Path Finding: Who Performs and When?

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Path finding is similar to a person compressing a balloon filled with air. You compress up to a point and when released, the balloon returns to its original form. Compress too much and the balloon bursts. Similar to a balloon, products have mechanical, thermal and electrical properties that degrade until permanent damage. The trick is to determine where these breaking points are and if or how they can be enlarged: this is path finding's value.

The End Goal: Successful Products

A product is purchased if its functionality and/or performance aid the consumer and it justifies the upfront and recurring operational costs. Before this purchasing decision can be made, product developers must define a product that meets or improves an unmet need. During this process, product designers design and then search for suppliers capable of manufacturing target unit volumes that are within costs targets. If each eco-system participant performs their roles (market analysis, pricing, functionality, performance, costs, etc), a product could soar in popularity. If they collectively miss on any aspect, a product would have a short lifespan. Successes are easy to identify, i.e. Apple's iPhones. Failures are difficult to list, since they normally do not last long in the market. In 1993, Apple released their first personal digital assistant (PDA), the Newton. The first month's sales vaulted the Newton as one of the top selling products within Apple. But this quickly faded as consumers found issues in the functionality promised, versus what was delivered. In time, Newton's handwriting recognition was mocked in a Doonesbury comic as well as on *The Simpsons* TV show. Years later, Apple applied the lessons learned from Newton and released a line of "i" products, all wildly successful with avid and repeat customers for each new "i" product generation.

How to Begin

Path finding methods, not necessarily tools, have existed for a long time. Time consuming and costly experimentation allowed engineers to analyze large amounts of data to determine optimum solutions (manufacturing, design, etc). Product designers have used path finding methods for decades. Spice, bread boarding and silicon bread boarding were methods to prove, disprove or improve an idea. Manufacturing companies ran design of experiments (DoE) where a matrix of material was manufactured and tested to determine whether correlations existed between process variables, throughput and yields. It helped manufacturers find the "sweet" spot where they could minimize waste (expenses) and maximize their return on investment (ROI). All of these path finding methods were costly in time, resources and dollars. Over time, with increased computing power and as models became more accurate, path finding tools were developed; reducing the cost, resources and time required in finding solutions. Experimentation became virtualized. As high technology enters the 2.5/3D packaging world, additional path finding tools are needed for mechanical, thermal and electrical (MTE) analysis that navigate tight costs constraints required by mass-produced products.

The Basics: Economics and Yields

To see how economics are defined by yields, a simple example is discussed. At each process step, yield is the critical factor in the end product's cost.

$$\textbf{Yield} = \frac{\textbf{Devices out of Process}}{\textbf{Initial Devices into Process}}$$

Scrapped units can be attributed to mechanical, thermal or electrical failures.

Anyone that has ever worked in a manufacturing environment understands the impact of yield on manufacturing costs. The manufactured cost is a function of the labor exerted and the raw materials used to create a manufactured unit. This can be calculated at each process step:

$$\textbf{Yielded} = \frac{\textbf{Unit's Incoming Cost + New Material + Labor Cost}}{\textbf{Yield at Process Step}}$$

Let's say an incoming product cost is $1.00 and a new operation adds $0.25 per unit. A yielded cost chart can quickly show how costs are dramatically affected by yield:

Figure 1

Yield	100%	90%	80%	50%	10%
Yield Cost ($)	1.25	1.39	1.56	2.50	12.50

Ideally each process step would result in 100 percent yield and the cumulative yield of the entire line would be 100 percent. In reality, this is rarely achieved. In silicon manufacturing, a "cook book" for each process is created showing the exact recipe to duplicate each process step. Process steps, materials and labor include:

- Implanting
- Annealing
- Depositing and Etching
- Wafer Probing
- Raw Materials of: Silicon wafers and various chemicals, gases, masks/images, etc
- All the 'handling' (machine or human) required for these steps

Yields: Caveat Emptor

High yields are not always the best metric. A high yielding process step early in the manufacturing process can lead to dramatic yield loss at the end of the manufacturing line. The key arbitrator is the end customer. End customers determine whether a product is good or not. The end customer cares about functionality, performance, battery life, etc. when the finished product is used.

