Influence of the Substrate Resistivity on the Broadband Propagation Characteristics of Silicon Transmission Lines[1]

Uwe Arz and Hartmut Grabinski
Laboratorium für Informationstechnologie, Universität Hannover
Schneiderberg 32, D-30167 Hannover, Germany
Ph: [+49] 511.762.5056 E-mail: uarz@lfi.uni-hannover.de

Dylan F. Williams
National Institute of Standards and Technology
325 Broadway, Boulder, CO 80303

***Abstract*- This work investigates the broadband propagation characteristics of transmission lines fabricated on silicon substrates of different conductivities. We compare calculations to measurements and examine the sensitivity of the frequency-dependent line parameters to substrate conductivity.**

INTRODUCTION

This work investigates signal propagation on the structures shown in Fig. 1, which are typical of interconnects in digital integrated circuits. The 10-µm wide signal line is separated from two 20-µm wide grounds by a 105-µm gap. The ground lines are connected to the silicon substrate with ohmic contacts of 10-µm width. The oxide layer is 500-nm thick, and the metal has a conductivity of 23×10^6 [S/m] and is 600-nm thick.

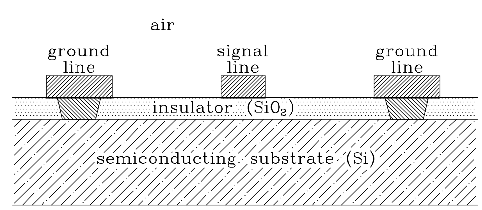

Figure 1: Cross-sectional view of the line structure investigated

We calculate the line parameters with the quasi-analytical procedure described in [1]. This approach uses Green's functions for layered media to derive analytical formulas for the distributed line impedances and admittances. We discuss the calculated frequency-dependent behavior of the line parameters and compare it to measurement.

NUMERICAL CALCULATIONS

Hasegawa et al. [2] identifies three regions of operation in their classic paper on the analysis of microstrip lines in Si-SiO_2 systems: the “slow-wave” region, the “skin-effect” region and the “dielectric quasi-TEM” region. Fig. 2 shows the frequency-dependent line parameters calculated using the method of [1] for silicon substrates with low (σ=60 S/m), medium (σ=600 S/m) and high conductivities (σ=6000 S/m). This combination of conductivities and frequencies spans all of Hasegawa’s three regions of operation.

The graphs of the distributed line parameters clearly show the influence of the skin effect in the substrate. At lower frequencies the current penetrates deeply into the substrate. Consequently, for the high-conductivity substrate and low frequencies, the resistance of the substrate is much smaller than the resistance of the ground lines and the majority of the return current flows in the substrate.

However, due to the strong skin effect in the substrate, the substrate resistance increases rapidly with frequency. This explains the increase in the total resistivity *R* of the transmission line for the high conductivity case (solid line of Fig. 2). The figure also shows that this increase in *R* becomes weaker for decreasing substrate conductivities.

The extent to which the substrate is penetrated by the magnetic field is also affected by the skin effect.

