Fabrication of High Density Multichip Modules

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Abstract—**This paper reviews the fabrication steps necessary to build high density multichip module substrates and covers some of the complex process decisions needed to obtain a system which will eventually be produced in high volumes. Thin-film-based high density multichip modules are necessary to achieve satisfactory performance in new electronic designs. Substrates built with vacuum deposited metal and polymeric insulators have evolved in much more complex structures than traditional thin film hybrids.**

I. Introduction

THE HIGH density multilayer interconnect (HDMI) technology in this paper describes an interconnect fabrication method for microelectronic circuits, based on vacuum thin-film metallization and polymeric insulation between layers, as shown in Fig. 1. HDMI technology allows completion of multichip modules of unprecedented density, complexity, and speed [1].

The multichip modules concept has been with us for two decades as an offshoot of thick-film and ceramic hybrid circuit technology. The term is now used for multilayer thin film circuits, for various miniaturized printed circuit board schemes, as well as for multilayer thick films, and for multilayer ceramics. Confusion arises from this terminology because of the vastly different resulting properties. To distinguish the circuits described in this paper from the ones derived from older, coarser interconnect technologies, the new type of multichip modules will be referred to as high density multichip modules. HDMI refers to the technology used to manufacture the new type of high density MCM's.

Polymeric insulating materials that are useable to fabricate high density interconnect circuits have been available for almost two decades. However, new improved polymers have recently been produced by the chemical industry in response to demands for higher performance. The imperious need to improve packaging and interconnect density, and the availability of new materials, have overwhelmed the reluctance to use polymers in high reliability interconnection circuits. There is a precedent in the use of polymers in complex multilayer electronic circuits. Furthermore, it has been accomplished without the benefit of improved materials which existed then, such as polyimides. Magnetic thin-film heads have been built with polymeric insulation for twenty years in research and development, and ten years in production, using crosslinked novolak layers obtained by overbaking positive photoresists. The

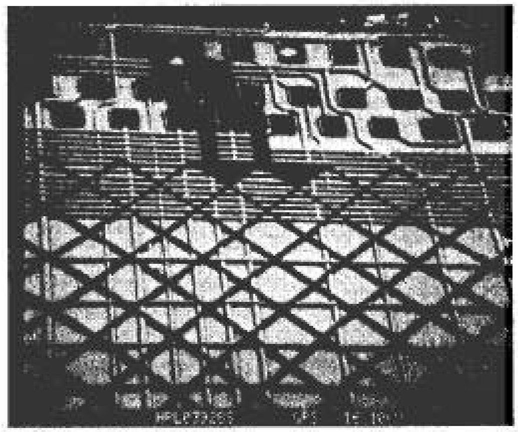

Fig. 1. SEM of a HDMI circuit. The polymer has been removed to expose the four metal layers.

choice of novolak was originally made simply because it was the most convenient material on hand and because inorganic dielectrics could not satisfy the unique circuit fabrication requirements.

The HDMI technology is under intense study for traditionally high reliability military and space applications and has already demonstrated exceptional reliability over functionally equivalent SMT assemblies [2], [3]. Tests on four metallization layers HDMI substrates have demonstrated the ability to withstand repeated large thermal shocks of 400°C, between 320°C and liquid nitrogen (− 195°C), without failure. The results of these and other reliability tests, mostly derived from relevant military specifications, will be published later. The most frequent modes of failure of multilayer SMT assemblies in avionics boards, which seems to be cracking in the z-axis of feedthrough holes and solder fatigue, are eliminated. Reliability issues are also investigated for demanding commercial and industrial applications, such as communication equipment, automotive, and large computer systems. The need for extreme reliability is not the exclusive privilege of military and space applications, considering the notoriously hostile environment under a car hood, or the demand for forty years of uncooled operation under any climatic conditions by communication companies.

II. Justification for the HDMI Technology

The need to fabricate large compact systems on a single substrate rapidly followed the invention of the integrated circuit as a natural extension of the monolithic concept. However, the realities of photolithographic fabrication yields have frustrated all practical implementations.

