110-GHz High-gain Flip-chip InP HEMT Amplifier with Resin Encapsulation on an Organic Substrate

Satoshi Masuda[1], Hidehiko Kira[2], and Tatsuya Hirose[1]

[1] FUJITSU LABORATORIES LTD.
10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan
[2] FUJITSU LTD.
4-1-1 KAMIKODANAKA, NAKAHARA, KAWASAKI 211-8588, JAPAN
Phone: +81-46-250-8244, Fax: +81-46-250-4337, Email: masuda@flab.fujitsu.co.jp

Abstract — **A high-gain amplifier monolithic microwave integrated circuit (MMIC) was developed using InP HEMT technology with inverted microstrip lines. The six-stage amplifier demonstrated a gain of 30 dB at 110 GHz. We also fabricated a resin-sealed flip-chip MMIC on a highly isolated cost-effective glass-epoxy substrate, achieving a gain of 28 dB at 110 GHz. To the best of our knowledge, this is the highest gain in the W-band for a flip-chip MMIC sealed with resin.**

I. INTRODUCTION

The emergence of millimeter-wave applications such as broadband wireless communication systems and 76-GHz automotive sensors is set to drive growth in MMIC and packaging technology. However, the RF modules developed for this new technology must meet stringent requirements for both low cost and high-performance. Flip-chip bonding (FCB) has potential for improving the performance of assembled MMICs because the connection between the chip and package substrate is much shorter than is possible with wire bonding, thus decreasing connection inductance. Several adequately performing FCB MMICs have been reported [1-2]. However, these MMICs are hermetically sealed in metal wall or ceramic packages that require a complicated packaging process. These materials are also expensive. Sealing FCB MMICs with resin is the best solution for simplifying the assembly process and reducing costs. Unfortunately, when resin is used to seal a conventional coplanar waveguide (CPW) MMIC, the underfill between the chip and assembly substrate has a significant influence on the MMIC electrical characteristics because it increases the parasitic capacitance of the transistors and transmission lines on the MMICs due to the higher dielectric constant of the underfill compared to that of air, as shown in Figures 1 and 2. This complicates not only the design of the FCB MMIC, but also KGD (known good die) by RF-on-wafer measurement before the FCB process. In addition, parasitic substrate modes, for instance, a parallel-plate (PPL) mode, in the motherboard greatly reduce the port isolation of the FCB MMIC and induce undesired feedback oscillation, especially for high-gain blocks. To address these challenges, we developed a high-gain amplifier MMIC based on multi-layer transmission lines using practical design techniques and cost-effective organic substrates. The fabricated FCB amplifier achieved a record gain at 110 GHz, demonstrating its potential to provide cost-effective MMIC modules in the W-band.

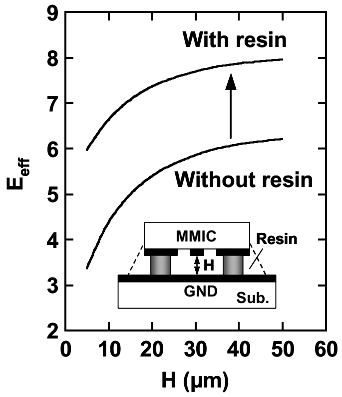


Fig. 1. Comparison of simulated effective dielectric constant (E_{eff}) of FCB CPW with and without underfill.

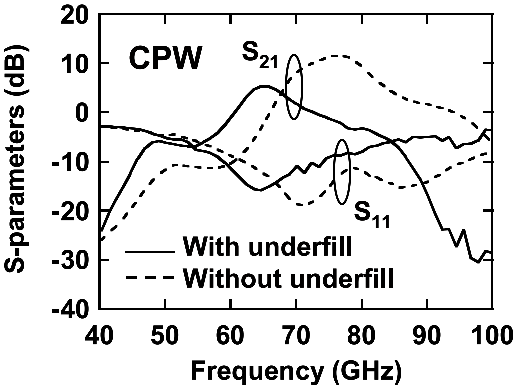


Fig. 2. Comparison of fabricated conventional FCB CPW MMICs with and without underfill.