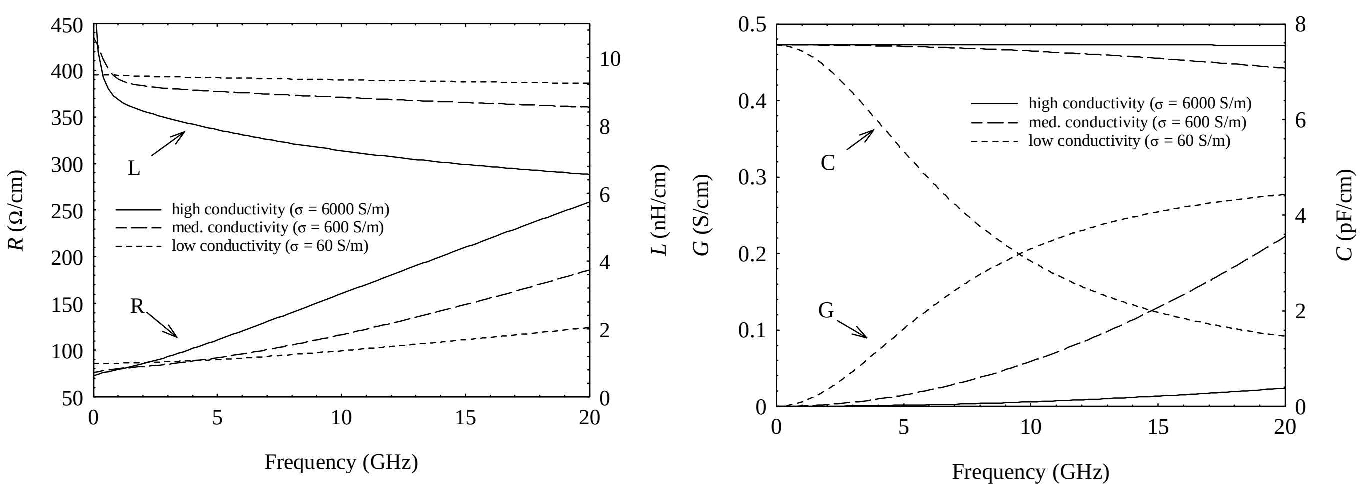

Fig.2. Line parameters per unit length for three typical values of the silicon substrate conductivity.

This can be seen from the inductance parameters in Fig. 2. For the lowest conductivity (short dashes) the inductance is nearly constant. For higher substrate conductivities and higher frequencies we observe a decrease of the inductance as the magnetic fields are expelled from the substrate. This is typical of the transition from the “slow-wave” to the “skin-effect” region.

The admittance parameters in Fig. 2 show the transition from the “slow-wave” to the “dielectric quasi-TEM” region. The high-conductivity substrate acts as a ground plane for the electric field. As a result, the capacitance remains nearly constant because the electric field is concentrated in the oxide. However, for lower conductivities and higher frequencies the penetration of the electric field in the substrate increases. This leads to the reduction in the capacitance shown in the figure.

EXPERIMENTAL RESULTS

We fabricated test structures corresponding to Fig. 1 on silicon substrates with conductivities in the ranges of 4,000 to 20,000 S/m (0.005 to 0.025 Ω-cm) and 50 to 100 S/m (1 to 2 Ω-cm). We measured the characteristic impedance Z_0 of these structures using the calibration comparison method of [3]. This method is a modification of that described in [4], which [3] shows is better able to take into account the large contact-pad parasitics encountered on lossy substrates. The method measures the error boxes describing the transition between probe tip and line segment and models these error boxes as a shunt admittance in series with a complex impedance transformer. We obtained the propagation constant γ of the structures from a multiline TRL calibration [5] and calculated R, L, G, and C from γ and Z_0 using the formulas $R+j\omega L=\gamma Z_0$ and $G+j\omega C=\gamma/Z_0$.

Figures 3 and 4 compare experimental results for line widths of 10 µm and 50 µm to calculations obtained from the calculation method of [1]. The agreement between experimental data and simulation is fairly good over the measurement range of 100 MHz to 40 GHz, with better agreement evident for the 50-µm line than the 10-µm line. The line parameters obtained from the new calibration comparison method clearly confirm the effect of the substrate resistivity on R, L, G, and C predicted by the simulations.

CONCLUSION

The agreement between simulation and experiment is fairly good for the impedance parameters *R* and *L*, indicating that the method of [1] employs an adequate model for the skin effect in the substrate. However, while [1] includes the skin effect in the substrate in the calculation of *R* and *L*, it does not take skin effect into account in the calculation of *G* and *C*. This might explain the deviations between simulations and experiment observed in *G* for the 10-µm wide line. Since the values of *C* are still in good agreement, and since the influence of *G* on signal propagation is usually negligible, the differences observed play only a minor role in signal propagation in any case.

The measurement results presented in this paper confirm the complicated behavior predicted by the simulations and demonstrate the potential of the new calibration comparison method for a wide variety of measurement applications on silicon.

