# BCB-bridged Ka-band MMICs using $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As$ metamorphic HEMTs

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**Keywords: BCB, Metamorphic HEMTs, Ka-band amplifier, Distributed switch.**

ABSTRACT

**The InAlAs/InGaAs metamorphic HEMT (mHEMT) two-stage Ka-band amplifier and DC-30 GHz distributed SPST switch were designed and fabricated using low-k benzocyclobutene (BCB) bridged technology. This fabrication technology takes the advantages of its low dielectric permittivity (2.7), low loss tangent (0.008), low curing temperature, low water up-take, and simple manufacturing process.**

**The MMIC fabrication process involves wet etching for isolation, alloyed ohmic contacts, NiCr resistor, $Si_3N_4$ metal–insulator–metal (MIM) capacitors, and the BCB via holes and bridges. The two-stage Ka-band amplifier can achieve a linear gain of 14 dB, and an input return loss of 15 dB at 34 GHz. The DC-30 GHz distributed SPST switch exhibits an insertion loss less than 5 dB and an isolation larger than 30 dB. As to the switch power performance, this switch can operate up to 12 dBm at 2.4 GHz without significant signal distortion. To further investigate the robustness of the DC-30GHz distributed SPST distributed switch, the reliability test of the insertion loss and isolation were carried out. After 250 hrs of 85–85 (temperature= 85$^o$C, humidity= 85%) environmental evaluation, this BCB passivated and bridged MMIC switch demonstrates reliable RF characteristics without any performance change, which proves that this process using the low-k BCB layer is attractive for millimeter wave circuit applications.**

## I. INTRODUCTION

$In_xAl_{1-x}As/In_xGa_{1-x}As$ metamorphic HEMTs (mHEMTs) on GaAs substrates have provided very promising advantages over the similar structures grown on InP substrates [1-3]. The high indium content channel layers, such as x = 50%, can improve device performance, resulting in high carrier mobility and saturation velocity; hence it is a promising device in the millimeter wave device and circuit operation.

In this paper, we developed the 0.25-µm T-gate $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As$ mHEMTs on GaAs substrates using the low-k benzocyclobutene (BCB) as a passivation and bridged layer. This fabrication technology takes the advantages of its low dielectric permittivity (2.7), low loss tangent (0.008), low water up-take, and simple manufacturing process, which is beneficial to reduce the parasitic capacitances and to enhance the device reliability.

In addition to the sub-micron mHEMT fabrication, after evaluating the device performance, we used the mHEMT to fabricate two-stage Ka-band amplifier and DC-30GHz distributed single-pole-single through (SPST) switch with the BCB technology.

## II. DEVICE CROSS SECTION AND CHARACTERISITCS

The $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As$ mHEMT structures, as shown in Fig. 1, were grown by the MBE on semi-insulting GaAs substrates. The grown wafers consist of an 1-µm thick composition graded $In_xAl_{1-x}As$ buffer layer with an indium content changing from x = 0% to 50%, followed by a 300 nm thick $In_{0.5}Al_{0.5}As$ buffer layer, a 15 nm $In_{0.5}Ga_{0.5}As$ channel layer, a 5 nm $In_{0.5}Al_{0.5}As$ spacer layer, a Si delta doped layer, a 15 nm $In_{0.5}Al_{0.5}As$ Schottky layer, and a 15 nm $In_{0.5}Ga_{0.5}As$ doped-cap layer. TEM cross-section photograph demonstrates that the dislocations are all confined in the graded InAlAs buffer layer, and the device active layers are basically defect-free. The Hall mobility and sheet charge density at room temperature are 9500 $cm^2/V$-sec and 3.35 x $10^{12}$ $cm^{-2,}$ respectively. The device fabrication was realized by the use of conventional lithography and lift-off techniques. A $H_3P0_4/H_20_2/H_20$ (1:1:40) solution was used for the mesa etching. Ohmic contacts were formed by electron beam evaporating Ni/Ge/Au metallization, followed by a 290$^o$C, 2 min hot plate annealing. TLM measurements show a typical ohmic contact resistivity of 0.2 Ω-mm. T-shaped gates with gate-lengths of 0.25-µm, locating in the center of the drain-to-source spacing (3-µm), were defined by using a bi-layer P(MMA-MAA)(11%)/PMMA(5%) resist process and an electron beam lithography system (Raith 150-model). As to the gate-recessed process, the selective gate recess etching was performed using a mixing solution of succinic acid and hydrogen peroxide [4]. The gate metals, Ti/Pt/Au (20 nm/ 20 nm/ 350 nm), were deposited, followed by a 1.5 µm-thick low-k BCB passivation and bridged layer, which was defined by photolithography and a curing temperature of 200$^o$C for 30 min to obtain an uniformed dielectric constant [5]. Finally a 1-µm-thick Ti/Au metal layer was used for the interconnection level.

