Experimental Determination of the Importance of Inductance in Sub-Micron Microstrip Lines

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Abstract

The importance of inductance in sub-micron cross-section lines is examined. We experimentally show that small cross-section, high-loss lines are RC dominated into the low GHz frequency range, and only begin to exhibit inductive effects above 10 GHz. We also show by comparing experimental data and a simple model that skin effect and substrate effects are small, if present, in these lines up to 40 GHz.

Introduction

As clock frequencies increase, there is concern that interconnect lines can no longer be modeled as simple RC transmission lines, using the DC resistance for R and the static capacitance as C . Contributions from inductance, the skin effect, and the substrate are of particular interest. This paper focuses on experimentally determining the effect of inductance, skin, and substrate effects on sub-micron interconnect lines

Experiments were carried out using microstrip test structures manufactured by SEMATECH. The wafers were processed using a three metal level, 0.35 µm, Al/SiO_2 process.[1].

Experimental Alpha and Beta

Three different widths of microstrip transmission line structures were studied. The signal lines for these structures were nominally identical except for width. The structures consist of a signal line 0.68 µm thick and 6400 µm long embedded in SiO_2. The nominal distance from the signal line to the silicon substrate, which acts as the ground plane, is 2.48 µm. The three widths used were 0.35 µm, 0.5 µm and 0.7 µm.

The S-parameters of the structures were measured between 400 MHz and 40 GHz using a network analyzer. The S-parameters were then converted into the propagation constant (gamma) and the characteristic impedance (Z_0). The phase constant (beta) and the attenuation constant (alpha) are shown in Fig. 1 for all three widths of line. These parameters were further converted into RLCG (resistance, inductance, capacitance, and conductance) transmission line parameters. R and ωL per unit length for all three lines are shown in Fig. 2. The extracted capacitance per unit length is shown in Fig. 3.

As shown in Fig. 1, alpha and beta are equal to each other at frequencies below about 3 GHz for each of the three lines. This is a characteristic of an RC transmission line. For all the lines, the slopes of alpha and beta have a $\sqrt{\omega}$ dependence at frequencies less than 3 GHz, again clearly indicating that the interconnects are RC dominated transmission lines below 3 GHz.

Above 3 GHz, alpha and beta start to separate and have different slopes. The frequency at which the alpha and beta start to separate varies with width of the signal line as shown in Fig 1. This is due to the loss increasing as cross-sectional area decreases, i.e., a higher resistance line is dominated by R to a higher frequency.

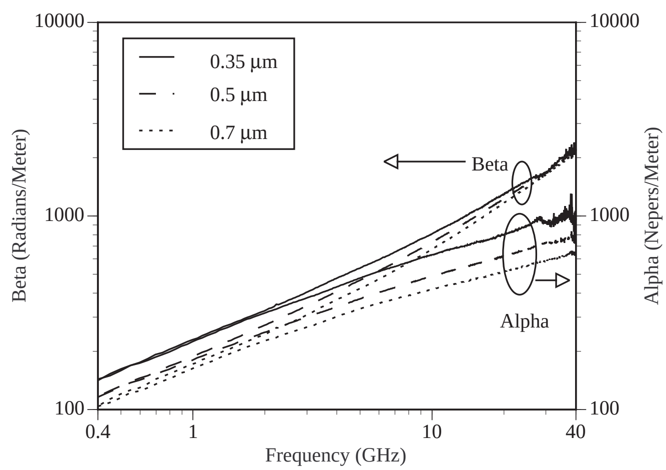

Fig. 1. Beta and alpha for three line widths.

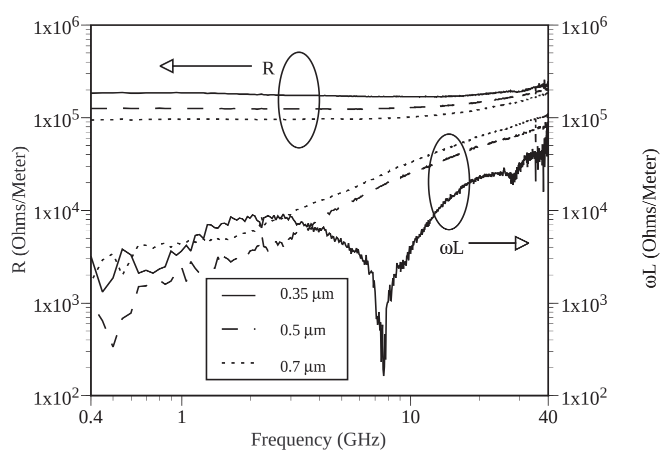

Fig. 2. R and ωL for three line widths.

