Wireless Interconnection on Si LSI using Integrated Antenna

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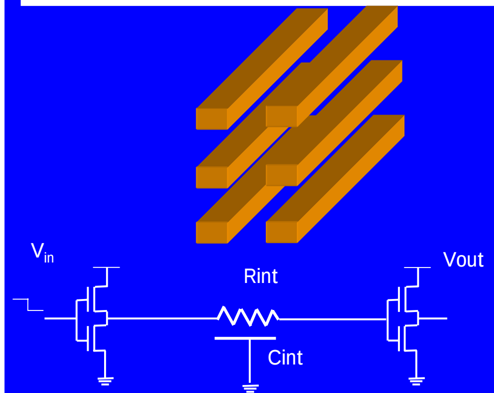
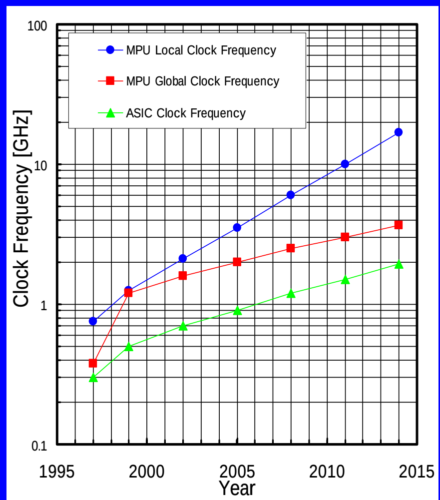
Outline

Limitation of Clock Frequency for ULSI

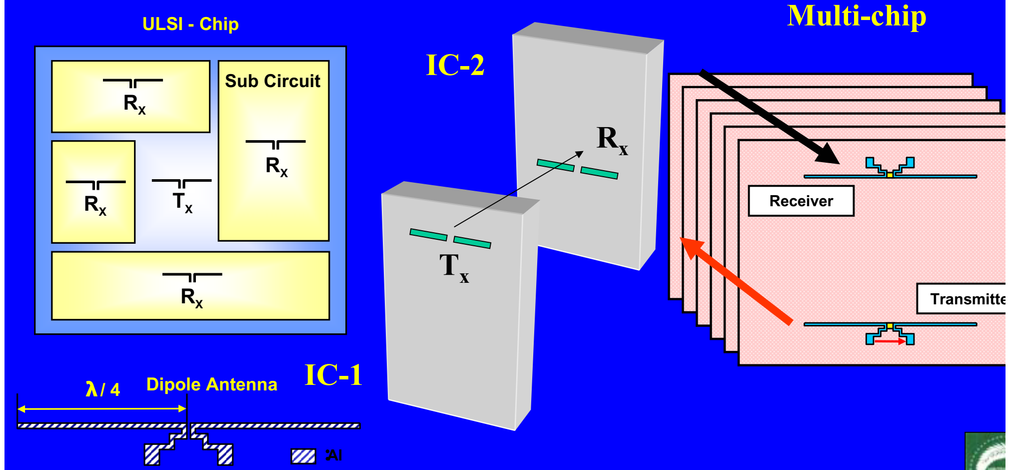


$$T_{90\%} = 1.0 R_{int} C_{int} + 2.3 (R_{tr} C_{int} + R_{tr} C_L + R_{int} C_L) \cong 2.3 (R_{tr} + R_{int}) C_{int} \quad (C_L << C_{int})$$

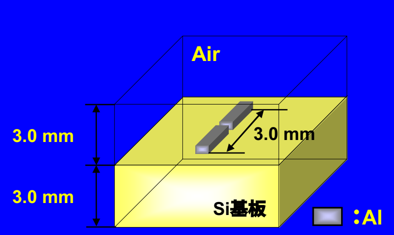


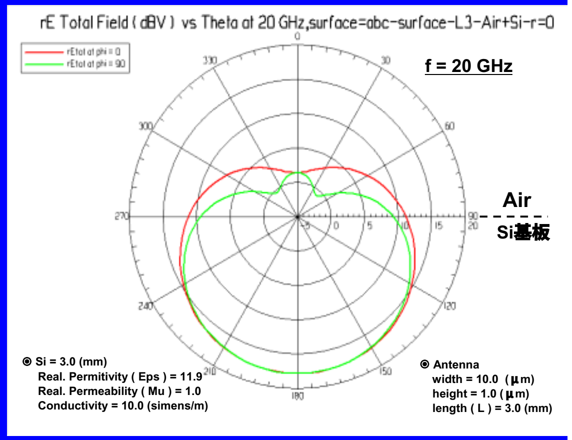
$$T_{90\%} \cong 2.3 (R_{tr} + R_{int}) C_{int} = 2.3 (178 + 2400) \times 3.54 \times 10^{-13} = 2.1 n\sec$$