The fact that an intact wafer makes it through this manufacturing gauntlet does not ensure it will perform as expected.   Any loss at this point can be attributed to handling/mechanical issues. Electrical tests must be performed to ensure functionality and performance goals are met across a specified temperature range. The good news is that foundries and OSATs are very good at these repetitive operations and yields are high. Otherwise, the economics would probably prevent many consumer products from being developed. In the process defined above, we have not created a through silicon structure to enable 2.5D/3D package structures. Additional processing steps such as grinding the backside of the wafer, capping, depositing/etching redistribution layer (RDL), adding passivation (glass) to protect the die and then adding bumping, wafer dicing along with bonding, more testing, etc are all required. Are these difficult steps? Maybe at first, but in time these steps are also mastered to optimize yield.

Manufacturers (silicon, interposers, packages, etc) are faced with all three failure mechanisms. The products they produce must be mechanically sound to survive all the handling and process steps required to manufacture their product. Too rigid or too flexible can cause yield issues during processing, so the wafer or package's thickness must be analyzed, in addition to via density and radius. Too dense and the resulting product becomes too fragile, too loose and the product size might become too large, costly and fragile. Once mechanical path finding has been finalized, a range of viable options will exist: each with various tradeoffs in MTE performances versus yield. These mechanical ranges start to hone the path finding required for thermal and electrical path finding. Why path find on variables that are not in the safe mechanical solution set? Remember: if we cannot manufacture the device, yield is zero percent. So thermal and electrical path finding will have restrictions based upon mechanical path finding. Rather than an infinite number of parameters and values, fewer variations can be considered.   Manufacturers should also perform thermal and electrical path finding on their material to find solutions that increase the thermal and electrical capabilities. As manufacturers improve their yields, they will continually modify the design rules provided to their customers. Without continual rule updates, products will produce inconsistent yields driving up costs to all.

Product developers and integrators must evaluate components that they will integrate from manufacturers. Some of their path finding is restricted to available process nodes, packages/lead frames, design rules, etc that will be used to manufacture their products. Mechanical is a lesser concern for product developers since many turn over manufacturing to their suppliers who must focus on maximizing yields. What the manufacturers do not understand is a design's specific functionality and performance. To manufacturers, this is a "black box". Product developers need to focus on the size, functionality and performance of their product. Depending on the architecture, operating frequency and process chosen, both electrical and thermal performance will be impacted by various decisions. As shown in the GSA Forum's March issue, electrical performance can be improved by shorter, larger vias that are spaced farther apart for printed circuit boards (PCB), as well as for silicon or glass interposers.

Winning the Battle but Losing the War?

Virtual prototyping (path finding focused on algorithms and architectures) can have a dramatic impact on performance and power. But without performing path finding on possible interconnects used to implement the architecture, a developer can overlook details preventing optimum performance. **Why spend all the time honing the architecture and then use sub optimal interconnects?** Figure 2A shows a simple comparison between wire bonding, through glass (TGV) and through silicon vias (TSV) up to 10GHz. A signal's insertion loss (IL) is critical to performance and functionality. By running a quick path finding experiment, users can demonstrate the significant difference between the various methods. TGV and TSV show very stable operation over frequency, while the third (wire bond) has wider variation based upon wire's length and operating frequency. Figure 2B is zoomed in showing less than 6GHz performance. Depending on the design's performance goal, any of these interconnects might be sufficient, but designing with wire bonds requires more rigorous analysis. Many might consider redistribution layer as a solution but depending on the RDL's layout and operating frequency, it might pose performance issues. As an example, an RDL line that is 2mm (78.74 mils) long and 5u wide approaches -4dB insertion loss at 10 GHz. Performance is a little better than a 100 mil long bond wire and much worse that either TSV or TGV solution.

