A Method for On-Chip Interconnect Characterization

A. W. Glaser[†], M. B. Steer[†], G. M. Shedd[‡], P. E. Russell[*], and P. D. Franzon[†]

[†] Electronics Research Laboratory, Department of Electrical and Computer Engineering,
North Carolina State University, Box 7911, Raleigh, NC 27695-7911
A. W. Glaser: phone (919) 515-3947, FAX (919) 515-5523, email awglaser@eos.ncsu.edu
M. B. Steer: phone (919) 515-5191, FAX (919) 515-3027, email mbs@ncsu.edu
P. D. Franzon: phone (919) 515-7351, FAX (919) 515-5523, email paulf@ncsu.edu

[‡] Burleigh Instruments, Burleigh Park, Fishers, NY 14453-0755
G. M. Shedd: phone (716) 924-9355 , FAX (716) 924-9072, email gmshedd@aol.com

[*] Department of Materials Science and Engineering,
North Carolina State University, Box 7907 Raleigh, NC 27695-7911
P. E. Russell: phone (919) 515-7501, FAX (919) 515-6965, email prussell@ncsu.edu

Abstract. We present a novel method for the measurement of interconnect capacitance, atomic capacitance microsopy. We also present VLSI structures which allow correlation of ACM and traditional (VNA, TDR, direct capacitance) measurement techniques.

1. Introduction

With the continual reduction of feature size in modern VLSI processes, the proper characterization and simulation of on-chip interconnect structures is becoming increasingly important in ensuring that current and future VLSI designs work properly at speed. Simulation models are relied upon to correctly predict such performance parameters as loading and delay; these simulation models must be butressed by an underpinning of experimental data to ensure their correctness and applicability.

This paper presents a novel method for directly measuring on-chip interconnect parasitics, Atomic Capacitance Microscopy (ACM). We also present hardware structures to facilitate these measurements, and to allow them to be correlated with measurements from standard instrumentation, such as vector network analyzers (VNA), time domain reflectometers (TDR) and capacitance meters. This hardware is currently under fabrication.

2. Atomic Capacitance Microscopy

Atomic capacitance microscopy is a technique for measuring very small capacitances based on atomic force microscopy (AFM). AFM uses uses a probe consisting of a cantilever arm and microscopic tip to measure the attractive force between the tip and the sample. A schematic view of ACM is shown in Figure 1(a), and an equivalent circuit representation is shown in Figure 1(b).

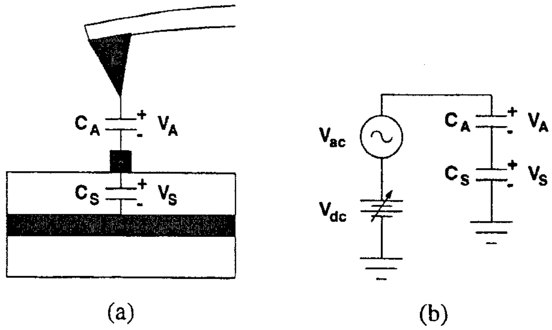

Figure 1: (a) Schematic view of ACM probing, showing AFM cantilever and probe tip, and interconnect test structure. (b) Equivalent circuit.

When a voltage V is applied betwen the tip and the lower level metal, the effective capacitance is that of two capacitors in series. One capacitance is between the tip and upper level metal, which are separated by a small air gap of tens of nm. The other capacitance is between the lower level metal and the upper level metal, which are separated by a dielectric layer. The total voltage, V, will be divided across the two capacitors such that the charge Q induced on each of the capacitors is the same—there cannot be a change in the net charge on the "floating" upper-metal electrode. This yields a simple relationship between the tip-to-sample voltage, V_A, and the two capacitances.

0-7803-3034-X/95/$4.00 © 1995 IEEE

$$V_A = V\left(\frac{C_S}{C_S + C_A}\right) \tag{1}$$

If V_A can be measured, then the ratio of the capacitances is known. V_A can be determined by a force measurement technique known as the Kelvin null technique.

