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Inter-chip Wireless Interconnection using Si Integrated Antenna

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1. Introduction

The fundamental limitations of conventional interconnect system in reducing signal propagation delay has lead to the proposal of intra-chip wireless interconnection using integrated antenna [1]-[3]. However, the growing complexity in integrated circuits design such as the design of system on a chip (SoC) has increased the urgency of 3-D ICs and stacked chip scale packaging. Inter-chip wireless interconnection using integrated antenna is very promising for such system with the potential to realize very high frequency data and clock transmission while eliminating the need of complex wiring.

In this paper we report the feasibility of inter-chip wireless interconnection using Si integrated antenna. The measured characteristics are compared with simulated results obtained by using Ansoft HFSS program. The improvement of inter-chip signal transmission by use of high resistivity Si substrate is also studied.

2. Fabrications and Measurement

Figure 1 shows the conceptual diagram of inter-chip clock and data transmission using integrated antenna. Figure 2 shows various configurations used for the evaluation of inter-chip signal transmission. Antenna test structures were fabricated on 260 μm thick Si wafer with 1 μm field oxide. A 1 μm thick aluminum layer was sputtered on top of the oxide and patterned to form the antenna. The antenna length and width was fixed at 2 mm and 10 μm, respectively. The setup for S-parameter measurement is shown in Fig. 3. Wafers were measured on a block of wood (2.6 mm thick) to eliminate the effect of metal chuck of the probe station. The relative dielectric constant of wood was 2.15 at 1 GHz.

3. Inter-Chip Signal Transmission on Standard Si

Inter-chip signal transmission was measured and simulated on standard p-Si with a resistivity of 10 Ω-cm. Figure 4 shows the measured reflection coefficient of the transmitting antenna on standard Si substrate. The reflection coefficient of the transmitting antenna is identical for all the configurations and it depends solely on the substrate material. Figure 5 shows the measured forward transmission coefficient (S_{21}) of the transmitter-receiver pair for various inter-chip configurations shown in Fig. 2. As seen from Fig. 5, the transmission coefficient of inter-chip signal transmission reduces by 3 dB compared to intra-chip when the two chips are placed close to each other with same antenna length. A part of this reduction is due to the ≈0.5 mm air gap between the two chips in inter-chip configuration which increases the antenna distance. When one of the chip is raised 2.6 mm above the other and without overlapping each other as shown in Fig. 2(c), the transmission coefficient decreases by about 5.6 dB. This reduction is due to the fact that the effective distance of the receiver increases in this case and also the major path of electromagnetic wave through the Si and wood layer is interrupted by the air gap before reaching the receiver. Figure 6 shows the simulated transmission coefficient for intra-chip and various inter-chip configurations. As seen from Fig. 6, when the two chips completely overlap each other as in Fig. 2(d), the transmission coefficient is about 5 dB greater than that without overlap (Fig. 2(c)). The measured transmission coefficient is compared with simulated value in Fig. 7. The measured and simulated data shows similar trend and a match within ± 2 dB. Figure 8 shows the measured transmission coefficient versus frequency when the transmitter receiver separation distance is varied from 3 mm to 10 mm in the horizontal plane with a fixed air gap of 0.5 mm between the chips. At 20 GHz, transmission coefficient is -48.7 dB and -57.9 dB at a distance of 3 mm and 10 mm, respectively. The effect of air gap on inter-chip signal transmission is shown in Fig. 9. As seen from Fig. 9, when both the chips are on wood, the increase of inter-chip antenna distance by increasing the air gap between transmitter and receiver gives the same transmission coefficient as in intra-chip for the same antenna distance. Since the Si layer is very thin, a large part of electromagnetic wave pass through the wood layer and hence air gap has negligible effect. On the other hand when the receiver chip is raised 2.6 mm above the wood with air gap between them, the gain reduces by about 3 dB.

4. Inter-Chip Signal Transmission on High Resistivity Si

In order to ease the design of analog interface circuits it is necessary to improve the inter-chip transmission coefficient. To improve the inter-chip transmission coefficient of integrated antenna we have increased the resistivity of Si substrate to extremely high value by proton implantation throughout the entire depth of the Si substrate[2]. The proton dose was 5×10^{14} cm^{-2} and implantation energy was 17.4 MeV. The measured value of resistivity after proton implantation was about 65 KΩ-cm. As shown in Fig. 10, after proton implantation the transmission coefficient for 2 mm long antenna pair separated by 10 mm is increased by 13.4 dB and 21.8 dB at 20 GHz and 25 GHz, respectively. Figure 11 shows the wave shape of inter-chip transmission of sinusoidal signal at 20 GHz on standard Si. The peak-peak amplitude of the received signal at the receiver antenna was 3.15 mV and 1.04 mV at a distance of 3 mm and 10 mm respectively. However, as shown in Fig. 12, at a distance of 10 mm the received signal peak-peak amplitude increased by 6 folds to 6.88 mV when high resistivity Si substrate is used.

