60GHz FLIP-CHIP ASSEMBLED MIC DESIGN CONSIDERING CHIP-SUBSTRATE EFFECT

Y.Arai, M.Sato, H.T.Yamada, T.Hamada, K.Nagai and H.I.Fujishiro

**Semiconductor Technology Laboratory, Oki Electric Industry Co., Ltd.
550-5, Higashiasakawa, Hachioji, Tokyo 193, JAPAN**

Abstract

In this paper, 60GHz MICs with flip-chip assembled pseudomorphic-HEMT is demonstrated. With electromagnetic field analysis, assembly effect was estimated. An amplifier has gain of 13 dB and a 30 /60GHz frequency doubler has gain of -3dB. Measured and simulated results clarifies potentiality of the structure and design method.

Introduction

Much has been researched regarding flip-chip technology as promising structure for microwave and millimeter-wave MICs(1) and MMICs(2). Especially in millimeter-wave region, short interconnection of flip-chip method is attractive.

Advantages of MICs with flip-chip assembled discrete transistor lead to design flexibility, high yield and low cost. In spite of these merits, influence of electromagnetic interaction between the chip and the substrate(3), which alters device parameters has limited the use of flip-chip assembly.

In this study we apply 3-dimensional field analysis to flip-chip assembled structure. The results of the analysis is calculated into circuit model for assembly. This model provides estimation of assembly-relating parasitics including interaction between chip and substrate, as we will call "chip-substrate effect".

With the use of the equivalent circuit, we discuss flip-chip assembled MICs with discrete pseudomorphic-HEMT (p-HEMT) on ceramic substrates in 60GHz, highest frequency ever reported in this structure. Through amplifier and frequency doubler design, we have confirmed the suitability of the structure for millimeter-wave application.

Analysis for Flip-chip Assembly for Equivalent Circuit Modeling

The total characteristics of the flip-chip assembled structure is not a mere combination of the each characteristics because of electro-magnetic effect. Therefore, accurate estimation of assembly effect is important.

We demonstrated electromagnetic simulation and calculated the results into circuit model for assembly.

3-dimensional field analysis with HP-HFSS™ using the structure in Fig.1 has been carried out. Each port represents for edge of

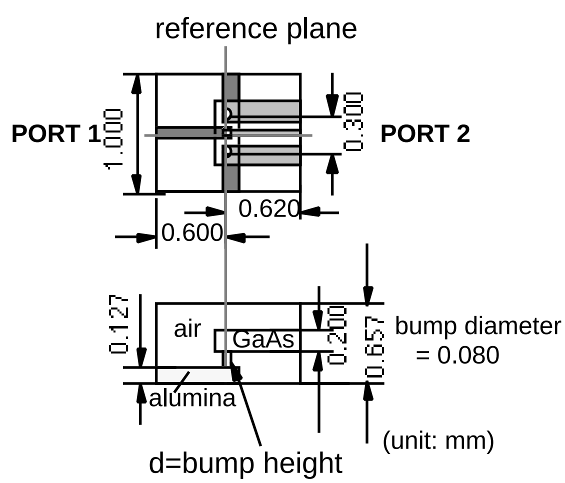

Fig.1 Structure used in the electromagnetic field analysis.

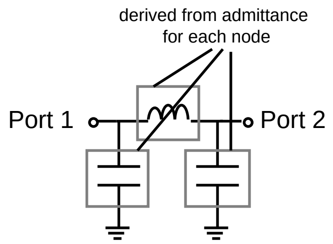

Fig.2 Equivalent circuit model for flip-chip assembly.

