BCB encapsulation for high power AlGaN/GaN-HFET technology

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Keywords: AlGaN/GaN HFET, HEMT, BCB, passivation, dispersion effects, processing

Abstract

GaN-HEMT technology with BCB encapsulation was successfully established without compromises in DC and RF performance. It was shown that same power levels of 6 W/mm and high efficiencies higher than 60% at 2 GHz can be achieved with BCB encapsulation as compared with reference air-bridge power bar design. However, transistor´s dynamic behavior especially with high Al-content barrier layer is still a topic of investigations.

INTRODUCTION

AlGaN/GaN-HFET fabrication for microwave, devices and MMICs has reached a mature state providing devices capable of delivering high RF power levels at high operating voltages. However, technological improvements as device encapsulation or tailored low-loss metal lines [1] are still in focus.

Bisbenzocyclobutene resins (BCB) are already well known as dielectric spin-on materials and are widely used in GaAs-based HBT fabrication. The suitability of BCB for microwave applications is mainly due to its low dielectric constant (2.65 – 2.50 in frequency range of 1 – 20 GHz) combined with low dielectric losses [2]. Further properties like low moisture absorption and excellent planarization just by spin-on coating enables BCB to be one of the first materials of choice for device passivation and/or encapsulation.

Despite of the wide use of BCB in mature III-V-based technologies only few reports on its application for GaN-HFETs are published [1]. This is obviously caused by the well-known problems with the introduction of multiple passivation layers in the active region of a GaN-HFET which could lead to increased leakage current levels and deteriorated dynamic behavior [3]. Thus, especially for AlGaN/GaN-HEMTs a careful optimization of the encapsulation technology is needed.

In this work we report on successful implementation of BCB as an encapsulation layer in the FBH´s baseline GaN-HEMT process for power applications and MMICs.

EXPERIMENTAL DETAILS

The details of the general GaN-HEMT processing are described elsewhere [3]. Here, we used a 2.6 µm thick BCB layer deposited on top of the final silicon nitride device passivation. This particular layer thickness was chosen in order to allow the direct comparison of transistor performances with our standard air-bridge technology. The BCB was cured at moderate temperature of 240°C and contact openings were dry etched by ICP plasma.

Finally, 6 µm Au was plated as a second interconnecting metal. Fig. 1 shows a viewgraph of a fabricated GaN-HEMT power bar with BCB encapsulation.

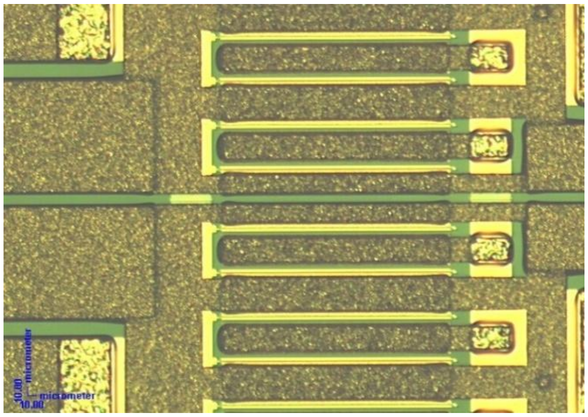

Figure 1. Chip photograph of a GaN-HEMT power bar with BCB encapsulation.

RESULTS AND DISCUSSION

The major point of interest addressed in this work is the question whether the additional BCB layer will impact the transistor´s performance. Fig. 2 shows a comparison of leakage currents measured on wafers without and with additional BCB layer. This result verifies that no increase in leakage current occurs when BCB encapsulation is used. Furthermore, there was no significant change of other transistor parameters like threshold voltage.

Fig. 3 confirms that the BCB layer does not affect the available RF power levels. For both wafers, with and without BCB, the same power dependency on drain voltage was measured. Furthermore, the transistors encapsulated with BCB achieved equally high power density of more then 6 W/mm at 50 V. Fig. 4 presents the resulting optimum load matching conditions for both wafers showing that the BCB does not change the matching impedance significantly at 2 GHz and operating voltage up to 50 V.

