

Low-Loss Metal-on-BCB Technology for Next-Generation GaN MMICs

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Keywords: GaN, BCB, power, efficiency, MMIC

Abstract

Metal-on-BCB technology has been integrated into a GaN MMIC process and used to achieve very high Power Added Efficiency (PAE) at X-band. The process utilizes a high-performance 0.1 μm GaN FET, thick ($>10 \mu\text{m}$) photo-definable BCB, and plated gold lines on top of the BCB to create a third layer of circuit metal. The metal-on-BCB lines are used to reduce circuit loss via higher Q inductors, reduced microstrip line capacitance, and increased microstrip line inductance. X-band Class E MMICs were built using this technology and yielded a 4% increase in efficiency compared to circuits without BCB. Absolute PAE values up to 69% were achieved on optimized 3 Watt amplifiers.

INTRODUCTION

GaN MMIC technology has been established as a means for delivering high power at high voltage. However, for next generation MMICs, additional capabilities are required to improve efficiency and incorporate higher levels of functionality. Metal-on-BCB technology is a promising candidate to meet these needs due to several advantages over conventional circuits. These include:

- A reduction in microstrip transmission line capacitance (useful for class E operation)
- An increase in transmission line inductance
- A reduction in circuit loss (e.g., higher Q inductors) by allowing wider lines for the same microstrip characteristic impedance
- A reduction in IR drop in drain bias feeds (higher V_{ds} at FET drains)
- A provision for 3-D routing capability
- Airbridge (AB) protection for automated pick and place assembly
- The incorporation of advanced 3-D structures (e.g., broadside couplers) into the MMIC design

To date, most reported work with BCB has involved its integration with GaAs MMIC technology [1,2]. In this work, we describe a 4" GaN-on-SiC MMIC process that incorporates a metal-on-BCB process along with a state-of-the-art 0.1 μm FET. The resulting MMICs built using this technology demonstrate extremely high levels of efficiency at X-band.

EXPERIMENTAL DETAILS

The GaN technology used for this work was a high-frequency process chosen for its ability to deliver high-efficiency at X and Ku band. A cross section of the device is shown in Figure 1. The key features are a thin, high aluminum content AlGaN barrier, 0.1 μm t-gate, and in-situ silicon nitride surface passivation. A low aluminum content AlGaN back-barrier is also included to reduce short-channel effects. All epitaxial layers and in-situ silicon are deposited by metal organic chemical vapor deposition (MOCVD) on 4" SiC substrates. The first step in the fabrication process is a selective re-growth of n^+ GaN layer in the source and drain regions to minimize the contact resistance. Ohmic contact resistances are typically in the 0.1 to 0.15 $\Omega\text{-mm}$ range using this process. Device isolation is achieved by helium implantation. The 0.1 μm t-gate is then patterned using a tri-layer resist and lifting off an evaporated Ni/Au gate. A self-aligned etch is performed prior to evaporation to remove the in-situ MOCVD silicon nitride. Following gate patterning, a PECVD nitride is deposited with a thickness tailored to both passivate the HFET and maintain high-frequency performance.

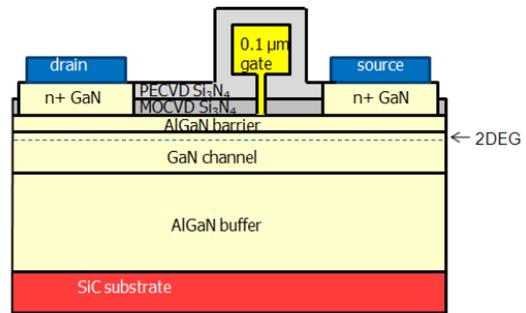


Figure 1. Schematic cross-section of the GaN 0.1 μm HFET unit cell used in this work.

Typical output HFET I_{ds} - V_{ds} characteristics are shown in Figure 2. The maximum device current is greater than 1 A/mm, with a pinch-off voltage of 1.6 V and peak transconductance of 450 mS/mm. Typical operating voltage

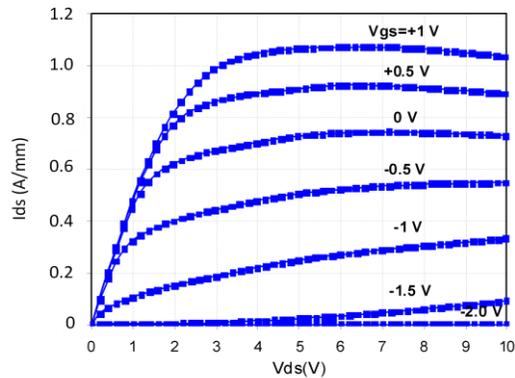


Figure 2. Typical I_{ds} - V_{ds} characteristics for the GaN FETs used in this work. The maximum current is >1 A/mm with a pinch-off voltage of approximately -1.6 V.