The force between two capacitive elements (in this case, the probe tip and the upper-level interconnect) is given by

$$F = -\frac{1}{2}V^2\frac{\partial C}{\partial z} \tag{2}$$

If a DC bias, V_{dc}, and an AC bias, $V_{ac}\cos\omega t$, are applied to the probe tip, the voltage V_A across the tip-to-sample capacitance C_A is given by

$$V_A = \Delta V_{dc} + V_{ac}\cos\omega t \tag{3}$$

where

$$\Delta V_{dc} = V_{dc} - V_S$$

Substituting into (2) gives

$$\begin{aligned} F &= -\frac{1}{2}\frac{\partial C}{\partial z}\left[\Delta V_{dc}^2 + \frac{V_{ac}^2}{2}(1+\cos 2\omega t)\right. \\ &\quad \left. + 2\Delta V_{dc}V_{ac}\cos\omega t\right] \end{aligned} \tag{4}$$

Thus the only force component of frequency ω can be controlled by varying ΔV_{dc}. If ΔV_{dc} is varied such that the force at frequency ω vanishes, we now have a very accurate measure of the tip-to-sample voltage V_A. Once we have determined V_A, we can use the functional relationship in (1) to determine the metal-to-metal capacitance C_S.

As an example of how ACM can be used to derive a capacitance matrix for a simple system of three parallel lines, we present a method for obtaining the matrix using six independent test structures. These structures are shown in cross-section in Figure 2. (Note that we assume that the capacitance matrix is symmetric.) We will measure seven different equivalent capacitances, but only six are required for the derivation of the matrix (the seventh can be for verification purposes).

The relationship between the measured capacitances and the capacitance matrix elements (as shown in Figure 2) can be written as a matrix equation:

$$\begin{bmatrix} C_A \\ C_B \\ C_C \\ C_D \\ C_E \\ C_G \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_{11} \\ C_{12} \\ C_{13} \\ C_{22} \\ C_{23} \\ C_{33} \end{bmatrix} \tag{5}$$

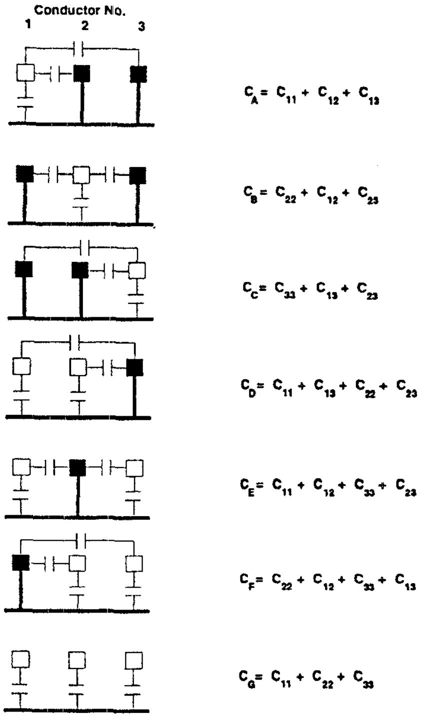

Figure 2: Three-line structures for capacitance matrix measurement. Structures in black are connected to the substrate and are thus grounded; structures in white are electrically connected (connections not shown) so that they are at the same potential.

If the coefficient matrix is invertible, then we can find the capacitance matrix elements by taking the inverse of the coefficient matrix and multiplying by the measured values vector. The above coefficient matrix is in fact invertible; thus our measurement set will suffice for the derivation of the capacitance matrix. Similar techniques can be used to find crossover and via capacitances.