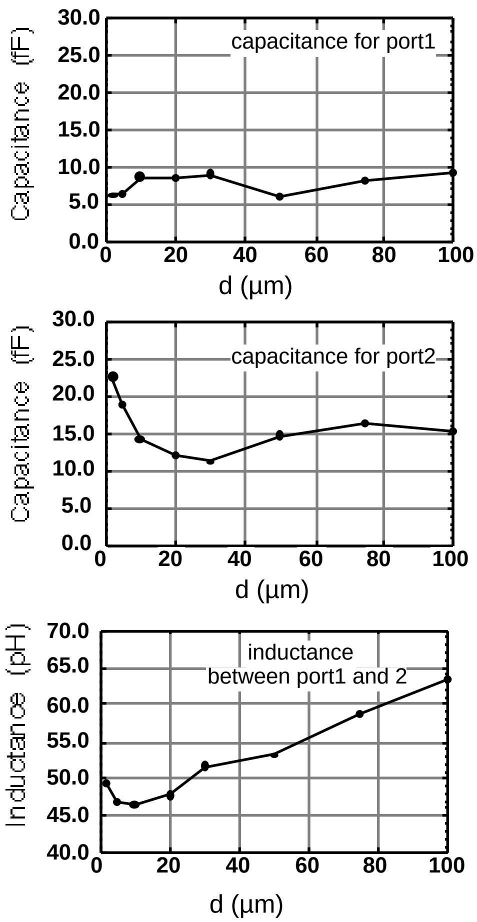

Fig.3 Calculated lump element value versus bump height.

the feedline, extended for calculation. The feedline on the alumina substrate (port 1) is microstrip whereas that on the GaAs chip (port 2) is coplanar waveguide. Bump diameter is 80 µm, bump height is d. S-parameters calculated from HFSS is de-embedded to the reference plane, then transformed into Π-section equivalent circuit. Each admittance of the Π-circuit is calculated into combination of lumped parameters[4].

Using above procedure, simulated S-parameters at 60GHz for various bump height d, have been transformed into lumped elements.

By neglecting the elements with little influence on characteristics, capacitance for port 1 and for port 2, and inductance between port are proved to be essential. Equivalent circuit model for flip-chip assembly was determined as shown in Fig.2.

Fig.3 shows these essential lumped parameters versus bump height. Though capacitance for port 1 is almost constant to bump height, capacitance for port 2 increases drastically for shorter bump height under 30µm.

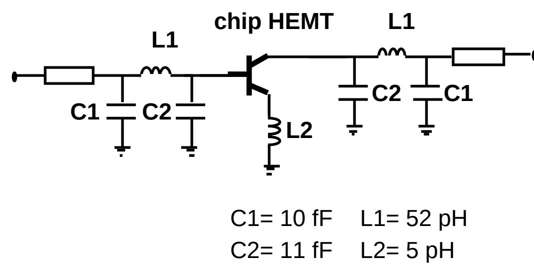

Fig.4 Equivalent circuit model for flip-chip assembled HEMT.

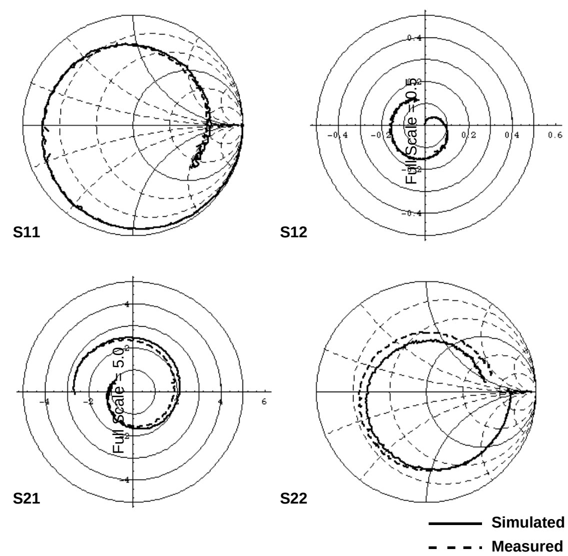

Fig.5 Measured and simulated S-parameters for flip-chip assembled HEMT.