Since the invention of the integrated circuit, the complexity of circuit integration has increased very rapidly. This is the

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direct result of shrinking the active elements sizes and of reducing the linewidth of the interconnection lines. Consistently over the past 30 a, the average number of active elements per circuits has increased by two orders of magnitude per decade. In contrast, the surface area of the same circuits has only doubled once per decade [4]. Today, silicon devices of approximately 16 mm by 16 mm are at the limit of manufacturability in volume. This is far from the wafer scale integration goals envisionned for large systems.

The HDMI technology now allows to make wafer scale integration realistic, by using a hybrid concept. Semiconductor devices can be built to the practical limit of reasonable yields and then are regrouped on a substrate to achieve the desired level of integration. The benefits are multifold. It is now feasible to separately test the integrity of each building block, and, therefore, this allows elimination of the need for built-in redundancy in the circuits. The interconnect is no longer limited to very lossy transmission lines imposed by the limitations of ULSI processes. The transmission lines can be built with acceptable losses in relation to the length of the data transfer lines. The mixing of otherwise incompatible semiconductor technologies is permissible. It is then possible to optimize semiconductor technologies uses and functions. The thermal management can be improved by using substrates that have better thermal conduction than silicon, which nevertheless satisfies most applications.

The problems in communication speed, occurring from large physical size imposed by discrete packages for each semiconductor circuits, were recognized long ago [5]. The integration of very large systems on a single substrate obviously eliminates the need for the large increase in physical size normally required by the next interconnection levels. It also considerably reduces the packaging difficulties, simply by eliminating all intermediate packaging levels. It reduces the packaging problem to the design of only one global package. It also reduces the need for a large number of I/O's by carrying the system to its functional completion. The celebrated Rent's rule no longer applies; it remains valid at intermediate system levels but eventually fails when the system is carried to completion. For example, much fewer I/O channels are needed for a computer to communicate with the external world than internal bus lines needed for the functional blocks to interact with one another.

III. Photolithography

HDMI substrates fabrication is based on optical photolithography, using contact printing [6] and wet metal etching as practiced since the inception of integrated circuits [7]. Projection printing, electron-beam photolithography, laser etching, laser pantography, etc., have all technical capabilities but also very high capital equipment cost. Except for projection photolithography, the techniques are too slow to be economical in a production environment, even if the relatively small surface area of an HDMI substrates is taken in account.

HDMI substrates are fabricated with a wet etching process whose origins can be traced back to the 19th century metal photo-engraving for printing. Materials and means of process control have improved tremendously, but the same chemical and physical principles still apply. The scale of the feature size has changed but there still are similarities in the type of difficulties encountered.

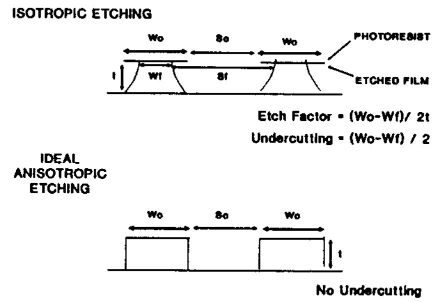

Fig. 2. Etch factor and undercutting.

We etching of a metal layer usually gives an isotropic etch profile. This is at the origin of the etch factor [8] shown in Fig. 2. The exact etch profile depends on such parameters as the nature of metal etched, the etchant's chemistry, agitation, temperature, photoresist adhesion, and resistance to etchants, etc., [9]. The etch factor is of extreme importance since it governs the ability to control the profile of etched conductor lines or the minimum attainable linewidth and separation between features.

Etching of metals can be looked at as an electrolytic cell or an accelerated corrosion process. Keeping this in mind, it is possible to control the etch wall profile by controlling the electrochemistry of the etching bath [10]. Aside from the etching bath, yields and quality of etching are also affected by the metals purity, grain size, particle contamination control, photoresist adhesion, photoresist resistance to the chemicals, resist residues, hydrogen gas evolution, etc.; all of which must be tightly controlled.

