3,000+ Hours Continuous Operation of GaN-on-Diamond HEMTs at 350˚C Channel Temperature

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Abstract

The authors report for the first time the observation of GaN-on-Diamond HEMTs each operating continuously at channel temperatures of 290˚C and 350˚C for 9,000+ hrs and 3,000+ hrs respectively per HEMT. No catastrophic failures were observed whereas all the control GaN-on-Si HEMTs exhibited catastrophic failures.

Keywords

Gallium Nitride, Diamond, HEMT, Power Amplifier, GaN-on-Diamond, Reliability.

Introduction

In recent years, Gallium Nitride (GaN)-based radio-frequency (RF) Power Amplifiers (PAs) have emerged as the leading solid-state candidate technology to replace traveling-wave tubes in many high power applications such as radar, satellite communications, wideband systems, and other applications [1]. GaN is attractive for these applications in part because of its fundamental materials and related electrical properties [2]. As a wide-bandgap material, GaN exhibits a relatively high breakdown voltage compared to established semiconductors, thus enabling high power and high efficiency transistors. Power densities and power added efficiencies of 40W/mm and more than 65% respectively at 10GHz have been reported [3]. However, engineers have struggled to reach the intrinsic electrical limits of the GaN material due to its thermal limitations. As state-of-the-art GaN-on-SiC devices are driven to produce more power, heat overwhelms the transistors' gates and the material's maximum performance is never realized. Simulations and recent experimental demonstrations have shown that a dielectric-coated GaN HEMT epitaxial layer upon which chemical vapor deposition diamond is grown can have up to a 3-fold higher power area density compared to GaN-on-SiC [4].

With GaN resting on a new foreign substrate, and one whose thermal expansion coefficient, crystal structure, and internal stress are very different from that of GaN, device reliability becomes a concern for potential engineers using GaN-on-Diamond. In a recent report, the authors showed that GaN-on-Diamond HEMTs when subjected to source-drain voltages of 24V and 48V, at a channel temperature of 200°C, the source-drain current did not drift by more than 10% over 17,500 Hrs of continuous operation [5].

Experiment

Wafer Preparation – The authors prepared GaN-on-Diamond wafers with the epilayers showing in Figure 1. The AlGaN/GaN HEMT layer structure was grown by metal-organic chemical vapor deposition (MOCVD) on a high resistivity Si (111) substrate by Nitronex Corporation (NC, USA). Starting from the silicon substrate, epitaxial layers included a 1.1 µm thick proprietary transition buffer, an 800 nm thick undoped GaN buffer layer, a 17 nm thick $Al_{0.26}Ga_{0.74}N$ Schottky barrier, and a 2 nm GaN cap layer. Electron mobility of 1400 cm^2/V-s, sheet charge density of 9.6×10^{12} cm^{-2}, and a sheet resistance of about 440 Ω/sq were measured on these wafers. A 100-µm thick CVD diamond layer was grown on a dielectric-coated GaN epitaxial substrate (GaN buffer, AlGaN barrier and GaN cap). The process for diamond growth is as follows: the host Si

(111) and transition layers beneath the AlGaN/GaN epitaxy are removed, a 50 nm thick proprietary dielectric is deposited onto the exposed AlGaN/GaN and finally a 100 μm thick CVD diamond film is grown onto the dielectric adhering to the epitaxial AlGaN/GaN films. In the previously reported work [5], the transition layers were preserved between the GaN and the diamond instead of being removed as they were in this experiment. Figure 1 shows the epilayer structure of the two types of devices tested in this work.

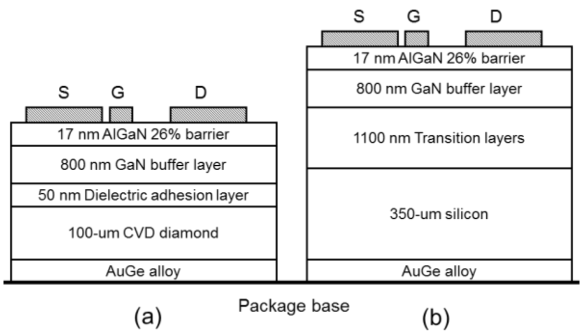

Figure 1 – Epilayer structure of the GaN-on-Diamond (a) and GaN-on-Si (b) transistors tested.