5. Conclusion

Inter-chip signal transmission between standard Si substrates shows a forward signal transmission coefficient of -57.9 dB at 20 GHz for 2 mm long antenna when the transmitter receiver separation distance is 10 mm and the receiver chip is at a height of 2.6 mm from the transmitter chip. However, when high resistivity Si substrate is used the transmission coefficient increases to -42.4 dB and -32.3 dB at 20 GHz and 25 GHz, respectively and the amplitude of the received sinusoidal signal at 20 GHz increases from 1 mV to 6.8 mV. This demonstrates the feasibility and the effectiveness of inter-chip wireless signal transmission using integrated antenna with high resistivity Si in 3-D ICs or in stacked chip scale packaging.

Acknowledgements

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References

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[3] A.B.M. H. Rashid et. al. Jpn. J. Appl. Phys. Part 1, 4B, **42**(2003)2204

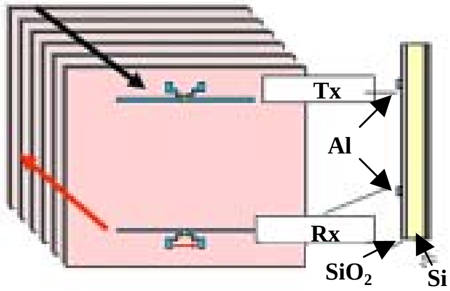

Fig. 1 The concept of inter-chip wireless signal transmission in stacked chip packaging. T_x-transmitting antenna, R_x-receiving antenna. Transmitting antenna will transmit clock and data to the receiver antenna within the chip or to another chip of the stacked package.

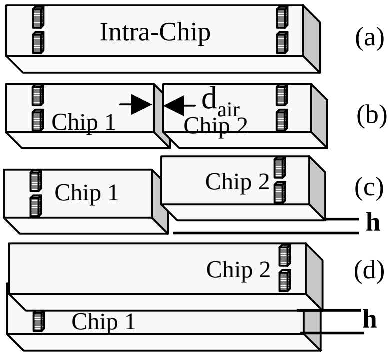

Fig. 2 Different configurations used for evaluation. (a) Intra-chip, (b) Inter-chip on same plane (h=0), (c) Inter-chip with height between the chips h=2.6mm, (d) Inter-chip overlapped with h=2.6 mm. d_{air} is the inter-chip air gap in horizontal plane.

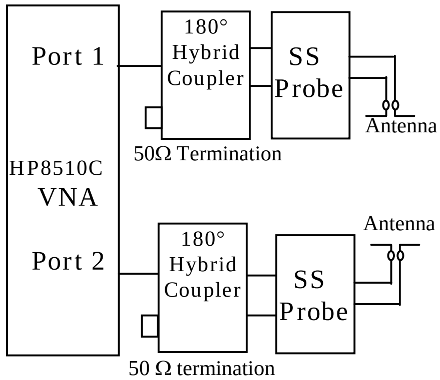

Fig. 3 Experimental setup for characterization of intra-chip and inter-chip signal transmission.

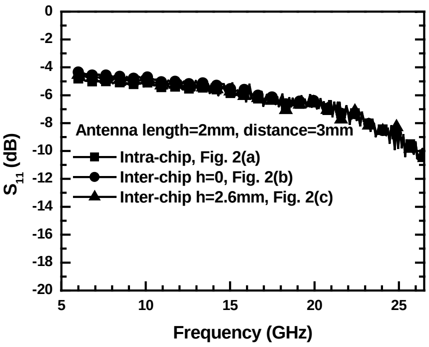

Fig. 4 Measured reflection coefficient (S_{11}) for various configurations. S_{11} depends solely on the substrate material

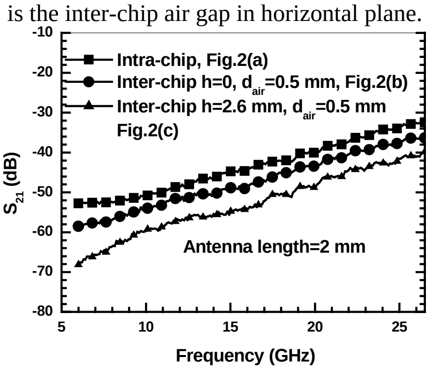

Fig. 5 Measured transmission coefficient of inter-chip wireless signal transmission in various configurations shown in Fig. 2

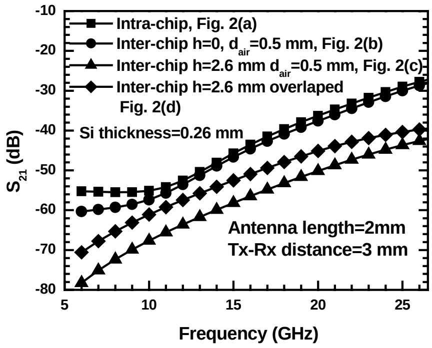

Fig. 6 Simulated s-parameter forward transmission coefficient for various inter-chip wireless configurations shown in Fig. 2.

