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Capacitance–voltage characterization of AlN/GaN metal–insulator–semiconductor structures grown on sapphire substrate by metalorganic chemical vapor deposition

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Electrical characterization of AlN/GaN interfaces was carried out by the capacitance–voltage ($C-V$) technique in materials grown by metalorganic chemical vapor deposition. The high-frequency $C-V$ characteristics showed clear deep-depletion behavior at room temperature, and the doping density derived from the slope of $1/C^2$ plots under the deep depletion condition agreed well with the growth design parameters. A low value of interface state density D_{it} of $1\times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$ or less around the energy position of $E_c-0.8\,\mathrm{eV}$ was demonstrated, in agreement with an average D_{it} value estimated from photoassisted $C-V$ characteristics. © *2000 American Institute of Physics.* [S0021-8979(00)09313-0]

I. INTRODUCTION

GaN-based materials are of great interest, not only for the recently reported high-efficiency blue/green light-emitting diodes and laser diodes but also for the realization of devices for high temperature electronics and high-power microwave electronics.[1] GaN-based field-effect transistors (FETs) or heterostructure FETs utilizing Schottky barrier gate have been fabricated and their potential use for the high-power electronics devices has been demonstrated.[2–5] However, formation of Schottky contacts stable at high temperatures has not yet been achieved. In contrast to Schottky gate structures, metal–insulator–semiconductor (MIS) structures have the advantage of utilizing chemically stable insulators at the interface. However, very little is known about interface properties of GaN MIS systems.

Recently, SiO_2/GaN and SiN/GaN structures have been fabricated and characterized by Gasey *et al.*,[6] Sawada *et al.*,[7] and Arulkumaran *et al.*[8] The reported results showed that the insulator–GaN interface may have a relatively low interface state density in the lower range of $10^{11}\,\mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$. AlN with its high dielectric constant (8.5) also has the potential to be good insulating material. It is also expected to form epitaxially grown high-quality heterostructures on GaN and SiC. In fact, Kawai and co-workers[9] have very recently demonstrated good dc performance of the insulated-gate heterostructure FET using a AlN/GaN MIS structure. However, there has been no report on the electrical characterization of GaN MIS interfaces utilizing epitaxially grown AlN. In this article, the electrical properties of AlN/GaN interfaces were evaluated by the capacitance–voltage ($C-V$) method in samples grown by metalorganic chemical vapor deposition (MOCVD).

II. EXPERIMENT

A schematic representation of the MIS structure is shown in Fig. 1. AlN/GaN heterostructures were grown on the c plane of sapphire substrates by MOCVD using trimethylgallium, trymethylaluminum, ammonia and silane. Following the deposition of an AlN buffer layer at 550 °C with a thickness of 40 nm, a 2 μm undoped GaN layer and a 300-nm-thick n-GaN ($n=5\times 10^{17}\,\mathrm{cm}^{-3}$) were grown at 1100 °C. The growth temperature was then reduced to 550 °C for the deposition of the 50–100-nm-thick AlN layer. A reduced growth temperature was needed to prevent tensile strain-induced cracking of AlN grown on GaN. The samples were prepared by etching the first AlN layer in places where ohmic contacts were to be deposited. Etching was carried out using a NaOH-based solution. Ohmic contacts were made by depositing Ti/Al/Ti/Pt and annealing at 800 °C for 30 s in N_2 atmosphere. Ti/Pt/Au was deposited on the AlN for gate contacts with $5\times 10^{-5}\,\mathrm{cm}^2$ area.

$C-V$ measurements were carried out at room temperature using a HP 4275A LCR meter. In order to avoid the impact of the series resistance of the epitaxial GaN layer on the $C-V$ measurements, characterization took place at a frequency of 200 kHz. $C-V$ curves were recorded at a sweep rate of 100 mV/s.

III. RESULTS AND DISCUSSION

Figure 2(a) shows typical $C-V$ characteristics of the fabricated MIS diode measured at room temperature. Also shown is the calculated curve based on the accumulation, depletion, and inversion behavior for the AlN/GaN structure.

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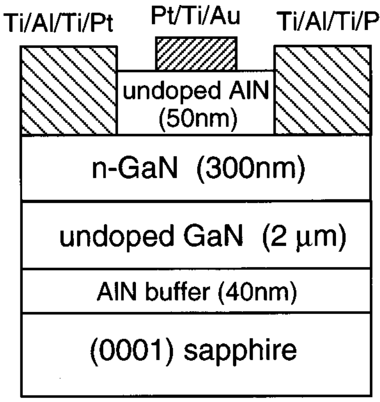
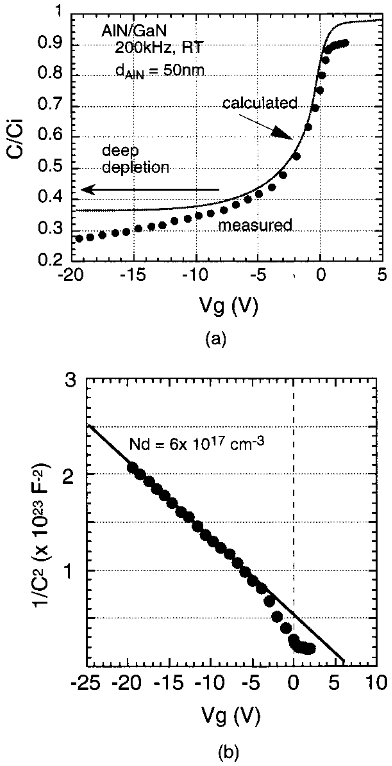


FIG. 1. Schematic representation of the fabricated AlN/n-GaN MIS structure.