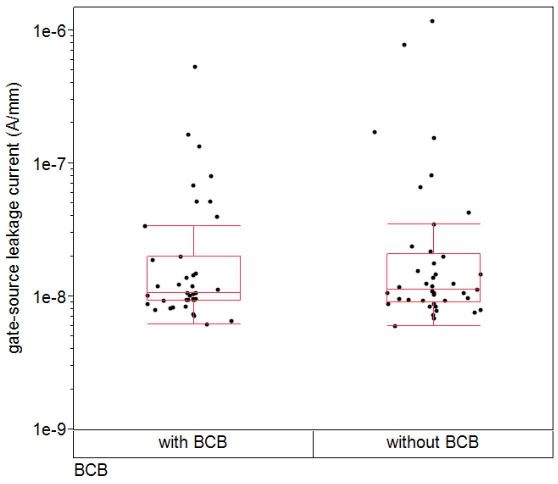

Figure 2. Comparison of gate-source leakage currents measured on 2x125-µm GaN-HEMT devices on wafers without or with additional BCB layer.

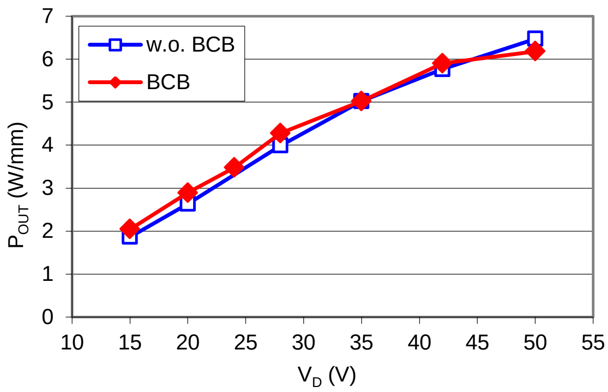

Figure 3. RF power in dependence on drain voltage for a GaN-HEMT with BCB in comparison with a reference transistor without BCB measured on 2x250-µm devices at 2 GHz.

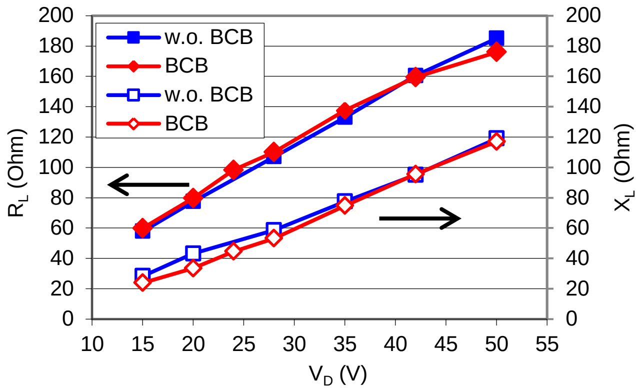

Figure 4. Matching impedance for a 2x250-µm GaN-HEMT with BCB in comparison with a reference transistor without BCB.

Similarly, figures 5 and 6 confirm that the same power-added-efficiency levels higher than 60% are available with BCB encapsulation, too.

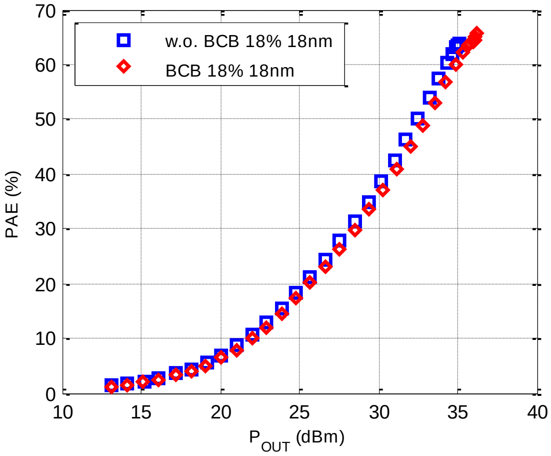

Figure 5. Power-added-efficiency (PAE) measured by RF power sweep on a GaN-HEMT with 18% Al concentration and 18 nm barrier thickness, with and without BCB, matched for maximum PAE (V_D = 28 V, 2 GHz).