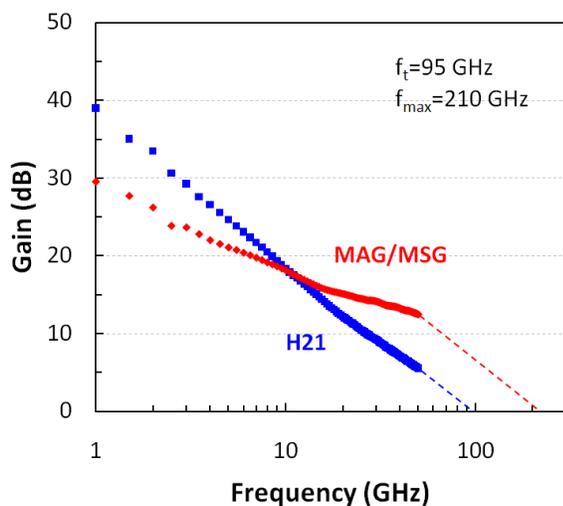


Figure 3. Small-signal h_{21} and MAG/MSG plots for the FETs used in this work. Typical performance metrics at $V_{ds}=15$ V include $f_t=95$ GHz and $f_{max}=210$ GHz.

is 15V, with breakdown voltages greater than 40 V. The small-signal rf performance of these HFETs is shown in Figure 3. Typical cutoff frequency (f_t) is 95 GHz and maximum oscillating frequency (f_{max}) is 210GHz. Load pull measurements at X-band show 3-4W/mm power densities at $V_{ds}=15$ -20V.

These devices have been integrated into a full GaN MMIC process that includes a third layer of metal interconnects on BCB. Following HFET fabrication, metal-insulator-metal (MIM) capacitors, NiCrSi thin film resistors, and two layers of circuit metal (the second including plated airbridges) are patterned on the wafers. Thick (>10 μ m), photo-definable BCB is then coated on the wafers and developed to remove it in regions where connections to underlying metal are required, or where the BCB is not

desired (Figure 4). The BCB is cured and a clean-up etch performed to remove residual material.

Following BCB patterning, plated metal lines are defined to route circuitry on top of the BCB and make connections to the underlying GaN. The wafers are then bonded to sapphire handle wafers, thinned to 100 μ m thickness, through-wafer vias etched, and backside metal plated and patterned.

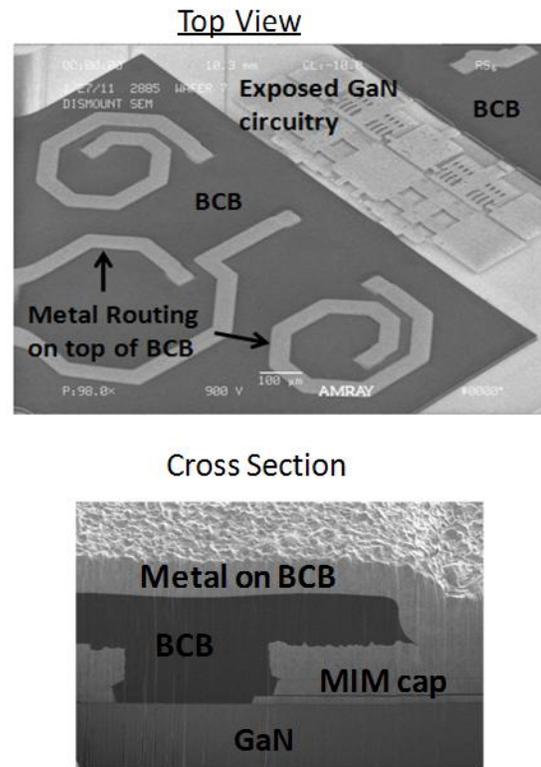


Figure 4. SEM images of GaN MMICs with metal-on-BCB, both from a top view and in cross section. Circuit metal is routed on top of the BCB in certain areas to reduce circuit loss; GaN circuitry is left exposed in others to avoid FET performance degradation.

