Multichip Modules: Buzzwords or Bonanza?

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New multichip interconnect technology outstrips PCBs, hybrids and even silicon

A new multichip interconnect technology is emerging, using thin-film layers and very fine lines insulated by polymers. The new High Density Multilayer Interconnect (HDMI) technology is used to fabricate multichip modules (MCMs), which can cope with higher computer clock rates and improve flow of information between semiconductor chips.

Relentless market demands for a decrease in size and an increase in speed have created the need for a new interconnect technology. Geometries in semiconductors have decreased more rapidly than in the hybrid or PCB industries. Over the past two decades, linewidths in ICs have gone down by two orders of magnitude, while the next levels of interconnection have only decreased by one.

For some time, the switching speeds achieved by small semiconductor geometries have exposed the problem of interconnect delays, which now become the major factor in overall system delays. Intense activity to advance all fronts in semiconductor technology exacerbates this interconnect problem. The result is a gap current technologies cannot fill from the semiconductor, hybrid or PCB sides.

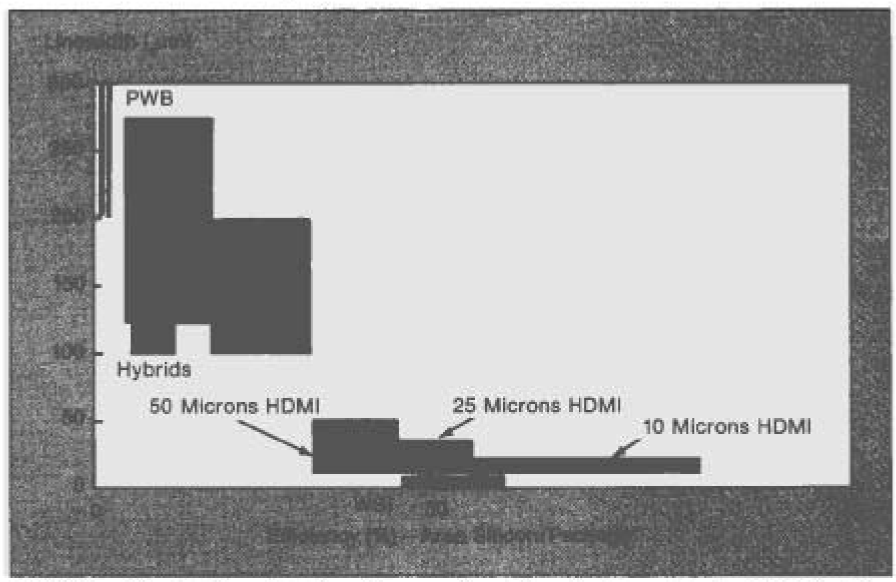

FIGURE 1: This plot of packaging efficiency shows the advantage of using HDMI to interconnect high-density circuits.

Because semiconductor fabrication has always been limited by yields over large areas, wafer-scale integration has failed. Beyond the yield problem, the high-speed transmission of information from one side of the wafer to the other demands controlled-impedance transmission lines—difficult to achieve with the established semiconductor materials and construction techniques. All known inorganic dielectrics for interconnection crack above 1 micron thickness and have too high a dielectric constant.

The hybrid and the PCB industries have technical limitations in producing satisfactory fine lines and, as a result, are unable to meet circuit-density needs. In addition, thick-film hybrids and their subset, multilayer ceramic interconnects, must deal with high trace resistivity and high substrate permitivity. Progress to reduce linewidth has been slow, and no breakthrough is expected.

Advantages of HDMI

One major advantage of HDMI technology is its ability to pack more circuitry per in.^{2} than feasible with any other technique. Packaging efficiency is defined as the ratio of substrate area to the area occupied by semiconductors. Often, the optimal packaging density is thought to be wafer-scale integration. However, even though WSI is monolithic, its packaging efficiency is less than 50% because of the area lost to built-in redundancy. HDMI efficiency can be over 90% using flip-chip dice (Fig 1).