II. W-BAND MULTILAYER AMPLIFIER DESIGN

Our FCB MMIC consists of a multi-layer MMIC with a layer of ground metal on the surface of the chip to shield the MMIC from the underfill and prevent changes in the electrical performance after FCB. The MMIC has four metal interconnect layers and four layers of benzocyclobutene (BCB) film. We designed the MMIC using inverted microstrip lines (IMSLs) [3] formed with the first layer and the top ground layer, as indicated by the rectangle outlined by dashed lines in Fig. 3. Electroplated pillars were formed on the MMIC to connect the chip to the substrate. The MMIC was

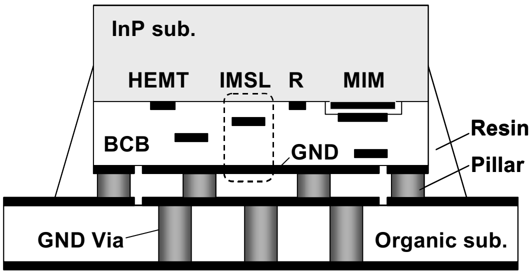


Fig. 3. Schematic cross-sectional view of FCB MMIC with encapsulating resin.

assembled on a glass-epoxy substrate and encapsulated in nonconductive adhesive, ensuring mechanical strength and reliability. Figure 4 outlines the NCP FCB process. We first applied an adhesive to the package substrate, and then mounted our MMIC using heat and pressure. This FCB method enables the use of cost-effective organic substrates rather than ceramic ones because it requires a lower assembly temperature (250°C) than that required for thermocompression FCB [4].

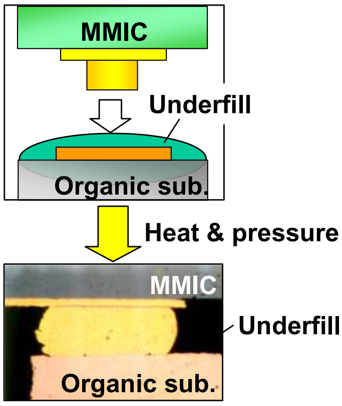


Fig. 4. NCP FCB process for MMIC assembly on organic substrate.

When designing the W-band high-gain amplifiers, we focused on isolating the transmission lines on the MMIC because cross talk causes feedback oscillation in MMICs especially at high frequencies, due to the short wave length. We calculated the isolation of the coupled IMSLs using an electromagnetic simulator, as shown in Fig. 5. A large line space improves isolation while higher frequencies reduce it. It is possible to achieve 30-dB isolation of coupled lines at 100 GHz with a line space of 40 μm, and we applied this design rule to the W-band amplifiers. An IMSL is much more effective in reducing circuit size than a CPW, which has ground planes on both sides of the signal line.

III. FABRICATED W-BAND AMPLIFIERS

We fabricated high-gain amplifiers with 0.13-μm InAlAs/InGaAs/InP HEMT technology (f_T=160 GHz, f_{max}=300 GHz) [5], as shown in Fig. 6. The chip is covered with a layer of ground metal except for the electrodes for the RF and the DC pads. A circuit without the top ground layer is also shown in Fig. 6. We designed 77-GHz and 110-GHz amplifiers to assess the design accuracy with IMSL. Both amplifiers have six stages with 2 x 20-μm InP HEMT. The matching circuits were designed with high-low impedance IMSLs. We used shunt RC networks in the bias circuits to ensure the unconditional stability of the circuits. The circuit size of the 77-GHz amplifier is only 1.8 x 0.5, which is half that of conventional CPW amplifiers. The measured S-parameters are shown in Fig. 7. The RF performance

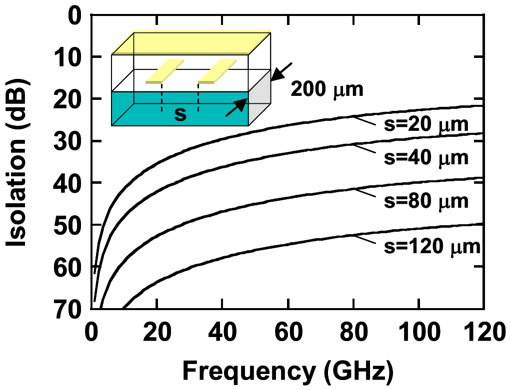


Fig. 5 Calculated isolation of coupled IMSL in MMIC.