The ability to accurately reproduce patterns by photolithography is strongly dependent on the aspect ratio defined by the linewidth to the height of the photolithographic step. Micrometer size lines are easy to produce providing the layer to etch remains very thin. This relates directly to the etch factor and the ability to control anisotropy in the etching. To obtain transmission lines with acceptable losses, relative to the distances the signal has to travel, HDMI must have thicker layers than those used in integrated circuits. Because the linewidths are larger, it does not necessarily make them easier to build since they must be thicker. Lines of width equal to the thickness of the material to etch, a 1:1 ratio, can be considered difficult to achieve consistently by simple etching, regardless of the actual linewidth dimensions. A 20-μm line formed in a 10-μm thick metal is as difficult to accomplish as a 2-μm line in a 1-μm thick metal.

IV. Effect of Three-Dimensional Topography

HDMI structures have been built with six metallization layers and an equivalent number of dielectric layers. As the number of layer builds up, the planarization factor of each layer compounds on the previous ones. Figs. 3 and 4 show the effects of planarization as layers accumulate. Fig. 3 shows a common polyimide with poor planarizing properties (Dupont 2555) and Fig. 4 shows multilevels obtained with bis-Benzocyclobutene.

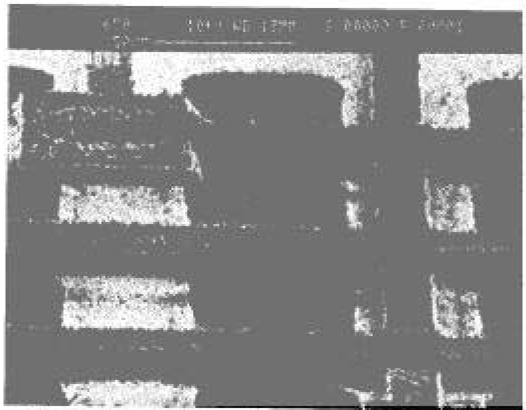

Fig. 3. Polymide insulation between line cross overs.

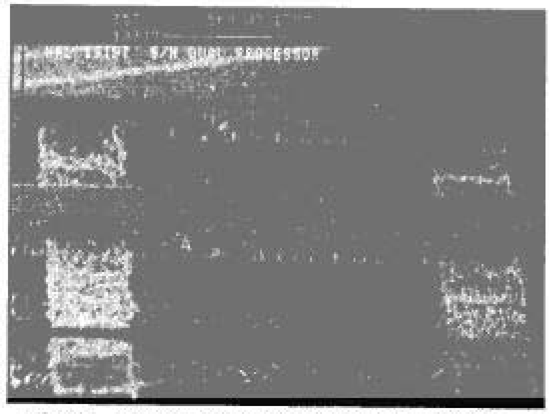

Fig. 5. Perfect planarization in bis-benzocyclobutene.

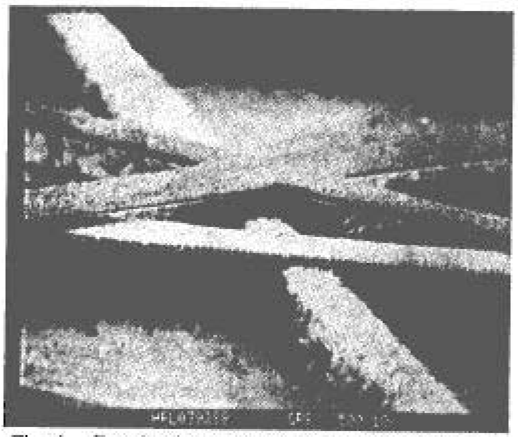

Fig. 4. Four level cross over in bis-benzocyclobutene.

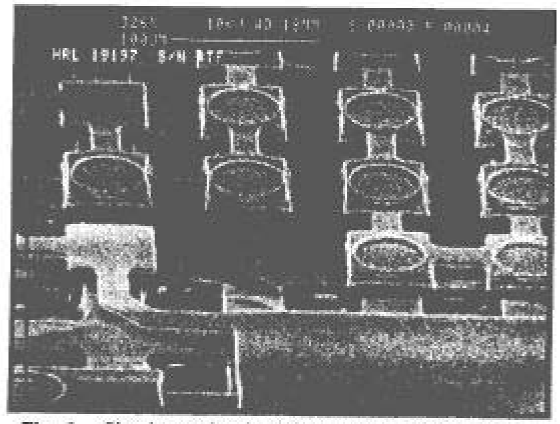

Fig. 6. Simple two-levels vias as used in HDMI process.

