Extended Abstracts of the 2000 International Conference on Solid State Devices and Materials, Sendai, 2000, pp. 418–419

A-8-3

Interconnect and Substrate Structure for High Speed Giga-Scale Integration

Akihiro Morimoto,[1] Koji Kotani,[1] Sigetoshi Sugawa,[1] and Tadahiro Ohmi[2]
[1]Department of Electronic Engineering, Graduate School of Engineering, Tohoku University,
05 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
Phone: +81-22-217-7122 / Fax: +81-22-224-2549, E-mail: moriaki@sse.ecei.tohoku.ac.jp
[2] New Industry Creation Hatchery Center, Tohoku University,
Aza-Aoba, Aramaki, Aobaku Sendai 980-8579, Japan

1. Introduction

In future miniaturized systems, speed performance of LSI will be mainly determined by interconnect delay, not by gate delay[1]. The analysis method is, however, mainly based on the simple RC delay model, which is determined by DC resistance and static capacitance. Moreover, in such model, inductance and skin effect, which are indispensable to analyze high frequency characteristics of interconnects are ignored. Another analysis method must be taken to estimate future interconnect characteristics precisely.

In this paper, we introduce a stacked coaxial structure and analyze signal propagation properties with 2-D effect or width effect, which was neglected in our previous analysis with infinite width interconnects[2] by solving Maxwell's equation for given interconnect structure. We also describe propagation properties of novel interconnect and substrate structure, such as gas-isolated and metal substrate structure, which is the most promising for future high speed giga-scale integration.

2. Solving Maxwell's equations with stacked coaxial structure

Since it is very complicated and difficult to analyze real interconnect structure directly by solving Maxwell's equations, we have introduced stacked coaxial structure which well reflect the real interconnect structure shown in **Fig.1**. Inner metal (interconnect) with its diameter: d is surrounded by interlayer dielectric having relative permittivity and thickness of ε_r and 1μm, respectively. Si substrate whose relative permittivity, resistivity and thickness are 11.9, ρ_{Si}, and 300μm, respectively, surrounds the interlayer dielectric. The Si substrate is wrapped with outer metal which is supposed to have infinite thickness. Both relative permittivity of metal and relative permiability for all materials are supposed to be 1. Loss tangent for both interlayer dielectric and Si substrate are neglected. To solve cylindrical Maxwell equations, the Newton method is used.

3. Results and Discussion

Fig.2 shows signal propagation properties as a function of interconnect diameter. The cases of Al, Cu and ideal metal whose resistivity are supposed to be 3, 1.7 and 0 μΩcm, respectively, for interconnect material are shown. If the interconnect diameter is larger than some critical diameter: d_{crit} of several μm, propagation properties are determined by substrate. On the contrary, for narrower diameter region, interconnect material determines the propagation characteristics. Interconnect resistivity must be as low as possible for future submicron interconnects.

Signal propagation properties as a function of substrate resistivity in the case of interconnect diameter of 100μm are shown in **Fig.3.** Solid line and dashed line are the cases of Cu and ideal metal for interconnect material, respectively. The result implies extremely conductive or resistive substrate can reduce both attenuation constant and phase constant much less than those in the case of substrate resistivity of middle resistivity range, i.e., signal attenuation can be reduced and propagation speed can be increased by such conductive or resistive substrate.

Substrate voltage fluctuation causes erroneous operation of neighboring transistors or cross-talk problem. **Fig.4** shows effective rms substrate voltage when $1V_{rms}$ signal is applied in the inner interconnect as a function of substrate resistivity, which enables us to evaluate cross-talk interference. Extremely conductive substrate can maintain substrate in quite low level. The results obtained from **Fig.2** to **Fig.4** indicate that introduction of metal substrate and resulting MIM interconnect structure are essential to propagate signals for long distance without substrate noise problem.

Fig.5 shows signal propagation properties as a function of interconnect diameter in the case of MIM structure, which is obtained by replacing the Si substrate with the same metal as the outer metal. Interconnect and substrate materials are supposed to be Cu. The result indicates that reduction of relative permittivity can reduce both propagation and phase constant. This result is essential because for the propagation characteristics improvement in narrow interconnect region, reducing relative permittivity to 1 is a physical limit. Isolation by air or another gases whose relative permittivity is 1 is the only way to obtain the high speed signal propagation characteristics.