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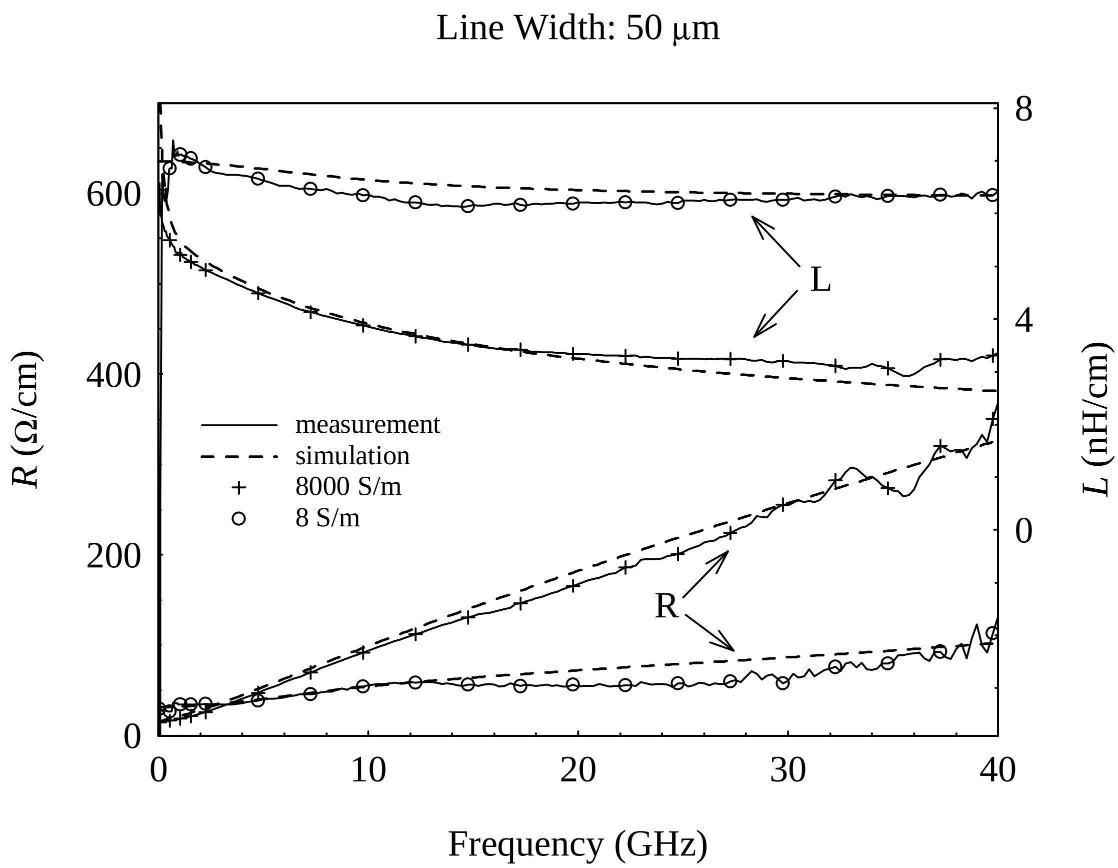