0-7803-4603-6/97/$5.00 (c) IEEE

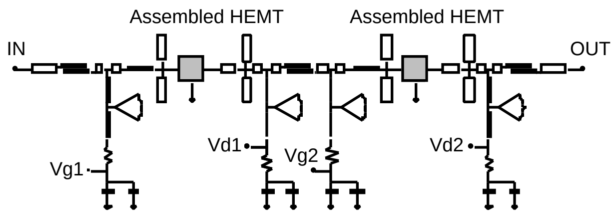

Fig.6 Circuit diagram of 60GHz two-stage cascade amplifier.

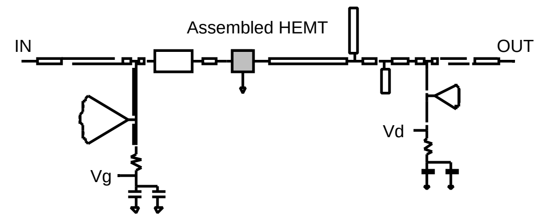

Fig.8 Circuit diagram of 30/60GHz frequency doubler.

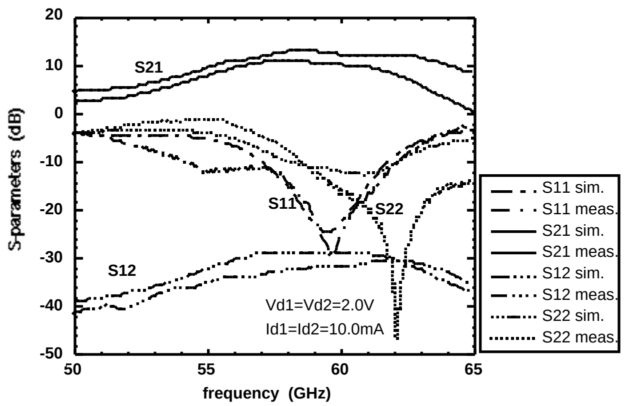

Fig.7 Measured and simulated characteristics of 60GHz amplifier.

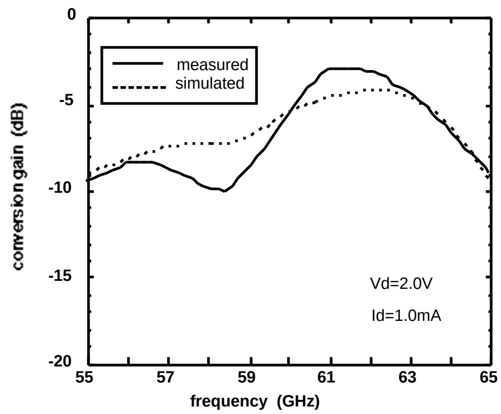

Fig.9 Measured and simulated characteristics of 30/ 60GHz frequency doubler.

In the case of coplanar waveguide (port 2), electromagnetic field expansion towards the vertical direction is much larger than in microstrip case (port 1), therefore chip-substrate interaction is more likely to caused. The excess portion of capacitance for shorter the bump height, exclusively appears in port 2, is thus estimated as the capacitance relating to chip-substrate.

Fig.4 show the equivalent circuit model for flip-chip assembled HEMT. Lumped element values are for the bump height of 30μm, where chip-substrate effect is suppressed and capacitance for each port are insensitive to bump height variation.

To testify the validity of the assembled HEMT model, S-parameter simulation has been carried out. Fig.5 illustrates the directly measured S-parameters of flip-chip assembled HEMT (= measured) and simulated S-parameters using the circuit in Fig.4, in which HEMT's on-wafer measurement results is used (= simulated). Good agreement for two sets of S-parameter data is the evidence of appropriate estimation of the flip-chip equivalent circuit HEMT model in Fig.4.

Circuit Design Procedure and Results

From electromagnetic simulation and construction of equivalent circuit for flip-chip assembled HEMT, 60GHz MIC circuit design can be realized.