The reduced footprint of HDMI leads to the feasibility of 3-D arrays with stacked HDMI wafers. This scheme offers great potential for size reduction of computer systems at low risk. Since the late 1970s, the same concept has been attempted with WSI silicon wafers and has not succeeded. Some experimental HDMI devices exploring the concept have been fabricated, using a memory array as a test bed. Therefore, very high packaging densities are within reach.

HDMI technology delivers a decrease in capacitance per unit of distance. However, the improvement over PCB technology is not overwhelming. Applying the customary TEM-mode transmission-line theory and assumptions, impedance defines the ratio of linewidth to dielectric thickness for a particular dielectric constant. Therefore, the choices to decrease the characteristic capacitance of a transmission line are limited. Most gains are derived from a low dielectric constant, which provides faster propagation velocity. Reducing the distance between chips is the most effective way of reducing the parasitic capacitance.

These reduced distances also increase the power dissipation per unit area of substrate since the chips are packed closer together. In addition, power dissipation per unit area increases with the square of the distance gained. Hence, the HDMI technology can place stringent demands on a substrate's power-dissipation capabilities. New substrate materials are being developed to accommodate this requirement. An increase in power density, accompanied by an overall system power decrease, is inherent in the technology. However, the amount of power consumed depends on the semiconductor technology being used. HDMI is a somewhat hybrid technology and allows mixing of semiconductors with few restrictions other than electrical compatibility.

The overall cost of HDMI is expected to be very competitive after the pioneering period, despite the fact that tooling—namely, the initial mask fabrication—costs more than tooling for PCBs or hybrids. Higher HDMI tooling costs stem from accuracy requirements currently met only by equipment designed for semiconductor needs, not for HDMI. The pricing trend of HDMI will resemble that of semiconductors. Lowering of price will result more from size reduction than from other factors because many small pieces can be handled simultaneously. Thus, there is incentive to achieve 10-micron linewidth.

At this early stage, HDMI modules can already compete in cost with the more complex MLBs, even when you disregard the added size and performance improvements of HDMI. Fabrication efficiency is expected to improve as volumes build up, which will lower costs.

Fabrication Steps

To manufacture an HDMI multichip module, one must create a database that will become the core of the fabrication steps—from mask making to final test. The database is built around spatial information, not unlike integrated or hybrid circuits. The first step, starting from a net list, is to route the circuit automatically. The second step is to check for design-rule violations and correct accordingly. The third step is to transfer the data to a pattern generator after dividing the pattern into small areas suitable for successive exposures of discrete chunks of the entire pattern. Alternatively, the pattern can be rasterized for exposure with a defocused electron beam. Defocusing adds speed since the patterns do not require the finest resolution of an E-beam system.

An important effort under way is the integration of all the data in the same database, from electrical-type simulations to design-rule check or probe placement in final test. Since little has been done yet to integrate electrical modeling, this represents a major task. To characterize electrical properties accurately , you need to build specialized test wafers. The ultimate goal is real-time circuit optimization as the designer, or the automatic router, places the interconnect.

The substrate is fabricated by depositing successive layers of metallization and polymer insulation after forming each one with a photolithographic process, similar to semiconductor practice. Depositing metals on polymers requires an in-depth knowledge of materials because of the vastly different mechanical properties of the films. The dielectric is deposited by spinning or spraying and then cured. Interlevel vias are opened by reactive ion etching through a suitable mask. Photosensitive polyimides can be used for this purpose, offering the advantage of fewer processing steps.

Metal deposition takes place in a sputtering system because of the variety of material choices and better control over material properties such as stress. The process is repeated on each successive layer until the structure is completed (Fig 2). Structures with six metallization layers have been built, although the majority of devices require four or five layers. More are feasible but have not yet been needed.