Wireless Clock and Data Transmission for Si ULSIs



Transmission through Si using Integrated Antenna





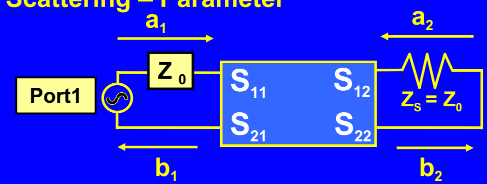
Radiation Pattern of Si Integrated Antenna

$$\lambda_{Air} = \frac{v_c}{f} = \frac{3.0 \times 10^8}{20 \times 10^9} = 1.5\ (cm)$$

$$\lambda_{Si} = \frac{\lambda_{Air}}{\sqrt{\varepsilon_{Si}}} = \frac{1.5\ (cm)}{\sqrt{12}} = 4.33\ (mm)$$

Measurement Setup for Transmission Gain

Scattering – Parameter



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

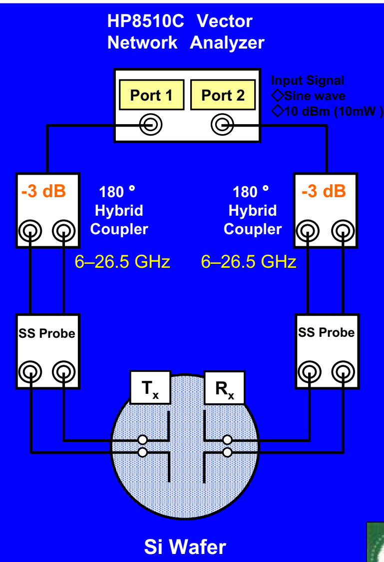
a_i - Incident wave
b_j - Reflected wave

$$S_{ii} = \frac{b_i}{a_i}\bigg|_{a_j = 0} \qquad S_{ij} = \frac{b_j}{a_i}\bigg|_{a_j = 0}$$

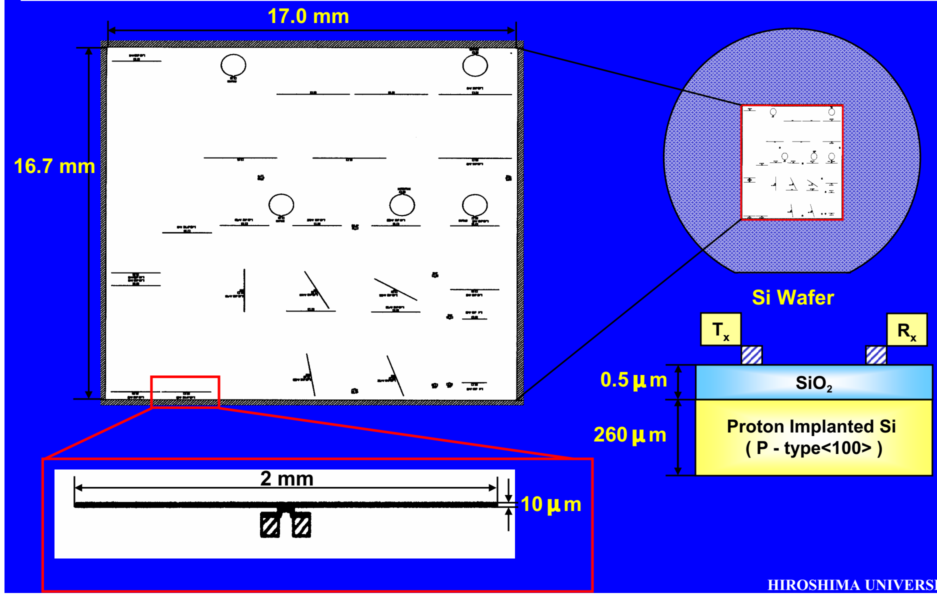
Antenna transmission gain (G_a)

$$G_a = G_r \cdot G_t \cdot \left(\frac{\lambda}{4\pi R}\right)^2 = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)}$$