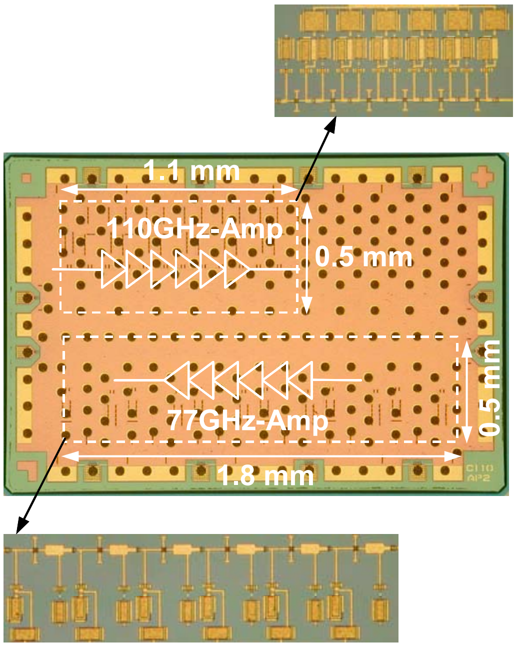


Fig. 6. Photomicrograph of fabricated W-band amplifiers (also shown without top ground layer).

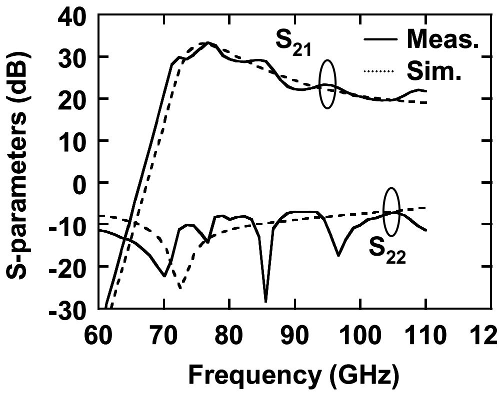


Fig. 7. Comparison between measured and simulated S-parameters of 77-GHz amplifier.

from 0.25 to 110 GHz was measured using an HP8510XF vector network analyzer (VNA). The test set was connected to coplanar wafer probes (GGB Industries) via a 1.0-mm connector. The dc bias was set at Vgs=-0.1 V, Vds=1 V, and Ids=55 mA. The fabricated amplifier achieved a gain of 33 dB at 77 GHz and over 29 dB from 70 to 110 GHz. The output return loss was better than 10 dB from 60 to 85 GHz. The simulation results, which are also plotted in Fig.7 agreed well with the measured data. We fabricated another amplifier with a higher operating frequency of 110 GHz. Its circuit size is only 1.1 x 0.5 mm, as shown in Fig. 6. The measured S-parameters of the 110-GHz amplifier are shown in Fig. 8. The dc bias was set at Vgs=0 V, Vds=1 V, and Ids=77 mA. The fabricated amplifier achieved a gain of 30 dB at 110 GHz. The output return loss was better than 10 dB from 104 to 110 GHz. These results indicate that our design using IMSL, which ensures isolation of the coupled lines, is a practical method of producing high-gain amplifiers in the W-band.

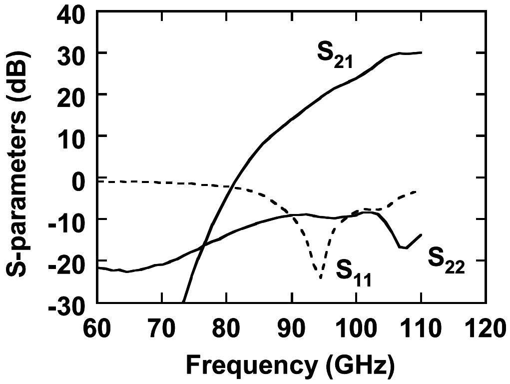


Fig. 8. Measured S-parameters of 110-GHz amplifier.