Relief existing on a surface prior to performing the photolithography will affect the resolution and quality of the operation. The linewidth definition in photoresists is dependant on precise control of exposure to UV light. Consider that the solubility of a photoresist in its developer is controlled by the amount of UV energy it has received. The UV dose necessary to optimize the solubility of the resist will, of course, depend on the thickness of the resist. Localized areas of thicker resist, created by topographical variations, will, therefore, need more exposure than the thinner areas. Should the variations be large, the reproduction of the mask image may be seriously compromised by the choice of exposure. As the number of layers grows, and should the HDMI be poorly planarized, the compromise may soon become unacceptable.

The magnitude of the problem, as seen earlier, relates to the relative magnitude of the linewidth to the vertical variations. The problem can be alleviated by eliminated variations in the vertical axis as much as possible. Planarization is a property of the dielectric used for the HDMI fabrication. In general, the planarization factor for polyimides depends on the surface rheology of the material, its basic viscosity, thixotropy, solid content, surface tension, cohesion, and adhesion. Some materials response to a leveling period, where the material is left to settle at room temperature prior to the first solvent drying step. Others do not improve. Initial thickness variations also depend on the change of viscosity with shear rate in the method of dispensing.

Some of the best planarizing polymeric materials used in HDMI's are some acetylene terminate polyimides, some fluorinated polyimides, and polyphenylquinoxaline. Bis-benzocyclobutene can yield perfect planarization as shown in Fig. 5. This may create temporary fabrication difficulties of its own, which can be surmounted, since masks aligners need some relief differences to make the alignment pattern visible after metallization.

Other approaches have been used to solve planarization problems. Plated via studs, grinding, lapping, and polishing are used for a larger geometries interconnect [11]. Plated via studs between levels, as a mean of leveling the structure, have been used in a variety of thin film MCM's. Aside from creating many fabrication steps, there is a danger of actually increasing the via resistance. The bulk of the resistance in a via can be attributed to the interface between levels. A semiconductor style via, as shown in Fig. 6, has only one interface between levels, while a plugged via has top and bottom interfaces.

V. Alternatives for Definition of Metal Patterns

In order to put the ability of a substractive process to produce controlled impedance transmission lines in perspective, it is useful to recall that transmission line impedances are also strongly dependent on the geometrical ratio of linewidth to thickness of the dielectric [12] as shown in Fig. 7. Ion milling, reactive ion etching, lift-off, polyimide lift-off [13], or addi-

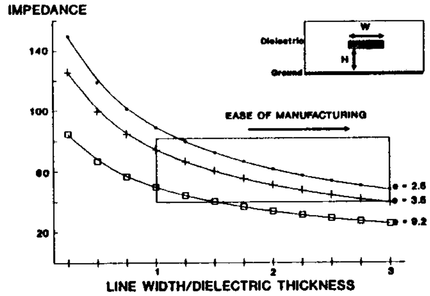

Fig. 7. Microstrip impedance versus the ratio of linewidth to dielectric thickness.

tive processes like plating are processes used to circumvent difficulties created by etching large aspect ratios, particularly when the thickness of the features equals or exceeds their lateral dimensions.

Additive processes, such as electrodeposition of copper confined by walls of photoresist, have been practiced for many years in magnetic thin film head fabrication [14]. The electrolytic film can also be confined by walls of polyimide. Partially cured photosensitive pre-imidized polyimides [15] or, for less critical applications, soft-baked polyimide are etched in mildly basic solution. One restriction is that the plating bath be neutral or acidic. The technique is also applicable to autocatalytic (electroless) deposition.