Device Design – The layout of the devices tested is shown in Figure 2. The same layout was used on both the GaN-on-Si and GaN-on-Diamond devices. The gate metallization was Ni/Au, while Si nitride was used for passivation. Target device physical dimensions were $W = 2 \times 200$ μm, $L_G = 1$ μm, and $L_{GD} = 3$ μm. The final chip size was 1.5 x 2 mm², and it contained six HEMTs per chip. The chips were packaged into Stratedge 580286 packages using AuGe eutectic alloy and two devices were wired to the external leads. The source terminal was connected to ground, while the gate and the drain terminals were brought to the package leads. The devices were stabilized inside the package by terminating each to ground through a series combination of a 50-Ω resistor and a 220-pF capacitor (shown in Figure 3). The package lid was omitted. The devices were fabricated on 25-mm diameter GaN-on-Diamond wafers by OEPIC in Sunnyvale, CA.

Device Test Setup – In the life test, we monitor the saturated drain current I_{DSS} and the gate leakage I_{GS} that is drawn under V_{DS} = 24V supply voltage. The circuit diagram shown in Figure 3 shows the connections within and external to the package in the life-test system. There are two coil-and-magnet ammeters per device and the full-scale (FS) measurement range of the ammeters is extended by measuring the current in one of two branches whose current ratio is defined by parallel resistors.

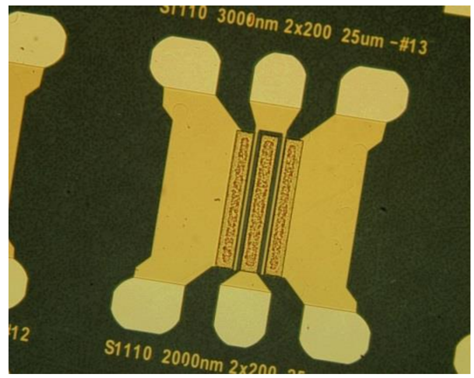

Figure 2 – Photograph of 2-gate layout of devices used in this experiment.

The full-scale drain current reading of the drain-ammeter is doubled by using two 10Ω resistors; the internal ammeter resistance is much less than one Ω. The gate ammeter has an internal resistance of 230 Ωs and its current reading is increased approximately threefold by using the 100Ω shunt resistor. The shunt resistors were not present on all of the devices – this depended on the starting value of I_{DSS}, but the current readings shown later in the graphs were all scaled appropriately. Typical values of the I_{DSS} were GaN-on-Si ~ 130 mA, GaN-on-Diamond ~ 60 mA. Using a digital resistance meter, the orientation of mounted and wired devices was confirmed and the zero-bias channel resistance noted. The GaN-on-Si devices had $R_{DS} \approx 18$ Ω, while GaN-on-Diamond had $R_{DS} \approx 24$ Ω (both with the gate shorted to ground). The packaged devices were first split into two groups for tests at different temperatures and each group (containing some GaN-on-Si and some GaN-on-Diamond devices) was mounted on a nickel plated copper plate, which was then attached to a temperature-controlled hotplate. We used two hotplates. The thermal resistances [6] of the GaN-on-Diamond and GaN-on-Si devices were measured when the devices were packaged in the same package on a similar, but smaller nickel-plated copper plate yielding an average of ~60°C/W for all devices. The value was not critical because self-heating contributed less than 10% of the total channel temperature rise.

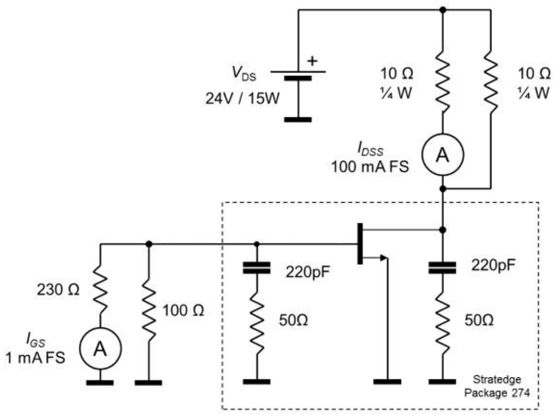

Figure 3 – Electrical wiring in the life-test system. The gate is at zero bias, connected to ground via ammeter, and the drain is connected to a 24-V power supply. We monitor I_{GS} (leakage) and I_{DSS} (drain current at zero gate bias).