VI. FLIP-CHIP MMIC SEALED WITH RESIN

A. Organic Substrate Design

We also fabricated a resin-sealed FCB MMIC on a 125-µm-thick glass-epoxy substrate, as shown in Fig. 9. The pillars were arrayed on the surface of the MMIC to suppress the PPL mode that propagates between the chip and substrate. The substrate was designed with a finite grounded CPW (FGCPW) because this layer prevents excitation of the PPL mode. In addition, via-holes underneath the chip were used to prevent a parasitic substrate mode from propagating and coupling to the desired CPW mode at any discontinuity, for instance, pillar interconnections and feed lines. To verify the effectiveness of this strategy, we measured the feed lines on the substrate with and without via-holes underneath the chip before FCB. Figure 10 shows the measured S-parameters for the feed lines. The S-parameters for “without via-holes” exhibited resonance at frequencies of 58, 80, and 108 GHz. This was due to the parasitic substrate mode, which caused instability in the circuit. In contrast, the S-parameters for “with via-holes” showed no resonance. The via-holes thus proved effective in reducing the excitation of parasitic substrate mode up to the W-band.

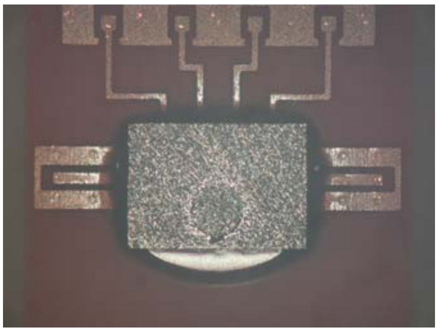


Fig. 9. Microphotograph of FCB amplifier sealed with resin on an FGCPW glass epoxy substrate.

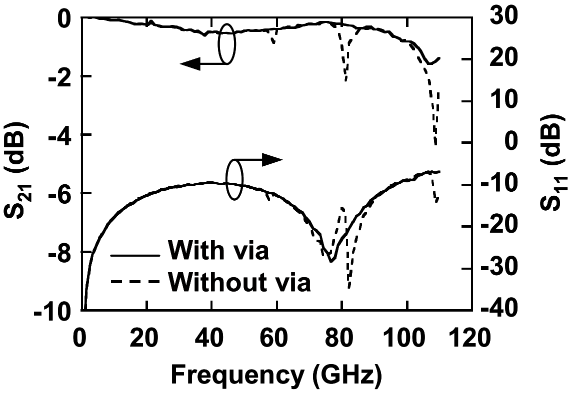
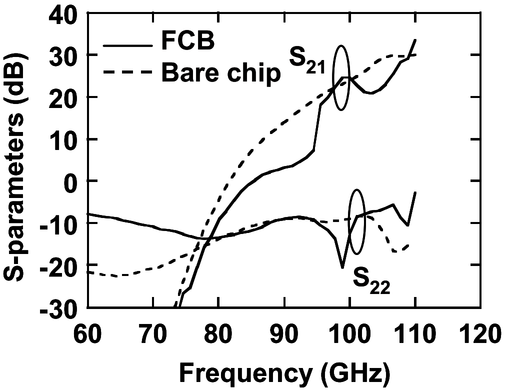


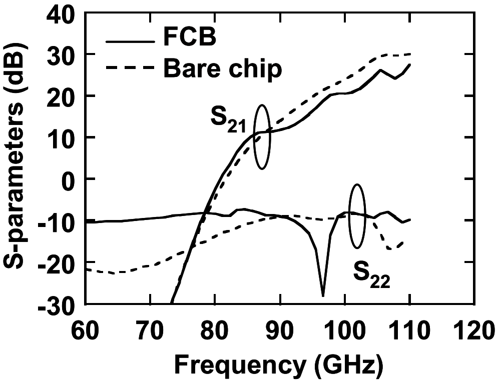
Fig. 10. Measured S-parameters of feed lines with and without via holes on organic substrate.