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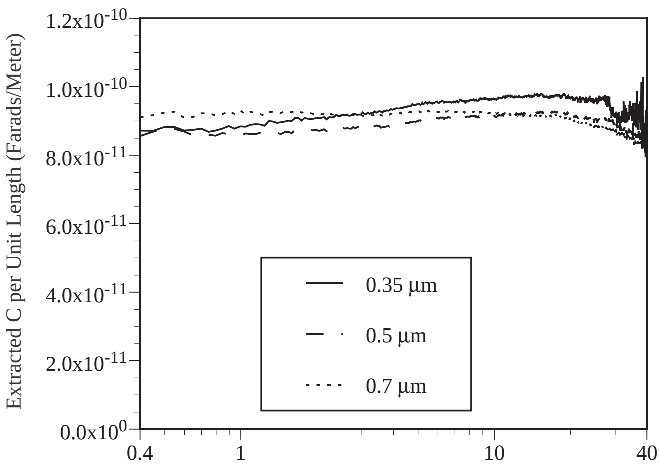

Fig. 3. Extracted capacitance per unit length for three line widths.

The relative importance of resistance and inductance is shown in Fig. 2. At frequencies less than 3 GHz, the resistance is greater than 10 times ωL for all three lines which implies that L does not contribute significantly to the series impedance. Above 3 GHz the R of the 0.7 µm line is greater than ωL but not 10 times greater. This indicates that ωL is important but R is still the dominant term in the series impedance. The other two widths of lines show similar behavior but the frequencies are higher.

The extracted capacitance per unit length shown in Fig. 3 is the same (within 10%) for all three widths of line. This is because for these geometries the fringe fields from the top and sides of the signal line contribute substantially to the overall capacitance.

Substrate Effects and Skin Effect

To determine the contribution of any high-frequency substrate effects, we modeled the microstrip lines using Wheeler's microstrip equations [2]. From Wheeler, we determined the inductance and capacitance per unit length in the high frequency limit. We then calculated alpha and beta using the L and C from Wheeler and the measured end-to-end DC resistance of the signal line. The comparison between experimental and modeled alpha and beta for the 0.5 µm line is shown in Fig. 4. The results for the other two lines are not shown but are similar.

As the figure shows, the model fits the data well, especially for alpha. The apparent disagreement in beta is due to our inability to exactly determine all the dimensions and material parameters needed by Wheeler. Since alpha is dominated by the DC resistance, an experimentally determined quantity, its agreement is better.

Based on these results, we conclude that the attenuation is predominately due to the DC resistance of the signal line and not skin effect or substrate effects. Any skin effect is difficult to measure because the high frequencies where it is likely to occur are also the noisiest in the measurement. This makes any small increase in loss difficult to assign to any specific cause because the error at those frequencies is likely larger than the small increase expected from skin and substrate effects. The model using Wheeler's equations only considers a perfectly conducting ground plane and works very well over the entire frequency range. This indicates that if skin effects or substrate effects are present they are small and dominated by the DC resistance term.

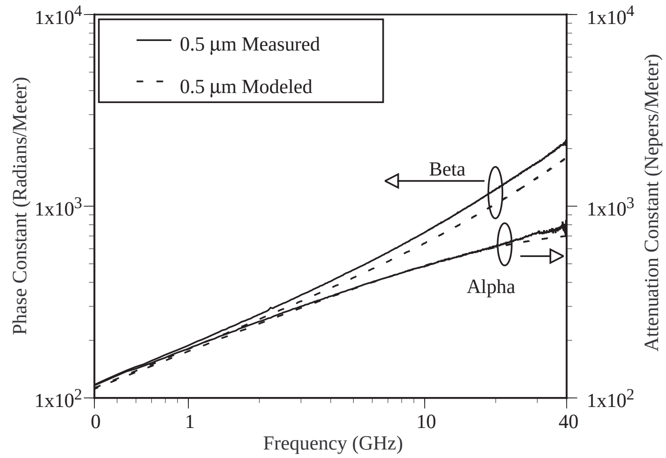

Fig. 4. Measured and simulated alpha and beta for 0.5 µm line.

Conclusions

Sub-micron cross-section microstrip lines are so resistive that L does not start to influence the series impedance term until at least 3 GHz, and is comparable to R only in the tens of GHz. Frequencies in excess of 40 GHz will be needed for these microstrip lines to exhibit true LC dominated behavior.

These lines do not exhibit any quantifiable skin effects up to 40 GHz. Any effect of the finite conductivity of the substrate is not measurable to at least 40 GHz. A simple quasi-static model can match both alpha and beta of all the measured lines without including skin effect or substrate effects.

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