SILICON HYBRID WAFER SCALE INTEGRATION INTERCONNECT PERFORMANCE EVALUATION AT RF FREQUENCIES

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ABSTRACT

The radio-frequency (RF) electrical characteristics of hybrid wafer scale integration (WSI) interconnections on silicon-polyimide-aluminum and silicon-benzocyclobutene-aluminum substrates have been evaluated. The silicon wafer substrates were five inches in diameter, and each contained an identical set of 200 photolithographically-patterned dielectric and aluminum interconnect test structures. The aluminum conductors were 2.5-microns thick, and half of the test structure conductors were 10-microns wide, while the remainder were 25-microns wide. The test structure configurations are representative of those designs envisaged for interconnecting IC die involved in hybrid WSI applications. Many of the test structure conductors were deliberately arranged to purposefully enhance electrical coupling effects. Measurements spanning the frequency range between 5 KHz and 220 MHz confirmed the expected transmission line behavior manifested by the longer interconnections. The measured coupling levels in the 400 line/cm density structures were low (< -25 dB), but nevertheless significant, especially when digital logic applications requiring low-noise margins are anticipated. More important were the attenuation effects manifested by the longer aluminum interconnections when they were combined with low-impedance matched terminations. These findings underscore the problems and critical design choices associated with achieving high-speed performance from prospective WSI systems.

INTRODUCTION

Wafer scale integration (WSI) refers to technologies which provide improvements in size, weight, power consumption, and operating frequencies through increased component densities on a system level. A proliferation of research efforts in WSI technologies has occurred, including monolithic, hybrid, and pseudo-hybrid (1, 2). However, the realization of a functional WSI circuit (WSIC) by any of these approaches is unusually complex. The challenges of yield, thermal dissipation, structural integrity, packaging, interfacing, and electrical performance must all be surmounted.

In particular, the electrical performance of WSI interconnections must be carefully studied (3). Due to the geometrical scales involved, transmission line and full-wave electromagnetic field effects will become more pronounced in wafer-scale systems. This phenomenon will be further accentuated by the physical length of the interconnections between discrete integrated circuits (ICs) and the requirement to operate the resulting WSICs at high frequencies (typically > 50 MHz). If deficiencies exist in the interconnection schemes proposed for the evolving WSI technologies, they need to be identified early through analysis and measurement so that they can be remedied by refining the fundamental electromagnetic design models.

To characterize the RF electrical performance of representative monolithic and hybrid WSI interconnect schemes (Figure 1), silicon test substrates (Figure 2) were fabricated with a high-density multilayer interconnect (HDMI) process developed by Polycon, Inc. (2686-B Johnson Drive, Ventura, CA) under sponsorship from the Naval Ocean Systems Center (San Diego, CA). Two of the silicon wafer structures evaluated in this investigation used a polyimide (PIQ) as the interlayer dielectric, while a third wafer was fabricated with a benzocyclobutene (BCB) dielectric. Aluminum was used throughout for the active conductors (10- μ m and 25- μ m linewidths) and their associated ground planes.

The structures on the test wafers were divided by location and function into several cells. Some cells were populated with structures designed to exploit yield-related phenomena (for example, via chains), while others were filled with transmission line structures designed with particular lengths (1 cm, 2 cm, and 10 cm). In the 10-cm length interconnect cell, a subset of 123 structures were intentionally meandered to form longer structures, with lengths up to 1.2 m. The scope of this investigation was limited to evaluating the performance of the transmission line structures contained in the 10-cm length line interconnect cell, since these structures displayed more pronounced transmission line effects at any given frequency.

THEORETICAL BACKGROUND

In order to gain acceptance as a veritable technology, WSIC interconnections must achieve acceptable and predictable electrical performance, even at operating frequencies where transmission line effects become significant. In this investigation, it was assumed that the WSIC interconnections behave as multiconductor transmission lines. For extremely long and closely-spaced lines operated at very high frequencies, it is anticipated that these structures will manifest electromagnetic field effects that will require full-wave analysis techniques to explain their behavior. However, this limiting behavior is in direct contrast to that manifested in the shorter interconnections used in contemporary integrated circuit die. Typically, VLSI designers do not consider transmission phenomena as they route interconnections between devices in an integrated circuit. However, in the hierarchy of electronic systems design, transmission line design considerations are often only relegated to printed circuit board (PCB) designers.

