RF PERFORMANCE OF A 77 GHz MONOLITHIC CPW AMPLIFIER WITH FLIP-CHIP INTERCONNECTIONS

K. Maruhashi, M. Ito, H. Kusamitsu*, Y. Morishita* and K. Ohata

Kansai Electronics Research Laboratories, NEC Corporation,
2-9-1, Seiran, Otsu, Shiga 520-0833, Japan

*Production Material Engineering Laboratory, NEC Corporation

Abstract

This paper describes an rf performance of a 77 GHz coplanar waveguide (CPW) monolithic three-stage amplifier connected with an alumina substrate using flip-chip technology. Key issues discussed here cover the substrate, MMIC and bonding structures to realize a good amplifier operation at this frequency. The flip-chip mounted GaAs monolithic amplifier exhibited a gain higher than 15 dB at around 77 GHz.

Introduction

Millimeter-wave packaging technologies for low-cost rf subsystems have rapidly progressed. As a part of these technologies, flip-chip bonding is promising because well-controlled, minimum length connections are possible between chips and substrates for inter-connections with high manufacturing throughput. Applying it to millimeter-wave circuits, the effect of the substrate faced to the MMIC chip, signal propagation characteristics and reliability should be carefully investigated. Recent reports utilizing flip-chip bonding include MIC's assembled with HEMT and HBT chips operating up to 60 GHz [1][2], and a planar patch antenna with a 51 GHz LNA MMIC chip [3]. At higher frequencies, theoretical and experimental investigations were carried out for GaAs coplanar waveguide (CPW) through lines mounted on substrates [4][5], and mixers with GaAs Schottky diodes [6][7].

In this paper, we demonstrate realization of a flip-chip mounted MMIC having gain (> 15 dB) at W-band. Some technological issues including the substrate, GaAs MMIC chip and bonging structures are described.

Substrate and MMIC

A. Substrate and CPW lines for Interconnections

A schematic cross-sectional view of an MMIC mounted on a substrate with flip-chip bonding is shown in Fig. 1. The alumna substrate was employed to carry the MMIC chip because its thermal expansion coefficient (6.3-6.7 ppm/°C) is close to that of GaAs (5.8 ppm/°C). A thin-film technique was used to pattern bonding pads and CPW lines for interconnections.

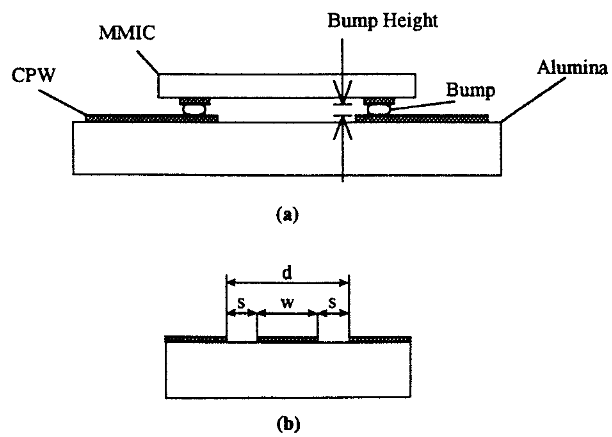

Fig. 1. Schematic cross-sectional view for (a) an MMIC mounted on an alumina substrate with flip-chip bonding and (b) coplanar waveguide on the alumina substrate.

The ground-to-ground distance of CPW, referred as d in this paper, is an important parameter for signal propagation and controllability of characteristic impedance. The measured insertion loss for 5 mm- long 50 Ω CPW with d = 150 μm and 250 μm is shown in Fig. 2. In both cases, ripples appeared but the degree was smaller for d = 150 μm than that for d = 250 μm. Using CPW with much smaller d is expected to reduce the ripple, however, requires severe patterning accuracy. In view of cost and yield for substrates, CPW with (d, width, spacing) = (150, 64, 43) μm is employed in this work. With ±3 μm line/space patterning accuracy, the variation of characteristic impedance is estimated to be ±2 Ω. The measured transmission loss was 0.30 dB/mm at 77 GHz.

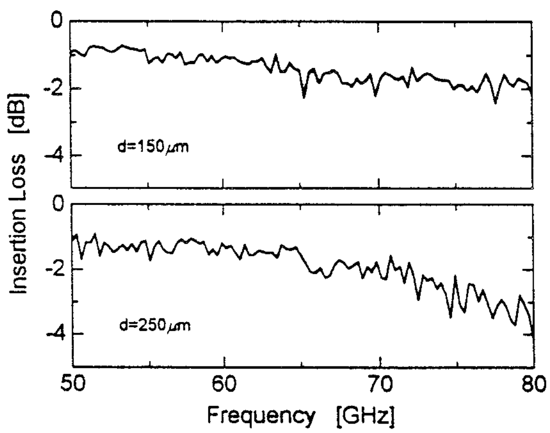

Fig. 2. Insertion loss for 5 mm - long 50 Ω coplanar waveguide on the alumina substrate with d = 150 μm (upward) and d = 250 μm (downward).

