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Inter-chip Signal Transmission using Si Integrated Antenna

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Introduction

According to the scaling rule [1], the reduction in device feature sizes improves the performance of ultra large scale integrated circuits (ULSI) in terms of operation frequency and power dissipation. However, the global clock frequency of ULSI is limited at 3-4 GHz for larger chip size with a few cm [2]. This is because the reduction in the interconnect feature size increases both interconnect resistance and parasitic capacitance, resulting in the increase of the RC signal delay. In addition, growing complexity in ULSI for system on a chip leads to 3-D ICs and stacked multi-chip packaging as shown in Fig. 1. In order to solve the global delay in the metal interconnects, silicon integrated antenna has been proposed to send signals by electromagnetic wave so that both parasitic capacitance and resistance can be eliminated [3,4]. The conceptual diagram of inter-chip wireless interconnection for stacked chip packaging using integrated antenna is also shown in Fig. 1. The integrated antennas are fabricated on Si-ULSI so that the global clock signals can be sent from a transmitting antenna of one chip and received by a receiver antenna of another chip by electromagnetic wave propagation [5]. Figures 2(a) and 2(b) show three-dimensional view of the integrated antenna on a Si substrate and the cross-sectional radiation pattern of electromagnetic wave from the antenna on a z-y plane. As can be seen, most of the radiated electromagnetic wave from the antenna on the Si substrate penetrates into the Si due to the difference in dielectric constants between Si (ε=12) and air (ε=1). Inter-chip wireless interconnection using integrated antennas have the potential to realize very high frequency data and clock transmission as well as reconfigurable interconnection among ULSI chips.

In this paper, the study on the feasibility of inter-chip wireless interconnection between Si chips using Si integrated antennas is carried out. The influence of Si substrate resistivity on inter-chip signal transmission is also studied.

Experimental

P-type (100) Si substrates with 10 Ω·cm resistivity were prepared. A 0.3 μm-thick SiO_2 was formed by pyrogenic oxidation at 1050°C on the 260 μm thick Si substrate surface. A 1.0 μm-thick aluminum layer was deposited on the SiO_2 by direct current magnetron sputtering. 10.0 μm-wide and 2 mm long dipole antennas were fabricated by use of HL-700 electron-beam lithography and subsequent wet etching. Figure 3 shows the measurement setup for scattering parameters of Si integrated antennas. It consists of a HP8510C vector network analyzer, 6.0-26.5 GHz 180° hybrid coupler, signal-signal probes and a probe station, so as to convert the unbalanced signals from the network analyzer to balanced signals used to excite the dipole antenna. Integrated dipole antennas fabricated on a wafer were measured on a 2.6 mm thick low-k substrate whose relative dielectric constant was 2.15 at 1 GHz and it was placed on the metal chuck of the probe station. The low-k substrate plays a role for separating the wafer and the bottom metallic chuck of the probe station to eliminate the reactive near field capacitive coupling between the antenna and the chuck. From measured S-parameters antenna return loss, or reflection coefficient (S_{11}) and transmission coefficient (S_{21}) were obtained so that antenna transmission gain (G_a) through Si substrates can be calculated.

Figure 4 shows 3-D view of integrated antennas on separate Si substrates structure used for the evaluation of inter-chip signal transmission. The Si wafers were separated vertically with 2.6 mm thick low-k chips inserted between the Si wafers. The vertical distance (h) was fixed and horizontal distance (d) and antenna length (L) were varied. The measured characteristics are compared with simulated results obtained by employing a 3D finite element method using the Ansoft HFSS program.

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Results and Discussion

Figure 5 shows comparison of measured and simulated reflection coefficients of a transmitter dipole antenna as a function of frequency. The resonant frequency of the 3 mm long integrated dipole antenna on Si was 21 GHz. Figure 6 shows the comparison between measured and simulated antenna transmission gains of dipole antennas as a function of frequency. As can be seen, measured characteristics were consistent with the simulated data. The inter-chip antenna transmission gain increases with increasing frequency, which was the same as intra-chip antenna transmission characteristics. Figure 7 shows measured antenna transmission gain of dipole antenna versus antenna length for various frequencies as parameters. The antenna transmission gain increased exponentially +15 dB with increasing antenna length from 2 mm to 4 mm. Figure 8 shows measured antenna transmission gain of dipole antenna as a function of horizontal distance between antennas for different frequency as a parameter. The antenna gain decreases exponentially with increasing antenna distance.

