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High Linearity Low-k BCB-Bridged AlGaAs/InGaAs Power HFETs

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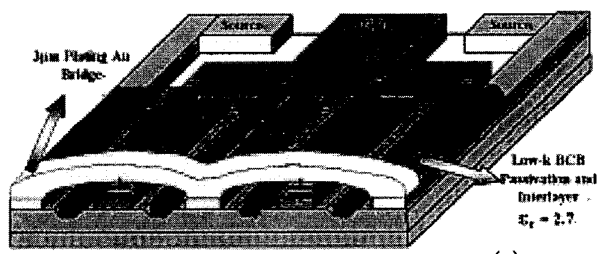
Abstract A novel low-k BCB (benzocyclobutene) bridged and passivated process for AlGaAs/InGaAs doped-channel power FETs with high reliability and linearity was characterized and developed. In this study, we applied the low-k BCB-bridged interlayer to replace the conventional air-bridged process and the SiN_x passivation technology of the 1mm-wide power device fabrication. This novel process technique demonstrates a lower power gain degradation under a high input power swing, and exhibits an improved adjacent channel power ratio (ACPR) than the air-bridged ones due to its lower gate leakage current. The power gain degradation ratio of BCB-bridged devices under a high input power operation (P_{in} = 5~10 dBm) is 0.51 dB/dBm, and this value is 0.65 dB/dBm of conventional air-bridged devices.

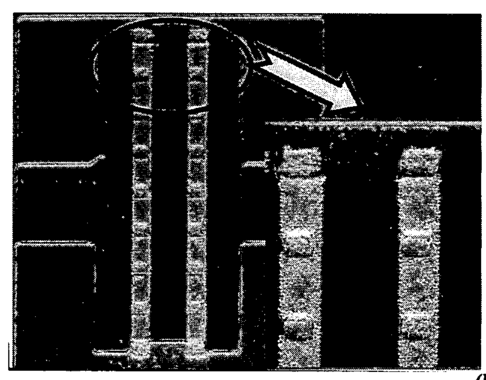
I.INTRODUCTION

In recent years, there has been a great demanding in developing high reliability and high quality GaAs power devices for wireless communication applications. In order to meet a strong demand of commercial mobile system, passivation technology for large area power device (gate width > 1mm) plays an important role for manufacturing the power amplifier module. Based on the previous reports, silicon nitride (SiN_x) fabricated by the PECVD is the most commonly used to deposit dielectric materials for the passivation of GaAs and InP-based devices and circuits [1-2]; however, the surface damage produced by the plasma can't be avoided [3]. These surface states lead to the trapping effect resulting in the device performance degradation. Furthermore, the dielectric constant of SiN_x is about 5.8~6.2, which will also cause substantial changes in the electrical characteristics for device operating at high frequencies. Therefore, we applied the low-k BCB dielectric layer to replace the conventional SiN_x passivation and air-bridged process simultaneously, not only simplifying the fabrication process but also enhancing the device performance. The BCB exhibits several merits for microwave power devices, including a low dielectric constant (2.7), a low dielectric loss tangent (0.0008), a low curing temperature, a low water up-take and simple manufacturing process. In addition, as compared with the traditional air-bridged power devices, BCB-bridged ones also provide a higher device yield after the thin-down and dicing process, which provide a good opportunity for high linearity and high power microwave device applications.

II.DEVICE STRUCTURES AND FABRICATION



(a)



(b)

Fig.1 The cross-section (a) and the SEM photography (b) of BCB-bridged AlGaAs/InGaAs power HFETs

The cross-sectional profile and SEM photography of the 1mm BCB-bridged AlGaAs/InGaAs power transistors grown by molecular beam epitaxy (MBE) on (100)-oriented

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semi-insulating GaAs substrates are shown in Fig. 1. Two $In_{0.15}Ga_{0.85}As$ doped channels($n = 2\times10^{18}\ cm^{-3}$) sandwiched a 5 nm undoped GaAs layer were grown on the top of an undoped GaAs buffer layer,followed by a 20 nm undoped AlGaAs Schottky layer. Finally, a 20 nm n^+-GaAs cap layer ($n = 5\times10^{18}\ cm^{-3}$) was grown to improve the ohmic contacts. For device fabrication, ohmic contacts of AuGeNi/Ti/Au metals were deposited by e-beam evaporation and patterned by a conventional lift-off process. An $NH_4OH/H_2O_2/H_2O$ solution was used for mesa etching reaching down to the GaAs buffer layer. As to the gate recess process, instead of using traditional wet etching, we applied the optimum reactive ion etching to achieve a high uniformity and yield. After the gate recess process, $1.0 \times 1000\ \mu m^2$ with ten fingers Ti/Au-gates were deposited and defined by a lift-off process. After a 30 seconds O_2 plasma treatment, a 2μm thick BCB was coated on the device by a spin coater, and via holes connecting all the source pads were defined by photolithography. To obtain a low dielectric constant and an extremely flatness, the defined BCB patterns were cured at 200°C for 30 minutes, and this low curing temperature makes it very attractive to the GaAs process. Finally, a 3μm thick top Au layer was electroplated for bridging the source pads. For comparison, the conventional air-bridged devices were also fabricated.