In plating, repeatability difficulties are common when producing lines below 25 μm over the entire wafer area. The bath composition and ionic flow must be tightly controlled in elaborate plating tanks [16], [17]. The baths are very sensitive to organic or ionic contamination [18] with implications on long term reliability. Stresses and film morphology [19] are also difficult to control reproducibility. Stresses in electrolytic deposits have been identified as a problem for many years. For most HDMI applications, the aspect ratio is not severe enough to justify the risks and difficulties of plating; furthermore, it can hardly be economically justified when all systems costs are included, although superficially it may appear low in capital equipment.

Ion milling is a very useful technique to form high aspect ratios in relatively thin films. However, because the process can generate excessive heat in the substrate, the etching must be kept at low levels. HDMI requires films considerably thicker than semiconductors and mediocre aspect ratios, therefore, the process becomes difficult to justify.

Plasma etching for metals is restricted to aluminum. Plasma etching and reactive ion etching (RIE) applications are limited by the ability to form gaseous chemical byproducts remaining gaseous at slightly above room temperature. Plasma etching of aluminum has been commonly used in the semiconductor industry for well over a decade [20], [21]. Most etchants, such as CCI4 and BCI3 are based on gases bearing chlorine or bromine molecules. There is currently no known plasma etchant for copper at useful rates. Gold is etchable in CI2 and C2CI4F4, but because it is slow and difficult, it is not worth the effort for HDMI applications.

In general, wet etching remains the metal etching method of choice for lines above 3 μm, that is, for all HDMI applications, since dry etching is not technically needed, and uneconomical because of capital equipment costs.

VI. Pattering of Polymers

Plasma techniques are on the other hand very useful for etching of polymers. They can be used to remove the photoresists as well as etch vias in the layers. HDMI, as we describe it, uses plasmas for both. The gases are oxygen or oxygen mixed with fluorine bearing molecules such as fluorocarbons. The composition of the mixtures of oxygen and fluorocarbons, the power, the pressure, or the flow rate vary with the particular polymer to etch and the type of plasma etcher. These parameters should be determined experimentally since they are strongly equipment dependant. The via wall profile is controllable at will, straight or sloped, to provide smooth transitions between levels. Photoresists are etched in oxygen plasmas at approximately the same rate than polyimides. It is, therefore, necessary to use a mask at least as thick as the polyimide layer to etch, or use a slowly erodible mask material.

Photosensitive polyimides were developed soon after the commercial availability of polyimides [22]. The concept was to use the polyimide as a permanent photoresist that was durable enough to be left in the structure, while other photoresists created reliability and thermal stability problems. With photosensitive polyimide, the number of conceptual steps in the process was less than for the dry processing [23], however, unavoidable geometrical distortions occurred during curing [24].

Patterning of *B*-staged, or partially cured polyimide, has been widely used because of its processing simplicity. *B*-staged polyimide films remain soluble in mildly basic solutions, therefore, they can readily be etched. The pattern is exposed in photoresist applied over the partially cured polyimide, then developed and etched. The film is subsequently cured, as in the case of photosensitive polyimide, with, of course, the same consequences for the geometrical distortions. Positive or negative photoresist can be used. Positive photoresist can be developed and etched in a single step since the resist developer is a mildly basic solution. Either positive resist developer or a mild aqueous sodium hydroxide, or ethylenediamine solution can be used with negative resist. It is recommended to quench the wafer in a 1% acetic acid solution, as an etch stop, immediately after completion of the *B*-staged polyimide etch, then rinse. Curing proceeds as usual.

VII. Conclusion

A new HDMI technology has been demonstrated to provide very high functional densities and a fabrication platform for extremely compact and complex systems. The technology brings to reality the goals of wafer scale integration.

Both matched impedances and low resistive losses are simultaneously required for high-speed transfer of information between digital blocks. Inorganic dielectrics and conventional semiconductor wafer processes do not economically allow the fabrication of transmission lines with sufficiently low losses to interconnect large functional blocks on a wafer scale. Furthermore, it does not allow for decoupling capacitors, good power distribution, and it needs a large amount of redundancy.

HDMI multichip modules solve these problems with today's technology.

It has been demonstrated that the fabrication steps to build multichip modules with HDMI technology are all well within controlled practical boundaries necessary for the high volume producibility of tomorrow.

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