Since the transmission loss in Si substrates was apparent, the influence of Si resistivity on the transmission characteristics must be investigated [6,7]. Figure 9 shows measured reflection coefficients versus frequency with Si substrate resistivity as a parameter. The dipole antennas were fabricated on the Si substrates whose resistivities were 10, 79.6 and 2290 Ω·cm, respectively. Figure 10 shows the antenna input impedance (Z_{11}) which was calculated from the measured S-parameters at various frequencies from 6.0 to 26.5 GHz for different Si resistivities. S_{11} increased with increasing Si substrate resistivity [8]. Voltage standing wave ratio increased with increasing the resistivity due to mismatching of impedance. Figure 11 shows S_{21} of inter-chip dipole antenna versus antenna length for different Si resistivities. Figure 12 shows dependence of Si resistivity on the transmission gain of inter-chip antennas with different antenna length at 20 GHz. The antenna transmission gain increased with increasing Si resistivity and antenna length. The transmission gain of 3 mm long antenna increased +25 dB as the resistivity of Si substrate increased from 10 to 2290 Ω·cm. Figure 13 shows dependence of horizontal distance on the transmission gain for 3 mm long inter-chip Si integrated antennas at 20 GHz. Inter-chip antenna transmission gain decreased exponentially as the horizontal distance increased. The transmission loss per distance decreased as Si resistivity increased so that the transmission losses per distance were -1.3, -0.8 and -0.4 dB/mm for 10, 79.6 and 2290 Ω·cm, respectively.

Conclusion

Inter-chip signal transmission using Si integrated antenna was demonstrated. Inter-chip antenna transmission gain could be improved by using high resistivity Si substrates. The transmission gain was improved +25 dB by changing Si resistivity from 10 to 2290 Ω·cm for 3 mm long and 10 mm distance Si integrated antennas.

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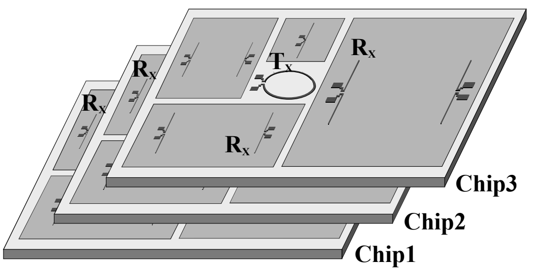
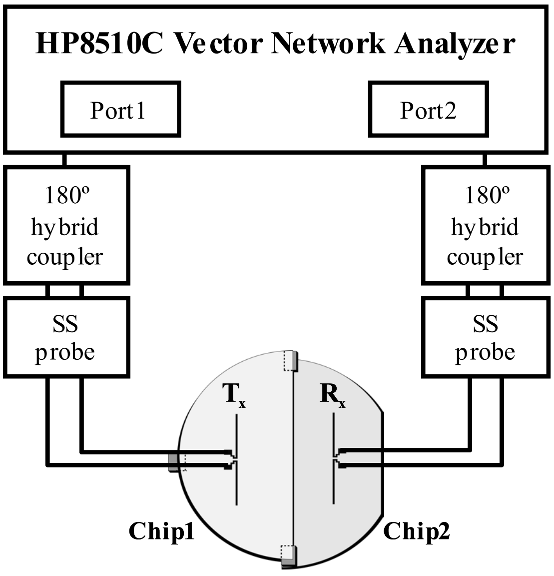


T_x : Transmitting antenna, R_x : Receiving antenna

Fig.1. Concept of inter-chip wireless interconnect using dipole antennas integrated in multiple Si ULSI chips.



T_x : Transmitting antenna, R_x : Receiving antenna

Fig. 3. Measurement setup for inter-chip antenna transmission characteristics.

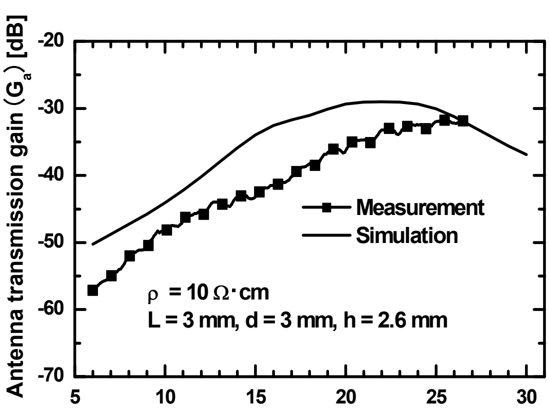
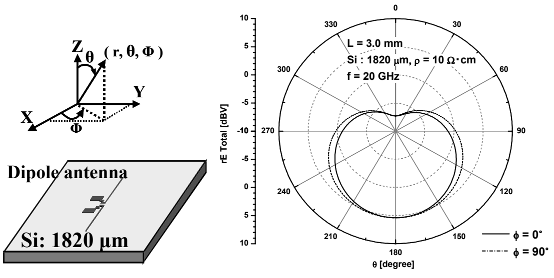
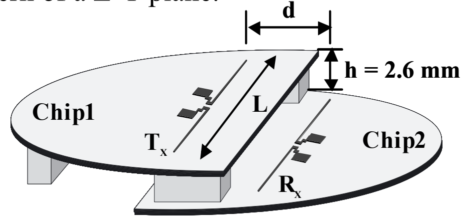