Figure 2A

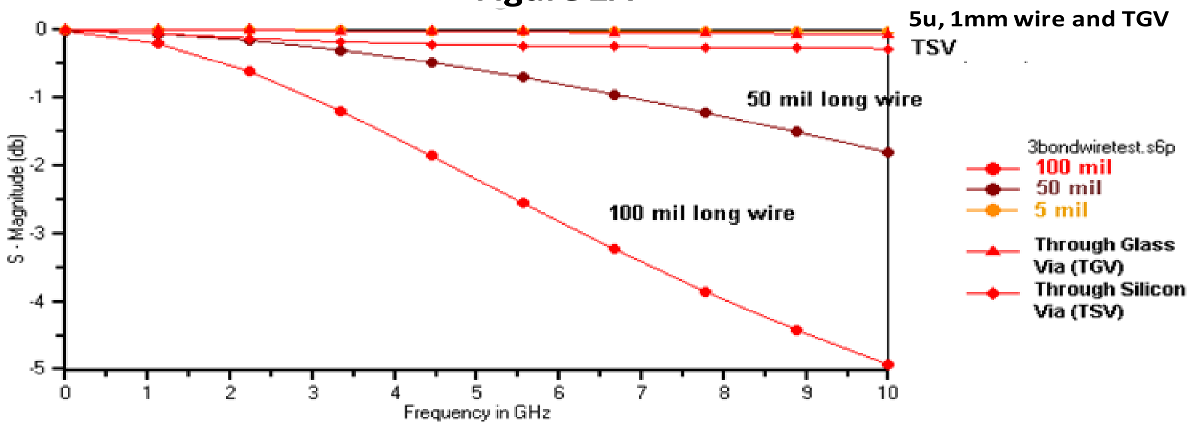
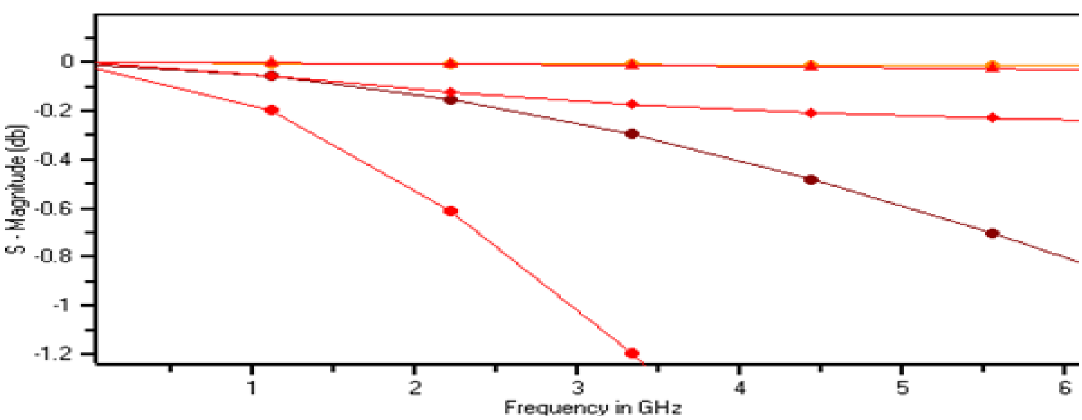


Figure 2B



Thermal is last to analyze since it can be improved internally and externally to a product. Once all internal thermal solutions have been analyzed, external thermal solutions are explored. External solutions can involve embedded heat slugs on packages, attached slugs and/or fins on packages and may even add fans to force air across the package. With 2.5/3D packaging, vias can be used not only as methods to efficiently route signals and power distribution networks (PDN), but also to improve heat dissipation throughout the structure. Path finding can help identify potential solutions and cost tradeoffs.

Who Owns Path Finding and When to Apply It?

Where and how path finding can be used spans the GSA's ecosystem: From foundries (silicon and interposers), OSATs (interposers and packages) to system integrators and product developers. Which path finding tools are used by each participant will depend on how much integration they perform in the overall process. Since the goal for each participant is to be profitable, each will want to maximize their yields. As shown earlier, yield loss can be attributed to mechanical, thermal and electrical causes. Path finding can help optimize solutions in MET and minimize yield loss.

Whether designing a product or a process, developers should understand how path finding tools can aid their decision making in a complex world and thus implement path finding tools into their development flows as early as possible. The worst and most costly situation is finding an issue when ramping up volume manufacturing.