As part of this study, the effect of the BCB dielectric on HFET performance was investigated. This was done to determine whether BCB should be left covering the active FETs or removed from these areas during BCB patterning. While BCB is a relatively low dielectric constant material, its presence on the HFETs is nonetheless expected to increase capacitance and reduce gain. To examine this, several standard test HFETs were fabricated where BCB was left covering the HFETs in some cases, and removed in others. The devices were otherwise identical. Small-signal S-parameters were measured afterwards to compare

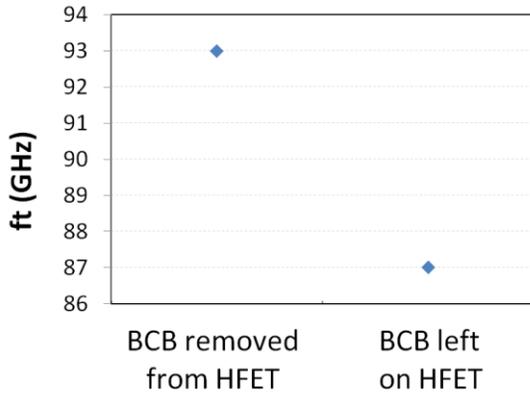


Figure 5. Comparison of cutoff frequency (f_t) for FETs covered with thick BCB vs. those without. The increased dielectric loading of the BCB causes a 6 GHz drop in f_t .

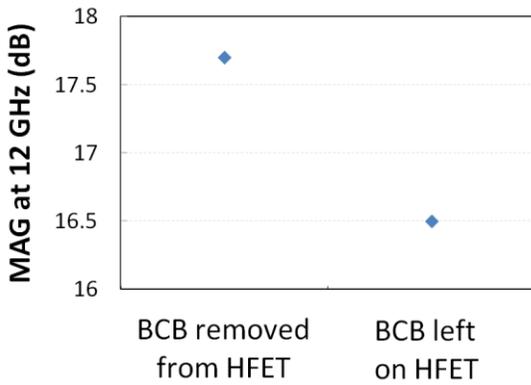


Figure 6. Comparison of MAG/MSG for FETs covered with thick BCB vs. those without. The presence of the BCB on top the FET causes a 1.2 dB drop in gain.

performance between the two cases, and are summarized in Figures 5 and 6. For the devices where BCB is removed from the HFETs, the average f_t is 93 GHz and MAG gain at 12 GHz is 17.7 dB. For devices where BCB is left covering the HFETs, the average f_t drops to 87 GHz and MAG gain drops to 16.5 dB. As a result of this difference, the BCB was removed above the active HFET regions during patterning for this work.

MMIC RESULTS

To demonstrate the benefits of this technology, several MMIC designs spanning C through Ku bands were fabricated and tested. Some designs employed Class E operation and targeted maximum power added efficiency (PAE). Other designs targeted unique circuit applications.

For the Class E designs, as a comparison, circuits without metal-on-BCB were fabricated alongside the standard MMICs to evaluate the benefits of the BCB.

A baseline 3W Class E X-band amplifier employed a 1mm GaN FET (consisting of two 0.5 mm cells) and BCB on the input and output matching networks. A “finite parallel inductance” output network topology [3] was adopted along with a reactance compensation circuit for harmonic filtering and broadband class E impedance synthesis. On-wafer pulsed power measurements were performed vs. frequency and input drive on several wafers from the fabricated lot. The wafer data for each design was averaged so that the statistical benefits of each approach could be evaluated. All MMICs were measured at a drain voltage of 15V. Fig. 7 shows the measured power output and power-added efficiency of the baseline 3W class E MMIC with BCB. A peak efficiency of 69% was achieved, along with an associated power output of 3 Watts.

A companion MMIC without BCB in the output network showed an average efficiency reduction of 4% and an average power output reduction of 0.25dB. This was due to the narrower microstrip lines required to maintain the proper class E impedances when the lines are placed on the SiC substrate as compared to being on top of the thick BCB layer. The difference in efficiency across the band between the version with BCB vs. without BCB is shown in Figure 8. As can be seen, significant benefits are achieved with the use of the metal-on-BCB technology.