3. Measurement Structures

Structures for the measurement of various interconnect parasitics have been designed to facilitate measurement in several ways: direct capacitance measurement, using on-wafer probes and a capacitance meter [2], transmission-line parameter measurement using on-wafer probes and either a VNA or TDR [1], and capacitance measurement using ACM. Standard probing is implemented using a ground-signal-ground pad configuration, using 50 μm square pads on 100 μm centers. ACM probing is accomplished using a 6 μm square pad with a 2 μm square passivation window attached to the

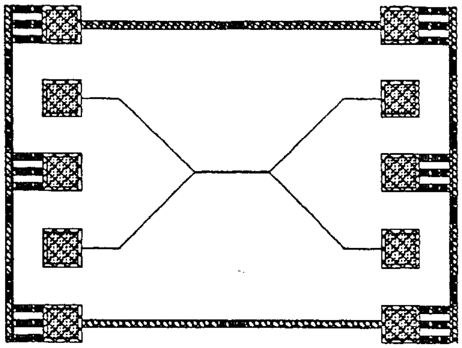

Figure 3: Coupled lines with standard probe fixturing (spacing between lines is too small to be seen at this scale). Note the guardband around the structure.

structure to be tested.

Figure 3 shows a representative example of a structure to be tested using conventional probing (i.e. direct capacitance, VNA or TDR). The figure shows a system of two capacitively coupled lines with probe pads and guardbanding. The guardband is a surrounding ring of wide lines on all three metal layers, with all layers connected to each other and to the substrate, as well as to the ground probe pads. This guardbanding is used on all structures, and isolates one structure from another.

Similar structures have been built but with variation in distance between the two lines and length of the coupled section. The variation of coupling with distance and the coupling per unit length can thus be measured. We have also constructed other structures, including three-conductor systems, parallel-plate capacitors, simulated bus structures, and lines over ground planes, both solid and gridded.

Figure 4 shows an example of a structure to be measured using ACM, a system of three coupled lines. The top section of the figure shows a magnified view of a single ACM measurement structure with pad attached, while the bottom section shows a complete test set, including guardbanding. Note that the complete test set allows full determination of the capacitance matrix of three coupled lines by implementing the grounding system described above and shown in figure 2.

As with the structures for standard probing, similiar structures have been built with variations in line length, distance between coupled lines, and line width, allowing measurement of coupling per unit length with various geometries.

Figure 5 shows an example of a structure uniquely suited to measurement by ACM. The structure implements a single crossover, with variation in length of the crossover arms. Theoretically, ACM will have the resolution to measure the capacitance of a single crossover such as this, as well as other structures common to VLSI designs that have until now been difficult, if not impossible, to measure accurately.

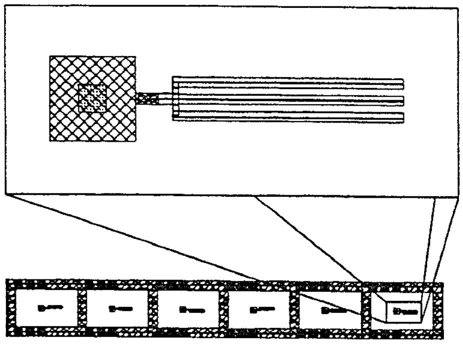

Figure 4: An example of a system for ACM probing. The top section shows a magnified view of one of the structures. The bottom section shows a full test set with guardbanding.

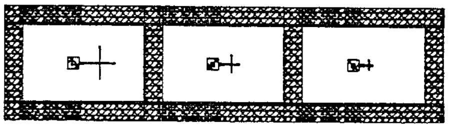

Figure 5: Single metal 2 line (connected to pad) crossing over metal 1 line. Three lengths of crossing lines are implemented per test set.

References

[1] S. B. Goldberg, M. B. Steer, P. D. Franzon, and J. S. Kasten, "Experimental Electrical Characterization of Interconnects and Discontinuities in High-Speed Digital Systems," *IEEE Trans. Components, Hybrids and Manuf. Tech.*, vol. 14, pp. 761-765, Dec. 1991.

[2] S. Lipa, M. B. Steer, A. S. Morris, and P. D. Franzon, "Comparison of Methods for Determining the Capacitance of Planar Transmission Lines with Application to Multichip Module Characterizaion," *IEEE Trans. Components, Hybrids and Manuf. Tech.*, vol. 16, pp. 247-252, May 1993.

[3] M. B. Steer, P. D. Franzon, A. W. Glaser, P. Russell, and G. M. Shedd, "Experimental Determination of On-Chip Interconnect Capacitances," North Carolina State University Technical Report No. NCSU-ERL-95-27.