The package leads were connected to the power supplies and ammeters via thin copper wire (lacquered transformer wire). The current readings were performed manually.

Results

The life test was performed in two phases: In the first phase (I), we selected channel temperatures 215°C and 290°C. During the first 5,000 hours, as shown in Figures 4A and 4B, we observed that at 215°C, both GaN-on-Diamond and GaN-on-Si devices degraded slowly with GaN-on-Diamond devices degrading slightly faster than GaN-on-Si devices. At the same time, as shown in Figure 5A and 5B, at 290°C we observed the opposite behavior: after the initial burn-in period, GaN-on-Si devices degraded dramatically faster than the GaN-on-Diamond devices whose I_{DSS} remained largely unchanged with time (during the first 5,000 hrs). In order to further examine this seemingly inconsistent behavior, we interrupted the 215°C test (at 5,000Hrs) and raised the temperature of that hot plate to channel temperature of 350°C. In this second phase, the channel temperatures of the two batches were 290°C (unchanged from before) and 350°C. We started the clock on the 350°C batch from zero. In this phase, we observed that GaN-on-Si degraded dramatically at 350°C as was previously observed at 290°C (Figure 6A), and that GaN-on-Diamond remained largely unchanged until around 1000 hours where the degradation in I_{DSS} appears to acquire a gradual downward slope.

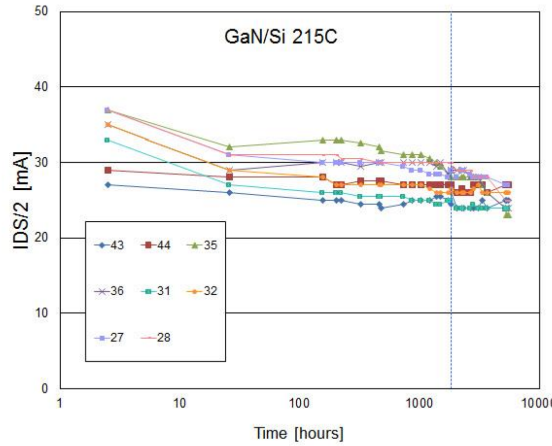

Figure 4A – GaN-on-Si devices I_{DSS} during first 5,000 hours of life-test at 215°C.

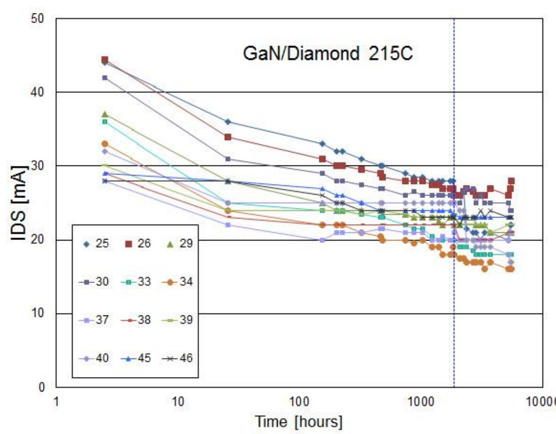

Figure 4B – GaN-on-Diamond devices I_{DSS} during first 5,000 hours of life-test at 215°C (phase I).

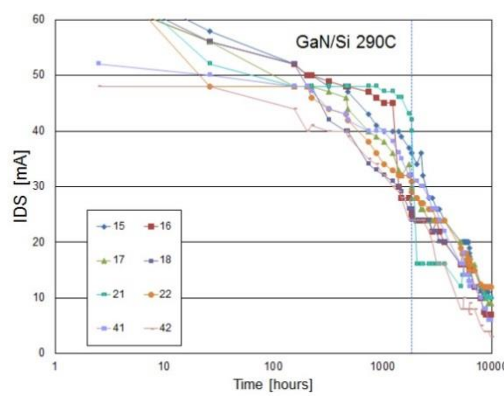

Figure 5A – GaN-on-Si devices I_{DSS} at 290°C (phases I+II)