The evolving IC design trends suggest that the future operating frequencies will continue to increase, due in part to smaller feature dimensions. In multichip modules and WSI systems, average interconnection lengths will also likely increase. As the dimensions of the system's interconnections approach the wavelengths of the signals impressed upon them, lumped-element circuit theory will not provide an adequate assessment of electrical performance. Thus, it is important to comprehend the transmission line effects that will influence WSI systems to predict their impact and to experimentally

verify the theoretical projections. Due to the small physical dimensions involved, the existing transmission line electromagnetic theory must be re-examined to justify its use for WSIC geometries.

Electrical analysis may be delimited into three regions depending upon the operating frequency, and each regime is successively more general and complicated. These regimes include: lumped element, transmission line, and full-wave. The proximity of WSIC interconnections (as close as 15- μm separation), creates some potentially challenging electromagnetic analysis issues, especially when inhomogeneous dielectrics are involved. To simplify such analyses, structures with simple propagation modes are sought. Since typical WSI interconnections have rectangular transverse cross-sections, they may be classified as microstrip-like transmission line structures. The term 'microstrip-like' refers to the class of planar transmission line structures such as: microstrip, stripline, coplanar strip, and coplanar waveguide. Microstrip-like structures with an inhomogeneous dielectric do not support transverse electromagnetic (TEM) modes exclusively. That is, depending upon their geometry, they will support transverse electric (TE), transverse magnetic (TM), or linear combinations of TE and TM (hybrid) modes. Normally, the non-TEM nature of such structures would present a dilemma when one-dimensional transmission line theory is applied. However, at frequencies below several GHz, the error is generally regarded as minimal. Consequently, only the TEM mode is generally assumed (referred to as the *quasi-static* approximation). Clearly, at sufficiently high frequencies, this assumption loses its validity due to significant skin effect losses and geometrically-dependent dispersion effects. In this event, a full-wave electromagnetic analysis is required.

When applicable, the *quasi-static* approximation yields significant benefits, and many transmission line analytical techniques can be applied to *quasi-static* structures. One important transmission line parameter, the characteristic impedance (Z_0), is particularly useful in WSIC design and analysis. In transmission line regimes, the termination of a transmission line with its characteristic impedance is necessary to eliminate undesirable reflections. In general, the characteristic impedance in TEM mode structures can be determined by considering the following relationship:

$$Z_0 = (C v_p)^{-1}$$

where C is the capacitance per unit length, and v_p is the phase velocity. The phase velocity in TEM mode structures can be approximated as:

$$v_p = c \sqrt{\frac{C_0}{C}}$$

where c is the speed of light, and C_0 is the capacitance per unit length of the same structure without the dielectric (that is, the dielectric material is replaced with air or a vacuum). Thus, for structures that only support the TEM mode, the phase velocity is:

$$v_p = \frac{c}{\sqrt{\epsilon_r}}$$

where ϵ_r is the relative permittivity of the dielectric surrounding the conductor, and the relative permeability (μ_r) is assumed to be unity.

Since most conductors in WSI systems are arranged in close proximity, it is not always accurate to treat them as independent structures. In the most generalized sense, WSI interconnections represent multiconductor transmission line structures. Three coupling arrangements are possible for TEM mode structures (Figure 1). The characteristic impedance concept becomes less useful in an intuitive sense for multiconductor transmission line structures, even for TEM mode structures, since the impedance must be expressed as a matrix quantity. The most generalized representation of multiconductor transmission lines is given by the classic transmission line equations:

$$\frac{d[v]}{dz} = -([R] - j\omega[L])[i]$$

and

$$\frac{d[i]}{dz} = -([G] - j\omega[C])[v]$$

where $[v]$ and $[i]$ represent column vectors of voltage and current, respectively, and $[R]$, $[L]$, $[G]$, and $[C]$ are the resistance, inductance, conductance, and capacitance matrices per unit length, respectively.

The analysis of an arbitrary system composed of multiconductor transmission lines may be accomplished as a two-phase process. The first phase of the analysis examines the geometry of the conductor-dielectric system and extracts the $[R]$, $[L]$, $[G]$, and $[C]$ matrices. The second phase of the analysis considers solutions to the classic transmission line equations, subject to the appropriate boundary conditions, using numerical techniques, such as finite-difference, finite-element, and moment methods (including spectral-domain techniques). The boundary conditions are obtained directly from the terminal relationships applicable to the particular transmission line configuration. Thus, once the voltages and currents are calculated, the transmission line coupling, and transmission- and driving-point impedances can readily be formulated.

