Development of an epitaxial growth process on European SiC substrates for a low leakage GaN HEMT technology with power added efficiencies around 65%

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Abstract

We report on a systematic comparison of semi-insulating SiC substrates from Cree and SiCrystal on substrate, GaN epiwafer and electronic device level. Epitaxial layers and AlGaN/GaN transistors with both low leakages and high power added efficiency are realized on both types of substrates with very similar quality. Minor differences in substrate quality, epitaxial growth and HEMT performance are discussed.

INTRODUCTION

Due to their wide band gap, high breakdown field, current density and saturation velocity, group III nitrides are well suited for high temperature and high power applications from RF to millimeter wave frequencies. SiC is the preferred substrate due to its high thermal conductivity, high resistivity as well as good lattice and thermal match to GaN.

Here we present an epitaxial growth process on semi-insulating 6H-SiC(0001) substrates from SiCrystal which is evaluated both on epiwafer level as well as on transistor level after subsequent device processing. For benchmarking at substrate, epitaxy and device level a comparison is carried out with epitaxial growth and processing performed in parallel on commercially available 4H-SiC(0001) substrates from Cree.

SUBSTRATES

The bulk crystals from SiCrystal were grown by physical vapour transport [1,2]. Substrates with around 360 µm thickness were cut from the boule and polished on both sides. The SiC substrates are structurally, electrically and thermally characterized by cross-polarizer imaging, x-ray diffraction and contactless resistivity measurements.

The cross-polarizer images (Figure 1) reveal a higher degree of strain inhomogeneity for the SiCrystal substrates compared to Cree material. This result is confirmed by x-ray rocking curves of symmetric 4H-SiC 00.8 and 6H-SiC 00.12 substrate reflections. The substrates resistivities were measured by contactless resistivity mapping (COREMA) are around 10^{10} Ω×cm for both types of SiC substrates.

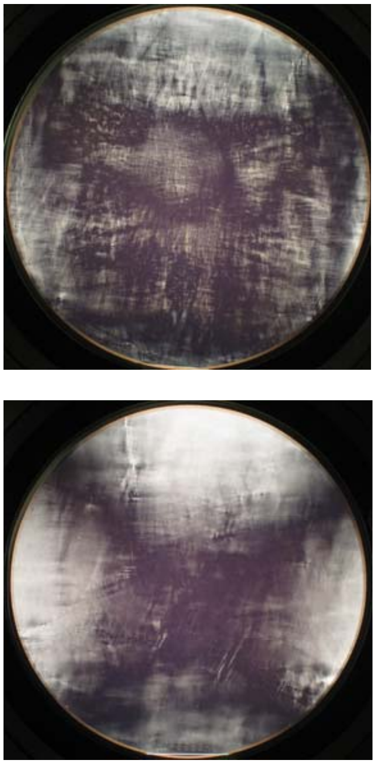

Figure 1: Cross-polarizer images of a SiCrystal (top) and a Cree (bottom) substrate indicating a higher degree of strain inhomogeneity on SiCrystal substrates.

However, we detect different activation energies around 0.8 and 1 eV for SiCrystal and Cree substrates, respectively. Additionally, we measure slightly different thermal conductivities of 420 and 400 W m^{-1} K^{-1} for Cree and SiCrystal substrates.

EPITAXIAL GROWTH

The growth of the AlGaN/GaN HEMT structure is performed by MOCVD in a 12×3-inch multiwafer reactor at Fraunhofer IAF. Growth on the SiC substrates is initiated by a thin AlN nucleation layer followed by a 1.8 µm thick GaN buffer that consists of a bottom Fe-doped and a top undoped part in order to achieve both a high buffer resistivity as well as a low trap concentration near the 2DEG region. [3] The