III. DEVICE DC AND RF POWER CHARACTERISTICS

To examine whether the BCB passivation indeed provides the similar passivation function versus the SiN_x passivation, the low-frequency noise measurement was applied, where this evaluation scheme is sensitive to the semiconductor surface.

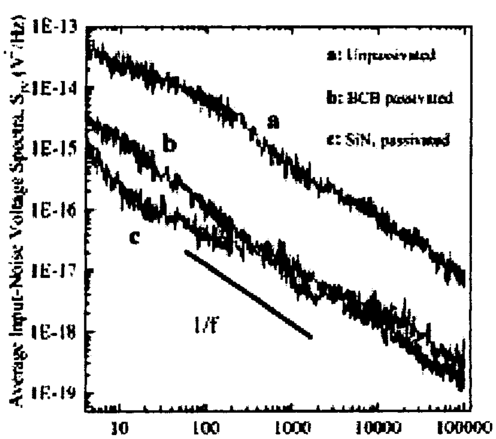


Fig.2 The low-frequency noise spectra of unpassivated, BCB passivated and SiN_x passivated AlGaAs surface at room temperature.

As shown in Fig. 2, the BCB passivated devices perform a similar 1/f noise spectra with the SiN_x passivated one, which demonstrate a much lower noise floor than the unpassivated one. It reveals the improvement of surface effect after the BCB passivation.

As to the device reliability testing, the hot electron stress was conducted under a high drain-to-source voltage (V_{ds}= 5V) and a strong reverse gate bias (V_g= -3V) for 2 hours. Fig. 3 shows the characteristics of the Schottky gate performance for both devices before and after the electrical stress, respectively. The diode performance of the BCB-bridged power device maintains a similar performance regardless the stress. Furthermore, air-bridged ones exhibit a 28 % drain-to-source current degradation after stress, and this degradation is only 7% for the BCB passivated devices. This current degradation is primarily associated with the oxidation of the AlGaAs surface near the recessed gate edges, where the electric field is the highest. Therefore, the BCB-bridged power transistor is more reliable for a long-term operation [4-5].

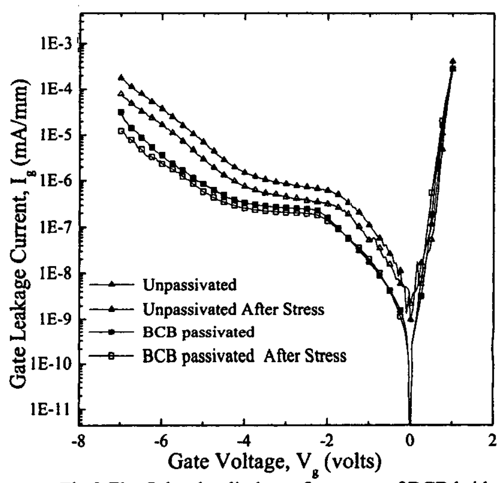
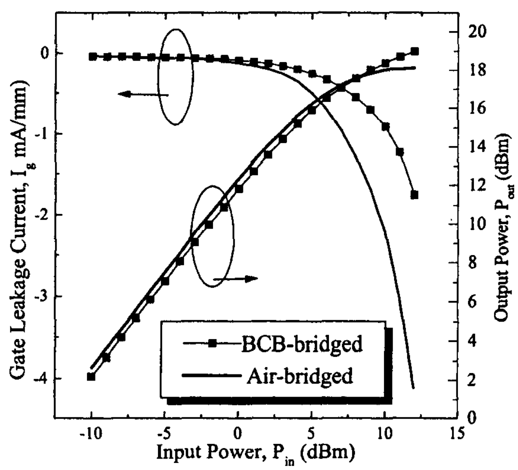


Fig.3 The Schottky diode performance of BCB bridged and air bridged power device before and after stress.

Microwave on-wafer S-parameters for 1μm × 1mm devices were measured by an HP-8510 network analyzer. Based on the S-parameter measured results, we obtain a maximum current gain cut-off frequency (f_T) of 9.6 GHz, and a maximum oscillation frequency (f_{max}) of 20 GHz for BCB-bridged device, and these values are 10 GHz and 21 GHz for the air-bridged ones. By extracting the equivalent circuit model for both devices, BCB-bridged devices exhibit a slight increase of feedback capacitance (C_{gd}), from 0.078 pF/mm to 0.081 pF/mm, as compared with the air-bridged ones. The rest elements in equivalent circuit model for both devices are similar. Therefore, we can conclude that the enhanced parasitics are limited after the BCB passivation, which will indeed benefit to the device operation for high frequency applications.