B. 77GHz Amplifier MMIC

The 77 GHz GaAs monolithic three-stage CPW low noise amplifier has been developed utilizing 0.15 μm gate heterojunction FET's for automotive radar applications. The chip photograph for the MMIC is shown in Fig. 3. A flat and high gain (~17 dB) across the frequency band was realized. The input and output return losses were better than 9 dB at 76 - 77 GHz.

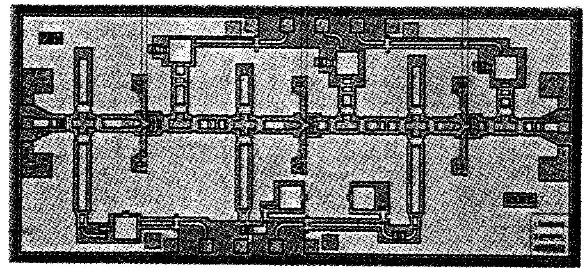

Fig. 3. Chip photograph for the 77 GHz CPW three-stage LNA (2.4 mm x 1.1 mm).

The MMIC chip was thinned to 150 μm and was left backside without metal. This structure does not suffer from surface wave leakage, which was pointed out by Krems *et al* [5]. The thickness was also chosen to sustain rigidity and to avoid breakage when flip-chip mounting. In addition, no backside metal enable to inspect bumps by infrared after flip-chip mounting.

Flip-Chip Bonding

The MMIC pad is connected to CPW on the substrate with gold ball bumps. The MMIC chip faces to the substrate, thus, the characteristic impedance of CPW on the GaAs chip is lower than that on the unflipped chip. The three-dimensional electromagnetic simulation based on the finite element method revealed that when the gap between the GaAs chip and substrate is greater than 20 μm, the characteristic impedance of a 50 Ω line changes by less than 1%.

In Fig. 4, an SEM photograph of the employed alumina substrate to carry the MMIC chip is shown with the gold ball bumps. The bonding temperature and pressure were 300 °C and 100 gram force per bump. The bonding time was 10 seconds. At this condition, a typical bump height was 15 μm after bonding. Adding pad thickness to this, the gap between the GaAs chip and substrate was controlled to be 20 μm. An average die shear strength was measured to be 57 gram force per bump. GaAs samples mounted on the substrates were

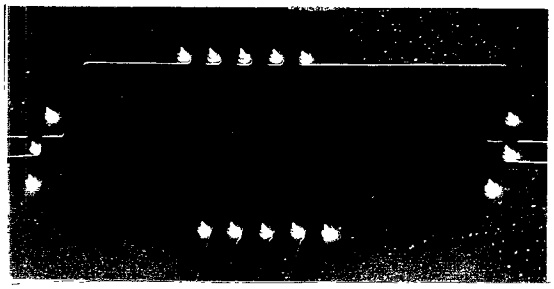

Fig. 4. SEM photograph for surface of the alumina substrate to carry the MMIC chip with gold ball bumps.

subjected to the thermal cycle test. No increasing resistance at bump interconnects has been observed over the 1000 cycle test from -55 to 125 °C.

RF Performance

A. Flip-Chip Mounted GaAs Through Line

The measured transmission characteristics for a flip-chip mounted GaAs CPW through line on the substrate are shown in Fig. 5. In this case, an insertion loss of 1.3 dB and a return loss of 14 dB were obtained at 77 GHz. The insertion loss included the loss in two sets of 1.1 mm - long CPW on alumina substrates for input and output interconnections.

The transmission loss in each bump interconnect, eliminating mismatch loss, was evaluated to be ~0.15 dB. Up to 80 GHz, the measured return loss was better than 12 dB. For more precise design, a technique to compensate discontinuity at interconnects will be needed to improve the return loss.

B. Flip-Chip Mounted 77 GHz Monolithic Amplifier

Small-signal characteristics of the three-stage amplifier MMIC were compared before and after flip-chip mounting as shown in Fig. 6. After flip-chip mounting, the gain was 15 dB or higher at around 77 GHz, and was reasonably reduced by ~1 dB. This gain reduction is comparable with loss in bumps and CPW

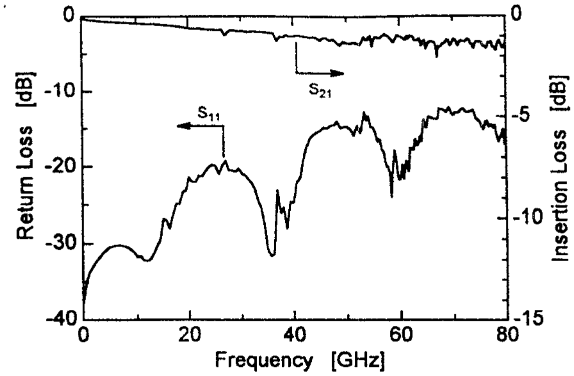

Fig. 5. Measured insertion and return loss of a flip-chip mounted GaAs CPW through line on the substrate.

on the alumina substrates. The isolation decreased by 15 dB at most, but remained greater than 25 dB while the gain was 15-19 dB.