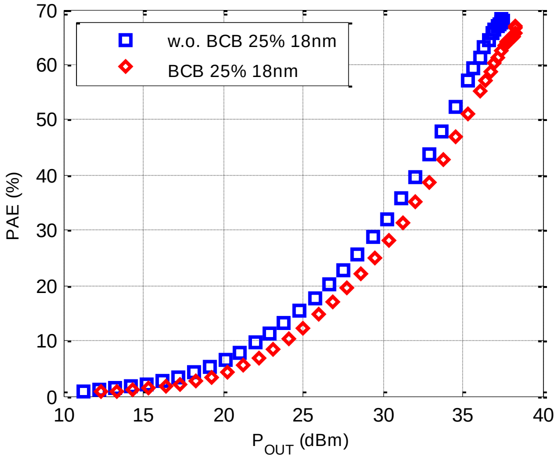

Figure 6. Power-added-efficiency (PAE) measured by RF power sweep on a GaN-HEMT with 25% Al concentration and 18 nm barrier thickness, with and without BCB, matched for maximum PAE (V_D = 28 V, 2 GHz).

Since trapping effects resulting in current dispersion are well known issues of AlGaN/GaN HFETs a special investigation was focused on determination of transistor behavior under pulse operation conditions. A standard evaluation method is now established at FBH [4] which allows for a reproducible comparison of transistor pulse responses with extreme long time-constants. The pulse sequence used in the measurements mimics the switching of the device to two distinct bias points and back. First the gate voltage is applied for some time with the drain voltage still turned off. Then, after 300s the drain voltage is turned on – the device operates in a class AB bias point. After further 300 s the gate bias is further increased to near class A conditions with a fix dissipated power and held there for another 300 s. The same switching sequence then follows in opposite direction. The drain current transient is always monitored throughout this test. Fig. 8 shows the pulse response measurements on transistor with BCB layer which confirms that no deterioration in dynamic behavior occurred here as compared with the reference transistor without BCB (fig. 7).

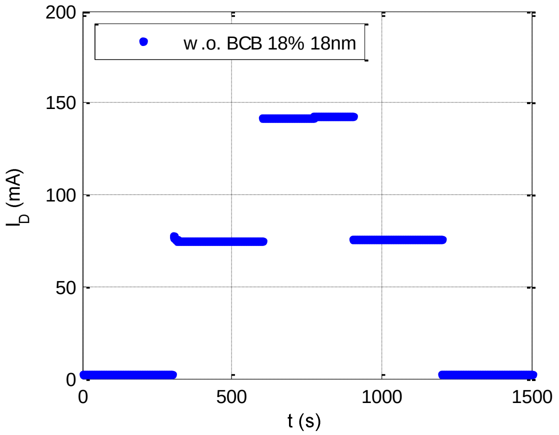

Figure 7. Pulse response results measured on a GaN-HEMT design without BCB encapsulation using an epitaxial structure with an Al content of 18% in the 18 nm thick AlGaN barrier layer.

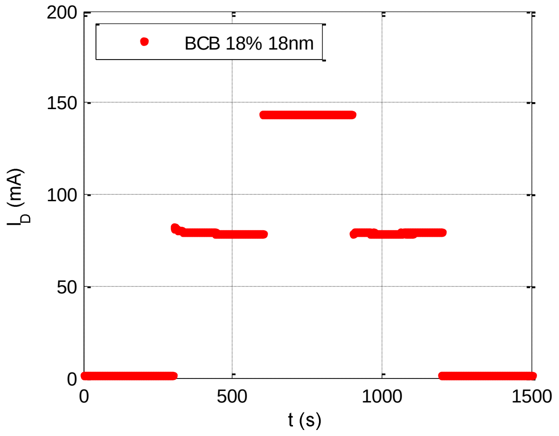

Figure 8. Pulse response results measured on a GaN-HEMT transistor with BCB encapsulation using an epitaxial structure with an Al content of 18% in the 18 nm thick AlGaN barrier layer.

