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Hall mobility (μ_H) and two dimensional electron gas density (n_s) have been measured from 77 up to 973 K in AlInN/AlN/GaN heterostructures, where the atmospheric condition is changed as measured in vacuum and air. The μ_H decreases monotonically with increasing the temperature. The characteristic feature is observed in n_s that it is almost constant up to around 540 K and shows sudden increase at higher temperatures when measured in the vacuum, while it is almost constant measured in the air. The surface barrier lowering originated from the decomposition of the surface oxide layer on AlInN is proposed as the most probable mechanism for the increase in n_s. © *2011 American Institute of Physics*. [doi:10.1063/1.3644161]

AlInN alloys are very promising materials for high power electronic and optoelectronic devices. Since the first proposal by Kuzmík in 2001,[1] many encouraging reports on AlInN/AlN/GaN HEMTs have been published.[2,3] The advantages of AlInN/GaN material structure, compared to that of AlGaN/GaN, are its high electron density induced at heterointerface[4] and lattice matching between AlInN and GaN, which lead to high current density and eliminate the strain-related instabilities.[5–7] In parallel to enhance HEMT performance, the properties of the two dimensional electron gas (2DEG) formed at AlInN/AlN/GaN interface have been investigated. Several reports on the 2DEG transport properties were focused on the low temperature mobility.[8,9] It was found that the interface roughness governed the mobility, and also, inserting a thin AlN spacer layer at AlInN/GaN interface increased the mobility by effectively reducing the alloy scattering.[8,9] The achieved mobility so far was as high as 23100 cm^2/Vs at 10 K.[8] In contrast to the low temperature, little is known on the high temperature properties. High temperature Hall measurements up to 620 K[10] showed that μ_H monotonically decreased in the temperature range from 77 to 620 K and 2DEG density (n_s) was almost constant. Higher temperature performance is only reported for HEMT DC characteristics,[11] where the saturation current density decreased with the increase of temperature from RT to 1300 K. Nevertheless, more detailed experiments on μ_H and n_s are needed for deeper understandings of 2DEG properties at high temperatures. In this work, temperature dependences of μ_H and n_s are measured from 77 to 973 K with varying AlInN barrier thickness (d_{AlInN}).

The epitaxial wafers used were grown on c-plane 2 in. sapphire substrates by metal organic vapor phase epitaxy (MOVPE). The growth sequences of layers were a 200 nm AlN nucleation, a 1900 nm undoped GaN buffer, a 1 nm undoped AlN spacer, and nearly lattice matched (LM) $Al_{1-x}In_xN$ ($x = 0.14$) barrier. Different d_{AlInN} of 5 and 15 nm were prepared. Before starting the device process, surface was cleaned by organic solvents (acetone and ethanol), buffered HF, and rinsed by de-ionized water. Device processing was initiated by reactive ion etching (RIE) with 100 nm depth isolation mesa using Cl_2 and BCl_3 gases. Ohmic patterns were formed with evaporating Ti/Al/Mo/Au (29/140/50/70 nm) metals to obtain the Van der Pauw configuration. The wafer was then alloyed at 850 °C for 30 s. No passivation layer was deposited on the wafer surface, and additional intentional surface treatment was not done after the ohmic alloy. Each processed wafer was cut to 7×7 mm^2. The sample was set to the Hall measurement system (Toyo technica ResiTest 8310). In order to investigate the influence of atmospheric condition, the measurements were executed in vacuum (around 1×10^{-3} Torr) and air, where the latter was done at 300–773 K due to the limitations of the measurement system.

Figure 1 shows the measured μ_H as a function of temperature, where the measurements were carried out in vacuum. The mobilities were 2085 and 983 cm^2/Vs at 77 K and decreased monotonically to 113 and 97 cm^2/Vs at 973 K for d_{AlInN} of 5 and 15 nm, respectively. The results were compared with analytically calculated ones, where the calculation

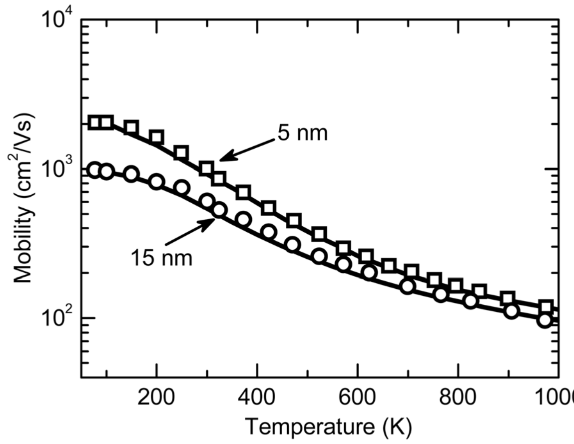

FIG. 1. Temperature dependence of Hall mobilities in AlInN/AlN/GaN for different AlInN barrier thicknesses measured in vacuum.