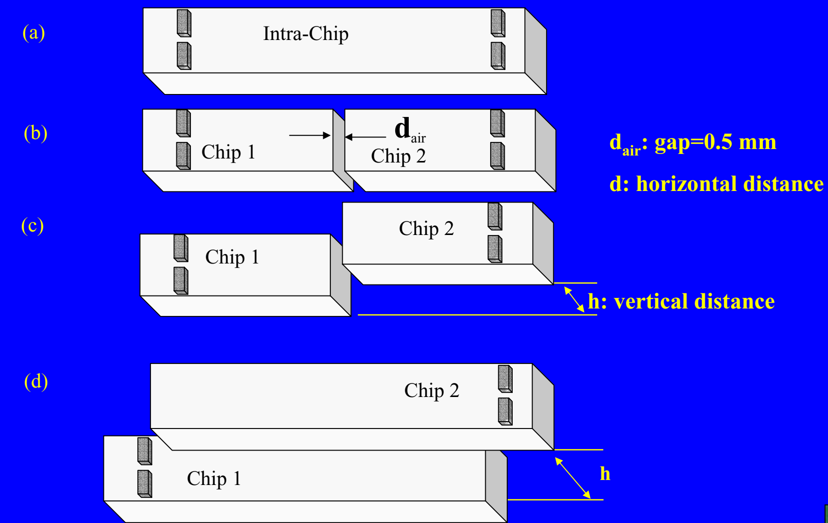
G_r = Receiver Gain, G_t = Transmitter Gain



Layout of Integrated Antenna for Intra-chip Transmission



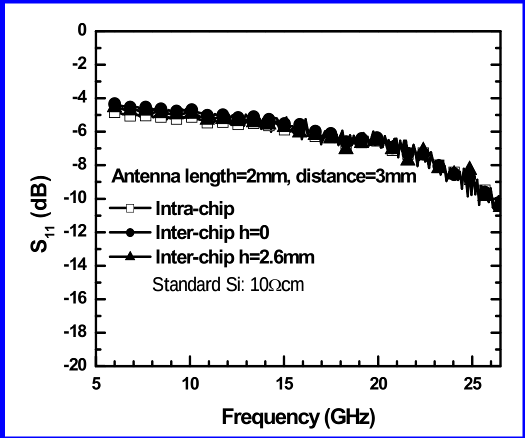
Configuration of Integrated Antennas for Inter-chip Transmission

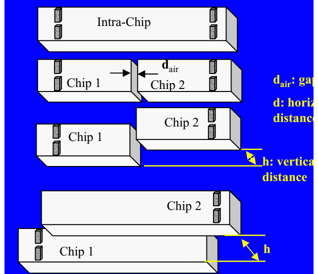


d_{air}: gap=0.5 mm

d: horizontal distance

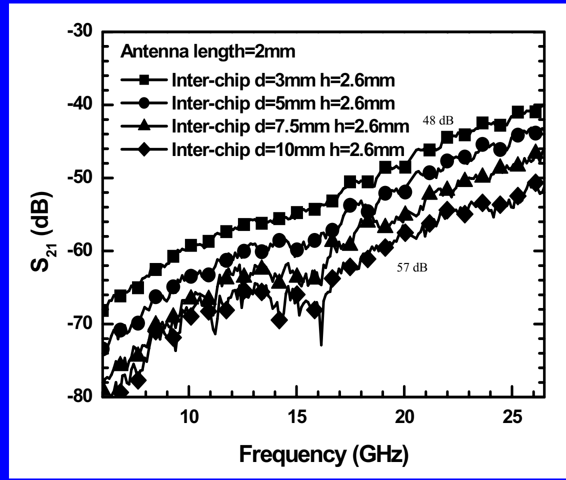
Reflection Coefficient (S_{11}) of Transmitting Antennas on Si

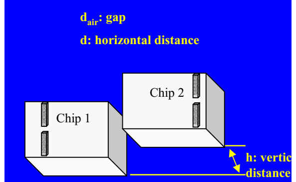




Reflection coefficients does not depend on the inter/intra-chip antenna configurations

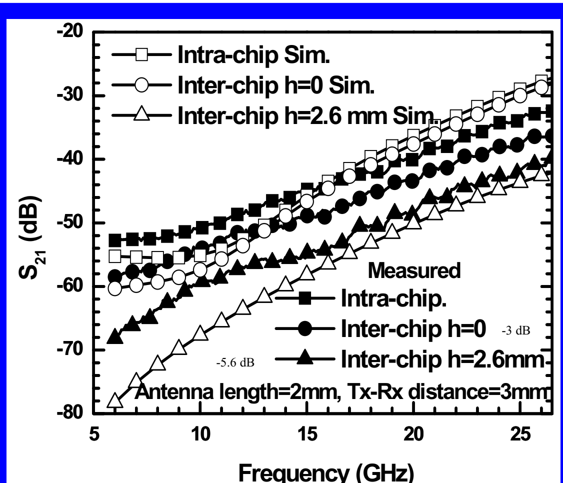
Inter-chip Transmission Coefficient versus Frequency
Dependence of Horizontal Distance on Transmission Coefficien

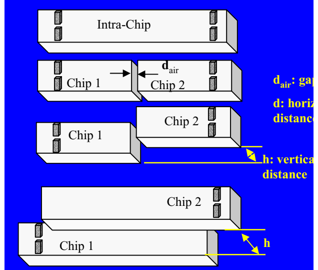




Transmission coefficients at 20 GHz are -48.7 and -57.9 dB at distances of 3 and 10 mm, respectively.