Figs.6 and 7 show waveforms of 100psec pulse signal propagating through Cu interconnect in the cases of interconnect diameter of 0.1μm and 2μm, respectively. (a) and (b) in both figure are the cases of conventional Si substrate with its resistivity of 1Ωcm and MIM(Cu/Gas/Cu) structure, respectively. It is clearly seen that the gas-isolated, metal substrate structure can propagate high speed signals without significant attenuation and delay. The gas-isolated, metal substrate structure is the most promising for future interconnects with giga-scale integration.

4. Conclusion

Interconnect and substrate structure suited for high speed signal propagation and giga-scale integration are discussed directly by solving cylindrical Maxwell's equations with stacked coaxial interconnect structure model. Introduction of metal substrate and gas-isolated interconnect is the most promising for future high speed giga-scale integration (**Fig.8**). Thermal through-hole shown in the figure effectively enhances thermal removal of interconnects and strengthens gas-isolated interconnect structure against mechanical stresses and it is discussed in the literature[3]. Production technology for metal substrate and gas-isolated interconnects have already been developed[3].

References

[1] M.T .Bohr, "Interconnect Scaling –The Real Limitter to Hig Performance ULSI," Tech.Dig. 1995 IEDM, pp.241-244,1995.

[2] T.Ohmi, S.Imai and T.Hashimoto, "VLSI Interconnects for ultra high speed signal propagation," Proceeding of V-MIC Conf. pp.261-267, 1988.

[3] T.Ohmi, "New Paradigm in Semiconductor Industry ~ An Approach to Smart Signal Processing and Perfect Scientific Manufacturing ~," Ultra Clean Technology Vol.11 Supplement 1, Ultra Clean Society, 1999.

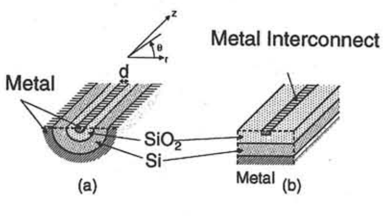
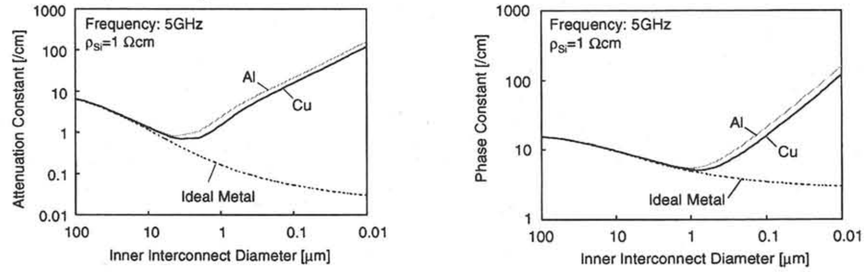
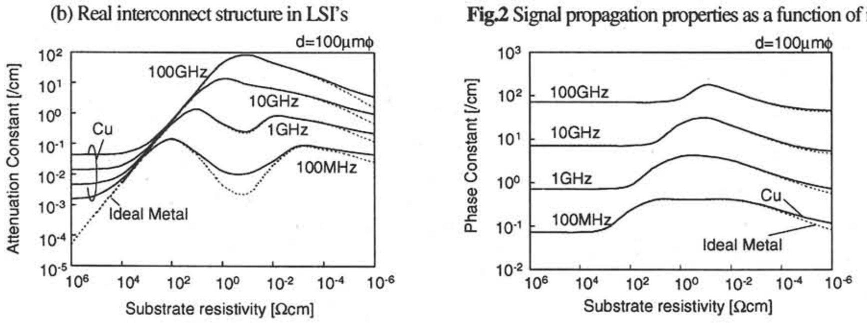


Fig.1 (a) Stacked coaxial structure in this study
(b) Real interconnect structure in LSI's



(a) attenuation constant (b) phase constant

Fig.2 Signal propagation properties as a function of interconnect diameter. The cases of Al and Cu are shown.