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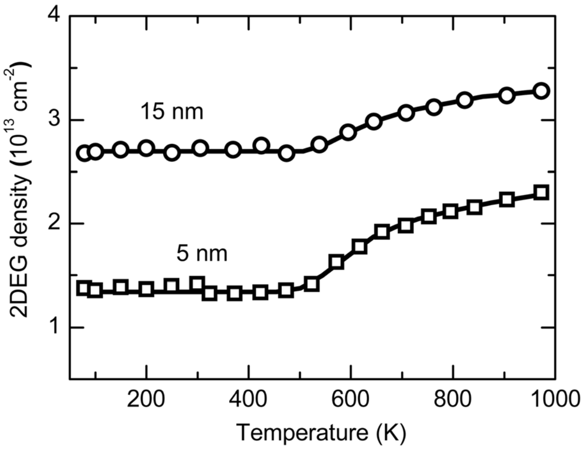

FIG. 2. 2DEG densities (n_s) as a function of temperature measured in vacuum.

procedure was found in Refs. 12–14, and the parameters used in Refs. 9 and 14. It was found that μ_H at low temperature was mainly governed by the interface roughness,[8,9] while it was not only governed by the polar optical phonon but also by the acoustic phonon (deformation potential and piezoelectric) and interface roughness scatterings played a role even at temperatures higher than 600 K.

Temperature dependence of n_s is shown in Fig. 2, where the measurements were done in the vacuum. The n_s varied from 1.4 to 2.3×10^{13} and from 2.6 to 3.3×10^{13} cm^{-2} for d_{AlInN} of 5 and 15 nm, respectively, at 77–973 K. The characteristic feature of n_s was that it was almost constant up to around 540 K and showed sudden increase over 540 K (520 and 540 K for d_{AlInN} of 5 and 15 nm, respectively). The temperature dependence of n_s was calculated using the analytical equation[15,16] and found to be almost constant at around 1.4×10^{13} and 2.7×10^{13} cm^{-2} for $d_{AlInN} = 5$ and 15 nm, respectively, up to 1000 K, which were different from the measured dependence (n_s increase). Regarding the temperature dependence of n_s, different tendencies have been reported. Tülek *et al.*[9] reported the increasing, while Xue *et al.*[10] showed constant tendency. Therefore, temperature dependence of n_s is still an open issue to be cleared. Since the calculated results give the constant n_s in the whole temperatures, a new attempt is needed to explain the sudden increase. There are several possibilities which bring the n_s change such as change of polarization charge (spontaneous and piezoelectric),[17–19] parallel conductions at AlInN/AlN interface and/or GaN layer,[8,16,20–22] and change of surface barrier height (Φ_B).[23–25] In order to get more detailed understandings on the n_s increase, the temperature dependence was investigated under different atmospheric conditions, i.e., in vacuum and in the air (oxygen contained ambient). The results are shown in Fig. 3(a), for $d_{AlInN} = 15$ nm. Increase in n_s was not observed when the measurement was carried out in the air (closed circles), while sudden increase occurred at above 540 K in vacuum (open circles). The measurement was continued in vacuum by decreasing the temperatures from 773 to 300 K, as shown in the open triangles. It was found that n_s in vacuum was almost constant at around 2.9×10^{13} cm^{-2} in the temperatures of 300–773 K, which was higher than that measured in the air. After completed the

