Intra/Inter-Chip Wireless Interconnect System for ULSI (1)
－Si Integrated Antenna－

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1. Research Target

According to the scaling rule of silicon ultra-large scale integrated circuits (ULSI) [1,2], transistor performance can be improved by reducing the feature sizes, but interconnect performance is degraded due to the increase of resistances (R) and capacitances (C) of the scaled interconnects. Thus a new technology solution must be adopted to overcome the delay problem of conventional interconnect system .

The goal of this research is to develop a signal transmission technology which can distribute the clock frequency higher than 10 GHz to circuit blocks as well as among ULSI chips. Furthermore, a novel signal transmission technique which can realize reconfigurable wireless interconnects having multiple-channels. For this purpose an ultra wideband (UWB) wireless interconnect systems using integrated antennas is developed [3-6] for future ULSI.

However, there are several issues to be solved. One of them is the transmission loss of electromagnetic waves in Si substrates because Si is a lossy material due to its conductivity. and lossy material properties. Measurement techniques must be developed for antenna propagation through Si and the influence of Si on the transmission characteristics. The transient response of the transmitting and receiving dipole antennas fabricated on a conductive Si substrate are also investigated so that baseband communication between ULSIs by UWB digital signal can be achieved.

Research on intra/inter-chip wireless interconnect system is a new interdisciplinary field so that it is necessary to apply not only electromagnetic wave transmission and antenna theory but also material science and Si integrated circuits technology.

2. Research Results

A concept of intra/inter-chip wireless interconnects using integrated dipole antennas in SI ULSI is shown in Fig. 1. Figures 2 and 3 show layout pattern and a plan-view of transmitting and receiving antennas on a Si substrate. Antenna test structures were fabricated on 260 μm thick Si wafer with a resistivity of 10Ω-cm or 2.29k Ω-cm using 0.5 μm field oxide. Proton implantation was then performed on the patterned wafer with a fixed dose of 10^{15} cm^{-2} and at a fixed energy of 17.4 MeV in a cyclotron chamber from the back side of the wafer. The wafers were kept in a circular flange covered by aluminum sheet and implantation was done in six steps by changing the aluminum absorber thickness in order to provide a uniform proton profile throughout the entire depth of the Si substrate. The thickness of the aluminum absorber was 1630 μm during the first implantation step. In each subsequent implantation steps, the thickness of the aluminum absorber was reduced by 40 μm from the previous value. The concentration profile of implanted proton in Si was calculated using the public domain software named Stopping and Range of Ions in Matter. A schematic cross-sectional diagram of proton implantation into Si substrate is shown in Fig. 4 and the resulting profile of the proton ion implantation at $1x10^{12}/cm^2$ of proton dose is shown in Fig. 5. Figure 6 shows a measurement setup for S-parameters of antennas. It consists of HP8510C Vector Network Analyzer, 180° Hybrid Couplers (6.0-26.5GHz), probe station and Signal-Signal probes. Wafers were measured on wood (2.6 mm thick) on the metal chuck of the probe station. The relative dielectric constant of wood was measured as 2.15 at 1 GHz. Figure 7 shows the measured transmission coefficient (S_{21}) of dipole antennas on a standard and a proton implanted Si substrates as a function of frequency. The transmission coefficient increases +20 dB at 20 GHz by proton implantation. Figure 8 shows the transmission coefficient versus antenna distance. The proton implantation could eliminate the effect of distance on the transmission gain. Figure 9 shows the measured result of the antenna transmission gain at 20 GHz versus the resistivity of the Si substrate with antenna lengths of 1.0, 2.0 and 3.0 mm and is fixed antenna distance of 10.0 mm. The every antenna length, the antenna transmission gain becomes saturated after the resistivity of the Si substrate exceeds 132 Ω·cm. Specifically, when antenna length is 3.0 mm and antenna distance is 3.0 cm, the antenna transmission gain is -43 dB for the Si substrate resistivity of 10 Ω-cm. On the other hand, the antenna transmission gain is -24 dB for the Si substrate resistivity of 2.29 kΩ-cm. The antenna transmission gain was improved by a maximum of +25 dB by making the resistivity of the Si substrate high.

Intra/Inter-chip configurations are shown in Fig. 10, and the measured inter-chip transmission coefficients as a function of frequency were shown in Fig. 11. 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. 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. 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. Received sinusoidal signals at the receiving antennas on the standard and proton implanted Si substrates were shown in Figs. 12(a) and 12(b), respectively. The peak-peak amplitude of the inter-chip transmission of received sinusoidal signal at 20 GHz at the receiver antenna on standard Si was 3.15 mV and 1.04 mV at a distance of 3 mm and 10 mm respectively. When high resistivity Si substrate is used, at a distance of 10 mm the received signal peak-peak amplitude increased by 6 folds to 6.88 mV.

