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Current-voltage measurement of $Al_xIn_{1-x}N/AlN/GaN$ heterostructures

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Current-voltage measurements with Schottky contacts in a planar back-to-back configuration have been performed for InAlN/AlN/GaN heterostructures with different AlN interlayer thicknesses. We have identified the onset of a 2-dimensional electron gas (2DEG) controlled conduction from current-voltage curves analyses. A model has been proposed to determine the 2DEG electrical properties and the effects of the AlN thickness on the measured current-voltage curves have been discussed. The 2DEG properties extracted from current-voltage analyses have been compared with Hall measurements which shows excellent agreement in values.

1 Introduction GaN based high electron mobility transistors (HEMTs) have attracted great attention due to their broad and important applications in high power and high frequency electronic devices [1, 2]. Various studies have been performed to improve the device performance by reducing the sheet resistance, such as increasing the Al composition of the AlGaN barrier [3], using AlN/GaN superlattices as a quasi-AlGaN barrier [4], and replacing the AlGaN by AlInN or AlN as the barrier [5, 6]. Among these studies, the use of a lattice-matched AlInN barrier is the most promising option to improve the HEMT performance [7]. Some earlier analyses have shown that $Al_{1-x}In_xN/GaN$ heterostructures with 17% In-content are lattice-matched and possess strong spontaneous polarization [5, 8]. For these reasons AlInN/GaN and/or AlInN/AlN/GaN are now used to realize high quality high-electron-mobility transistors HEMTs. A thin AlN interlayer can be inserted between the AlInN barrier layer and the GaN substrate to achieve a larger separation of the electron wave function from the AlInN barrier, to decrease the impact of interface roughness and alloy scattering and to obtain an overall improvement of the lateral transport properties of the two-dimensional electron gas (2DEG) [5, 6].

The work presented here is focused on the electrical characterization of $Al_xIn_{1-x}N/AlN/GaN$ heterostructures by current-voltage (I-V) measurements which are used to directly derive the main 2DEG electrical transport properties, such as sheet carrier concentration and sheet resistance, for optimizing device applications. We also report on the effect of AlN interlayer thickness up to 7.5 nm.

2 Experimental Five samples with AlInN/AlN/GaN heterostructures were grown in an AIXTRON metal organic chemical vapour deposition (MOCVD) reactor on c-plane sapphire substrates. AlInN layer was approximately 15 nm thick, the AlN layer thickness was 0, 0.5, 1, 2.5 and 7.5 nm respectively, while the 3 μm thick GaN layer has been grown on sapphire. Indium content varies from 13% to 14% as assessed by high resolution x-ray diffraction (HR-XRD) [9]. Current-voltage measurements have been performed at room temperature with back-to-back Schottky contacts in a planar configuration directly formed by In-Ga alloy with a spacing of 2 mm.

3 Results and discussion We have carried out I-V measurements on all samples and we have observed a change in the curve slope that occurs at different applied bias in different samples, except for the sample with a 7.5 nm thick AlN interlayer. Figure 1a shows a typical I-V curve observed for samples with 2.5 nm thick AlN structures, indicating a clearly visible change in slope. We can understand the I-V behaviour by considering that for low bias the current transport is limited to the top AlInN barrier layer. As the applied bias increases, for one of the reverse biased Schottky diodes (shown in Fig. 1b), the depletion region extends further through the AlInN and AlN layers, allowing the current flow to reach the interface with the GaN substrate, where the 2DEG is located [10]. The onset of the 2DEG contribution is revealed by the marked current increase observed in the S-shaped I-V curves (Fig. 1a). The 1D Schrödinger-Poisson equation [11] has been also solved and it results the formation of a triangular potential well at AlN/GaN interface and shown in Fig. 1c.