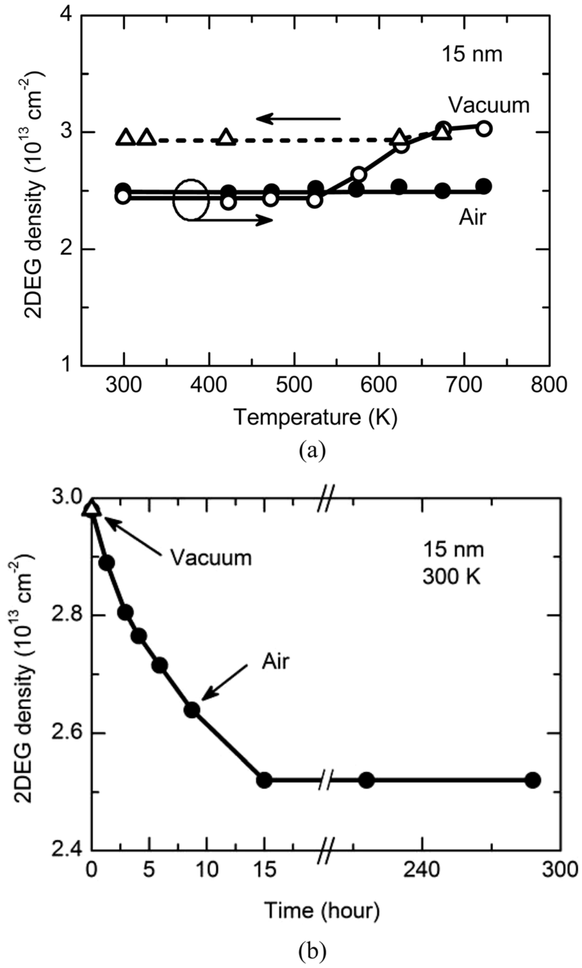

FIG. 3. (a) Temperature dependence of n_s measured in vacuum (open symbols) and air (closed symbols) for $d_{AlInN} = 15$ nm. Open triangles show the measured values in vacuum with decreasing temperatures from 773 to 300 K. The arrows indicate the measurement directions. (b) The change of n_s with time after introducing the air at 300 K.

measurements in vacuum, n_s was again measured in the air at 300 K. The time dependence of n_s after introducing the air into the measurement chamber is shown in Fig. 3(b). The n_s decreased to be around 2.5×10^{13} cm^{-2} within 15 h, which was almost the same as starting value measured in the air. The n_s did not change after leaving the sample in the air for 9 (216 h) and 12 days (288 h). The results imply that the surface became stable with exposing in the air about 15 h. Similar results were observed for the samples with $d_{AlInN} = 5$ nm, that is, n_s was constant of 1.4×10^{13} cm^{-2} when measured in the air, while showed sudden increase at above 520 K in the vacuum. As for the mobility, no remarkable differences were observed in vacuum and air (not shown). The results shown in Figs. 3(a) and 3(b) clearly suggest that the n_s increase is not originated from the bulk effects in the heterostructures but surface related. Therefore, the possible mechanisms such as change of polarization charge and parallel conductions are excluded.

The most probable mechanism of the n_s increase in vacuum is the decrease of Φ_B. This is because it is surface related and brings sudden change at certain temperature. Several reports have been made on surface states and Φ_B change for AlGaN/GaN hetrostructures.[23–25] Higashiwaki *et al.*[23,24] reported that Φ_B increased with the oxidation of

AlGaN surface. Such kind of change may also occur in AlInN surface. Kováč *et al.* showed in Ni/ox-InAlN/GaN structure that Φ_B had the different values of 2.57 and 1.46 eV for the oxidized and non-oxidized AlInN surface, respectively.[26] The results shown in Fig. 3(a) are interpreted as follows. AlInN surface is oxidized in air and native oxide is formed at the start of the measurements (300 K), and it decomposes at around 540 K when measured in vacuum. The decomposed surface has a reconstructed structure, which leads to the lowering of Φ_B. By introducing the air, the AlInN surface is again oxidized, which brings the Φ_B increase (n_s decrease) as shown in Fig. 3(b). The results shown in Fig. 3 seem to be the direct evidence of Φ_B change, and the Φ_B change is the only way to explain the n_s change observed in vacuum and at above 540 K.

In conclusion, this work is focused on the temperature dependent 2DEG properties of AlInN/AlN/GaN heterostructures measured by Van der Pauw technique from 77 to 973 K. The Hall mobility decreases monotonically with the increase of temperature. The 2DEG densities are found almost constant up to 540 K and show sudden increase over that temperature when measured in vacuum, while they are constant measured in air, which are independent of AlInN barrier thickness. It is shown that surface barrier height lowering is the most probable to explain the n_s increase, which is brought from the surface reconstruction accompanied by the decomposition of the oxide layer on the AlInN surface.

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