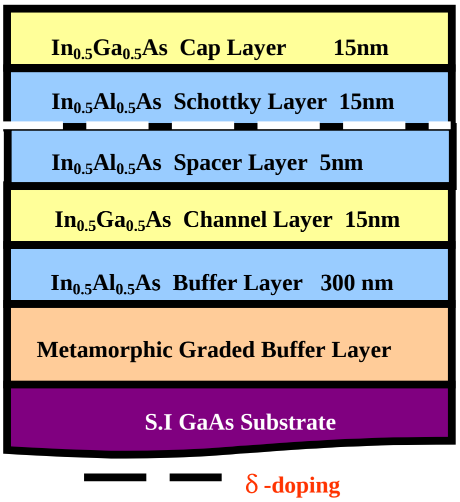


Fig. 1 The device cross-section of the $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As$ metamorphic HEMTs

As to the mHEMT dc performance, the maximum drain-to-source current ($I_{ds}$) and transconductance ($g_m$) are 630 mA/mm, 580 mS/mm, respectively. In order to obtain a high uniformity and a high yield of 0.25-µm InAlAs/InGaAs mHEMTs, the high selective succinic acid solution was adopted for the gate recess etching. As shown in Fig. 2, the devices achieve an average threshold voltage ($V_{th}$) of -0.9 V with a standard deviation of 79 mV. As to rf characteristics, the current gain cut-off frequencies ($f_T$) and maximum oscillation frequency ($f_{max}$) are 80 and 120 GHz, respectively.

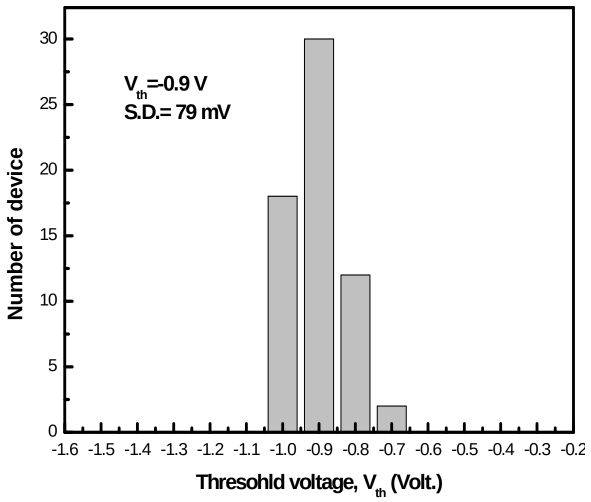


Fig. 2 The histogram of $V_{th}$ for0.25-µm gate-length $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As$ metamorphic HEMTs using succinic acid in the gate-recess fabrication.

III. TWO-STAGE KA-BAND AMPLIFIER

The MMIC fabrication process involves wet etching for isolation, alloyed ohmic contacts, NiCr resistor, $Si_3N_4$ metal–insulator–metal (MIM) capacitors, and the BCB via holes and bridges as shown in Fig. 3. In addition, we adopted the coplanar waveguide (CPW) transmission line configuration for MMIC application, which allows uniplanar design without complex process and expensive facilities.