For calculation, an effective electron mass of $0.22\,m_0$, an effective hole mass of $0.8\,m_0$, a dielectric constant of 9.5, and an energy gap of 3.39 eV were used for GaN at room temperature. The dielectric constant of AlN was considered to be 8.5.



(a)

(b)

FIG. 2. (a) Typical $C-V$ curve of the fabricated MIS diode measured under dark condition at room temperature. The solid line indicates the calculated curve based on the accumulation, depletion, and inversion behavior. (b) $1/C^2$ characteristics as a function of bias voltage.

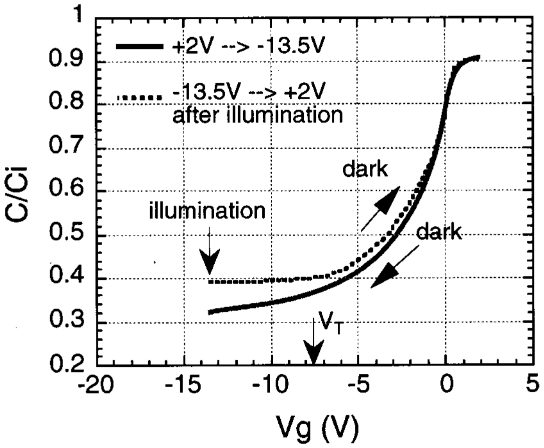


FIG. 3. Photoassisted $C-V$ curves of the AlN/n-GaN structure at room temperature.

The measured $C-V$ curve showed clear deep depletion behavior for negative bias voltages and no measurable hysterisis was observed. This deep depletion feature with no inversion capacitance characteristics is typical of wide-gap semiconductor MIS structures such as SiO_2/SiC[10,11] and AlN/SiC,[12] because the generation rate of the minority carriers (holes) is extremely low at room temperature. In the case of SiC, Wang and co-workers[13] reported in fact that it could take years to tens of years to reach thermal equilibrium in the inversion region at a given bias voltage at room temperature. However, such deep depletion behavior has not been observed so far in plasma-enhanced chemical vapor deposition (PECVD) prepared SiO_2/n-GaN MIS structures.[7,8] This indicates that the investigated AlN/GaN MIS structures have much better interface properties than the deposited insulator/GaN interfaces. The $1/C^2$ characteristics of the investigated MIS structures are shown in Fig. 2(b) as a function of the applied voltage. The characteristics showed good linear behavior in the bias range of $V_g = -7$ V to -20 V, which resembles that of AlN/SiC structures,[12] again indicating the presence of deep depletion by pronounced band bending. From the slope of the plots, the doping density of the n-GaN layer was determined to be $6 \times 10^{17}\,\mathrm{cm}^{-3}$, reasonably close to the value of $5 \times 10^{17}\,\mathrm{cm}^{-3}$ expected from the design.

In order to obtain a better insight into the interface properties of the fabricated AlN/GaN MIS structures, photoassisted $C-V$ measurements were carried out. Because of the wide-gap nature of GaN, it is difficult to characterize interface states located in the vicinity of midgap. Electrons initially captured in the deep-lying states cannot emit to the conduction band at room temperature because the emission time constant increases exponentially with energy separation from the band edge according to the Shockley–Read–Hall statistics. For example, the electron emission time from the state located around $E_c - 1.5$ eV is estimated to be 10^7-10^8 yr even at room temperature. In addition, the inversion layer cannot form in the time scale of the $C-V$ measurement due to the extremely large time constant of minority carrier generation as mentioned above. These facts imply that the change in charges of the interface states by emitting electrons or by capturing minority carriers (holes) is negligible at room temperature. In order to estimate the average interface state density even at room temperature, a photoassisted $C-V$ method has been proposed.[11] The results using this technique are shown in Fig. 3. After sweeping the bias from the accumulation range ($+2$ V) to the deep-depletion range (-13.5

