Transmission and Coupling Characteristics of Transmission Lines in IC Chip

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***Abstract*— Establishment of signal integrity over a broad band as well as suppression of electromagnetic coupling between wirings in ICs are significant problem, because packaging density in ICs is very high. To clarify the electromagnetic compatibility (EMC) problems that related to the interconnection in the IC chip, transmission characteristics and electromagnetic coupling between wirings in the specially designed model transmission lines in IC chip were investigated by experiment and simulation. At first, model transmission lines, implemented in the bear chip with the size of 4,800μm square, were designed as model parallel transmission lines. The measurement methods, usually used for transmission line in the printed circuit board, are applied to the sample IC device under test. It was demonstrated that the decrease of transmission coefficient and the dramatically large far-end cross-talk which is thought to be enough to cause serious errors arise at gigahertz frequency band.**

Key words: Interconnection in IC, parallel transmission lines, transmission characteristics, electromagnetic coupling

I. INTRODUCTION

In recent years, the clock frequency is becoming higher and the packaging density of electronic devices is increasing. The devices must satisfy the requirements of electromagnetic compatibility (EMC) that do not emit electromagnetic interference (EMI) [1]. Hence, general methods for predicting and suppressing EMI as well as establishment of signal integrity over a broad band are required.

So far, many papers have been published and contributed to the EM radiation from printed circuit boards (PCBs) [2]-[7]. The mechanism of the generation of EM noise is investigated on the basis of the source-path-antenna model. The “source” refers to high frequency current of the integrated circuit (IC) and large-scale integration (LSI), because the switching current of ICs is primary source of EMI. So equivalent circuit model describing RF power current produced by an IC and EM radiation caused by the switching noise on the high-speed digital PCB have been demonstrated [3], [4]. However, many of these conventional studies had been focused on not IC itself but IC mounted on PCB. So, the characteristics of the electromagnetic coupling and reflection phenomena for the transmission line in an IC are not completely cleared, which allows to study possible means for suppressing the unintentional high-frequency current leakage. The coupling between a high-speed signal trace and a low-frequency signal trace can be a primary EMI coupling path. However, this description is insufficient for phenomena in the interconnection/transmission line in the ICs. It is desired that the establishment of EMC guideline and designing ways for the transmission line in the IC at high frequency should be based on the research works on the fundamental knowledge. Although, the predictions of electromagnetic coupling in the practical high-density packaging ICs have not yet been completely performed due to the difficulty of applying the theory to complex geometries. It is important and new engineering point to clarify the transmission characteristics and electromagnetic coupling in the transmission line in the IC at high frequency. The main goal of this study is to clarify the EMC problems related to the interconnection in the IC chip [8]-[10].

In this paper, some basic studies on the transmission characteristics and electromagnetic coupling between transmission lines in the specially designed model transmission lines in IC chip are performed. The layout of test IC model and experimental method of transmission characteristics are described in Section 2 and 3, respectively. In Section 4, the frequency responses are discussed from view point of signal integrity.

II. IC MODEL

A. *Design of IC Model*

A generalized simple model is indispensable to investigate the complicated coupling mechanism in integrated circuit geometry, and the effective suppression of the coupling. There are many angle patterns on the transmission lines and spacing between two transmission lines pair is very narrow. So, simple transmission line models with typical two angle patterns are prepared.

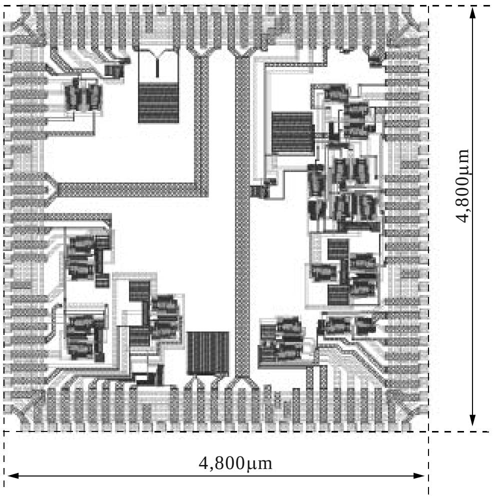
B. *Structure of IC Model*

Changing the geometry of a transmission line causes a change in the magnetic flux which wraps the victim trace and electric field. Hence, the followings parameters affect the transmission and EM coupling characteristics.