For MIC design, we employed InGaAs/GaAs p-HEMT which has 0.10μm-long and 100μm-wide mushroom-shaped gate(5)(6). FET Root model used for circuit design has been extracted from on-wafer S-parameter measurement, using HP IC-CAP™ software. Substrates for MICs are 0.127mm-t alumina ceramic substrates. Bump height of 30μm and bump diameter of 80μm is employed.

Two-stage cascade amplifier and frequency doubler in 60GHz were developed. Fig.6 shows a circuit diagram of two-stage cascade amplifier. Amplifier has input and output matching circuit and interstage circuit, designed with small-signal simulation. Fig.7 shows the comparison of S-parameters for the amplifier measured with network analyzer and theoretical values from circuit simulator. Drain bias level is $Vd_1=Vd_2=2V$. Drain current is $Id_1=Id_2=10mA$. Analogous frequency characteristics of all the S-parameters are confirmed. Obtained S21 is maximum at 59GHz, 13dB.

Fig.8 shows 30/60GHz frequency doubler circuit diagram, designed with primary small-signal simulation and succeeding harmonic-balance simulation. Frequency doubler has input matching circuit for fundamental frequency, output matching circuit for second harmonic and quarter-wave length open stub as band-rejection filter for fundamental and third harmonic frequency. Load has been optimized by harmonic-balance simulation in order to maximize circuit conversion gain. Fig.9 shows the measured and simulated characteristics for frequency doubler at Vd=2V and Id=1mA. Agreement in frequency trends between measured and simulated results, are observed. Conversion gain obtained is -3dB at 61GHz.

These observed performance are fairly high as 60GHz flip-chip assembled MICs. Good agreements between the measured and the simulated frequency characteristics for the both circuits are the clear evidence for the validity of designing method.

Conclusion

Through 3-dimensional electromagnetic field analysis of flip-chip assembled structure, parasitic due to assembly including chip-substrate electromagnetic interaction has been accurately analyzed. Chip-substrate effect for the bump height under 30µm was indicated.

Equivalent circuit for flip-chip assembled HEMT has been derived from the results of field analysis. Two-stage amplifier and frequency doubler MICs in 60GHz-band were designed with HEMT. Fairly high performance as 60GHz MICs have been achieved. Two-stage amplifier has gain of 13dB. Frequency doubler has conversion gain of -3dB. Obtained frequency characteristics of MICs were similar to that of simulation. This fact suggests that the designing method demonstrated in this paper is fully adequate.

We conclude that flip-chip assembled MICs presented in this study are with great potentialities in millimeter-wave application.

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", IEEE MTT-S Digest, pp.1763-1766, 1994

(2)G.Baumann, H.Richter, A.Baumgartner, D.Ferling, D.Hollmann, H.Muller, H.Nechansky and M.Schlechtweg, "51GHz Frontend with Flip Chip and Wire Bond Interconnections from GaAs MMICs to a Planar Patch Antenna", IEEE MTT-S Digest, pp.1639-1642, 1995

(3)R.Sturdivant, "Reducing The Effects Of The Mounting Substrates On The Performance Of GaAs MMIC Flip Chips", IEEE MTT-S Digest, pp.1591-1594, 1995

(4)J.C.Rautio, "Synthesis of Lumped Models from N-Port Scattering Parameter Data", IEEE Trans. MTT 42(3), pp.535-537, 1994

(5)K.Ohmuro, H.I.Fujishiro, M.Itoh, H.Nakamura and S.Nishi, "Enhancement-Mode Pseudomorphic Inverted HEMT for Low-Noise Amplifier", IEEE Trans. MTT 39(12), pp.1995-2000, 1991

(6) M.Kasashima, Y.Arai, H.I.Fujishiro, H.Nakamura and S.Nishi, "Pseudomorphic Inverted HEMT Suitable to Low Supplied Amplifier", IEEE Trans. MTT 40(12), pp.2381-2386, 1992