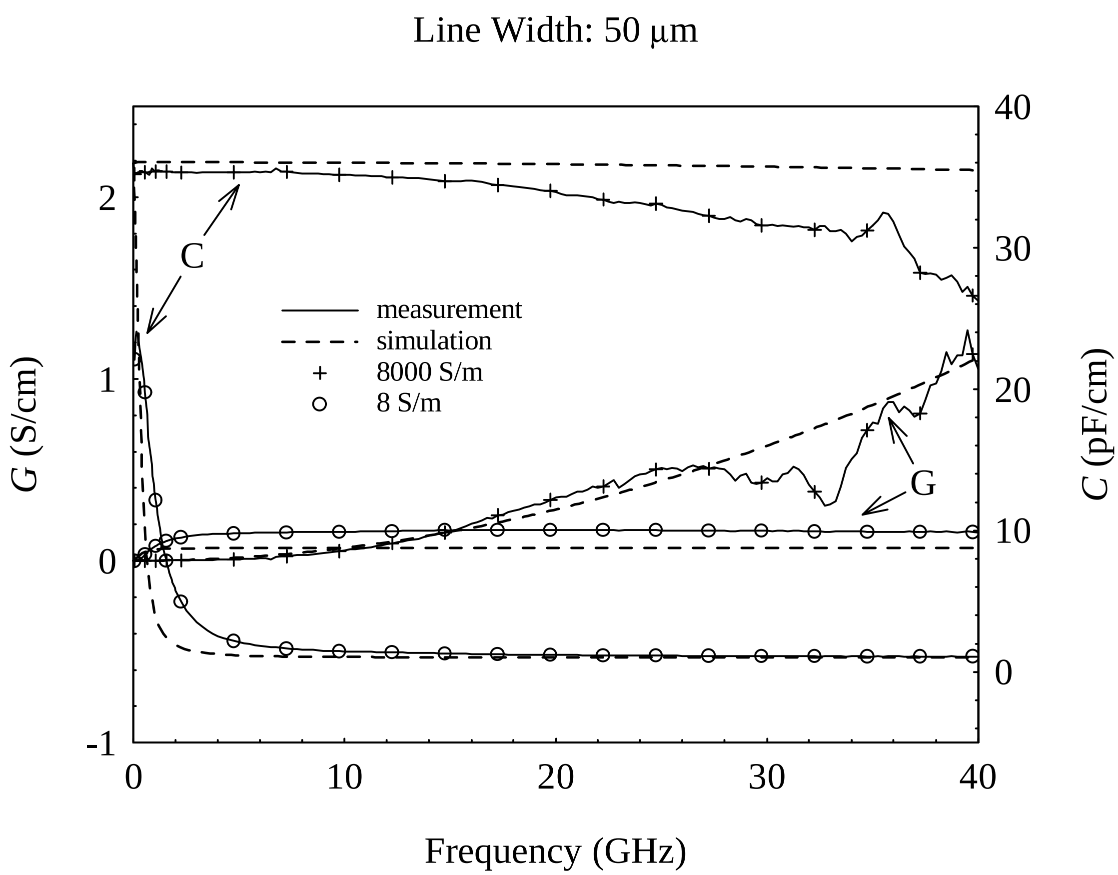
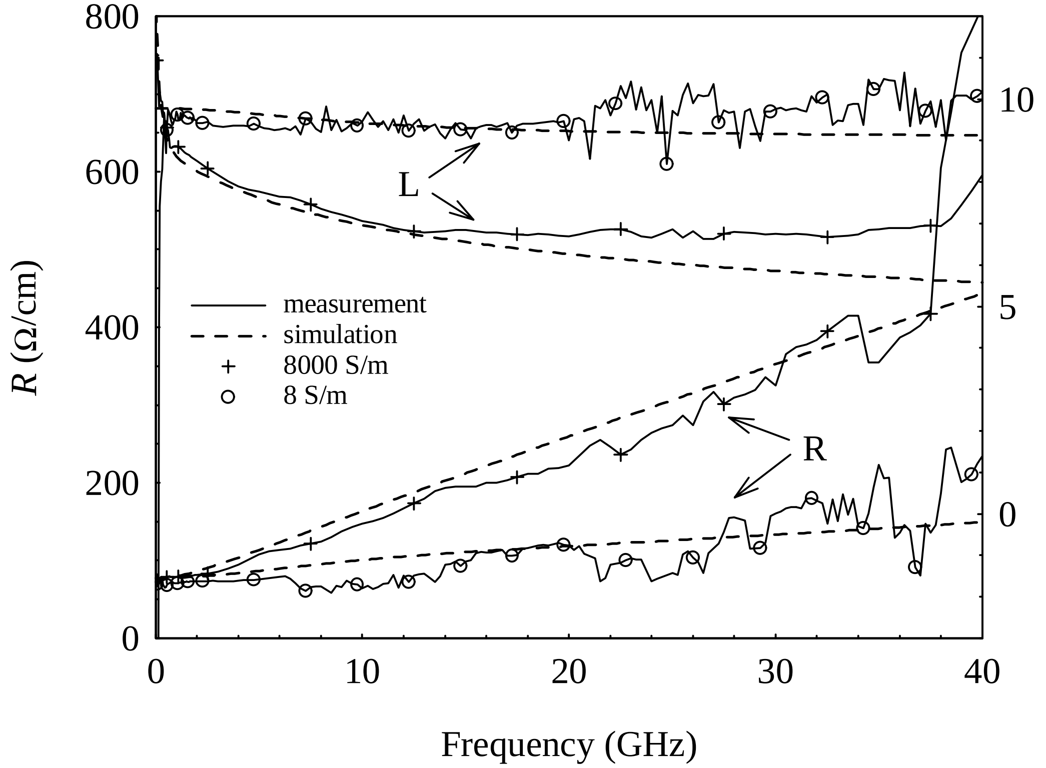


