The University of California Santa Barbara (UCSB) and Japan’s Rohm Co Ltd have produced enhancement-mode (E-mode) nitride semiconductor heterojunction field-effect transistors (HFETs) with a threshold voltage of +3V and on/off current ratio of 4x10^6 [Tetsuya Fujiwara et al, Appl. Phys. Express, vol4, p096501, 2011]. Enhancement-mode, or ‘normally-off’, operation is seen as being particularly important for power switching devices because one wants such devices to switch off if they fail.

Nitride semiconductor HFETs (also known as high-electron-mobility transistors, HEMTs) usually operate in depletion-mode (‘normally-on’ at zero gate potential). A number of techniques have been used to shift the threshold in a positive direction, but the threshold voltage has fallen short of the +3V or more needed to choke off leakage currents at zero gate potential.

Most previous devices have used c-plane oriented crystal nitride semiconductor material where the difference in the c-direction polarization field between the gallium nitride (GaN) buffer and the aluminum gallium nitride (AlGaN) barrier layers creates a two-dimensional electron gas (2DEG) at the AlGaN/GaN interface that carries current at zero gate potential.

In 2009, UCSB researchers created an HFET with +2V threshold by using instead non-polar m-plane nitride crystal material to avoid these polarization fields. Now, the UCSB/Rohm group has added a layer of aluminum oxide to insulate the recessed gate from the channel region (Figure 1).

The devices were grown on m-plane GaN substrates using metal-organic chemical vapor deposition (MOCVD) and atomic layer deposition (ALD). Mitsubishi Chemical supplied the substrates. The semi-insulating iron-doped layer was achieved using the metal-organic bis(cyclopentadienyl)-iron. The ohmic titanium/aluminum/nickel/gold source–drain contacts were applied with electron-beam evaporation and subjected to rapid thermal annealing at 870°C for 30 seconds in nitrogen.

The recess for the gate was achieved with boron tetrachloride plasma etching. The Al₂O₃ dielectric was...
then deposited. The platinum–gold gate metal was applied using e-beam evaporation. The dielectric was removed from the source–drain contact regions using a wet etch. The gate was 1μm long and 150μm wide. The source–drain spacing was 3.4μm.

The contact resistance of 3Ω-mm and sheet resistance of 2000Ω/square were characterized using transmission line structures on the epitaxial material.

DC characterization (Figure 2) showed a threshold voltage of +3V and maximum drain current (I_{ds(max)}) of 138mA/mm at a gate potential (V_{gs}) of +7V. The maximum transconductance of 45mS/mm occurred at V_{gs} of +5V. The researchers attribute the high positive threshold to the use of non-polar m-plane GaN, Al2O3 dielectric, and a recessed gate.

The sub-threshold performance was assessed at a source–drain potential (V_d) of 10V. The device is described as being completely off at V_{gs} of 0V with a leakage current (I_{off}) of 3.46x10^{-8}A/mm. The on/off ratio (I_{ds(max)}/I_{off}) is thus 4x10^6. The researchers say that this value is higher than that reported for other E-mode m-plane AlGaN/GaN HFETs.

The sub-threshold slope properties of the structure from 270mV/decade to 170mV/decade. The lower pressure deposition used a pure argon carrier.

The density of traps between 0.2eV and 0.6eV from the conduction is estimated at 1–2x10^{12}/cm^2-eV. The researchers comment: “This value is almost comparable with reported values of Al2O3/c-plane GaN”.

There is a peak of 5x10^{12}/cm^2-eV around 0.9eV that is attributed to holes that can be generated by the ultra-violet (UV) radiation used in the C–V measurements. The UV light source had wavelength peaks at 365nm, 405nm, and 436nm. These peaks are the i-, h- and g-lines, respectively, of the mercury emission spectrum.

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The Al2O3 ALD (in both the interface characterization and in the final HFET) was preceded by a hydrochloric acid treatment at room temperature. The 20nm Al2O3 layer was deposited in two stages: 2nm at 200mTorr and then 18nm at 20mTorr. The higher-pressure step (with hydrogen/argon carrier) has been found to reduce the subthreshold slope properties of the structure from 270mV/decade to 170mV/decade. The lower pressure deposition used a pure argon carrier.

The sample was annealed at 400°C in 10%/90% hydrogen/nitrogen forming gas. A titanium-gold contact was used on the Al2O3 and an aluminum-gold contact was recessed into the n-GaN layers.

Figure 2. Transfer characteristics at a source–drain voltage of 10V for UCSB/Rohm E-mode m-plane AlGaN/GaN HFETs.