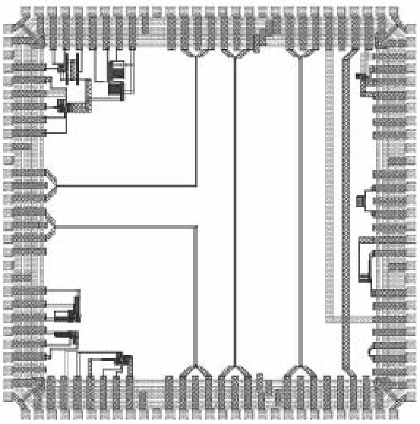
- height of dielectric substrate h
- relative permittivity ε_r
- width of the signal trace w_t
- distance between two traces s

A general method for suppressing cross-talk is to keep away two lines whenever possible [1]. One problem with a rule like this is that as the IC design density continues to increase, designers can no longer afford the space on the IC to follow this guideline, and two traces are placed closer. So, this study specially focuses on the effect of the width of the signal trace.

Designed transmission lines are shown in Fig. 1. Although two angle patterns are constructed, we focus on straight line only in this paper. Figure 1(a) and (b) are for the “w_t=76.22μm” and “w_t=15.17μm and 7.59μm” cases respectively. Cross-sectional view is shown in Fig. 2. The transmission line structure consisted of microstrip line which is commonly used in high frequency integrated circuits. The metal layer as transmission line, with width w_t=76.22, 15.17 and 7.59μm, is located on the insulating layer (SiO_2) with 1.2μm thickness and permittivity of ε_r=3.8. Sheet resistance of Al is 0.050Ω/Square. One transmission line is signal trace, and other transmission line routed in parallel to the signal trace is victim trace. The distance between two transmission lines is 1.48μm which is limited by IC production process. The transmission line is centered on substrate to decrease coupling to another circuit. Length of the transmission line for the “straight” case is 4,660 μm. The model transmission lines, designed on the bear chip with the size of 4,800μm square, were created.



(a)w_t=76.22 μm case



(b) w_t=15.17μm and 7.59μm cases

Fig. 1 Layout of IC under test.

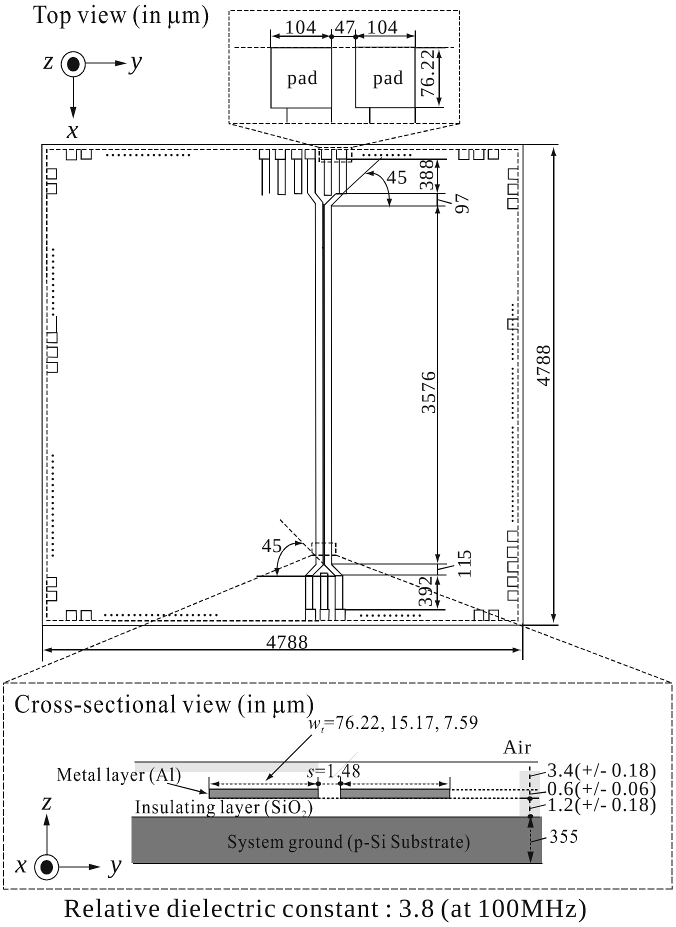


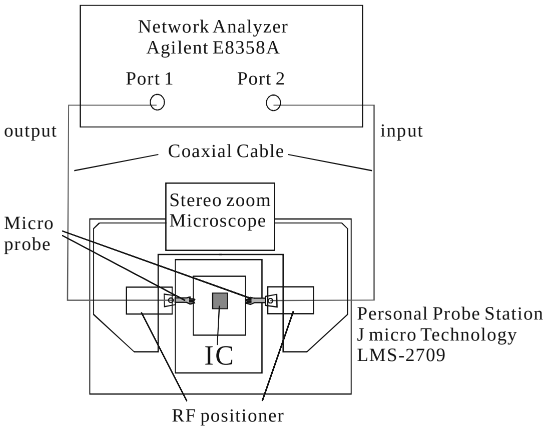
Fig. 2 Cross-sectional view of IC.