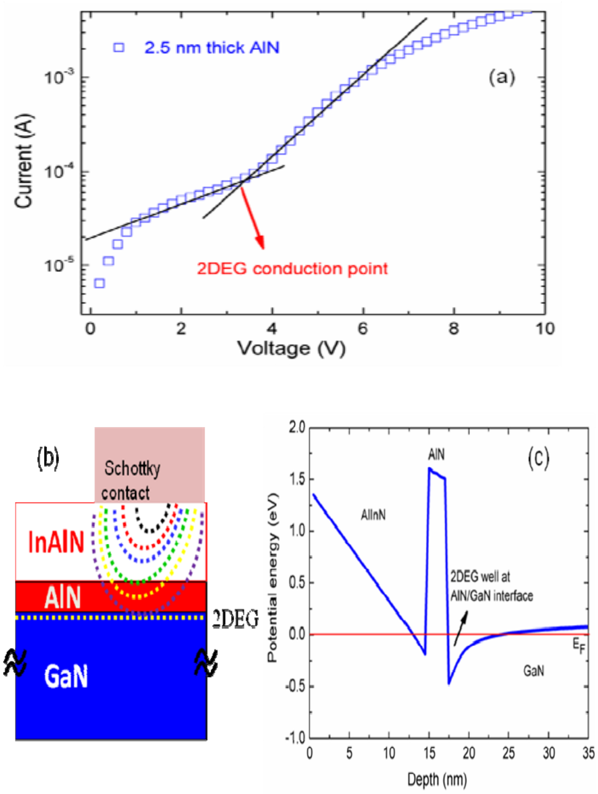

Figure 1 (a) Current vs. voltage plot showing change of slope as 2DEG conduction in sample with 2.5 nm thick AlN interlayer (blue). (b) Depletion of reverse-biased Schottky with increasing bias and (c) shows the formation of 2DEG potential well at AlN/GaN interface in reported structures.

We noted that the bias value corresponding to the onset of 2DEG conduction, V_{2DEG}, varies linearly as a function of the AlN interlayer thickness for thicknesses up to 2.5 nm. The sample with a 7.5 nm AlN thick layer did not show an evident change in slope at this scale.

In order to understand the origin of the different behaviour of sample with the 7.5 nm thick AlN layer, we carried out atomic force microscopy analyses of samples with different AlN thicknesses, details of which will be reported elsewhere [12, 13]. We clearly identified the formation of nanocracks on the AlInN surface that become more pronounced as the AlN layer thickness increases, becoming macroscopic defects (micron-sized) in heterostructures with a 7.5 nm thick AlN layer. Other recent results report the formation of cracks in AlN/GaN heterostructures [6]. Thus, we could relate the presence of cracks in samples with a 7.5 nm thick AlN layer to the observation of large currents at very low bias voltages, due to high leakage effects.

To calculate the 2DEG sheet carrier concentration, we determined the total effective polarization charge density from the data in Fig. 2. The slope of the linear region of V_{2DEG} vs AlN thickness (t_{AlN}) gives

$$\frac{dV_{2DEG}}{dt_{AlN}} = \frac{e(\sigma_{AlN/GaN} + \sigma_{AlInN/AlN})}{\varepsilon_0 \varepsilon_r} \quad (1)$$

where e is the electron charge, $\sigma_{AlN/GaN}$ and $\sigma_{AlInN/AlN}$ are the effective polarization charge densities of the AlN and the AlInN layers, respectively, ε_0 is the free space permittivity and ε_r is the relative permittivity averaged over the AlN (~10.3) and AlInN (9.8) layers. From Eq. (1) the total effective polarization charge density ($\sigma_{AlN/GaN}$ + $\sigma_{AlInN/AlN}$) was calculated and E_{total}, the total electric field across the AlN and AlInN layers is then,

$$E_{total} = \frac{V_{2DEG}}{t_{AlN} + t_{AlInN}} \quad (2)$$

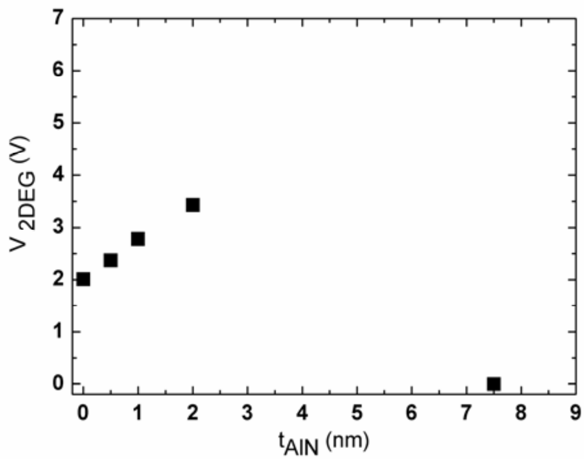

Figure 2 Variation of V_{2DEG} vs. AlN thickness.