(a) attenuation constant (b) phase constant

Fig.3 Signal propagation properties as a function of substrate resistance.
The cases of Cu and ideal metal interconnect are shown.

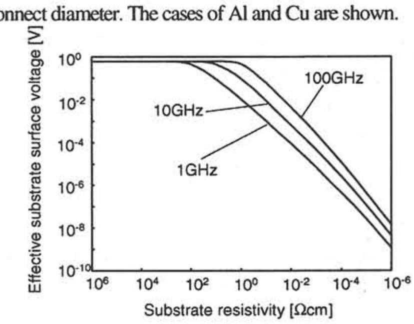
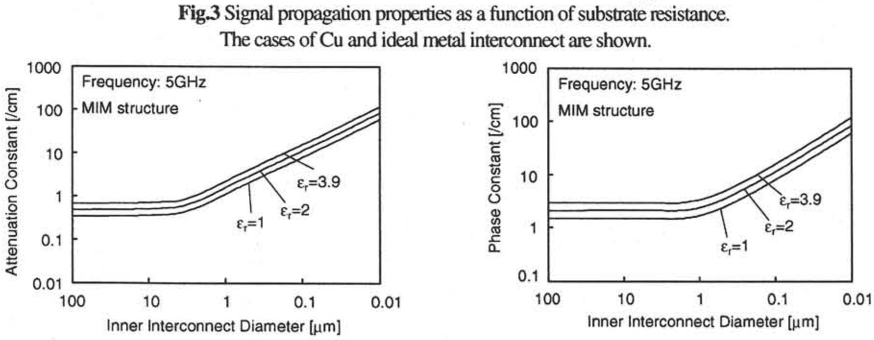
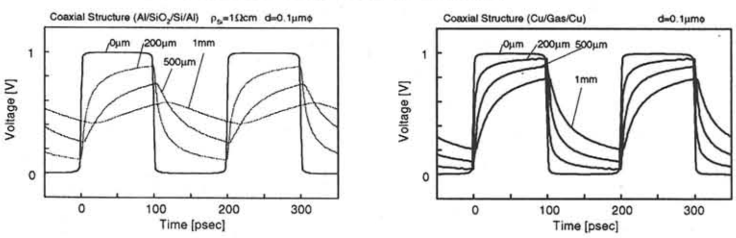


Fig.4 Effective rms substrate voltage for evaluation of cross-talk interference.



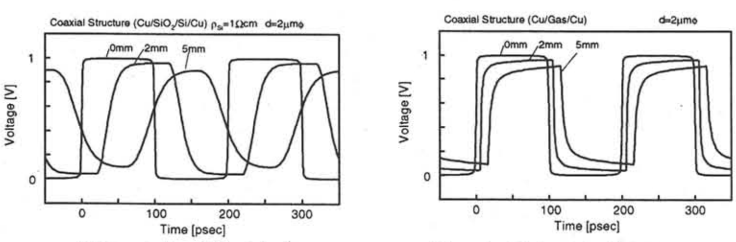
(a) attenuation constant (b) phase constant

Fig.5 Signal propagation properties as a function of interconnect diameter in MIM structure.
The cases of relative permittivity of 1, 2, 3.9 are shown.



(a) conventional Si substrate (b) gas-isolated metal substrate structure

Fig.6 Waveforms of 100psec pulse signal for short interconnect



(a) conventional Si substrate (b) gas isolated metal substrate structure

Fig.7 Waveforms of 100psec pulse signal for long propagation

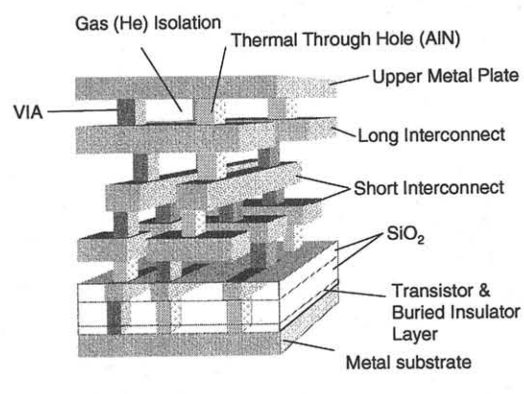


Fig.8 Schematic view of gas-isolated interconnect, metal substrate structure.