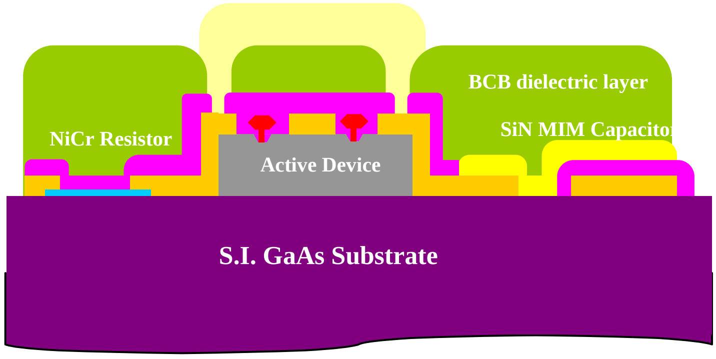


Fig. 3 The cross section of BCB-bridged MMIC process including active device, NiCr resistances, SiN capacitors.

Fig. 4 shows the schematic diagram and photography of the two-stage Ka-band gain amplifier with coplanar waveguide (CPW) design by using 0.25-µm gate-length, two-fingers, 50-µm wide mHEMTs (D1, D2), where the chip size is 2.4 mm x 1.2 mm. The total dc power consumption of two-stage gain amplifier is 120 mW with bias conduction of $V_{ds}$=2V, and $I_{ds}$ = 30 mA ($V_{gs}$=-0.3V) for each stage.

The simulated and measured results of amplifier are shown in Fig. 5. The input and output return loss is –16 dB and –5 dB at 34 GHz, corresponding to the small signal gain is 14dB.

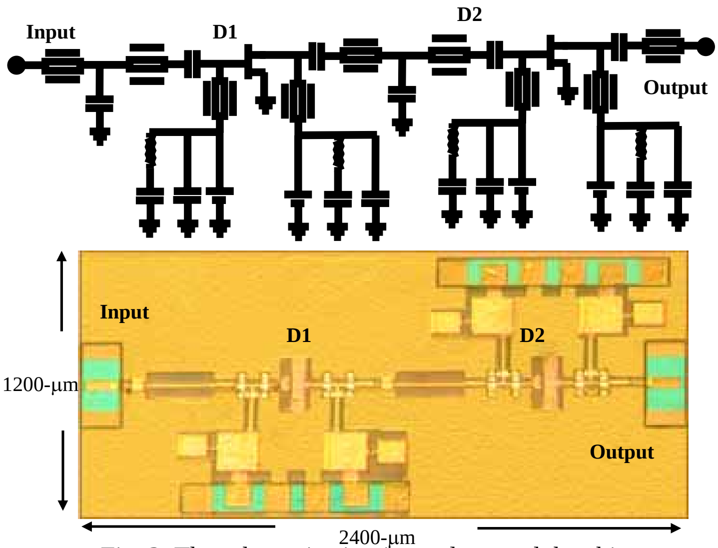


Fig. 3 The schematic circuit topology and the chip photograph for monolithic Ka-band gain amplifier