The loss mechanisms in WSIC interconnections must also be considered. They include conductor, dielectric, skin effect and dispersive losses. Conductor losses are those attributable to the series resistance of the conductor, while dielectric losses are those due to conduction currents which flow through the surrounding dielectric. Series conductor losses are highly detrimental in matched or low impedance terminated transmission line structures because they manifest themselves as voltage-divider losses. On the other hand, dielectric losses are detrimental in any transmission line structure, regardless of how it is terminated. Skin effect losses for WSIC geometries are difficult to analyze due to the small physical dimensions involved. Conventional macroscopic geometry skin effect loss estimates, such as Wheeler's incremental inductance rule, do not apply to integrated circuit geometries. Finite element techniques have been applied to model the current density distributions inside the conductors as a method for obtaining more accurate estimates of the skin effect (4).

At the higher operating frequencies, dispersive losses are due to the electromagnetic coupling of the structures to TE or TM surface modes, or other hybrid modes, which represent departures from the aforementioned *quasi-static* approximation. When the behavior of dispersive losses can be determined, they are usually accommodated by specifying a frequency-dependent effective permittivity.

EXPERIMENTAL AND COMPUTATIONAL METHODOLOGY

The following metrics were applied to characterize the 10-cm long transmission line interconnects:

1. Direct current continuity
2. Characteristic impedance (1-700 MHz)
3. Coupling and transmission (1-100 MHz)
4. Pulsed-signal response (5 KHz-250 MHz).

The direct current continuity measurements were performed to provide practical information concerning the electrical conductivity and leakage mechanisms on the test wafers and to screen those structures with obvious fabrication defects. The characteristic impedance metric was considered because of its critical significance in the associated transmission line analysis. The coupling metric was selected because of its importance in practical applications, and the transmission or forward gain metric was identified to provide insight into the attenuation manifested by the WSIC structures. Finally, the pulsed-signal response metric was employed as a qualitative metric for examining the quality of the signals impressed on representative wafer-scale interconnections.

Each characteristic impedance estimate was formulated from two driving-point impedance measurements. These measurements were accomplished using an RF impedance analyzer (Hewlett-Packard, Inc., model HP 4191A, Colorado Springs, CO). The first measurement was performed on a test structure with the opposite end of the structure short-circuited. The second measurement was similar to the first, except that the structure's free end was left open-circuited. The characteristic impedance (Z_0) was calculated using the common transmission line formula:

$$Z_0 = \sqrt{Z_{sc} Z_{oc}}$$

where Z_{sc} and Z_{oc} are the short-circuit and open-circuit driving-point impedance measurements, respectively.

The coupling and transmission measurements were performed as simple two-port measurements using a gain-phase analyzer (Hewlett-Packard, Inc., model HP 4194A). A typical three-conductor transmission line system composed of two active conductors and a common ground can be modelled as a canonical coupler, as depicted in Figure 3. This structure is representative of many of the structures present on the test wafers used in this investigation. The coupling measurements were primarily those termed as *backward-coupling* measurements. That is, for any two conductors (i, j) in a multiconductor transmission line system, the *backward-coupling gain* (A_c) of the i th conductor with respect to the j th conductor (in dB) is defined as:

$$A_c = 20 \log \left(\frac{v_i(0)}{v_j(0)} \right)$$

where $v_i(0)$ and $v_j(0)$ represent the voltages of the two conductors measured with respect to a common point in the transmission line structure. (For example, in Figure 3, the *backward-coupling gain* can be measured between ports 1 and 2 or ports 3 and 4.) Using a similar nomenclature, the *transmission gain* (A_t) of the i th conductor is defined as:

$$A_t = 20 \log \left(\frac{v_i(0)}{v_i(l)} \right)$$

where $v_i(l)$ is the voltage of the i th conductor measured at the opposite end of the transmission line assembly. (In Figure 3, the *transmission gain* can be measured between ports 1 and 4, or ports 2 and 3). All two-port measurements were terminated with 50 ohms at the measurement port; the remaining ports of the test wafer structures were left open-circuited during the measurement.