Inter-chip Transmission Coefficient versus Frequency
Dependence of Vertical Distance on Transmission Coefficient (S

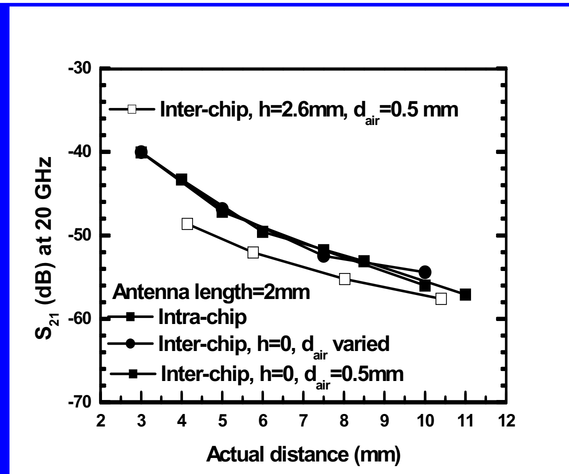


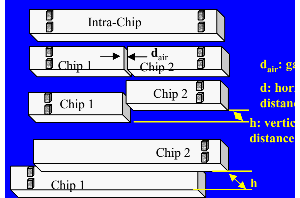


Inter-chip transmission coefficient decreases

-3 dB by a horizontal gap of 0.5 mm and -5.6 dB by 2.6 mm vertical distance.

Inter-Chip Transmission Coefficient versus Actual Distance





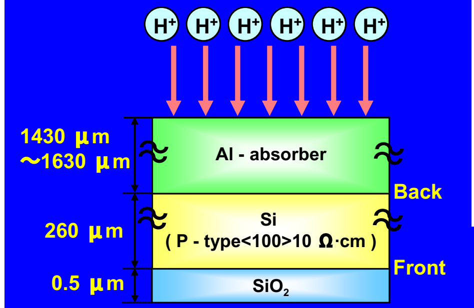
Transmission coefficients depends on effective distances between antennas

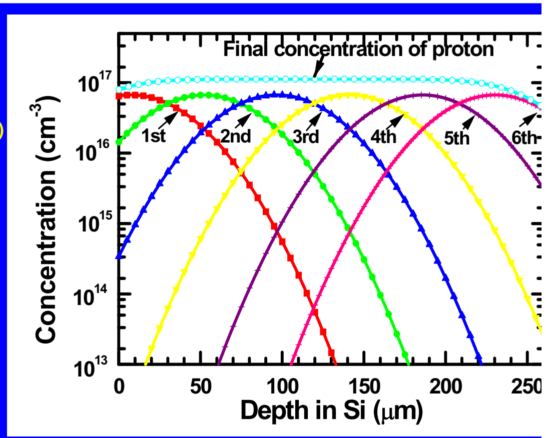
The major path of EM wave is in the low-k substrate so that air gap has negligible effect.

Effect of High-Resistivity Si Substrate by Proton Implantation

Proton Energy : 17.4 MeV
Proton Dose : 5x10^{12} ~ 1x10^{15} /cm^2
No. of Implantation = 6
Range control : by varying Al
Al absorber thickness : 1630µm - nx40µm (n = 0 ~ 5)

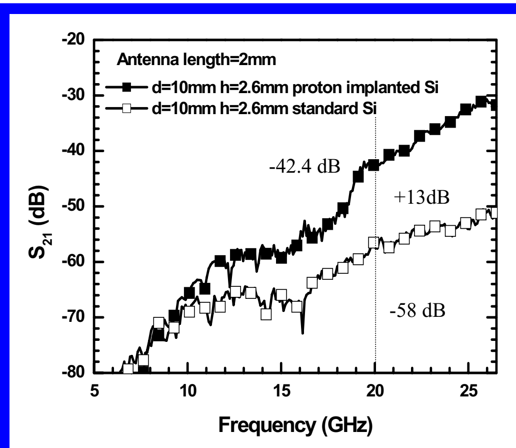
Si Resistivity : 65 kΩ·cm (5x10^{14} /cm^2)