Fig. 6. Measured and simulated antenna transmission gains of a dipole antenna versus frequency (L = 3 mm, d = 3 mm, h = 2.6 mm).



(a) (b)

Fig. 2. (a) Three-dimensional view of the integrated antennas on a Si substrate for simulation. (b) The cross-sectional radiation pattern of a Z-Y plane.



T_x : Transmitting antenna, R_x : Receiving antenna

Fig. 4. 3-D view of inter-chip measurement structure.

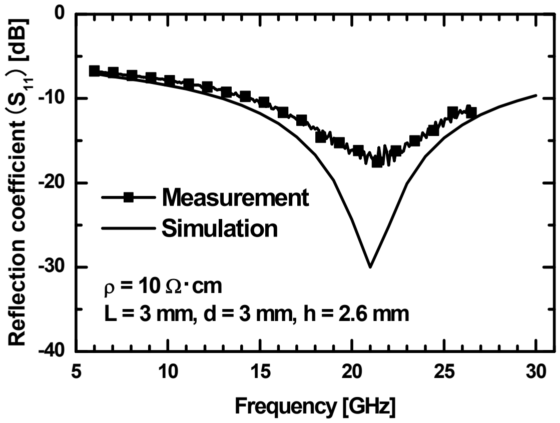


Fig. 5. Measured and simulated reflection coefficients of a dipole antenna versus frequency (L = 3 mm, d = 3 mm, h = 2.6 mm).

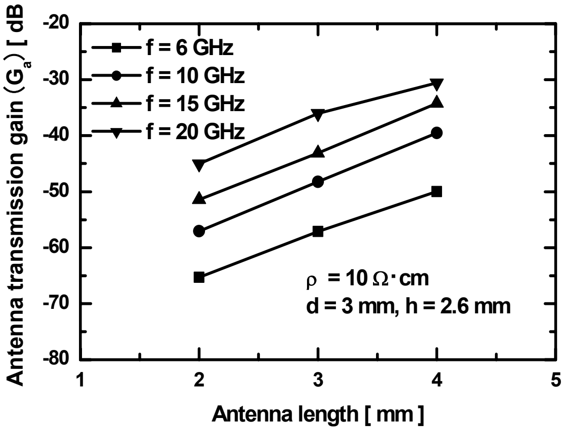


Fig. 7. Measured antenna transmission gain of dipole antenna versus antenna length for different frequency as a parameter (d = 3 mm, h = 2.6 mm).

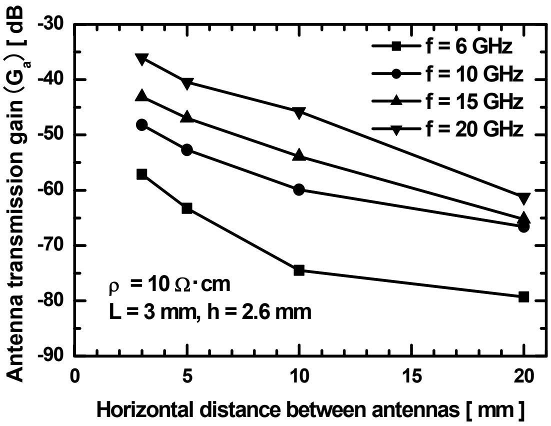


Fig. 8. Measured antenna transmission gain of dipole antenna versus horizontal distance between antennas with frequency as a parameter (L = 3 mm, h = 2.6 mm).