3. **Summary and Future Plan**

A novel signal transmission technology among ULSI chips was developed, which could distribute clock frequencies higher than 10 GHz to circuit blocks as well as among ULSI chips. An ultra wideband (UWB) wireless interconnect system using integrated antennas was developed for reconfigurable multi-channels. It was demonstrated for the first time that a sinusoidal wave clock having frequency of 20GHz could be transmitted between Si chips.

The influence of Si substrate resistivity on the transmission characteristics of integrated antennas was investigated. It is found that Si substrates with the resistivity of 75 Ω-cm as well as the proton implanted Si substrate can minimize the Si substrate loss. A feasibility study of inter-chip characteristics of the integrated antennas was also conducted and consistent results with intra-chip were obtained. The results of transient responses of UWB signals will be reported at IEEE Antenna Propagation Society Conference in June, 2004.

4. References

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5. Achievement

Published papers

1. S. Watanabe, A.B.M.H. Rashid and T. Kikkawa, "Effect of High Resistivity Si substrate on Antenna Transmission Gain for On-Chip Wireless Interconnects, Japanese Journal of Applied Physics Vol. 43, No. 4B, 2004, pp.2297-2301.

2. A.B.M.H. Rashid, S. Watanabe and T. Kikkawa, "Characteristics of Si Integrated Antenna for Inter-Chip Wireless Interconnection," Japanese Journal of Applied Physics Vol. 43, No. 4B, 2004, pp.2283-22287.

3. A.B.M. H. Rashid, S. Watanabe and T. Kikkawa, "High Transmission Gain Integrated Antenna on Extremely High Resistivity Si for ULSI Wireless Interconnect", IEEE Electron Device Letters, Vol. 23, No.12, December 2002, pp.731-733.

4. A.B.M. H. Rashid, S. Watanabe and T. Kikkawa, "Characteristics of Integrated Antenna on Si for On-Chip Wireless Interconnect", Japanese Journal of Applied Physics, Vol. 42, No. 4B, April 2003, pp. 2204-2209.

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5. T. Kikkawa, A.B.M. H. Rashid, and S.Watanabe, "Effect of silicon substrate on the transmission characteristics of integrated antenna," Proc. 2003 IEEE Topical Conference on Wireless Communication Technology , s09p06, Honolulu, Oct. 15-17, 2003.

6. A.B.M. H. Rashid, S. Watanabe and T. Kikkawa, "Crosstalk Isolation of Monopole Integrated Antenna on Si for ULSI Wireless Interconnect", Proceedings of IEEE International Interconnect Technology Conference, 2-4 June,(SanFrancisco, USA, 2003) pp.156-158.

7. A.B.M. H. Rashid, S.Watanabe and T. Kikkawa, "Inter-chip Wireless Interconnection using Si Integrated Antenna, " Ext. Abst. of Inter. Conf. on Solid State Devices and Materials, Tokyo, Sept. 16-18, 2003, pp. 394-395.

8. S. Watanabe, A.B.M. H. Rashid and T. Kikkawa, "Effect of High Resistivity Si Substrate on Antenna Transmission Gain for On-Chip Wireless Interconnects," Ext. Abst. of Inter. Conf. on Solid State Devices and Materials, , Tokyo, Sept. 16-18, 2003, pp. 668-669.

9. S. Watanabe, A.B.M. H. Rashid and T. Kikkawa, "Influence of Si Substrate Ground on Antenna Transmission Gain for on-chip Wireless Interconnects," Abst. Advanced Metallization for ULSI Application, pp. 94-95, 2002, Conference Proceedings, pp.543-548.

10. A.B.M. H. Rashid, S.Watanabe and T. Kikkawa, "Wireless Interconnection on Si using Integrated Antenna", Extended Abstract of 2002 International Conference on Solid State Devices and Materials, (Nagoya, Japan, September, 2002), pp.648-649.

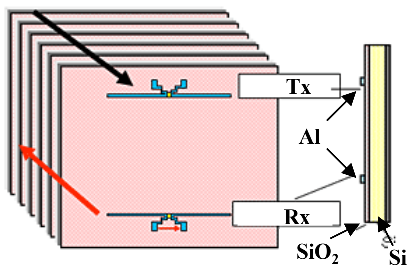

Fig. 1 The concept of inter-chip wireless signal transmission in stacked chip packaging.

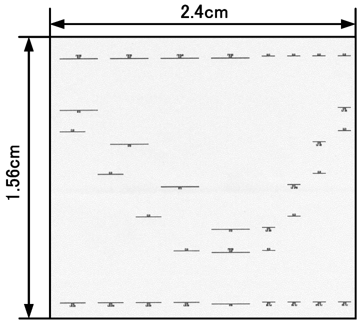

Fig.2. Layout pattern of integrated antennas for intra-chip transmission on silicon.

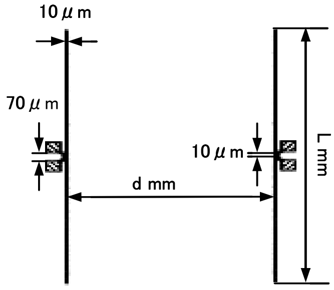

Fig.3. A plan-view of transmitting and receiving antennas on a Si substrate.