It has turned out that the question whether or not the BCB encapsulation influences the outcome of the switching test strongly depends on specific epitaxial design of the active device region. The tests shown in Figures 7 and 8 reflect that properties of GaN HEMTs fabricated on epi stacks with a comparable low Al concentration of 18% and 18 nm barrier thickness. As the Al concentration increases to 25%, lagging effects became more pronounced as shown in fig. 9. Here, the incorporation of BCB encapsulation further increases the time constant for current recovery during the pulse, especially after increasing the current (fig. 10). Thus, severe charging effects at the scale of 10s of seconds are determined for this wafer type.

These results could indicate a higher sensitivity of higher-current related epitaxial designs toward changes in local strain situations. This effect may be explained by the higher local fields at the drain side edge of the gate for designs with higher Al content in the AlGaN barrier.

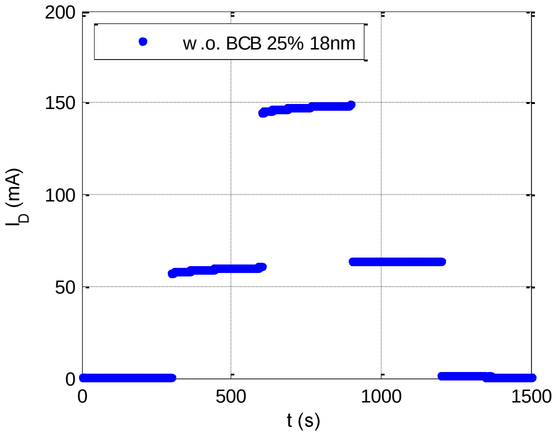

Figure 9. Pulse response results measured on a GaN-HEMT transistor without BCB encapsulation using an epitaxial structure with an Al content of 25% in the 18 nm thick AlGaN barrier layer.

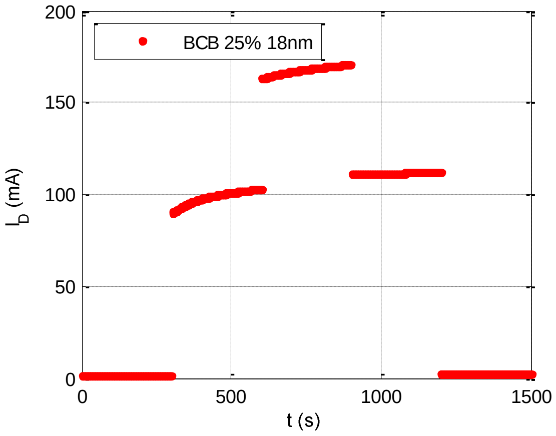

Figure 10. Pulse response results measured on a GaN-HEMT transistor with BCB encapsulation using an epitaxial structure with an Al content of 25% in the 18 nm thick AlGaN barrier layer.

In case that BCB is placed close to the drain side edge of the gate the electric field penetrates deeper into the original SiN_x passivation layer giving rise to enhanced electron injection in this region if the fields are high enough. It is believed that if the electrons are injected in the SiN_x they can remain there for quite some time before getting back to steady-state conditions. This would explain the large time constant responses. A detailed explanation is matter of ongoing investigations.

CONCLUSIONS

In conclusion, GaN-HEMT technology with BCB encapsulation was successfully established without compromises in DC and RF performance. However, transistor´s dynamic behavior needs to be considered especially if epitaxial layer combinations are applied that create very high field concentrations at the drain side edge of the gate.

ACKNOWLEDGEMENTS

The authors would like to thank colleagues who helped to take the measurements. Additionally, support from the wafer processing area is appreciated.

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ACRONYMS

HFET: Heterojunction Field Effect Transistor
SEM: Scanning Electron Microscope
2DEG: Two-Dimensional Electron Gas
MMIC: Monolithic Microwave Integrated Circuits
R_L: resistance
X_L: reactance