Combining Eqs. (1) and (2),

$$E_{total} = \frac{e(\sigma_{AlN/GaN} + \sigma_{AlInN/AlN} - n_{2DEG})}{\varepsilon_0 \varepsilon_r} \quad (3)$$

The room-temperature 2DEG carrier concentrations of the investigated AlInN/AlN/GaN structures vs. AlN thickness are plotted in Fig. 3, as determined from I-V curves (solid squares) and Hall measurements (open squares). The error associated to our experimental data has been estimated to be ±0.01 x 10^{13} cm^{-2}. Our results are in good agreement with the theoretical calculation by Ambacher et al. [14].

In Fig. 3, the last point (for 7.5 nm thick AlN layer) of the 2DEG concentration curve has not been directly determined from experimental data. In fact, as is clearly shown in Fig. 2, the I-V curves relative to the thicker AlN sample (7.5 nm) do not allow to extract the 2DEG concentration from the V_{2DEG}, possibly because of the deterioration of the AlInN barrier layer morphology that induces the flow of a very high current at very low voltages. This effect hinders the direct application of the I-V method to the study of samples with a cracked or dislocated barrier layer that acts as a lower resistance path for the injected carriers, inhibiting the direct assessment of the 2DEG properties by I-V measurements. Nonetheless, if we extrapolate the V_{2DEG} vs AlN thickness curve obtained from thinner AlN interlayers (Fig. 2), and we use the extrapolated values to estimate the 2DEG concentration, we obtain a very good agreement with the experimental values obtained from Hall measurements performed on the same samples (Fig. 3).

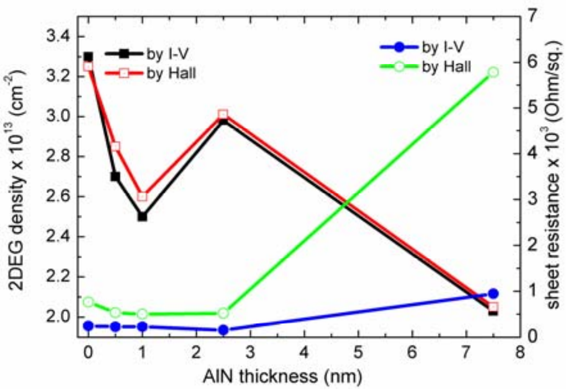

Figure 3 2DEG density as a function of the AlN interlayer thickness (left axis). Our data are obtained from I-V curves (solid squares in black) and Hall measurements (open squares in red). The last point (7.5 nm) of our I-V curve has been extrapolated. The lines are plotted only for eye-guidance. Sheet resistance (in blue solid circles and green open circles) variation with AlN interlayer thickness has also been shown (right axis).

Hall measurements were also performed to determine the sheet resistivity as a function of the AlN interlayer thickness, shown in Fig. 3 (right axis). The sheet resistance behaviour (Fig. 3) further supports the results so far discussed: the quite large value for the sample with 7.5 nm AlN thickness well correlates to its strong morphological deterioration and significant 2DEG mobility decrease as discussed above. It has to be noted that the sheet resistance has been measured both with the Hall method and with the I-V method (also reported in Fig. 3, right axis), using the slope of the I-V curve after the onset of the 2DEG conduction, providing results in very good agreement.

4 Conclusions We have investigated the current transport properties of nearly lattice-matched AlInN/AlN/GaN heterostructures with various AlN interlayer thicknesses using I-V measurements at 300 K with Schottky contacts in a planar back-to-back configuration. A model has been developed to straightforwardly extract the 2DEG electrical properties from room-temperature current-voltage curves. By comparing I-V and Hall measurements we could assess the reliability of common I-V analyses in the determination of the major transport properties of the 2DEG. Our results show the crucial role of AlN layer insertion and their effect on device properties which is correlated to surface morphology of structures. The proposed model can also be applied for different structures like AlGaN/GaN etc.

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