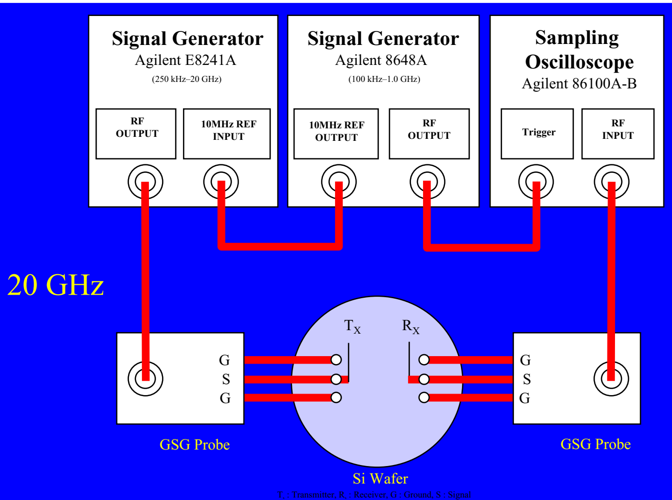
Proton Dose : 5x10^{14} /cm^2

Effect of High-Resistivity Substrate on Inter-Chip Transmissio

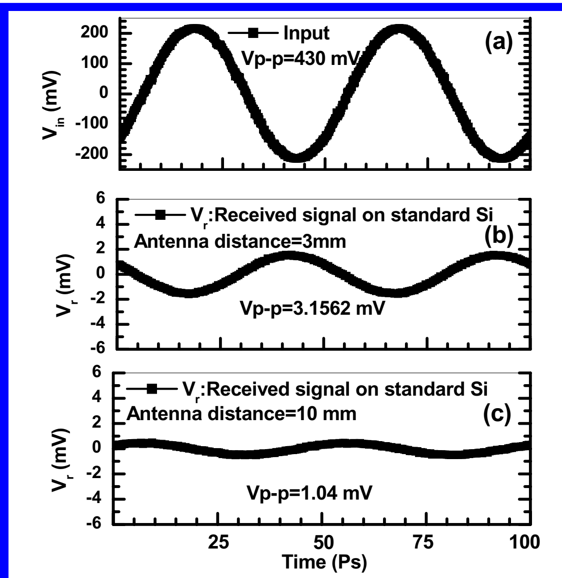


Transmission coefficient of -57.9 dB at 20 GHz for horizaontal separation distance of 10.5 mm and the vertical distance of 2.6 mm.
High resistivity Si substrate by proton implantation improved the transmission coefficient to -42.4 dB.
The transmission coefficient on the proton implanted Si substrate increased 13.4 dB at 20 GHz

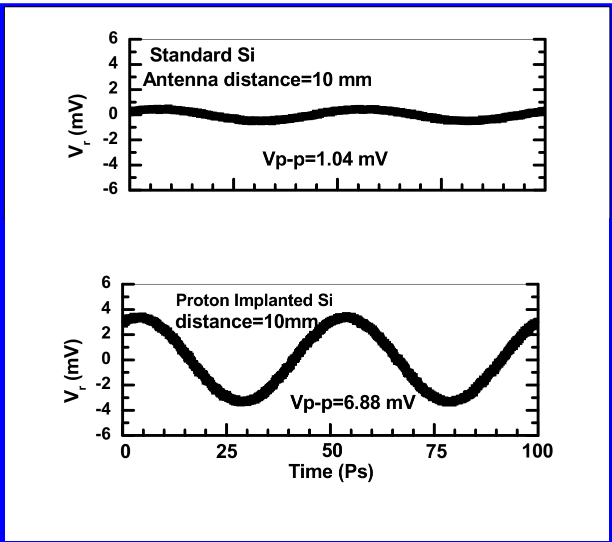
Measurement for Time Domain Signal Transmission



Inter-chip Transmission of Sinusoidal Signal at 20GHz on 10 Ωcm Si



Effect of High Resistivity Si on Inter-chip Transmission of Sinusoidal Signal



Conclusion

Inter-chip signal transmission between Si substrates shows a transmission coefficient of -57.9 dB at 20 GHz for 2 mm long antenna when the transmitting and the receiving antenna separation distance is 10.5 mm and the receiver chip is at a height of 2.6 mm from the transmitter chip.

When high resistivity Si substrate is used the transmission coefficient increases 13.4 dB at 20 GHz 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.