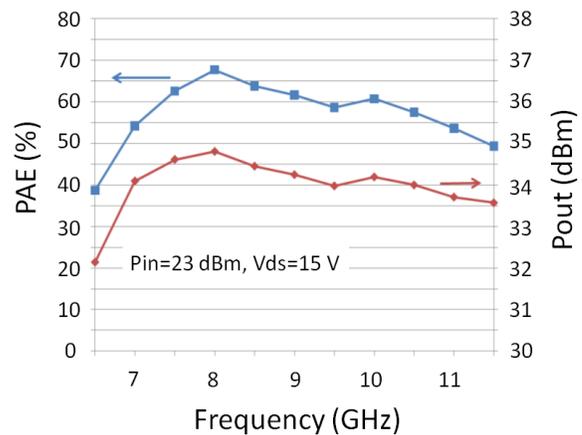


Figure 7. Power Added Efficiency (PAE) and output power vs. frequency for a 3 Watt X-band Class E amplifier with BCB on the input and output networks. A peak PAE of 69% is achieved at 8 GHz.

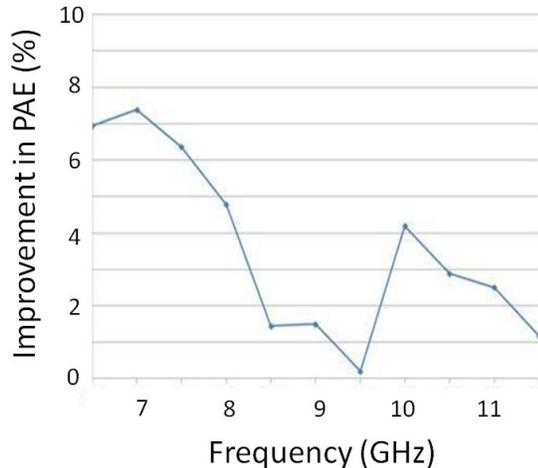


Figure 8. PAE improvement vs. frequency for a 3 Watt Class E amplifiers with BCB on the output network vs. an identical version without BCB. An average of 4% improvement is achieved across the band.

A wideband “multi-push-pull” power MMIC is shown in Figure 9. This two-stage design uses broadside coupled 180° Marchand baluns, with BCB as the dielectric spacer, at the input and output to develop the desired push-pull operation. Since wider line widths are realized, the broadside coupled baluns have lower loss than the conventional interdigitated baluns typically employed in MMIC design. Crossover networks in the inter-stage network produce the multi-push-pull effect in which the phase alternates at each of the four output FET cells. This arrangement produces a number of virtual grounds on the top surface of the MMIC for low inductance rf grounding. In addition, the push-pull operation provides a vastly reduced 2nd harmonic output, important in a amplifier. Measure results showed better than 25 dBc 2nd harmonic rejection across the entire operating bandwidth.

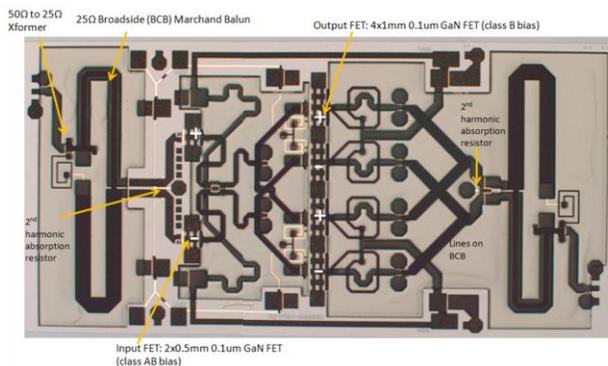


Figure 9. Photo of a wideband multi-push-pull power amplifier. Broadside 180° Marchand baluns using BCB as the dielectric spacer were employed at the input and output.

CONCLUSIONS

In conclusion, a GaN MMIC technology has been demonstrated that incorporates a third layer of circuit metal on BCB for reduced circuit loss. A 3 Watt Class E X-band was fabricated using this process and showed a 69% PAE using BCB in its output network, with an average 4% improvement in efficiency vs. an identical circuit without BCB. This represents a promising technology for next generation MMIC applications.

ACKNOWLEDGEMENTS

The authors would like to thank Andris Ezis, Joe Faulkner, and Mike Lee for their support and contributions to this work.

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ACRONYMS

- GaN: Gallium Nitride
- BCB: Benzocyclobutene
- MMIC: Monolithic Microwave Integrated Circuit
- PAE: Power Added Efficiency
- HFET: Heterojunction Field Effect Transis