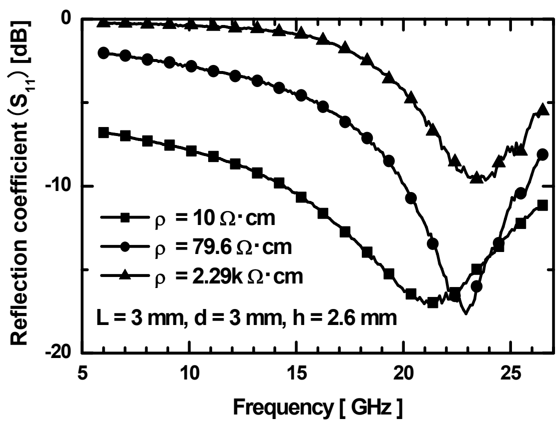


Fig. 9. Measured reflection coefficient versus frequency with Si substrate resistivity as a parameter (L = 3 mm, d = 3 mm, h = 2.6 mm).

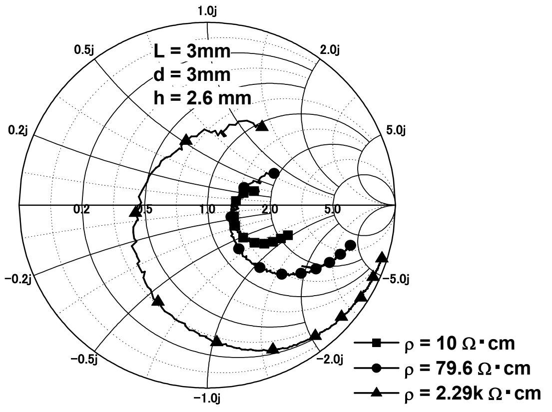


Fig. 10. Measured smith chart (antenna input impedance versus frequency) (L = 3 mm, d = 3 mm, h = 2.6 mm).

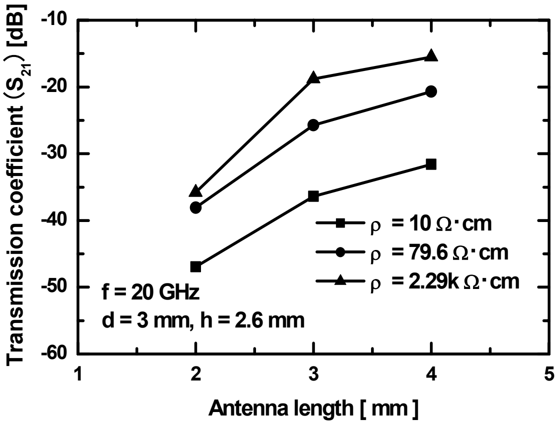


Fig. 11. Measured transmission coefficient versus antenna length with Si substrate resistivity as a parameter (f = 20 GHz, L = 3 mm, h = 2.6 mm).

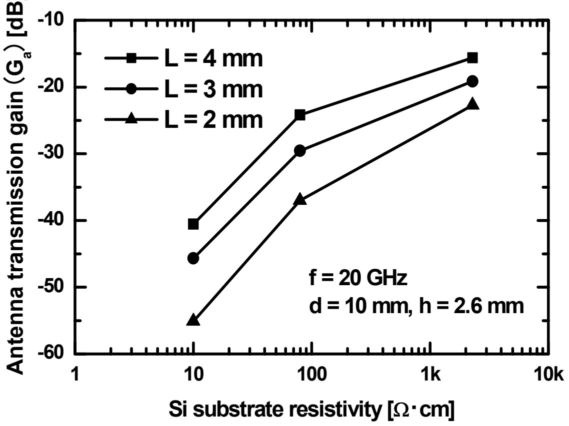


Fig. 12. Measured antenna transmission gain of dipole antenna versus Si substrate resistivity with antenna length as a parameter. (f = 20 GHz, d = 10 mm, h = 2.6 mm).

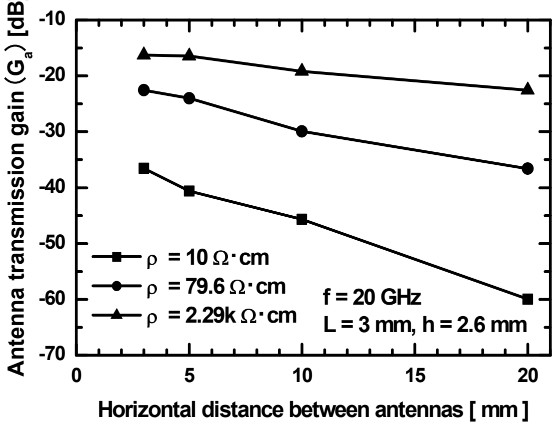


Fig. 13. Measured antenna transmission gain of dipole antenna versus horizontal distance between antennas with Si substrate resistivity as a parameter. (f = 20 GHz, L = 3 mm, h = 2.6 mm).