B. Fabricated Flip-chip MMICs

We mounted our MMICs on organic substrates with and without via-holes underneath the chip to check whether resonance had a significant influence on the performance of the FCB MMIC. Figure 11 shows the S-parameters for FCB MMICs on substrates with and without via-holes underneath the chip. The bias condition was the same as that used to measure the bare chip. The FCB MMIC without via-holes underneath the chip exhibited a small and fluctuating gain profile from 70 to 110 GHz, as shown in Fig. 11 (a). This indicated the circuit was unstable due to the parasitic substrate mode. In contrast, the FCB MMIC with via-holes underneath the chip achieved a gain of 28 dB at 110 GHz with unconditionally stability at all frequencies. In addition, the gain profile was almost the same as that of the bare chip (indicated by dotted lines). This was because the MMIC has a layer of ground metal on the surface of the chip that screens the resin as well as via-holes underneath the chip. The small difference between the measurements shown in Fig. 11 (b) can be assessed by totaling the feed-line loss for all the RF ports in Fig. 10. To check this, we modeled a FCB MMIC with measured MMIC and transmission lines on the substrate. The model included a parasitic shunt capacitance (C_b) for the bump interface, as shown in Fig. 12 (a). Figure 12 (b) shows a comparison of the measured and simulated S-parameters for the 110-GHz FCB amplifier, which agreed well. Therefore, the difference between the bare chip and the FCB MMIC was mainly due to the characteristics of the transmission lines on the substrate. Figure 13 shows the



(a) Without via-holes on organic substrate



(b) With via-holes on organic substrate

Fig. 11. Comparison of measured S-parameters of 110-GHz FCB amplifier and bare chip.

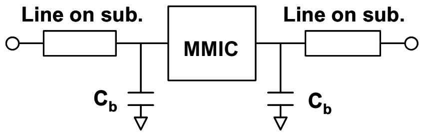


Fig. 12(a) Simulation model of FCB MMIC on organic substrate.

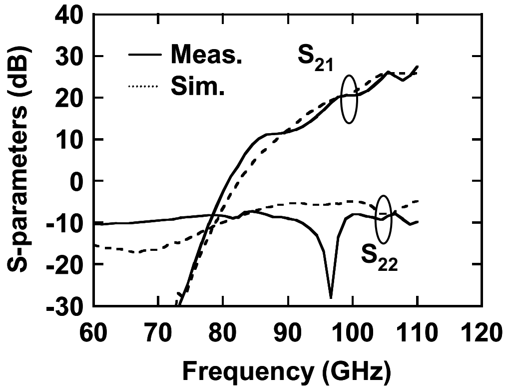


Fig. 12(b) Comparison of measured and simulated S-parameters of 110-GHz FCB amplifier.

performance of our resin-sealed flip-chip MMIC, which is the best-performing example reported to date. Our FCB amplifier has the highest gain at this frequency of any resin-sealed FCB MMIC.

V. CONCLUSION

Glass-epoxy based MMIC packages up to 110 GHz were developed. Fabricated 77-GHz and 110-GHz amplifiers with a multi-layer transmission line structure achieved gains of 33 dB and 30 dB, respectively. In addition, a 110-GHz amplifier, which was sealed on a cost-effective organic substrate with resin, performed extremely well, producing a 28-dB gain at 110 GHz. Our technology thus has excellent potential for producing cost-effective MMIC modules for future millimeter-wave applications.

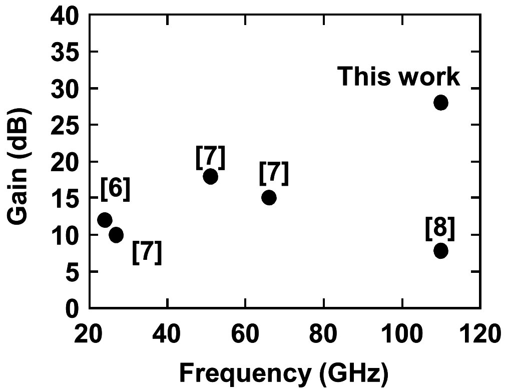


Fig. 13. State-of-the-art FCB amplifier sealed with resin.

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