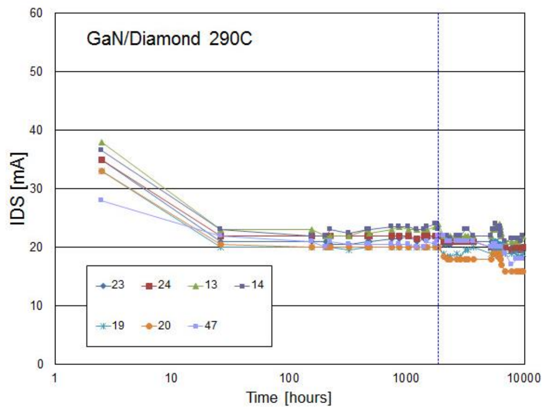

Figure 5B – GaN-on-Diamond devices I_{DSS} at 290°C (phases I + II).

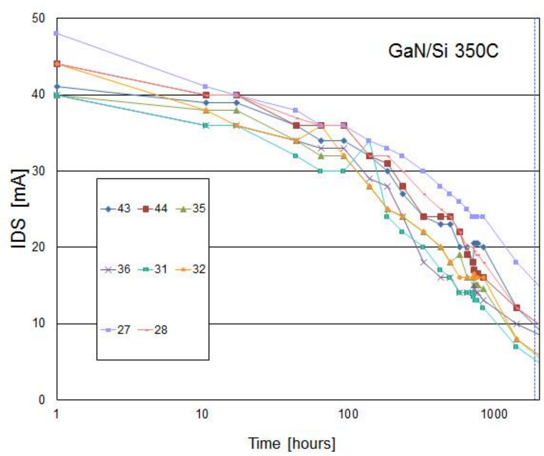

Figure 6A – GaN-on-Si devices I_{DSS} at 350°C (phase II).

A key observation taken from these results was that after the first burn-in period (<100 hours), GaN-on-Diamond devices degrade significantly slower than their GaN-on-Si counterparts of the same layout and similar device process. Furthermore, no catastrophic failures were observed on any of the GaN-on-Diamond devices. The vertical dashed lines in the life-test data in figures 4A, 4B, and 5A, and 5B indicate the time when the life-test systems were geographically relocated causing a slight shift in the measurements. The noise in the appearance of the data is attributed to the fact that the meters are analog and measured by the human eye; data can thus be subject to changes in the physical perspective of the observation. In Figures 7 to 10, we show the time dependence of the gate leakage currents in all the aforementioned devices. In all cases, time and temperature appear to improve the leakage current.

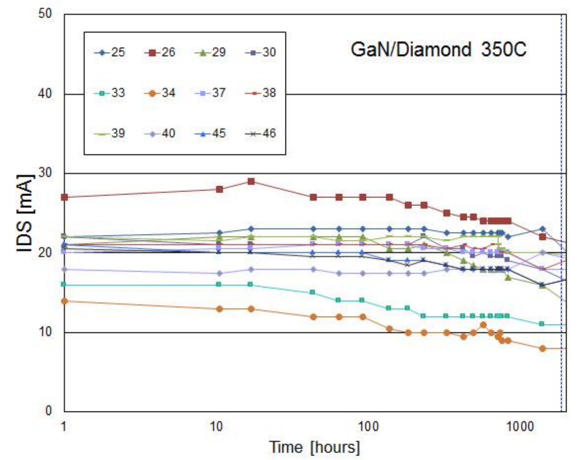

Figure 6B – GaN-on-Diamond devices I_{DSS} at 350°C (phase II).

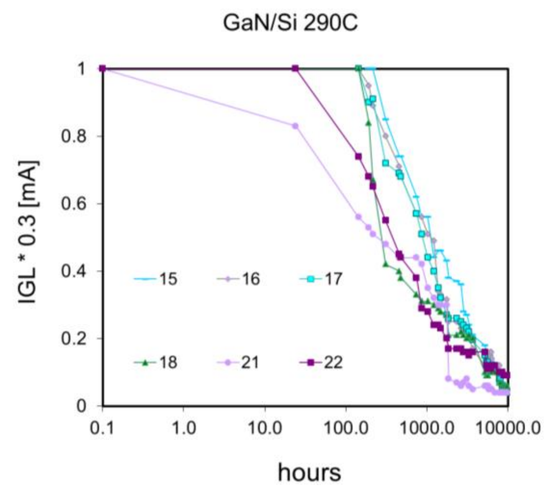

Figure 7 Gate-leakage current measured on 6 GaN-on-Si devices biased with a Source-Drain voltage of 24V. Channel temperature is maintained at 290C.