To verify the harmonic excitation measurands (characteristic impedance, coupling, and *transmission gain*), several theoretical techniques were implemented. For the characteristic impedance, several standard closed-form expressions, along with finite-difference and LINECALC® (EEsof, Inc., Westlake Village, CA) estimates were used. For the coupling and *transmission gain* estimates, LIBRA® (EEsof, Inc.) models and two analytic methods were implemented. The first analytic method was based upon a simplified lossless analysis (5) for which closed-form analytical expressions can be used to estimate coupling and transmission levels. The second analytic method considered the solution of the multiconductor transmission line equations (6) for similar estimates.

To glean a qualitative perspective of the WSIC's performance, a set of pulsed-input response measurements were accomplished. These time-domain measurements consisted of sets of pulsed-signal response measurements at selected frequencies spanning 5 KHz to 220 MHz; signal levels consistent with conventional digital systems were utilized. For these measurements, no previous prediction techniques were performed; the goal was to simply observe how pulsed-signal inputs, such as those encountered in digital logic circuits, would be affected by propagation through WSI interconnections.

All probing operations associated with the electrical measurements were conducted with coaxial probes (Micromanipulator, Inc., model 44, Carson City, NV) designed for a nominal 50-ohm input impedance. For certain pulsed-signal response measurements, active probes (Micromanipulator, Inc., model FET-1) were used to simulate high impedance loads.

RESULTS AND DISCUSSION

Due to the large number of structures on each wafer, a representative subset was identified to provide a comprehensive analysis of the most relevant structures. The structures investigated were selected based upon the results of an initial set of measurements, with the goal being to explore at least one structure from each major structural category. The categories of the structures on the test wafers -- which represent a fundamental classification scheme -- included two- and three-conductor edge-coupled striplines (ECS), coplanar waveguides, and meander lines (Figure 4 depicts the three-conductor ECS and meander structures). According to the exact definition, many of the two-conductor, edge-coupled structures were fabricated with meshed ground planes, and some did not possess superficial ground planes. By strict definition, only those structures possessing solid superficial and substrate ground planes were classified as striplines (6).

The characteristic impedance analysis revealed that loss in the WSIC structures manifested specific frequency dependencies in the measured driving-point impedances. The curves generated through the swept-frequency measurements from 1-700 MHz produced impedance curves that converged upon infinity at decreasing frequencies and asymptotically approached a constant value at higher frequencies. Based upon simulations of the multiconductor transmission line equations (6), this theoretical value was, in fact, the static value of the characteristic

impedance (Z_0). In practice, however, the measurements did not always converge upon this theoretical value (Figure 5). As an approximation, a simple linear extrapolation technique was applied to the measured data to estimate the asymptote. When these results are compared to the closed-form analytic approximations (*LINECALC*®, finite-difference, and the solution of the multiconductor transmission line equations), the correlation of the results is varied. The correlation accuracy was seldom within 10 percent. However, the manifestation of transmission line behavior in the WSIC structures was clearly obvious, based upon the similar behavior of the swept-frequency measurements and the analytical simulations. Also, the establishment of the analytic characteristic impedance estimates were based upon estimates of several geometrical parameters that could not be verified, since no destructive cross-sectional profiles of the test wafers were performed. The uncertainty of at least one geometric parameter, the vertical separation between ground planes, was known to be as large as 20 percent.

The bulk of the gain-phase measurements performed were those used to obtain the *backward-coupling gain*. When compared to the analytic simulations, a common frequency-dependent behavior was identified in the WSIC structures through the swept-frequency measurements which spanned 1-100 MHz. The analytic simulations also revealed that the *backward-coupling gain* was very sensitive to certain geometric parameters, such as the vertical separation distance between ground planes. However, at the frequencies investigated, little effect was noted in the simulation with the inclusion of dielectric loss or the consideration of discontinuities. In general, the maximum coupling gains measured for the WSI structures were less than 25 dB. These findings were based upon the measurements associated with several structures possessing 10- μ m and 25- μ m linewidths and inter-conductor lateral spacings as small as 18 μ m. The differences between the measured and analytically simulated results were sometimes large -- as much as a 20 dB difference throughout the measurement range -- but, nevertheless, the general shapes of the curves were very similar (Figure 6). Since the differences were nearly constant and essentially translational, the dependencies observed strongly suggest that the WSIC structures behave very much like transmission lines. The transmission measurements revealed significant attenuation for matched loads, especially for the structures having 10- μ m linewidths. The small coupling gains observed were encouraging for digital applications. However, the attenuation loss manifested by these structures effectively mitigates the coupling advantage since the signal strength must be increased to compensate for this loss.

