Metal-oxide barrier extraction by Fowler-Nordheim tunnelling onset in Al_2O_3-on-GaN MOS diodes

V. Di Lecce, S. Krishnamoorthy, M. Esposto, T.-H. Hung, A. Chini and S. Rajan

Investigation of the properties of Al_2O_3-on-GaN metal-oxide-semiconductor diodes is reported. A new method is shown to calculate the metal-oxide barrier height based on the onset of the Fowler-Nordheim tunnelling current regime in direct bias. The Ni/Al_2O_3 barrier was extracted, for the first time with this method, and it was found to match other reports in the literature. The dependence of the effectiveness of this method on the oxide thickness is discussed. The breakdown field for Al_2O_3 was also measured and found to be in agreement with previous reports.

Introduction: The performance and reliability of GaN power devices is limited by gate leakage currents. Their detrimental effects include reduction of the breakdown voltage and degradation of the RF performance, causing the power-added efficiency to drop severely. One way to suppress gate leakage currents is to make use of metal-insulator-semiconductor (MIS) or metal-oxide-semiconductor (MOS) structures. Several oxides have been studied for this purpose: among them are SiO_2 [1], Si_3N_4 [2], HfO_2 [3], Al_2O_3 [4]. However, an uncertainty in the metal-oxide barrier height may lead to a great inaccuracy in the electron tunnelling probability evaluation and in the band alignment analysis. In this Letter we focus our attention on Al_2O_3, which has been proven to be effective in suppressing the gate leakage in GaN HEMTs [4]; it has a large bandgap (9 eV), a high dielectric constant ($\varepsilon_r = 9$), and high breakdown field. Atomic layer deposition (ALD) in particular, has become one of the most used techniques of deposition of Al_2O_3, owing to its low-defect density and high uniformity, and is the technique used for the oxide deposition in our samples. We report on the analysis of direct and Fowler-Nordheim (FN) tunnelling current in metal/Al_2O_3/GaN MOS diodes; we discuss a new method to calculate the metal-oxide barrier height based on the onset of the Fowler-Nordheim tunnelling current regime in direct bias, and show how the value of this barrier can be easily inferred by current–voltage measurements.

Devices: The samples used for this experiment were discussed by Esposto *et al.* in [5]; a brief recap of the fabrication process is reported here. Samples were grown using an RF-plasma molecular beam epitaxy (MBE) system on semi-insulating GaN templates on sapphire; 200 nm of UID-GaN were grown, followed by 100 nm of silicon-doped GaN (doping density: $1 \times 10^{18}\ cm^{-3}$). Different Al_2O_3 thicknesses were deposited in an ALD system on different pieces cleaved out of the same sample. Gate pads were defined by optical contact lithography (area: $3 \times 10^{-5}\ cm^2$), and the features of large contacts were defined in the photoresist. Buffered oxide etch (BOE) 10:1 was used to remove locally the oxide layer in these large features to achieve good ohmics. A Ni/Au/Ni stack was e-beam evaporated and post-metallisation annealing was finally performed on all the samples at 400°C in forming gas for 5 min. The inset in Fig. 1 shows the stack grown and processed.

Results and discussion: The thicknesses of the oxide in our samples were 6, 12 and 18 nm. In Fig. 1 the simulated band diagram for the 6 nm samples is shown both at zero bias ($V_G = 0$), and in direct bias for $V_G = V_{SW}$. The conduction band offset between Al_2O_3 and GaN was assumed to be 2.13 eV [5]. Simulations were carried out using BandEng, a one-dimensional Schrödinger-Poisson solver developed by Grundmann [6]. At the flat-band voltage (0.8 V [5]), the two-dimensional electron gas (2-DEG) starts forming and the GaN conduction band gets pinned at the Fermi level. At $V_G = V_{SW}$ the potential barrier seen by electrons in the 2-DEG in the GaN becomes triangular; it can be easily inferred that V_{SW} is simply equal to Φ_B/q (where Φ_B is the barrier height at the Ni/Al_2O_3 interface). Therefore the voltage $V_G = \Phi_B/q$ should represent the onset of the Fowler-Nordheim (triangular barrier) tunnelling regime for the electrons in the 2-DEG. Fig. 2 shows the current–voltage measurements for the 6 nm samples in direct bias. A voltage at which the slope of the logarithmic *I-V* curve clearly increases can be noticed; from the second-order derivative of the curve (shown in the inset), such voltage is calculated to be 3.45 V. Further analyses of the experimental *I–V* characteristics actually confirmed that the current above 3.45 V is due to FN tunnelling whereas the current below 3.45 V is not.