Substrates

A large number of materials can be used as HDMI substrates; the more

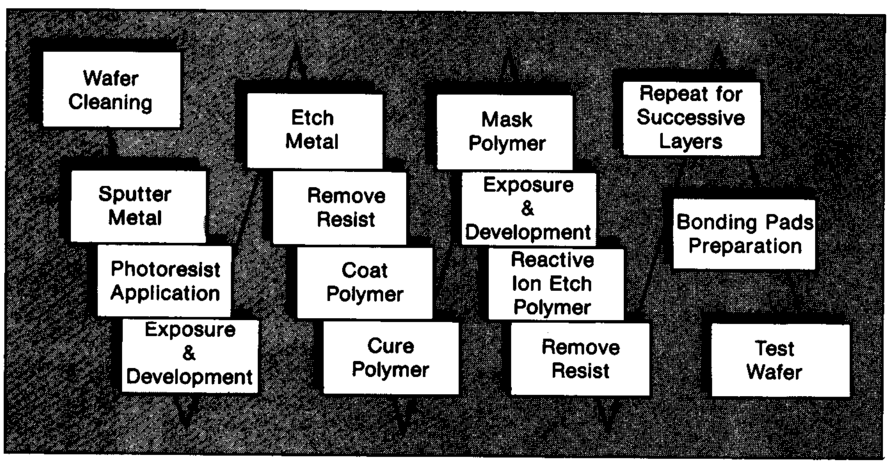

FIGURE 2: The process flow for an HDMI multichip module.

	Density g/cc	TCE ppm/°C	Thermal conduction W/m°C	ε	
[illegible]	[illegible]	[illegible]	148	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	175-100	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	17	[illegible]	[illegible]
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TABLE 1: Substrate materials.

common ones are listed in Table 1. A subset of HDMI technology is known as *silicon on silicon* because of the choice of substrate. Silicon evidently offers the advantage of matching the coefficient of thermal expansion of the chips. The heat conduction of silicon is fair compared to metals or heat-conductive ceramics. Considering both specific heat and heat conduction, silicon makes a good heat sink. The quality and repeatability of the surface finish is superior to any other materials. Many materials have better individual characteristics but silicon has a well-balanced combination of properties difficult to match.

A few ceramic materials have the electrical, mechanical and thermal properties necessary. With smaller grain size and uniformity, good heat conduction and favorable TCE, silicon carbide (SiC) and aluminum nitride (AlN) are certainly much better suited to HDMI applications than alumina ceramic. Beryllium oxide (BeO) was for a long time the best heat-conductive ceramic commercially available for packaging. Unfortunately, BeO is mildly toxic under certain circumstances that can occur during machining or surface finishing. It is now being replaced by other ceramics that have excellent thermal properties but are safer to lap, polish or machine.

SiC has been produced commercially for some time but has not gained popularity, presumably because of its hardness. It can exhibit excellent thermal properties, particularly if it is allowed to become semiconducting. This is acceptable since the substrate can be electrically insulated, and traces can be routed around the chips on insulated tracks. In cases requiring substantial heat conduction, chips should be directly bonded to the heat sink to maximize heat transfer. SiC can also have an excellent surface finish.

AlN is also a very good choice of material. Its heat conduction is lower than that of semiconductive SiC but is nevertheless excellent. TCE is slightly higher but still very favorable. AlN's main advantage stems from the possibility of making multilayer ceramic packages similar to those made of alumina.

Finally, photosensitive glass-ceramics have unequalled advantages in special applications with stringent space and weight restrictions.

Dielectric

The dielectric properties of the insulating material chosen have great repercussions on the fabrication steps, the electrical performance and the reliability of the circuit. Most polymers offered as a thin-film insulator can be used for HDMI fabrication (Table 2). Four- and five-layer structures have been successfully built in our laboratory with many polymers. However, some polymers are more convenient, more reliable and better electrical performers than others. Polyimides or modified polyimides are prevalent in this application. Some polymers are photosensitive and behave like a thick negative photoresist.