III. EXPERIMENTAL AND MODELING METHODS

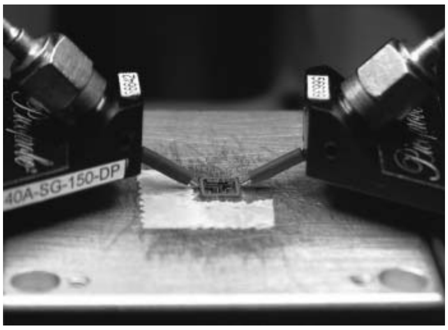
A. Experimental Method

The experimental method, usually used for transmission line in the printed circuit board, is applied to the developed samples. The experimental setup for transmission characteristics is shown in Fig. 3. Figure 3(a) and (b) are experimental setup and photograph, respectively. The reflection and transmission coefficients, input impedance and far-end cross-talk were measured using a network analyzer (Agilent E8358A), micro probe (GGB ECP18-GSG) and a micro probe station (J Micro Technology Inc. LMS-2709). The micro probe is used to connect between transmission line and measurement system. The space between signal and ground of the micro probe is 150μm. The micro probe station can adjust the location of the micro probe. The network analyzer is calibrated on the tip of the micro probe. The measured frequency range was from 10MHz to 9GHz.

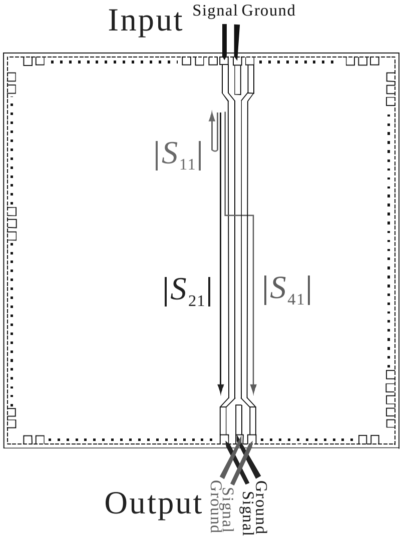
At general measurement for Scattering-parameters, ends of the transmission lines should be terminated with its characteristic impedance. Although the ends of lines are connected to micro probe with 50Ω, 50Ω is not matched to the characteristic impedance of the transmission line. However, it is considered that the estimation of the transmission characteristic is possible. Therefore, the terminations of transmission lines, which are not used in measurement, are opened as shown in Fig. 3(c).



(a) Experimental setup



(b) Photograph of the probe on the model IC chip



(c) Input and output ports for S-parameter measurements

Fig. 3 Experimental setup for the transmission characteristics.

B. FDTD Modeling

FDTD method is used for numerical analysis. An analytical space was composed from non-uniform size of the cells. The size of cells in coarse region are $\Delta x=\Delta y=\Delta z=25\mu$m and that in fine region near the signal trace and dielectric substance is $\Delta x=25$, $\Delta y=0.74$, $\Delta z=0.60\mu$m, respectively. PML of 12 layers was used for the absorbing boundary condition. The metal is modelled as a perfect electric conductor without thickness.

C. Equivalent Circuit Model

An equivalent circuit model for parallel transmission lines is used for calculations of the transmission and EM coupling characteristics. Figure 4 shows the equivalent circuit model for calculating the EM coupling ($|S_{41}|$). The equivalent circuit consists of three parts: a source, a transmission line based on the TEM assumption in consideration of EM coupling, and a termination (load). The length of the sub-section illustrating the coupling phenomena Δx is 466μm. So, transmission line is represented by cascade connection of 10-sections. The circuit parameters were calculated by 2D-field solver (Ansoft, Maxwell EZ2D Calculator).

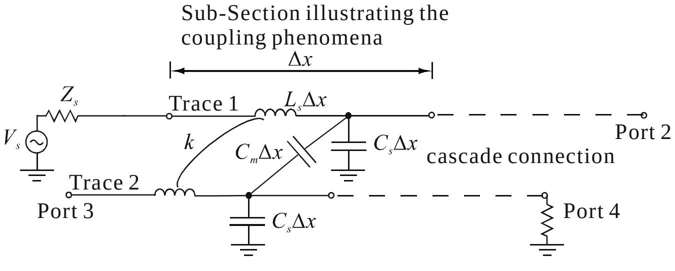


Fig. 4 Equivalent circuit model.

IV. RESULTS AND DISCUSSION

A. Transmission coefficient $|S_{21}|$

Frequency response of transmission coefficient $|S_{21}|$ for the "straight" case is shown in Fig.5. The solid, dashed and broken lines indicate measured, equivalent circuit model calculated and FDTD calculated results, respectively. Result on equivalent circuit model and FDTD results are in good agreement. On the other hand, there is difference between calculation and measured results. This difference may result from loss factor due to the aluminum conductor and SiO_2 dielectric substrate.