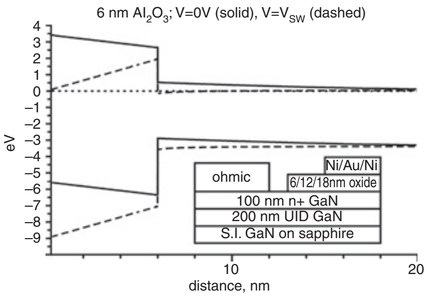

Fig. 1 *Simulated band diagram of 6 nm sample both at zero bias and at $V_G = V_{SW}$*

Inset: Stack grown and processed

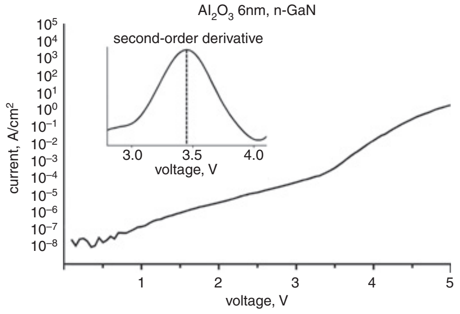

Fig. 2 *Current–voltage characteristic for 6 nm samples*

Inset: Second-order derivative of curve

The current in the Fowler-Nordheim tunnelling regime is given by:

$$J_{FN} = A \times F_{OX}^2 \times \exp\left(-\frac{4}{3\hbar qF_{OX}}\sqrt{2m^*\Phi_{Barr}^3}\right) \qquad (1)$$

where m^* is the tunnelling effective mass, Φ_{Barr} is the barrier seen by the tunnelling electrons (ΔE_C in our case), F_{OX} is the electric field in the oxide, and A is a parameter that depends on Φ_{Barr} and on the tunnelling mass. Such behaviour is confirmed by the straight line in the FN plot for V_G higher than 3.45 V in Fig. 3, whereas the same plot for V_G below 3.45 V (in the inset) shows a clear non-FN behaviour.

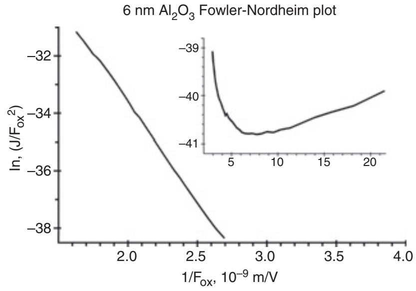

Fig. 3 *Fowler-Nordheim plot for current in 6 nm samples above 3.45 V*

Inset: FN plot below 3.45 V

Therefore, since it has been verified that $V_{SW} = 3.45$ V is the onset voltage for the Fowler-Nordheim tunnelling regime, the barrier height Φ_B between Ni and Al_2O_3 is simply found to be equal to 3.45 eV; this value matches previous reports [7] and can be easily inferred by the logarithmic *I–V* curve itself, for at 3.45 V its slope increases (Fig. 2).

Energy band diagram analysis was then used to find the electric field in the oxide given the gate voltage for all the samples, and to plot the current against the field in the oxide. Neglecting the distance between the Fermi level and the conduction band edge in the GaN, we obtain the approximate expression:

$$-qV_G + \Phi_B + qF_{OX}t_{OX} - \Delta E_C = 0 \qquad (2)$$

where V_G is the voltage applied to the gate, Φ_B is the barrier height at the Ni/Al_2O_3 interface (3.45 eV), and ΔE_C is the conduction band offset at the Al_2O_3/GaN interface (2.13 eV).

From (2), Fig. 4 shows the current against the field in the oxide for the 6, 12, and 18 nm samples. The current observed for the 12 and 18 nm samples though was entirely due to Fowler-Nordheim tunnelling. The reason for this is that, because of the higher oxide thickness, a voltage higher than Φ_B/q is required to induce a field in the oxide high enough to trigger a measurable tunnelling current, so when the current eventually becomes higher than the noise floor of our instruments, the Fowler-Nordheim regime has already been entered. However, the current–field characteristics in the Fowler-Nordheim regime is the same for all the thicknesses (Fig. 4), with the 6 nm samples showing a clear switch at 3.5 MV/cm, which is simply equal to $\Delta E_C/q$ (2.13 V) divided by the oxide thickness (6 nm). Breakdown measurements for Al_2O_3 were also carried out in forward bias. From (2), Al_2O_3 showed a breakdown field of 6–7 MV/cm (Fig. 4); this value is in agreement with previous work [4, 8].

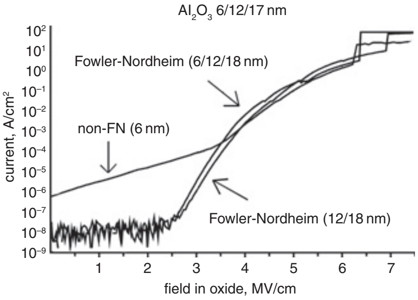

Fig. 4 *Current density against field in oxide for all samples*

Conclusions: We have reported on our investigation of the properties of Al_2O_3-on-GaN MOS diodes and discussed a new method to calculate the metal-oxide barrier height based on the onset of the Fowler-Nordheim tunnelling current regime in direct bias; in the Ni/Al_2O_3 case, such a barrier was extracted and it was found to be 3.45 eV, as in previous reports. We have discussed the reasons why the oxide thickness can be a major factor influencing the effectiveness of this method, and corroborated our hypotheses with measurements of the breakdown field of Al_2O_3, which was found to be in agreement with other reports.

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