Fig. 3: Experimental results compared to simulations (line width of 50 μm)

Line Width: 10 μm



Line Width: 10 μm

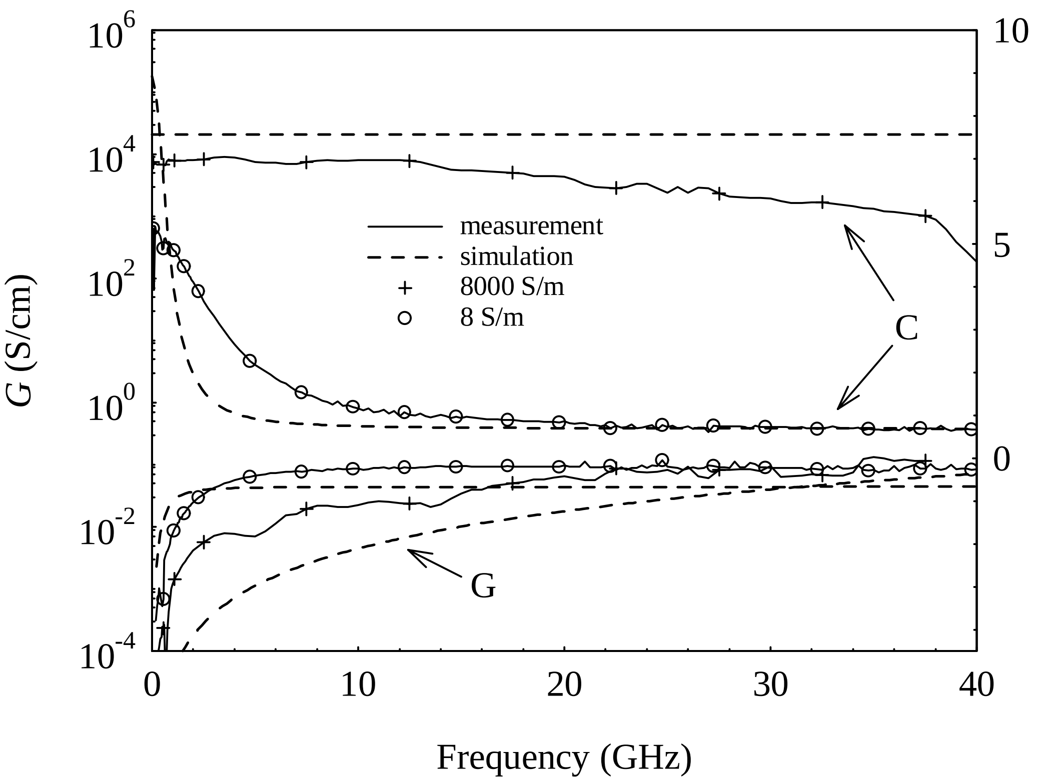


Fig. 4: Experimental results compared to simulations (line width of 10 μm)