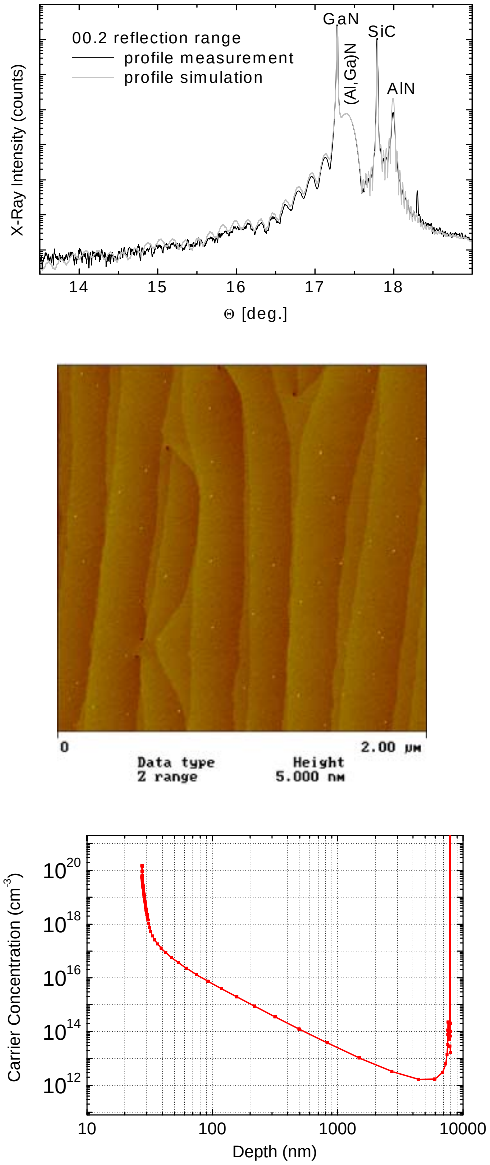

Figure 2: X-ray diffraction profile (top), atomic force micrograph (center) and depth-profile of carrier concentration from capacitance-voltage profiling (bottom). The depth information near the substrate is limited by the measurement accuracy.

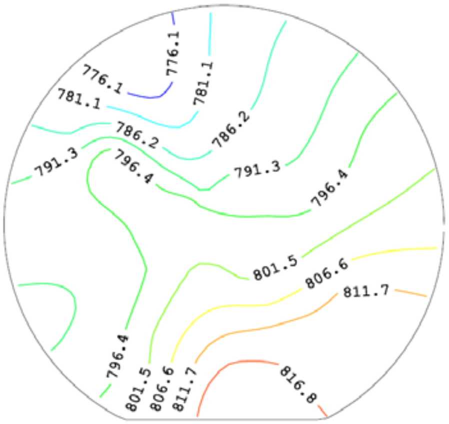

Figure 3: Sheet resistance mapping of an $Al_{0.18}Ga_{0.82}N$/GaN HEMT epitaxial structure grown on SiCrystal substrate: 797 Ω/sq ± 1.4%

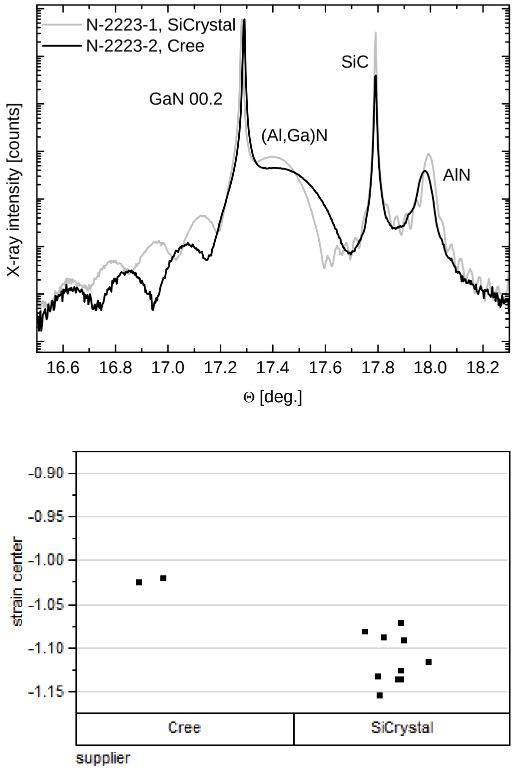

Figure 4: Comparison of x-ray diffraction profiles for samples grown on Cree and SiCrystal substrates within the same epitaxial run (top). Note the different AlN peak position as well as the clear difference in AlGaN composition and thickness as discussed above. Summary of out-of-plane strain (%) of the AlN layer for a set of samples grown on Cree and SiCrystal substrates (bottom).

barrier and the cap layer of the HEMT structure consist of a 22 nm $Al_{0.18}Ga_{0.82}N$ barrier and a 3 nm GaN cap [4]. The barrier thickness and composition was determined by high-resolution x-ray diffraction in conjunction with dynamical simulations, see Figure 2 top. For similar nominal structures it was necessary to perform individual growth runs for both substrate types. For instance, special attention was paid to substrate differences such as the different thermal conductivities of SiCrystal and Cree substrates leading to different surface temperatures (10 K lower for SiCrystal substrates in our machine) during growth. This effect results in lower Al-contents (about 2.5% absolute) and thicker AlGaN layers (about 3 nm) on SiCrystal substrates w.r.t. Cree substrates when growing on both substrate types simultaneously.