Polymers other than polymides can be used to fabricate multilayer structures. Parylene has been commercially available about as long as polyimides have. Its dielectric constant and low water absorption make it attractive. However, the conforming nature of the coating makes it difficult to build multilayer structures. Photolithography becomes extremely complicated because of the difficulty in etching vias. Yet, we have completed four-layer structures successfully in experimental devices.

Other polymers have recently become available with characteristics more favorable than polyimides. Polyphenylquinoxaline has a dielectric constant of 2.7 and lower water absorption than polyimides. It has been successfully used for any of the above-mentioned applications. Benzocyclobutene has a dielectric constant of 2.56, low water absorption and has been demonstrated in the Polycon laboratory for applications of up to five metallization layers of aluminum as well as copper. High-speed CMOS circuits based on BCB have been successfully operated at nearly 90 Mhz and have shown exceptional performance.

There is a need for a layer of high-dielectric-constant material to provide capacitive decoupling. A thin, high-dielectric constant layer between the power and ground distribution planes is ideal to minimize the parasitic inductance and provide the surge power to the chips. This is a complex problem because of the low defect requirement on the dielectric.

TABLE 2: Polymer properties.

solved, it would completely eliminate the need for chip capacitors and recover the surface area they occupy.

Metallization

The primary requirements for a metallization scheme are good conductivity, long-term resistance to corrosion and good thin-film deposition characteristics. The three metals of choice are aluminum, copper and gold. Copper has the lowest resistivity but is the most difficult to fabricate in casted polyimide structures. During curing, polyimide releases water that in turn, oxidizes the copper. Copper oxides adhere poorly to copper or polyimides.

Gold also has low resistivity but requires a large capital investment in targets if the metal is to be sputtered. Evaporation is easy, but the films can have defects due to degassing. Electroplating is undesirable from a reliability aspect since precise plating control of any metal is difficult at best.

Aluminum is the easiest metal to work with and has a natural, good adhesion to polymers. Its conductivity is good, the internal stresses in thick sputtered films can be controlled and the reliability in semiconductor applications is well documented. Polyimide-aluminum HDMI have shown excellent resistance to temperature cycling and temperature shocks ranging from 350°C to that of liquid nitrogen. Using silicon wafers, this material combination offers low radiation absorption—a factor of interest for space applications.

Differing from the norm in semiconductor work, HDMI layers are a minimum of two to three times as thick. Because the metals are deposited on polymers that have low rigidity, internal stresses in each successive layer must be carefully controlled.

Photolithography

Ten microns represents the optimal linewidth currently foreseen, considering the overall interconnect efficiency and practical aspects of manufacturing. A 10-micron linewidth allows the shortest route and can accommodate virtually any I/O pad density at this time. The total number of interconnect wires is limited by the number of bonding pad locations that can be placed around the periphery of the dice. This means that the number of interconnect wires increases linearly, while the surface of the die follows a square law. From a fabrication viewpoint, 10-micron lines can provide controlled impedance in the vicinity of 50 Ω with realistic dielectric thicknesses.

In practice, 25-micron linewidth appears to be the minimum size currently adopted for most circuit designs supplied to our labs. Although these designs may be considered advanced, they do not optimize the use of the HDMI technology. A bandwidth demanding nearly 0.5 GHz has demonstrated that, at the very least, it can work with any CMOS device. Already under way are strict measurements of electrical parameters in a wide variety of transmission lines and materials.

HDMI technology is providing a solution to critical delays occurring in electronic systems. Incidentally, it also offers a way to achieve compact packaging when speed may not be the essence but small size is critical. The new technology is based on the use of new well-known materials in new ways.

The benefits and full capabilities of the new HDMI technology are still being explored. Few areas of the electronics industry will escape the use of HDMI because of the universal need for faster, smaller, cheaper and more reliable systems. ◻

Acknowledgements

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