The results of the time-domain measurements were mixed. For the low frequency pulses (≤ 50 KHz), the most important result observed was that the pulse amplitude was attenuated for the 50-ohm load (Figure 7), while it was relatively unattenuated for a high-impedance load (Figure 8). At the higher frequencies, the reflections caused by a high-impedance load were catastrophic in certain structures (Figure 9). The worst-case distortions were observed in the coplanar waveguide structures. Even with low-impedance terminations, these structures manifested significant signal distortion at frequencies as small as 50 KHz. It was concluded that these distortions were caused by reflections occurring as the result of impedance mismatches. Furthermore, even though the 50-ohm terminations produced relatively low reflections in the stripline structures, a more distorted signal response was evident at higher frequencies. Some of the higher frequency responses would even be considered unacceptable for digital systems. However, signal cou-

pling of the digital signals did not appear to pose a problem in these structures in the time-domain measurements.

CONCLUSION

The primary objective of this investigation was to characterize the transmission line behavior of WSIC interconnect structures using analytical simulation and experimental measurements. In particular, the undesirable transmission line effects of reflection, coupling, and attenuation were considered. A related topic of interest, the propagation of a pulsed-signal through the WSIC interconnect structures, was qualitatively pursued.

The results distinctly revealed that transmission line behavior is manifested in WSIC interconnections. Although some discrepancy exists between the electromagnetic theory based models and the measured results for the characteristic impedance and coupling, the performance trends were functionally very similar. The coupling gains of these structures were found to be sufficiently small; therefore, digital systems can be implemented and operated with relative immunity from noise coupling. The requirement imposed on this application would be that the circuit design must allow for a sufficient noise margin and signal attenuation. The time-domain performance revealed that reasonable propagation of high-speed pulse signals (≤ 250 MHz) is possible in a select group of elongated (10 cm) WSIC structures. Proper termination of signals was observed to be critical for achieving signal fidelity at the higher frequencies. However, these terminations contributed significant signal attenuation in the 10-cm long structures, even for the 25- μ m wide conductors. For certain structures, including the coplanar waveguide structures, poor pulsed-signal response behavior was evident at frequencies below 5 MHz. When the more practical high impedance terminations were considered, the signal level was preserved at the expense of signal fidelity. The impedance mismatch between the WSIC interconnect structures and the terminations also created reflections which contributed to this distortion. For certain structures, significant signal distortion was observed at frequencies greater than 500 KHz, even when 50-ohm terminations were used.

It is noted that the 10-cm long interconnections investigated represent a practical upper limit that will be utilized in most WSIC applications. When shorter length interconnections are used, the coupling, attenuation, and pulsed-signal performance is significantly improved. From this perspective, the results of this investigation are encouraging, and further theoretical and experimental investigations at frequencies above 100 MHz for the shorter length interconnections are motivated.

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Figure 1. Representative canonical wafer scale integrated circuit (WSIC) interconnection and coupling structures.

Figure 2. WSIC test wafer used in the interconnection electrical performance investigation.

Figure 3. Coupling arrangements for the transverse electromagnetic (TEM) structures.

Figure 5. Comparison of the measured and calculated results of the characteristic impedance (Z_0) for a 25- μm wide ECS WSIC structure.

Figure 6. Comparison of the measured and calculated (*LIBRA*®) coupling for a 10- μm wide, dual-conductor ECS WSIC structure fabricated with the polyimide (PIQ) dielectric.

Figure 4. Two representative WSIC structures investigated -- the upper frame depicts the dual-conductor edge-coupled stripline (ECS) -- the lower frame illustrates the meander line (embedded microstrip).

Figure 7. Response of the 25- μm wide, 3-conductor ECS structure fabricated with the benzocyclobutene (BCB) dielectric for a 50 MHz pulse waveform (50-ohm impedance termination; 2-V pulse amplitude).

Figure 8. Response of the 10- μm wide, 2-conductor ECS structure fabricated with the PIQ dielectric for a 500 KHz pulse waveform (high-impedance termination; 5-V pulse amplitude).

Figure 9. Response of the 25- μm wide, 3-conductor ECS structure fabricated with the BCB dielectric for a 50 MHz pulse waveform (high-impedance termination; 2-V pulse amplitude).