Calculated results indicate that as the width of the signal trace becomes wider, $|S_{21}|$ at higher frequency decreases. The $|S_{21}|$ at 9GHz for the "w_t=7.59, 15.17 and 76.22μm" cases are -3, -6 and -18dB, respectively.

On the other hand, measured result indicates that $|S_{21}|$ at lower frequency (up to 100MHz) is approximately -2dB. Comparing three different layouts, there is no remarkable difference. The $|S_{21}|$ at 9GHz are approximately -20dB.

These results indicate that received voltage decreases to 10% of input voltage enough to cause serious errors. Even if length of transmission line in the IC is very short, attenuation can not be disregard in this experiment.

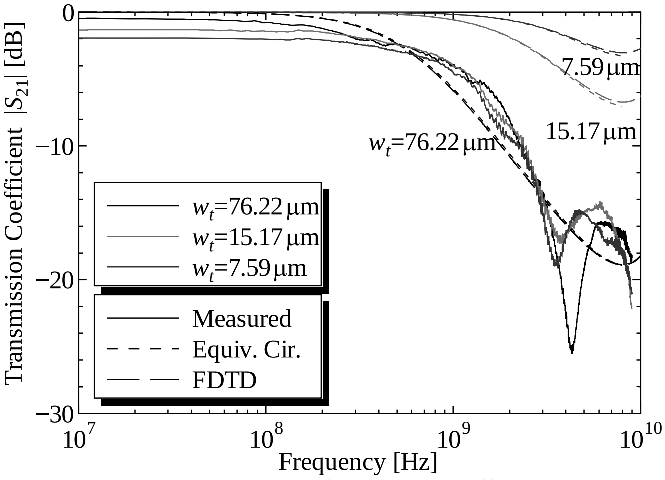


Fig. 5 Frequency response of transmission coefficient $|S_{21}|$.

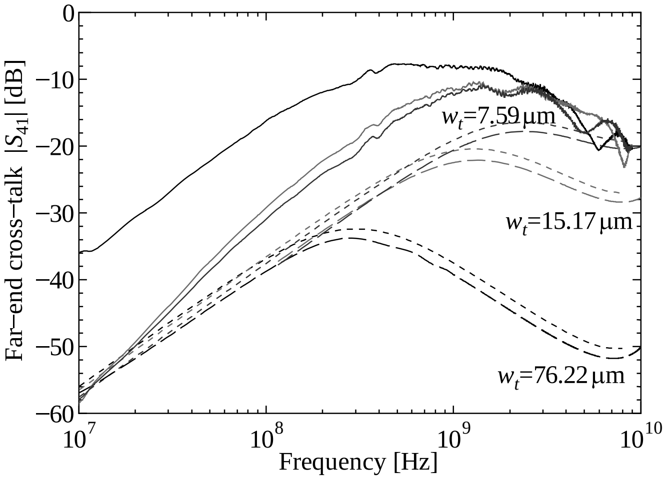


Fig. 6 Frequency response of far-end cross-talk $|S_{41}|$.

B. *Far-End Cross-Talk* $|S_{41}|$

Frequency response of far-end cross-talk $|S_{41}|$ is shown in Fig.6. There are two coupling mechanisms: mutual capacitance and mutual inductance. In this study, mutual capacitance is dominant coupling factor, because the terminations of transmission lines, which are not used in measurement, are opened.

The measured results indicate that as the frequency increases, far-end cross-talk $|S_{41}|$ up to 1GHz increases. The $|S_{41}|$ at 1GHz is peak value of approximately -8dB. This result indicates that 40% of input voltage is coupling (leaking) to another (victim) line, enough to cause serious errors. The $|S_{41}|$ at 9GHz is approximately -20dB. At higher frequencies, far-end cross-talk decreases, with comparing for 1GHz. This decrease may result from the decrease of transmission coefficient $|S_{21}|$.

The calculated results indicate that $|S_{41}|$ in the "w_t=76.22 μm" case is the best case from the viewpoint of the variation of layout. Wider signal trace has relatively large self-capacitance between a signal trace and a ground plane. Hence, effect of mutual capacitance between the signal trace and a victim trace is smaller than that in the narrower signal trace case.

V. CONCLUSION

Basic studies on the transmission characteristics and electromagnetic coupling between transmission lines in the specially designed model transmission lines in IC chip were performed. The basic data for the discussion on EMC issues in the IC chips was described. It was demonstrated that decrease of transmission coefficient and dramatically large far-end cross-talk enough to cause serious errors arise at gigahertz frequency band.

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