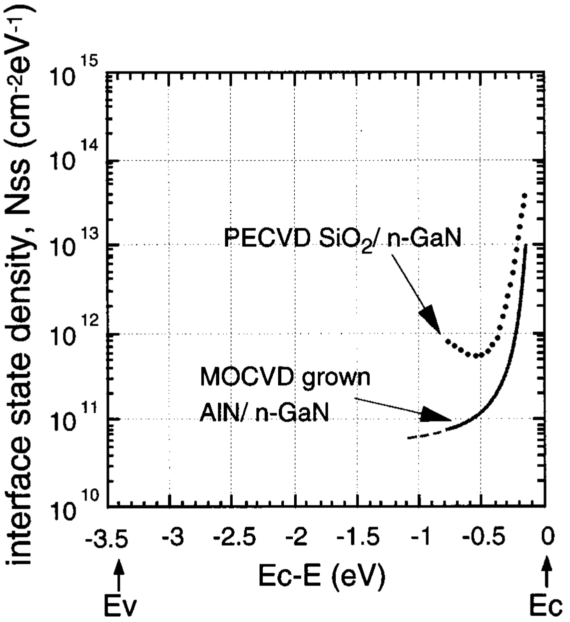


FIG. 4. Distributions of interface state density for the MOCVD grown AlN/n-GaN MIS structure and the PECVD SiO$_2$/n-GaN MIS structure.

V) in the dark, the sample was illuminated by a tungsten lamp while the bias remained at -13.5 V. The formation of an inversion layer raised the capacitance to a high-frequency inversion value, as shown in Fig. 3. This capacitance value was maintained after turning off the illumination. The $C-V$ characteristics in the case where the bias is swept toward accumulation are shown by the broken line of Fig. 3. A small voltage shift can be observed, reflecting differences in charging conditions of deep-lying interface states with and without illumination. From the voltage shift ΔV_g, the average interface state density can be estimated using the simple equation of $D_{\mathrm{it}}^{\mathrm{av}}=C_I\Delta V_g/qE_G$,[11] where $D_{\mathrm{it}}^{\mathrm{av}}$ is the average value of interface state density, C_I is the insulator capacitance, q is the electron charge, and E_G is the band gap of GaN. $D_{\mathrm{it}}^{\mathrm{av}}$ is estimated to be 9.5×10^{10}–$1.4\times10^{11}\,\mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$ for the MIS structures used in this study.

An estimate of the interface state density was also made by applying the Terman method to the measured $C-V$ curves.[14] Figure 4 shows the obtained distribution of interface state density of the MOCVD grown AlN/GaN MIS structure. For comparison, a typical D_{it} distribution for the PECVD SiO$_2$/n-GaN samples is also plotted. As mentioned earlier, the interface states beyond about 0.7–0.8 eV from the conduction band edge cannot sufficiently respond during the $C-V$ measurement time, therefore limiting the D_{it} characterization to the region near the conduction band. Low D_{it} values were obtained for the AlN/GaN interface. Under these conditions, no minimum point in D_{it} distribution was found within the energy range from E_c to about $E_c-1.0\,\mathrm{eV}$, a feature which clearly distinguishes the AlN/GaN characteristics from the distribution observed in the PECVD SiO$_2$/n-GaN interface, as shown in Fig. 4. D_{it} values below $1\times10^{11}\,\mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$ were obtained at around $E_c-1.0\,\mathrm{eV}$, in good agreement with $D_{\mathrm{it}}^{\mathrm{av}}$ estimated from the photo $C-V$ characteristics. These results indicate that the investigated AlN/n-GaN interface has a wide D_{it} distribution with a minimum value in the range of $10^{10}\,\mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$. Previous reports[6–8] demonstrated that the *ex situ* PECVD technique can lead in good SiO$_2$/n-GaN interfaces with low D_{it} values. However, problems still remain in PECVD SiO$_2$/n-GaN structures, such as for example, high-density interface states near midgap[7] and a large voltage shift in the photo $C-V$ characteristics.[6] A comparison with the structures reported by Arulkumaran *et al.*[8] was not possible since this work only reports an estimate of the fixed charge density from the flat-band voltage shift and no information about the interface state density distribution is provided. Comparing the published results on the SiO$_2$/GaN system with our $C-V$ characterization, the present AlN/n-GaN structure has better interface properties.

For electron device applications, further investigation is needed to evaluate the interface properties, especially under elevated temperature condition.[15] A study of the band offset of the AlN/GaN interface could also be required because reliable knowledge of the valence band and conduction band discontinuities for the interface is extremely important for device design and performance prediction.[16] A systematic study of leakage properties of AlN films and the stability of AlN/GaN interfaces is also necessary. Although additional characteristics of this type would be useful, the results presented here show that the AlN/GaN structure is very promising for the realization of GaN MIS devices.

IV. SUMMARY

Electrical characterization of AlN/GaN interfaces was carried out by the $C-V$ technique in samples grown by MOCVD. The high-frequency $C-V$ curve showed clear deep-depletion behavior at room temperature, and the doping density derived by the slope of the $1/C^2$ plots at the deep depletion agreed well with the growth design. A low value of interface state density D_{it} of $<1\times10^{11}\,\mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$ was achieved around the energy position of $E_c-0.8\,\mathrm{eV}$, which is consistent with the average D_{it} value estimated from the photoassisted $C-V$ characteristics. These results indicate that the AlN/GaN structures have good interface properties with low interface state density, and are very promising for advanced MIS devices.

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