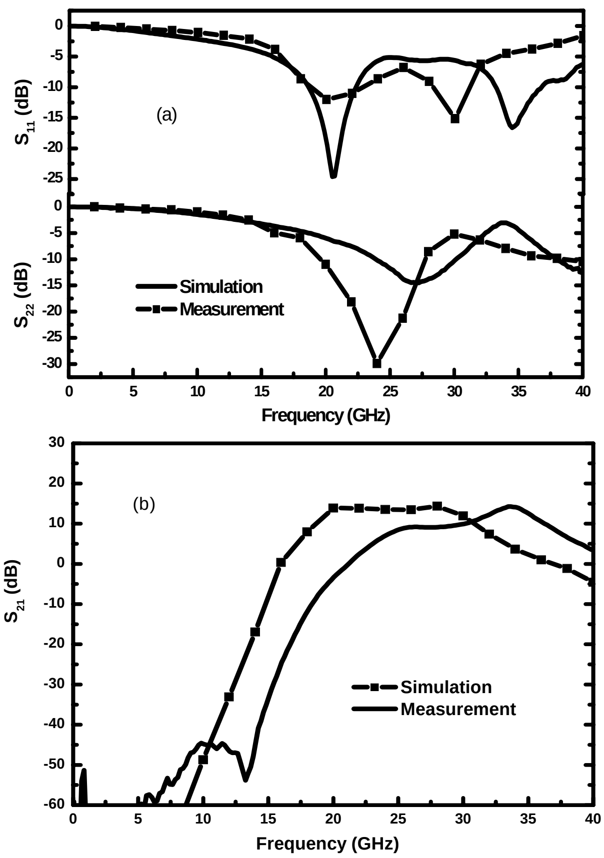


Fig. 4 The simulated and measured results of S11and $S_{22}$ (a), and small signal gain, $S_{21}$ (b).

## IV. DC-30 GHz Distributed Switch

As to the millimeter wave communication system, transmitter/receiver (T/R) switch is an important component to control the RF signal flow. In order to increase the bandwidth of the switch, a distributed circuit topology, which combines a high impedance line and a shunt discrete FET to form an artificial 50-ohm transmission lines, has been developed [6-9]. In this paper, the wideband SPST switch was designed and fabricated by using the 0.25-μm T-gate, two-fingers, 50-μm wide $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As$ mHEMTs. Fig. 6 shows the completed circuit schematic and photography of the distributed coplanar waveguide (CPW) SPST switch, where the chip size is 1.8 mm x 0.85 mm.

The small-signal performance of this distributed switch was on wafer measured by using the network analyzer from 50 MHz to 40 GHz. The distributed SPST switch demonstrates an insertion loss less than 5.5 dB and isolation larger than 30 dB from 50 MHz to 30 GHz. Table 1 summarizes the reported characteristics of the distributed switches at high frequencies. By adding a series mHEMT, the distributed switch of this work shows the excellent isolation performance; however, it slightly pays for a higher insertion loss.

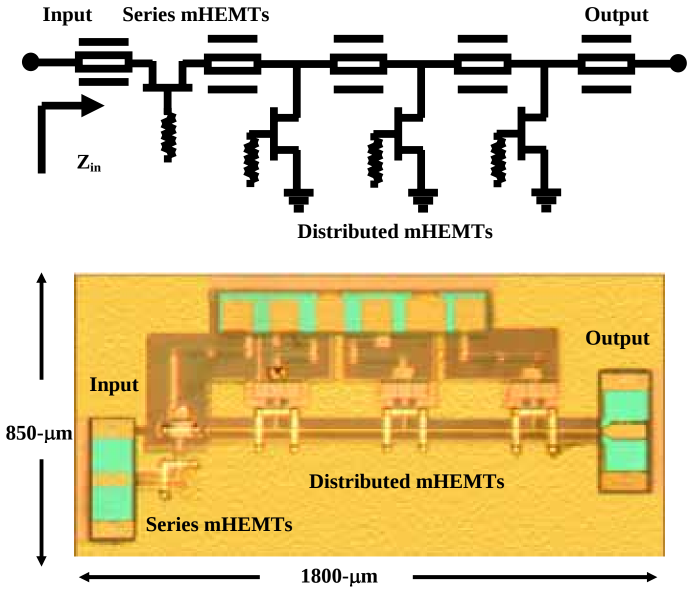


Fig. 5 The schematic circuit topology and the chip photograph for monolithic distributed SPST switch using 0.25-μm T-gate In0.5Al0.5As/In0.5Ga0.5As mHEMTs.

To further investigate the robustness of the dc-30GHz distributed SPST switch, the lifetime testing was carried out, and the results are shown in Fig. 6. After over 250 hrs of 85–85 (temperature= 85°C, humidity= 85%) environmental evaluation, the BCB passivated and bridged switches demonstrate very repeatable rf characteristics without any performance change.