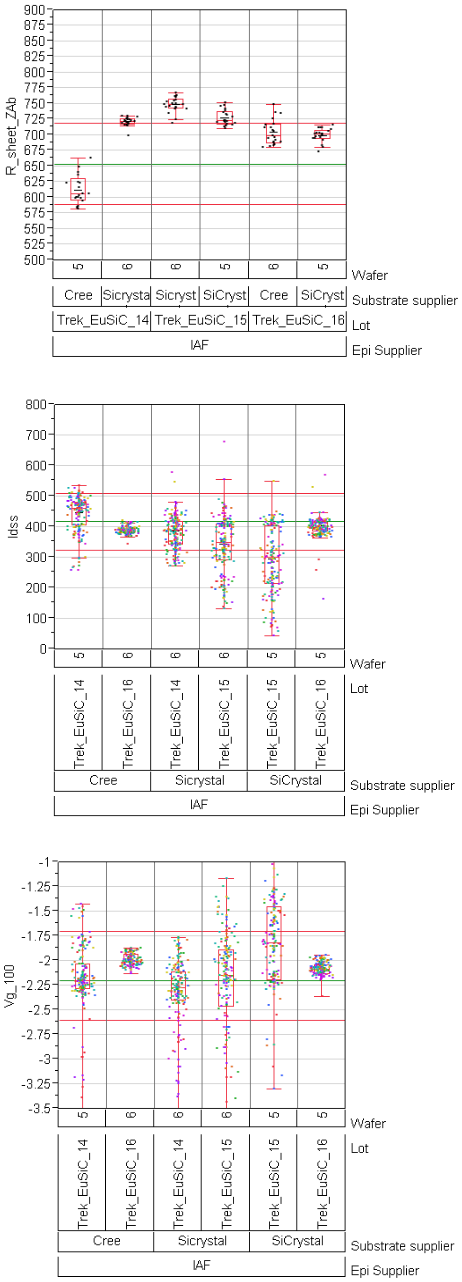

Figure 5: Trend charts of sheet resistance (top, Ω/sq), drain saturation current (center, mA/mm, $U_{GS} = 0$ V) and threshold voltage (bottom, V, defined by 1% of I_{DSS}) of PCM transistors processed on AlGaN/GaN epitaxial layers fabricated on SiCrystal and Cree substrates. The variations from wafer to wafer originate from varying Al-contents during optimization of the growth process. The center and outer horizontal lines represent target mean value and specification limits, respectively. Each data point corresponds to a site on each wafer, the individual data point colors indicate different transistor geometries. The boxes indicate median value and 25%/75% quantiles; the vertical lines represent the complete spread per wafer.

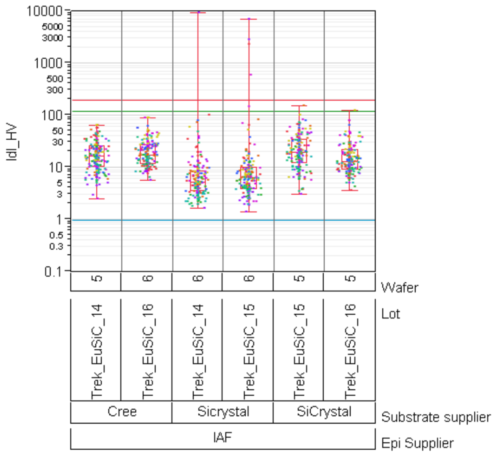

Figure 6: Trend charts of drain leakage current (µA/mm) at 50 V drain bias. The center, upper and lower horizontal lines represent target mean value as well as upper and lower specification limits, respectively. Each data point corresponds to a site on each wafer, the individual data point colors indicate different transistor geometries. The boxes indicate median value and 25%/75% quantiles; the vertical lines represent the complete spread per wafer.

The growth conditions of the AlN nucleation layer and of the GaN buffer were optimized for a low dislocation density (low 10^8 cm^{-2} range as determined by plan-view transmission electron microscopy), smooth surfaces (root mean square roughness well below 0.2 nm over an 2×2 μm^2 area, see Figure 2 center), and low carrier concentration in the buffer (Figure 2 bottom) and high buffer isolation (above 10^{12} Ω/sq). Figure 3 shows a sheet resistance mapping, evidencing a homogenous two-dimensional electron gas.