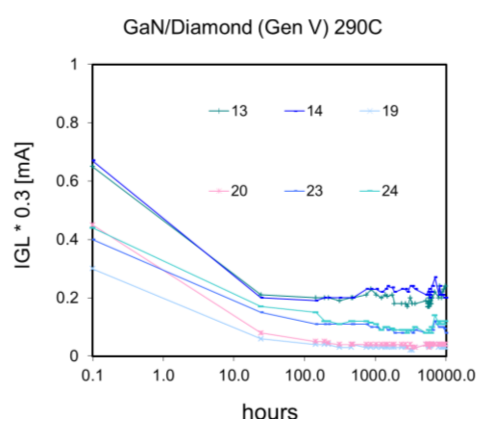

Figure 8 Gate-leakage current measured on 6 GaN-on-Diamond devices biased with a Source-Drain voltage of 24V. Channel temperature is maintained at 290C.

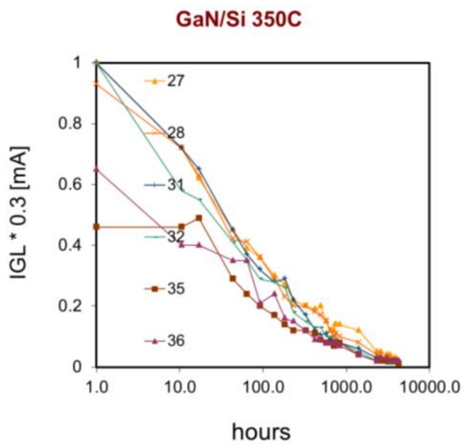

Figure 9 Gate-leakage current measured on 6 GaN-on-Si devices biased with a Source-Drain voltage of 24V. Channel temperature is maintained at 350C.

At 290C, GaN-on-Diamond devices appear to heal faster (within 10hrs) than the GaN-on-Si (within several thousand hours). The reasons for the phenomena observed in these experiments are still under investigation, but there is a clear resilience of GaN-on-Diamond devices to high channel temperatures as compared to GaN-on-Si devices. The reason for leakage current annealing is also unclear, but may imply material and contact annealing.

Summary

In summary, the authors have shown that GaN-on-Diamond HEMT devices outlast GaN-on-Si in high-temperature operating life/endurance tests by thousands of hours – usually never failing; GaN-on-Si devices failed very shortly after start in almost all cases. The results also show that the method for making GaN-on-Diamond wafers does not negatively affect the HEMTs. The GaN epitaxy, device structure and geometry are the same across all the devices. Temperatures of ~ 215˚C, 290˚C, and 350˚C were used for the test that spanned up to 10,000 hrs for many of the device batches.

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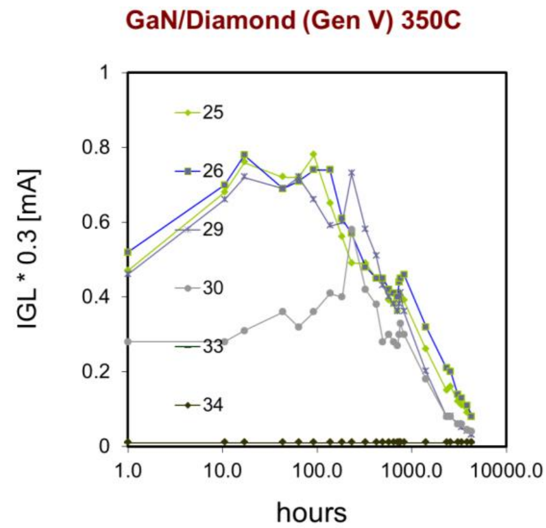

Figure 10 Gate-leakage current measured on 6 GaN-on-Diamond devices biased with a Source-Drain voltage of 24V. Channel temperature is maintained at 350C.

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