As to the switch power performance, the input P1dB at 2.4 GHz is 12 dBm without a significant signal distortion. To ensure a stable performance of this distributed dc-30 GHz MMIC switch after a long-term operation can be achieved, the switch was subject to a high temperature testing, which can also confirm the reliability of BCB interlayer.

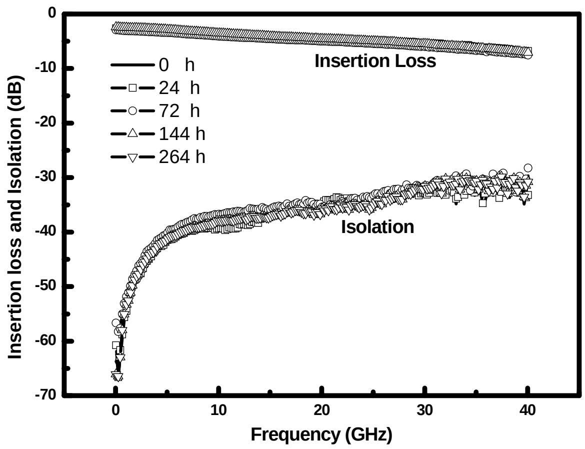


Fig. 6 The insertion loss and isolation of SPST switch measured under an 85-85 environment for 264 hrs.

Temperature dependent microwave power measurements were performed at 2.4 GHz, and the results are shown in Fig.7. After raising the temperature up to 85 oC, the BCB passivated switch reveals almost the same performance without any significant performance change, which demonstrates that thermally stable characteristics of BCB passivated MMIC can be achieved.

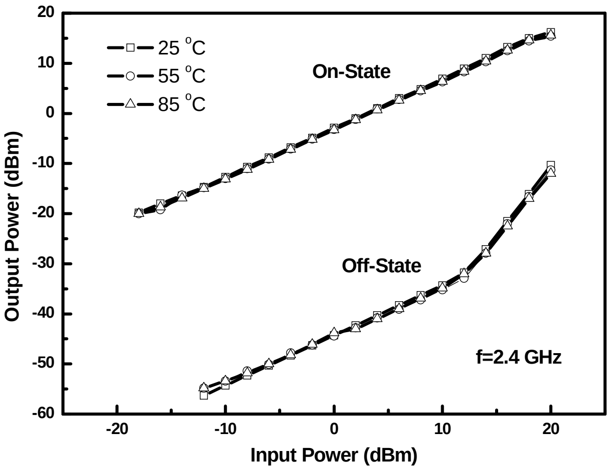


Fig. 7 Measured the on and off states output power versus input power characteristics at 2.4 GHz of SPST switch from 25 °C to 85 °C.

## V. CONCLUSIONS

In summary, the submicron gate-length $In_{0.5}Al_{0.5}As$/ $In_{0.5}Ga_{0.5}As$ mHEMTs have been fabricated and characterized. The low-k BCB dielectric material for mHEMT MMIC fabrication has been sucessful achieved. Reliable and thermally stable performance of mHEMTs distributed switch by using a low-k BCB as a passivation and a bridged layer has also been demonstrated. Based on temperature dependent microwave power measurements, and the 85-85 lifetime evaluations, this simplified process technique provides a great potential for future millimeter wave circuit fabrication.


## ACKNOWLEDGEMENTS

The authors are grateful to the financial support from the Ministry of Education under the Program for Promoting Academic Excellence of Universities. (Grant number 91-E-FA06-1-4) and the Ministry of Economic under the Program for Industrial Technology Development (91-EC-2-A-17-0285-029).


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## ACRONYMS

mHEMT: Metamorphic High Electron Mobility Transistor
SPST: Single Port Single Throw
BCB: Benzocyclobutene
MIM: Metal-Insulator-Metal
MMIC: Monolithic Microwave Integrated Circuit
PMMA: Polymethylmethacrylat
CPW: Coplanar Wave Guide