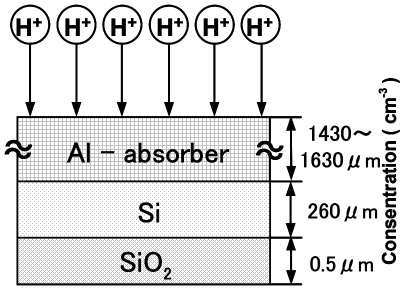

Fig.4. Schematic diagram of proton implantation.

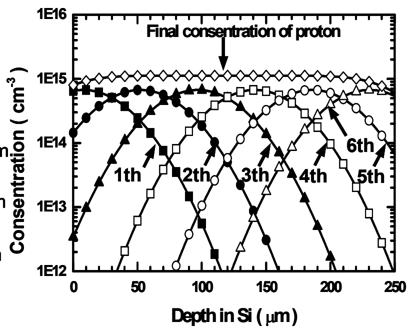

Fig.5. Simulated concentration profile of proton in Si.

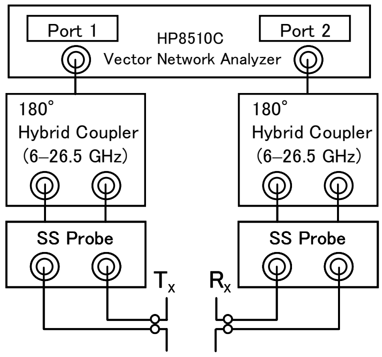

Fig.6. Experimental set-up for inter /intra-chip antenna characterization.

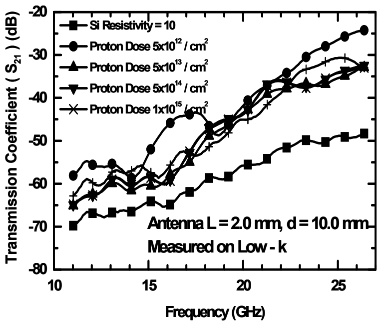

Fig.7 Transmission coefficient (S_{21}) versus frequency. (Effect of proton dose) (Antenna L=2.0mm, d=10.0mm)

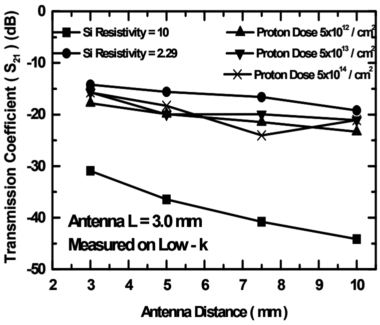

Fig.8 Transmission coefficient versus Antenna Distance. (Effect of proton dose) (Antenna L=3.0mm)

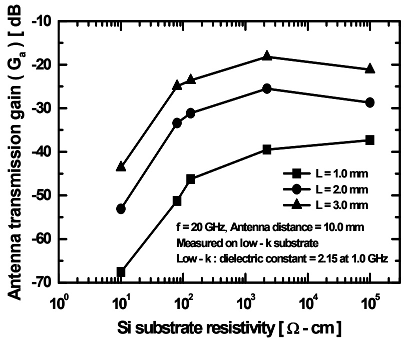

Fig. 9 Antenna transmission gain of dipole antenna versus Si substrate resistivity (ρ) with antenna length (L) as a parameter .

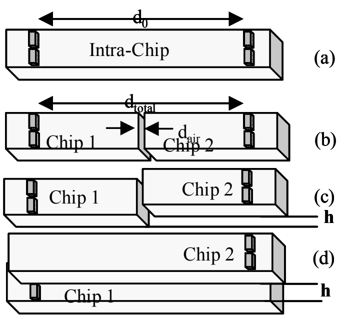

Fig.10 Different configurations used for evaluation. (a) Intra-chip, (b) Inter-chip on the same plane (h=0), (c) Inter-chip with height between the chips h=2.6mm, (d) Inter-chip overlapped with h=2.6 mm.

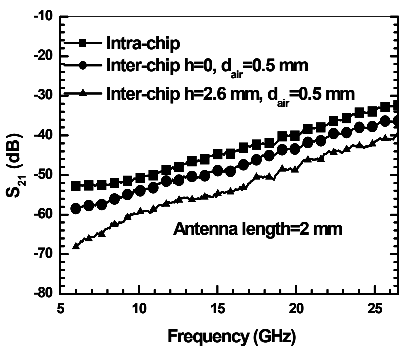

Fig. 11 Measured transmission coefficient of inter-chip wireless signal transmission in various configurations.

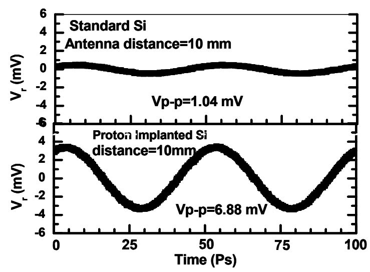

Fig.12 Peak to peak amplitude of received signal increases from 1 mv to 6.9 mV by using proton implanted Si.