 50%, respectively. By in situ curvature measurement, the LT-AlGaN interlayer is observed to induce the compressive stress during the growth of the proposed structure. As shown in the weak-beam dark-field TEM analysis, the number of dislocations in the upper Al$_{0.1}$Ga$_{0.9}$N back barrier is reduced by the insertion of the LT-AlGaN interlayer, especially for screw dislocations. Compared with the other conventional structures, the double heterostructure with the LT-AlGaN interlayer markedly improves the breakdown voltage of the device. The proposed structure with breakdown voltage higher than 600 V is demonstrated in this work. Overall, it is demonstrated that the proposed approach is very effective for increasing the buffer breakdown voltage of the double heterostructure and very promising for realizing devices for high-power applications.

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