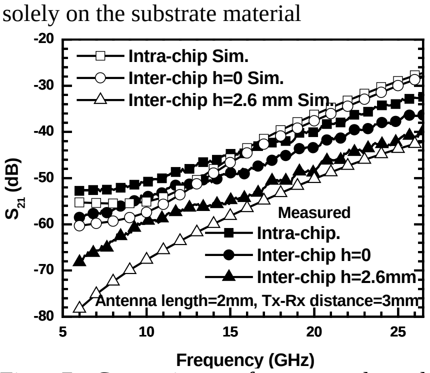

Fig. 7 Comparison of measured and simulated S_{21} versus frequency for various inter-chip configurations.

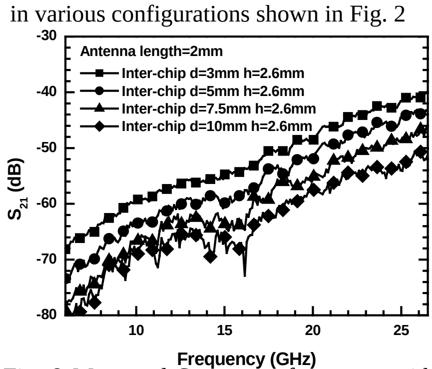

Fig. 8 Measured S_{21} versus frequency with the distance between the antenna varied.

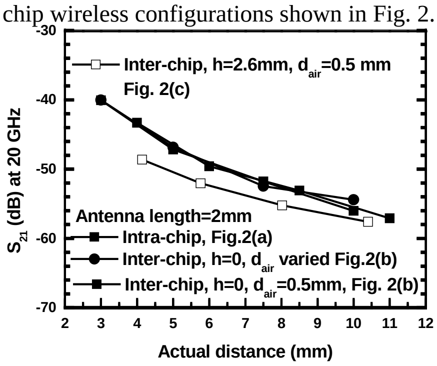

Fig. 9 Variation of S_{21} with actual distance between antennas for intra and inter-chip configurations. The actual distance is the minimum distance between antennas.

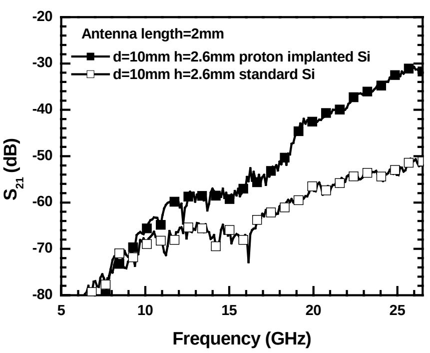

Fig. 10 Improvement of inter chip signal transmission coefficient by using high resistivity Si substrate.

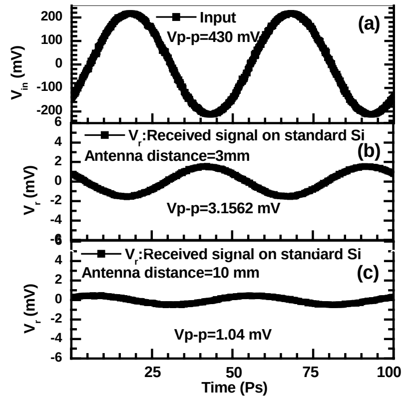

Fig. 11 Inter-chip transmission of sinusoidal signal at 20 GHz. Antenna L=2 mm, inter-chip h=2.6mm. Input signal (a), received signal at a distance of 3mm (b) and 10mm (c)

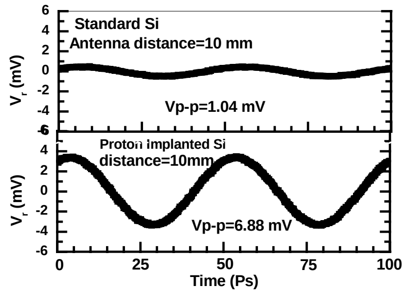

Fig.12 Peak to peak amplitude of received signal increases from 1 mv to 6.9 mV by using proton implanted Si for an antenna length of 2 mm and transmitter receiver distance of 10 mm. Inter-chip h=2.6 mm