The microwave power measurements were performed by a load-pull Maury system with automatic tuners to measure the optimum load impedance for maximum output power. Microwave load-pull power performance was carried out at 2.4 GHz with a drain bias of 3.0V for both devices. The Γ_{Load} was $0.67\angle 147^{\circ}$ for BCB-bridged device, and this value was $0.68\angle 143^{\circ}$ for air-bridged one. The Γ_{Source} was $0.68\angle 138^{\circ}$ for BCB-bridged device, and this value was $0.69\angle 135^{\circ}$ for air-bridged one. Based on these results, the device matching condition for maximum P_{out} turns out to be very similar for the two different bridged processes.



Fgi.4 Gate leakage current and PAE versus input power of BCB bridged and air-bridged devices for 1 μm × 1mm device

Fig.4 shows the gate leakage current versus input power for a gate dimension of 1.0μm ×1mm devices. The BCB-bridged device performs a lower gate leakage current than that in air-bridged one versus input power levels, and both leakage currents increase by increasing the input RF powers. As to the results shown in Fig. 5, the air-bridged device achieves a higher power gain than the BCB-bridged device under low input power operation owing to a higher dc performance; however, the air-bridged device exhibits a higher power gain degradation ratio (0.65 dB/dBm) than that in BCB-bridged device (0.51 dB/dBm), resulting in a better device linearity for BCB-bridged devices. This phenomenon is attributed to the fact that the lower leakage current in BCB-bridged device results in a better device linearity and therefore a lower output power degradation. The maximum PAE is 36 % for BCB-bridged device and this value is 28 % for air-bridged one at an input power of 10 dBm and 9 dBm, respectively. Therefore, the microwave power performance is improved by the BCB-bridged process, and the power gain degradation is also suppressed in the high input power regime.

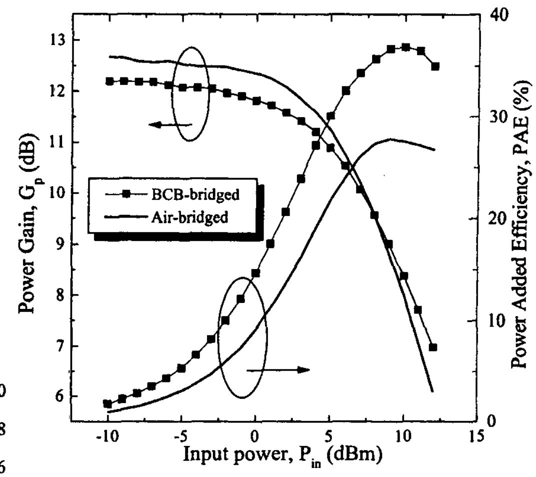
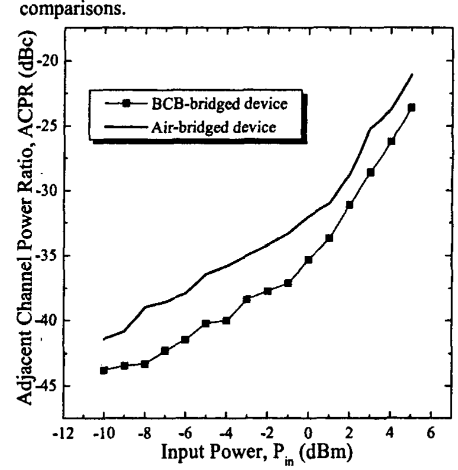


Fig.5 Power performance comparison of both devices

The reduction of the gate leakage in BCB-bridged device provides a significant improvement in device linearity. The adjacent power product from device output spectra, an important index of device linearity [6], can also be expected the improvement in BCB-bridged devices. As shown in Fig.6, BCB-bridged devices lead to a lower adjacent channel power ratio under the π/4 DQPSK modulation scheme at 2.4 GHz. The ACPR can be as low as –36 dBc for BCB-bridged devices, where air-bridged device can only reach –32 dBc under an input power of 0 dBm. Finally table I summarizes the measured dc and rf results obtained from both devices for comparisons.



Fgi.6 Adjacent channel power ratio (ACPR) versus input power of both devices under the π/4 DQPSK modulation scheme at 2.4 GHz.

Table. I		
The parameters comparisons of BCB-bridged and air-bridged power transistor		
FET Parameters	**BCB-bridged**	**Air-bridged**
I_{dss} (mA/mm)	**270**	**280**
I_{dss} after stress	**250**	**200**
g_m (mS/mm)	**228**	**230**
C_{gd} (pF)	**0.081**	**0.078**
f_T (GHz)	**9.6**	**10**
f_{max} (GHz)	**20**	**21**
P_{out} max.(dBm)	**18.4**	**18**
PAE	**36**	**28**
ACPR(dBc) Under P_{in} =0dBm	**-36**	**-32**
Gain Degradation Ratio (dB/dBm)	**-0.51**	**-0.65**

Table.I Summaries of device dc and microwave characteristics of both devices

IV. CONCLUSION

In summary, BCB-bridged power AlGaAs/InGaAs HFETs with a better reliability, microwave power performance, and device linearity have been demonstrated, as compared with the conventional air-bridged ones. This novel process with a low-k passivation and bridged technology provides a great potential for future power transistor fabrication.

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