Gallium Nitride (GaN) High Electron Mobility Transistors (HEMT)

With increasing technology development in the automotive, information processing and communication industry, the demand for high speed and low loss high power systems with reduced footprint is on the rise. In the scenario, wide band gap semiconductor-based devices are set to replace Silicon based devices. Due to its wide band-gap (3.4 eV), high breakdown field (3.3 MV/cm), good thermal conductivity (1.3 W/cm^2 K) and wide application areas including white LEDs, GaN has turned out to be most viable alternative for Silicon.

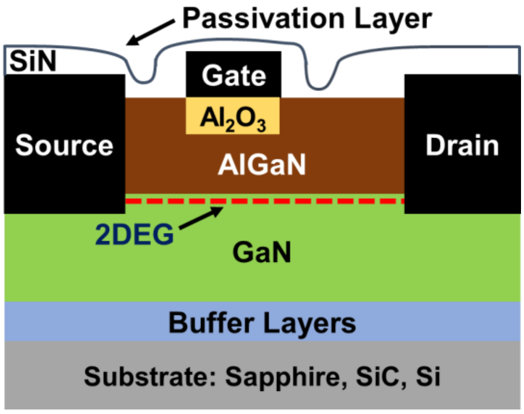

Figure 1. Basic device schematic of AlGaN/GaN HEMTs

AlGaN/GaN high electron mobility transistor (HEMT) is the most prominent GaN based three terminal device for power as well as RF applications. Figure 1 shows a basic device schematic of an AlGaN/GaN HEMT. The stack arrangement as shown in Fig. 1 and typical growth in [0001] direction results in polarization-induced 2-Dimensional Electron Gas (2-DEG) at the AlGaN/GaN interface. This 2-DEG channel is characterized by high electron density ($\sim 10^{13}\ cm^{-2}$) and high electron mobility ($\sim 1500-2000\ cm^2/V-s$) resulting in a lower ON resistance and higher speed of operation. However, GaN HEMT fabrication on Si and device reliability poses some serious challenges for device engineers.

(a) ***Fabrication of Normally-OFF transistors***: AlGaN/GaN HEMTs by virtue of the 2DEG offer normally-ON operation. However, power applications require normally-OFF devices for reliable and low loss operations. Recessed gate architecture has recently gained prominence for e-mode AlGaN/GaN HEMTs as they are capable of demonstrating higher threshold voltages. However, recessing the AlGaN barrier under gate can lead to channel degradation due to plasma damage besides significantly increasing the gate leakage. This necessitates deposition of a gate oxide for the e-mode HEMTs. However, the unavailability of a native oxide for AlGaN/GaN system makes fabrication of e-mode AlGaN/GaN MOSHEMTs very challenging. Our major thrust is on developing a reliable gate oxide for normally-OFF HEMT operation.

(b) ***GaN HEMTS for RF applications:*** Improving RF performance of GaN HEMT device is imperative for the commercial applications. However, the experimental cut-off frequencies in AlGaN/GaN HEMT are still far lower than the theoretical values largely due to short channel effects and resultant delay in these devices. In addition, the RF GaN devices have associated reliability issues which is a major bottleneck for commercialization of RF GaN devices, despite of excellent intrinsic performance. Our group is working towards these challenges to propose a reliable, high performance GaN RF design technology.

(c) ***Reliability of GaN HEMT devices:*** Despite promising performance by GaN devices in high power and high frequency applications, it suffers serious reliability issues which pose bigger challenge to its wide spread adoption. These degradation phenomena in GaN devices are associated to their extreme operating conditions like higher current densities, higher temperatures, and higher electric fields and are native to material properties like piezoelectric nature, high defect density and thermal mismatch due to heteroepitaxy. A clear understanding of reliability mechanisms will pave way to robust device technology while reaping the intrinsic benefits of GaN. Therefore, GaN device reliability is receiving an increasing attention across the globe.

At MSDLab, we intensively study physical mechanisms which deteriorate the performance and limit device lifetime during operation. The in-house developed, fully automated on-the-fly electro-optical characterization techniques allows device-material co-study under pulsed and dc conditions. The pulse transient studies, using transmission line pulsing (TLP) method, give insight into the device physics under switching dynamics encountered in power converters. A full fledge, high power characterization setup allows high current injection up to 300A and ultra-high voltage up to 3kV and is used to study device physics under extreme stress conditions encountered at SOA (safe operating area) boundary. Device reliability in unlikely events like ESD (electrostatic discharge) is studied over a wide temperature range (10 K – 873 K). Another integrated setup with LHe/LN2 based cryogenics on a semiautomated 8-inch prober with Raman spectrometer and photoluminescence (PL) enables spatial and temporal mapping of mechanical stress, defect evolution, morphological / elemental changes in device during operation. Optical pump and probe technique which uses 325nm, 365nm and 532nm wavelengths is helpful in trapping analysis, carrier-phonon scattering investigations and current transport studies in devices. 40GHz VNA (vector network analyser) is helpful to understand RF reliability issues like non-linearity in GaN HEMTs. Moreover, the other long-term reliability issues like hot electron degradation, time dependent dielectric breakdown, buffer reliability, contact degradation etc. are studied using a curve tracer with 6 SMUs, CV meter (1 kHz to 10 MHz) integrated with 8 x 24 switching matrix.

(d) ***TCAD support for AlGaN/GaN HEMTs:*** Silicon devices were largely benefited by TCAD based analysis into device physics and failure mechanisms. A similar support for AlGaN/GaN HEMTs is however missing. Our research group works actively on development of computational models for device physics exploration and analysis. TCAD support is then used to explain physical phenomena responsible for unique failure modes observed in AlGaN/GaN HEMTs. This physics-based understanding leads to proposals for improved device performance and reliability.