We do observe differences in the high-resolution x-ray diffraction ω-scan 00.2 and 10.2 GaN linewidths, namely around 0.04° and 0.03° in the 00.2 reflection and 0.05° and 0.07° in the 10.2 reflection for Cree and SiCrystal substrates, respectively. We assume this difference is due to the different nucleation on 4H and 6H substrates leading to slightly different defect structures.

A systematic difference in AlN out-of-plane strain is detected for samples grown on different substrates, even

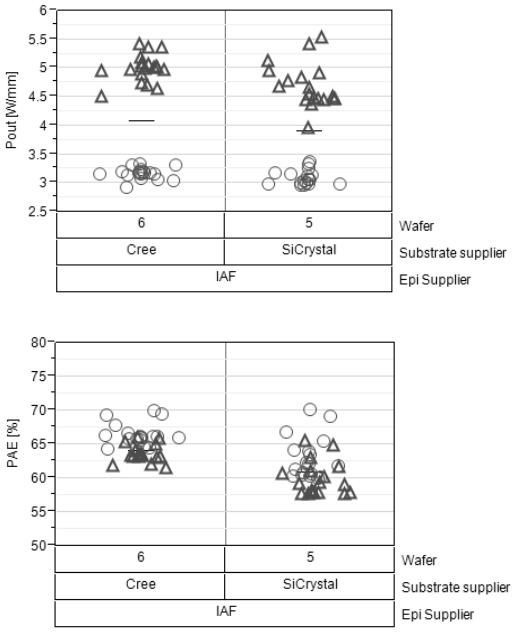

Figure 7: Trend charts of output power density (W/mm, top) and power added efficiency (%, bottom) from loadpull measurements at 50 V drain bias and 2 GHz operating frequency for epiwafers on Cree and SiCrystal substrates. The blue and red data points correspond to optimum tuning for power and efficiency, respectively. Each data point corresponds to one measurement site.

within a single epitaxial growth run, see Figure 4. The peak position of the AlN 00.2 peak in symmetric high-resolution x-ray diffraction profiles is also given for a set of samples. We attribute this additional tensile strain of the AlN layer on the SiCrystal substrate to the different surface conditions originating from different surface treatments during wafer polishing.

DEVICE PROCESSING

Device processing of several iterations of epitaxial material is carried out using the qualified GH50 technology (for applications up to 7 GHz) from United Monolithic Semiconductors [5]. We do observe an improvement in sheet resistance, drain saturation current and threshold voltage (see Figure 5) towards achieving homogeneous PCM parameter distributions within the target range which we attribute to optimizations of the epitaxial growth process. The level of leakage at 50 V drain bias is around 10 µA/mm (see Figure 6) and remains below 100 µA/mm up to the highest voltage of 150 V tested. Loadpull measurements at 50 V drain bias and 2 GHz operating frequency yield a power density of 5 W/mm and a power added efficiency around 65% when tuned for optimum power and efficiency, respectively, see Figure 7. These values are achieved on both substrate types (although a slight trend to lower PAE is visible for SiCrystal substrates), indicating that we have indeed realized epitaxial material of very similar high quality on both SiCrystal and Cree substrates.

CONCLUSIONS

We have performed a systematic comparison of semi-insulating SiC substrates from Cree and SiCrystal on substrate, epiwafer and device level. Overall the substrates are of very similar quality with slightly better structural properties for the Cree material. Epitaxial growth by MOCVD returns homogeneous AlGaN/GaN HEMT wafers on both kinds of substrates with differences in AlGaN barrier composition and thicknesses. This effect is probably due to the different thermal conductivity of 4H-Cree and 6H-SiCrystal material. Devices fabricated on epiwafers on both Cree and SiCrystal material show high-quality HEMTs with low leakage currents and high power-added efficiency. Future work in epitaxial growth and device processing is mainly directed towards a further evaluation and improvement of SiCrystal substrates.

ACKNOWLEDGEMENTS

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ACRONYMS

HEMT: High Electron Mobility Transistor
HRXRD: High-resolution x-ray diffraction
MOCVD: Metal Organic Chemical Vapor Deposition
2DEG: Two-Dimensional Electron Gas
PCM: Process Control Monitor
PAE: Power Added Efficiency