The measured input and output return losses are depicted in Fig. 7. At frequencies from 76 to 77 GHz, the measured input and output return losses were better than 8 dB and 14 dB, respectively. The small-signal characteristics versus frequency appeared a little bit bumpy. It might result from wide d for CPW discussed previously. However, these results are sufficiently applicable to rf module design using low-cost substrates for interconnections.

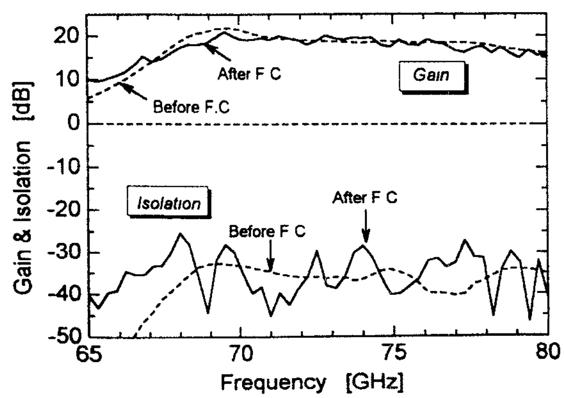

Fig. 6. Gain and isolation characteristics of the three-stage amplifier MMIC before and after flip-chip (F.C.) mounting.

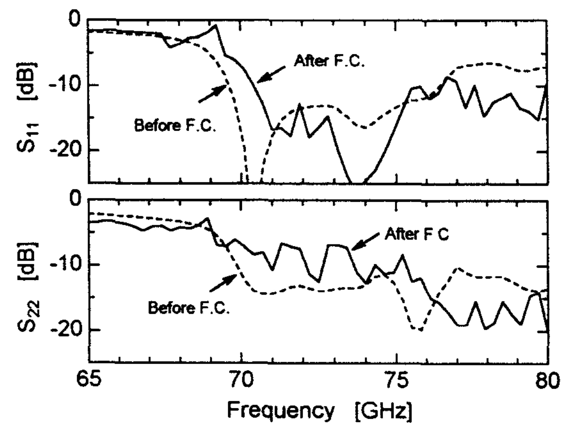

Fig. 7. Measured input and output return losses of the three-stage amplifier MMIC before and after flip-chip mounting.

Summary

An rf performance of a 77 GHz CPW monolithic amplifier connected with an alumina substrate using flip-chip technology was described. The substrate, MMIC and bonding structures were discussed to realize an amplifier operation at this frequency. The flip-chip mounted monolithic amplifier exhibited a gain higher than 15 dB at around 77 GHz. This result shows great potentiality for realization of low-cost millimeter-wave T/R modules with flip-chip technology.

Acknowledgments

The authors wish to thank L. Desclos and M. Madihian for their valuable technical discussions. Support from I. Morisaki, A. Dohya, T. Uji and M. Ogawa is appreciated.

References

[1] H. Sakai, Y. Ota, K. Inoue, T. Yoshida, K. Takahashi, S. Fujita and M. Sagawa, "A Novel Millimeter-Wave IC on Si Substrate Using Flip-Chip Bonding Technology", *in 1994 IEEE MTT-S Int. Microwave Symp. Dig.*, San Diego, CA, pp.1763-1766, June, 1994.

[2] Y. Arai, M. Sato, H. T. Yamada, T. Hamada, K. Nagai and H. I. Fujishiro, "60GHz Flip-Chip Assembled MIC Design Considering Chip-Substrate Effect," *in 1997 IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, pp.447-450, June, 1997.

[3] G. Baumann, H. Richter, A. Baumgärtner, D. Ferling, R. Heilig, D. Hollmann, H. Müller, H. Nechansky, M. Schlechtweg, "51 GHz Frontend with Flip Chip and Wire Bond Interconnections from GaAs MMICs to a Planar Patch Antenna," *in 1995 IEEE MTT-S Int. Microwave Symp. Dig.*, Orlando, FL, pp.1639-1642, May, 1995.

[4] S. Aoki, H. Someta, S. Yokokawa, K. Ono, T. Hirose and Y. Ohashi, "A Flip Chip Bonding Technology Using Gold Pillars for Millimeter-Wave Applications," *in 1997 IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, pp.731-734, June, 1997.

[5]T. Krems, W. H. Haydl, H. Massler, J. Rüdiger, "Advantage of Flip Chip Technology in Millimeter-Wave Package," *in 1997 IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, pp.987-990, June, 1997.

[6] S. Raman, F. Rucky and G. M. Rebeiz, " A High-Performance W-Band Uniplanar Subharmonic Mixer," *in IEEE Trans. Microwave Theory and Tech.*, vol. 45, No.6, pp.955-962, June, 1997.

[7] R. S. Virk, S. A Maas, M. G.Case, M. Matloubian, P. Lawyer, H. C. Sun, C. Ngo and D. B. Rensch, "A Low-Cost W-Band MIC Mixer Using Flip-Chip Technology," *in IEEE Microwave and Guided Wave Lett.*, Vol.7, No. 9, pp.294- 296, Sept, 1997.